Title: Search for Lensed Gravitational Waves from LIGO/Virgo Binary Black Hole Mergers: Intriguing Candidates in O2

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Series: Cosmology & Gravitation

Date: September 29, 2020 - 4:00 PM

URL: http://pirsa.org/20090020

Abstract: Current and forthcoming observing runs at ground-based laser interferometry detectors are starting to uncover gravitational waves from binary black hole (BBH) mergers at cosmological distances, and a fraction of them are expected to be gravitationally lensed by intervening galaxy or cluster lenses with multiple images. Such strongly lensed events, if discovered, may offer a precious opportunity to localize BBH host galaxies and probe global and small-scale property of the lens mass profile. We investigate multiple BBH events showing parameter coincidence in the LIGO/Virgo O2 run, and search for additional sub-threshold signals that may be fainter lensed images. For the first time, we factor in the effect of the Morse phase shift in the analysis, and demonstrate how to measure the relative Morse phase via joint parameter inference. We confirm curiously high level of intrinsic and extrinsic parameter coincidence between GW170814 and GW170104, and uncover a third sub-threshold candidate lensed image, GWC170620, in a single-template search, which amounts to an estimated 10^-4 overall chance of statistical fluke. The measured relative Morse phases among the three events, although consistent with ray-optics lensing, point toward a complicated and unexpected image topology with a magnified image at a local maximum of the Fermat potential, which however casts doubt on the lensing hypothesis. The long time delays on the order of months necessarily require a massive lens of galaxy cluster scale. If a genuine set of multiple lensed images, we localize the source to ~ 16 deg^2 on the sky and suggest a range 0.4 < z < 0.7 for its redshift. Optical follow-up observations are encouraged to collect any additional information that may further shed light on the case.

Search for Lensed Gravitational Waves from LIGO/Virgo Binary Black Hole Mergers

Liang Dai
UC Berkeley

Recent work with Barak Zackay (Weizmann), Tejaswi Venumadhav (UCSB), Javier Roulet (Princeton) and Matias Zaldarriaga (IAS)

Seminar at Perimeter Institute, Sep 2020

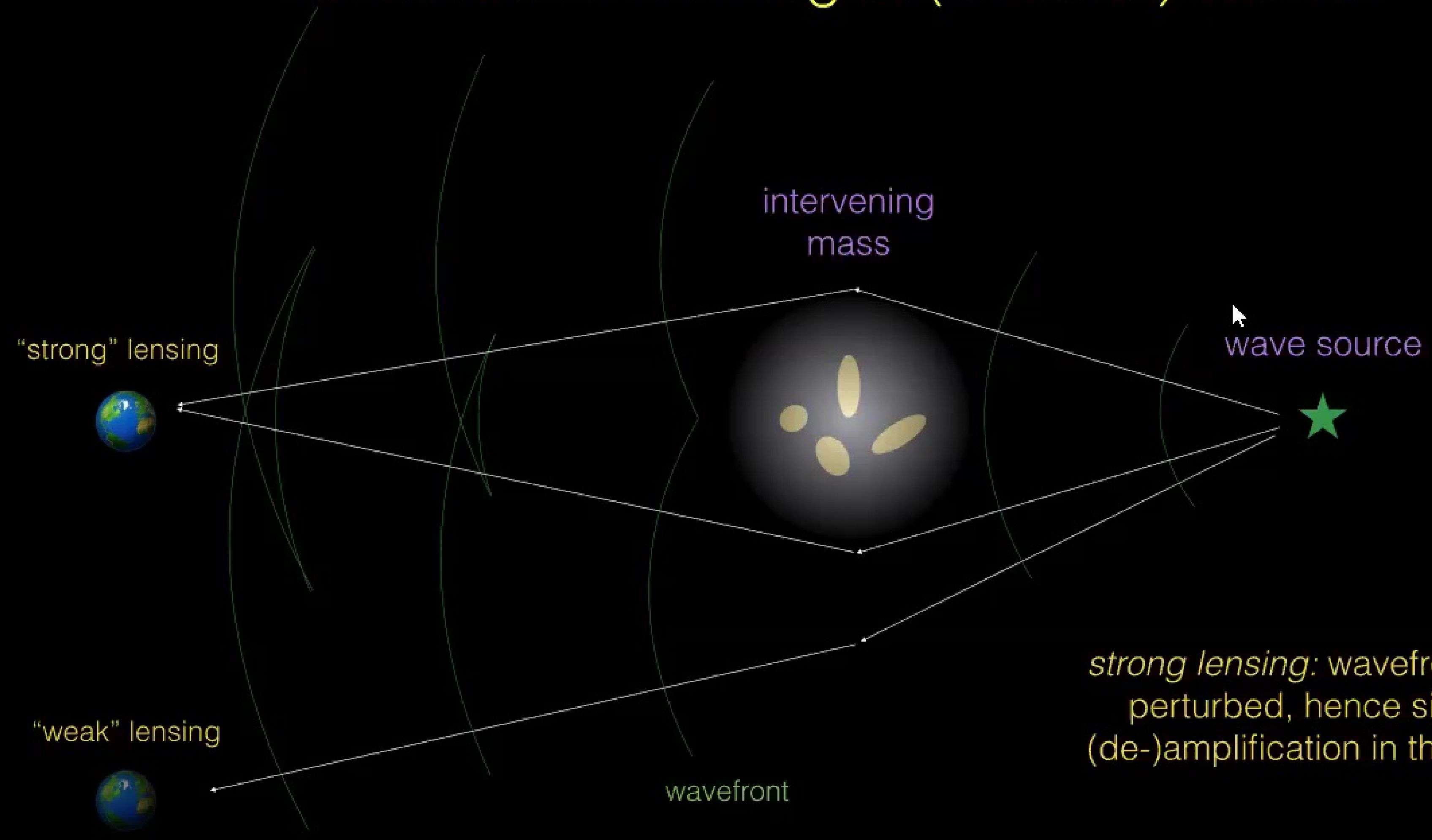
Outline

- Lensing of gravitational wave signals: (short introduction)

- Previous search efforts

- Our new analysis of O2 BBHs and intriguing lensed candidates Dai++ 2007.12709

Gravitational Lensing of (General) Waves



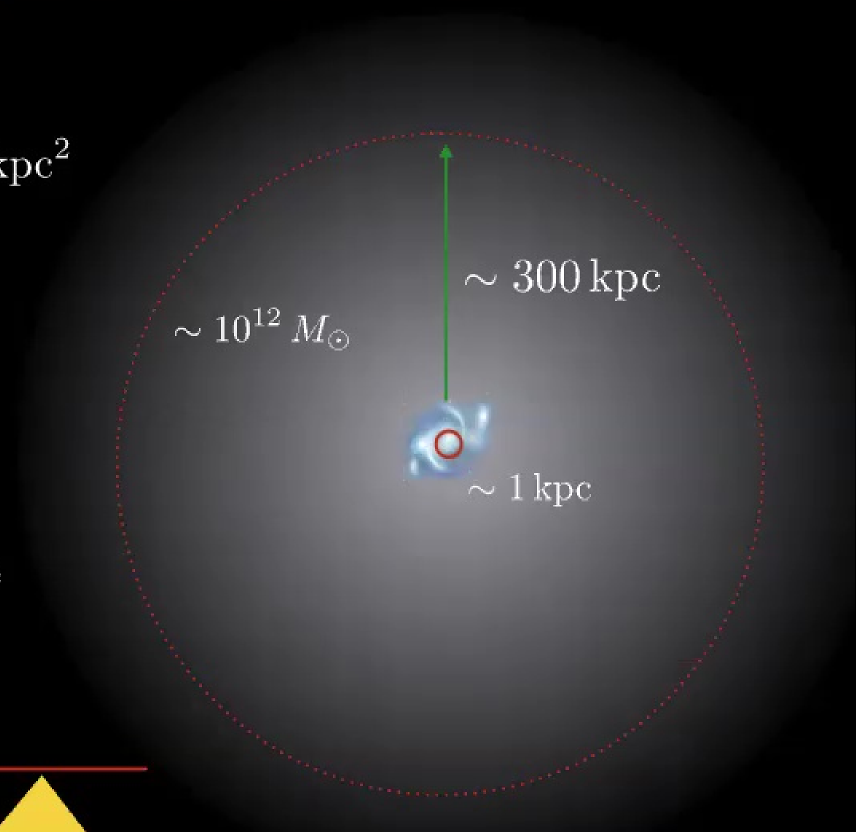
strong lensing: wavefront strongly perturbed, hence significant (de-)amplification in the wave flux

Strong Lensing of Extragalactic Sources

critical surface density $\Sigma_c \sim \frac{1}{4\,\pi\,G}\,\frac{1}{r_H} \sim 10^8\,M_\odot/\mathrm{kpc}^2$

strong lensing if super-critical $\Sigma \gtrsim \Sigma_c$

optical depth from these cosmic islands of density peaks $\tau_{\mathrm{SL}} \gtrsim \frac{10^8\,M_\odot}{10^{12}\,M_\odot} \sim 10^{-4}$



a typical galaxy in the present universe

Most Common LIGO/Virgo Sources: (heavy) BBHs

O1/O2 runs

GWTC-1 Abbott++ 2019

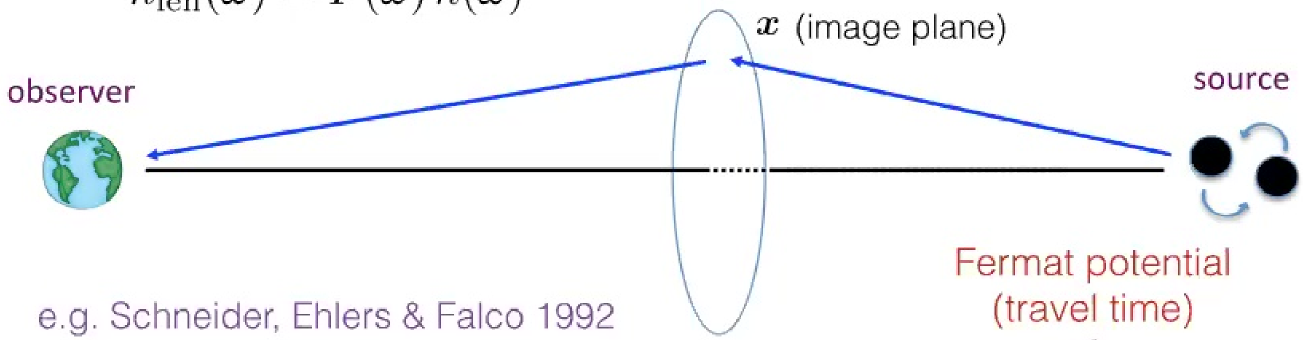
More BBH candidates from independent analyses:
Zackay++ (2019), Venumadhav++ (2020), Nitz++ (2020)

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/(\rm erg\,s^{-1})$	d_L/Mpc	z	$\Delta\Omega/\rm deg^2$
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0} \times 10^{56}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	39
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1} \times 10^{56}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666

Starting to probe **cosmological distances**; O3 was sensitive to even more distant BBH sources.
Just like distant galaxies, quasars, and SNe, strong lensing of BBHs expected!

Amplification Factor

$$h_{\rm len}(\omega) = F(\omega)\, h(\omega)$$



e.g. Schneider, Ehlers & Falco 1992

Fermat potential
(travel time)

Diffraction integral $$F(\omega) = \frac{\omega}{2\pi\, i} \int \mathrm{d}^2\boldsymbol{x}\, e^{i\,\omega\,\tau(\boldsymbol{x})}$$

Diffraction regime: delay time ~ $\dfrac{G\,M_L}{c^3} \lesssim \dfrac{2\pi}{\omega}$

Geometric (or ray-optics) regime: delay time ~ $\dfrac{G\,M_L}{c^3} \gg \dfrac{2\pi}{\omega}$

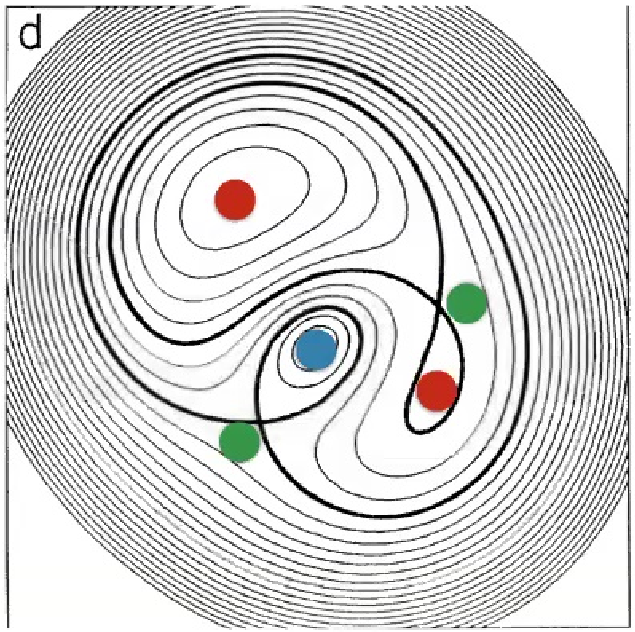
flux magnification

$$F(\omega) \approx \sum_I |\mu(\boldsymbol{x}_I)|^{1/2}\, e^{i\,\omega\,\tau(\boldsymbol{x}_I)}\, e^{i\,\mathrm{sgn}(\omega)\, n_I\, \pi/2}$$

time delay

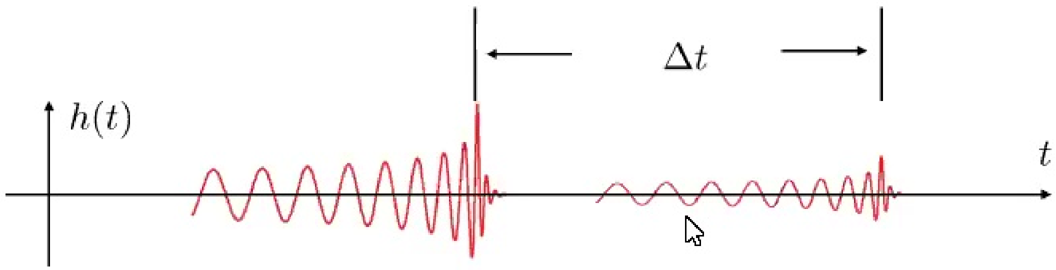
Morse phase

minima
saddle points
maxima

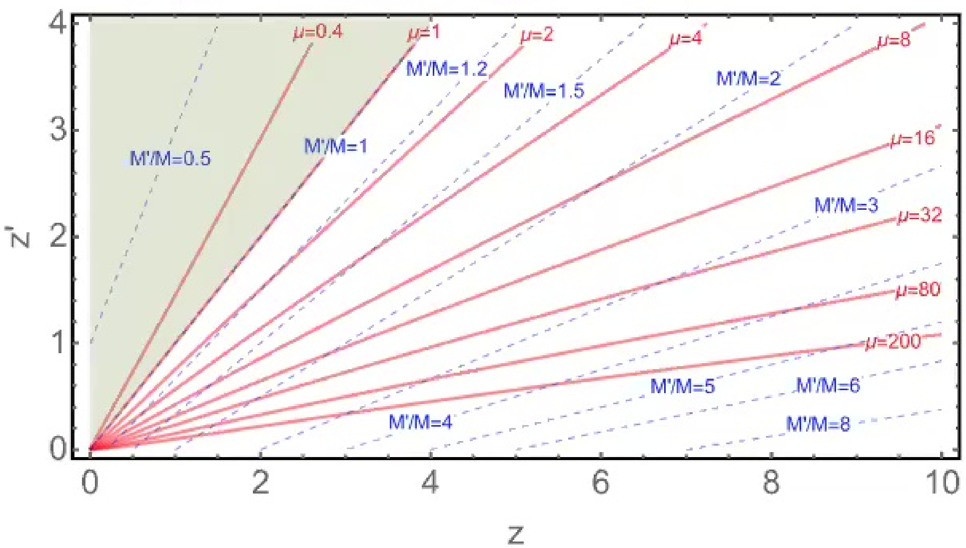


Blandford & Narayan 1986

Lensed BBH Signals in Geometric Lensing



Dai, Venumadhav & Sigurdson 2017



Multiple lensed images:

Rescaled overall amplitudes
Mutual time delays
Identical frequency chirping

A lensed BBH signal resembles an unlensed waveform but with biased **inferred mass/ redshift bias**

$$M\,(1+z) = M'\,(1+z')$$

$$\frac{\sqrt{\mu}}{d_L\,(z)} = \frac{1}{d_L\,(z')}$$

Magnified signals:
BHs appear heavier and closer

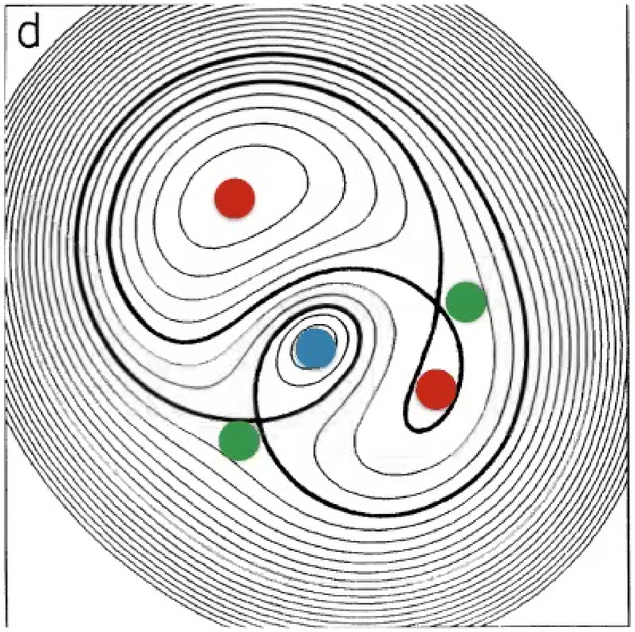
De-magnified signals:
BHs appear lighter and further   Oguri 2018

A Topological Phase Shift

Morse phase

$$F(\omega) \approx \sum_I |\mu(\boldsymbol{x}_I)|^{1/2}\, e^{i\,\omega\,\tau(\boldsymbol{x}_I)} \boxed{e^{i\,\mathrm{sgn}(\omega)\, n_I\, \pi/2}}$$

$$n_I = \#\text{ of negative eigenvals} = \begin{cases} 0 & \textbf{minima} \\ 1 & \textbf{saddle points} \\ 2 & \textbf{maxima} \end{cases}$$



Observational consequence for BBH signal:

(assume **circular orbit** and domination of **(2,2)** harmonics)
Equivalent to discrete change in the **orbital phase**

Dai & Venumadhav 1702.04724; lately see Ezquiaga++ 2008.12814

$$\Delta\varphi = \frac{\pi}{4} \times \begin{cases} 0 & \textbf{minima} \\ 1 & \textbf{saddle points} \\ 2 & \textbf{maxima} \end{cases}$$

Rate of Strongly Lensed BBHs

e.g. Dai, Venumadhav & Sigurdson (2017); Ng, Wong, Broadhurst & Li (2018); Li, Mao, Zhao & Lu (2018); Oguri (2018); Hannuksela++ (2019); Contigiani (2020);

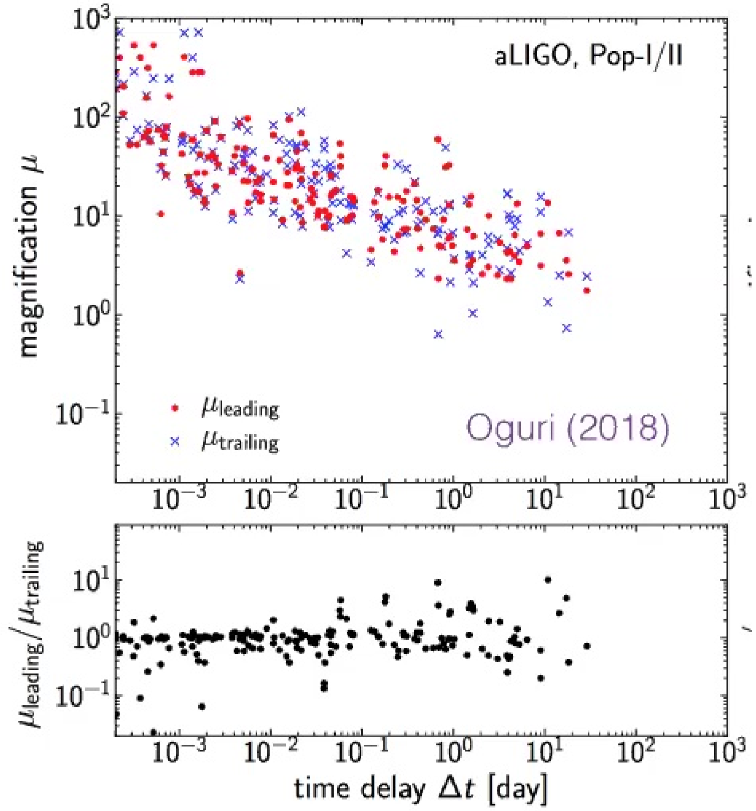
Semi-analytic calculations:

Individual galaxy lenses as **singular isothermal ellipsoids;** Galaxy groups or galaxy clusters neglected.

BBH mergers from field binary evolution (uncertainty in the delay time distribution and redshift evolution)

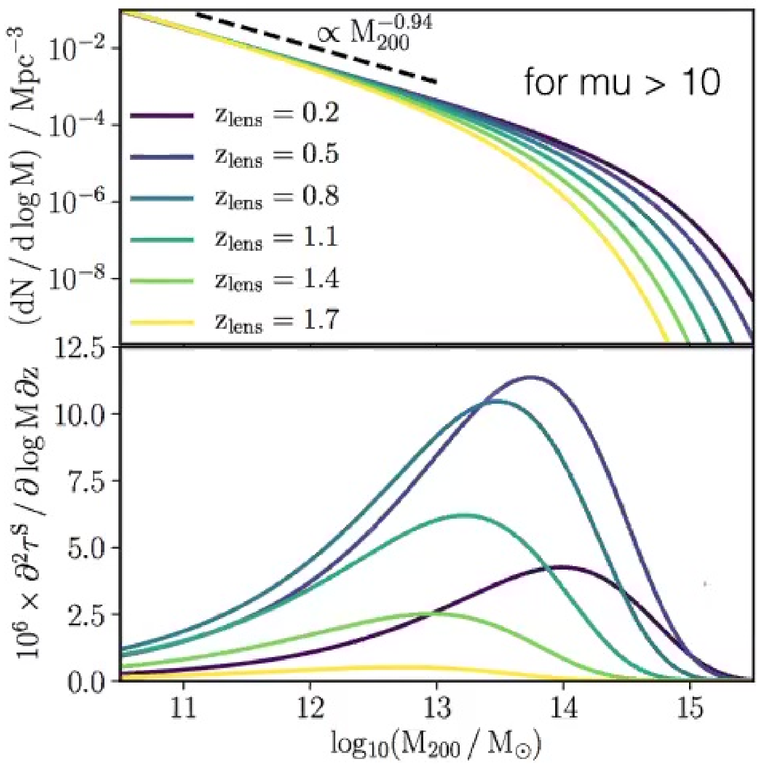
Volume limited at Advanced LIGO/Virgo, and hence boost from **magnification bias**;

~ 0.01 yr^{-1} lensed multiple image sets at O1/O2;
~ 0.1 —1 yr^{-1} at fully upgraded Advanced LIGO/ Virgo

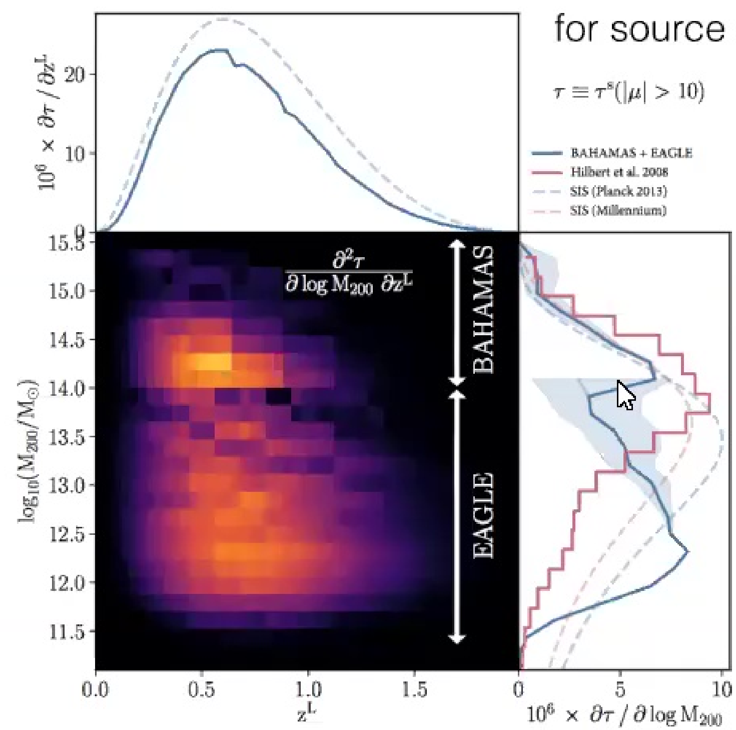


Group and Cluster Lenses

Lenses extracted from cosmological hydrodynamic simulations   Robertson++ (2020)



Followed some toy prescription converting halo mass to isothermal lens profile.



Group and cluster lenses not negligible.

What we can learn from lensed BBHs?

- Probe BBH sources beyond the usual detection horizon (in particular in the era of 2G detectors)

  Mukherjee++ 2006.03064; Buscicchio++ 2006.04516

- Opportunity to associate a BBH source with a host galaxy, or even localize it within the host galaxy

  Hannuksela, Collett, Caliskan & Li 2004.13811;
  Yu, Zhang & Wang 2007.00828

- Probe profile of galaxy or cluster lenses complementary to lensed EM sources: central images; faint images;

- Probe (non-luminous) substructure content within the lens and learn about the small-scale property of the Dark Matter: wave diffraction effects

  Dai, Li, Zackay, Mao & Lu (2018)
  Oguri & Takahashi 2007.01936

Previous Search for Lensing in O1/O2

Hannuksela++ (2019)

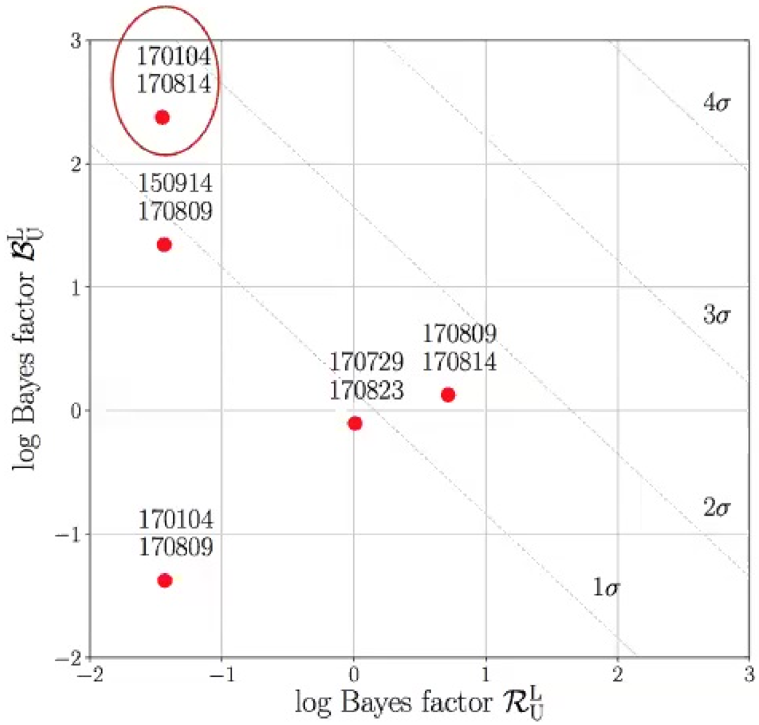
Looked for lensed pair of events in O1/O2

Quantified parameter (masses, spins, sky position) coincidence through the **Bayes evidence ratio** Haris++ (2018)

$$\mathcal{B}_U^L = \frac{\int \mathrm{d}\theta\, L(d_1|\theta)\, L(d_2|\theta)\, \pi(\theta)}{\left(\int \mathrm{d}\theta\, L(d_1|\theta)\, \pi(\theta)\right)\, \left(\int \mathrm{d}\theta'\, L(d_2|\theta')\, \pi(\theta')\right)}$$

Selected short time delays

$$\mathcal{R}_{\mathrm{U}}^{\mathrm{L}} = \frac{P(\Delta t_0|\mathcal{H}_{\mathrm{L}})}{P(\Delta t_0|\mathcal{H}_{\mathrm{U}})}$$

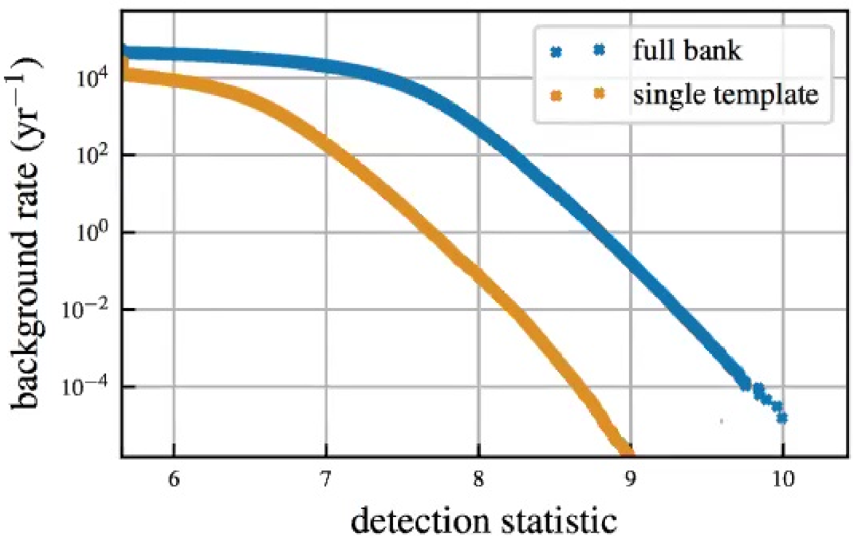


Background distribution derived from injection of unlensed events;
No significant pairs found.

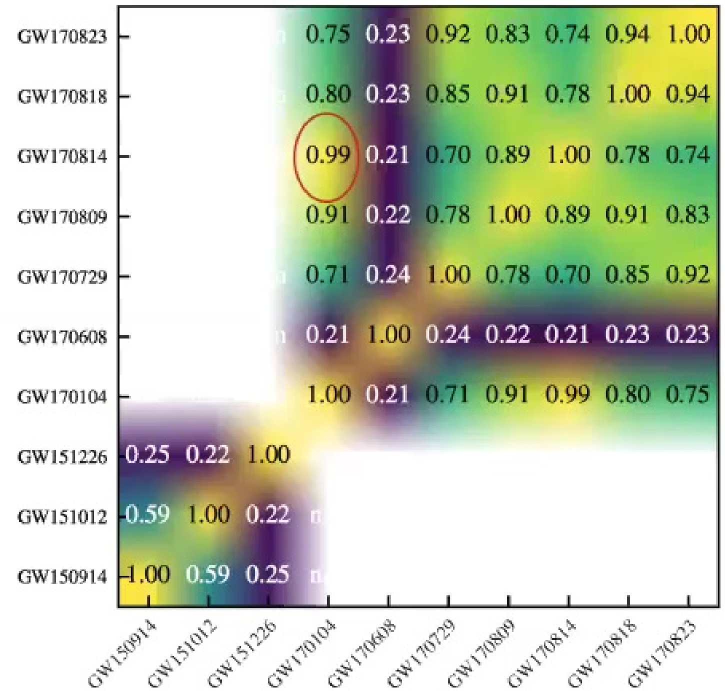
Previous Search for Lensing in O1/O2

McIsaac++ 1912.05389

“Single-template” search for (~13%) weaker duplicate signals



Top candidates in Venumadhav++ (2020) catalog; Lensing disfavored due to long time delays



waveform match between LVC BBH events

Our Investigation of Lensed BBH Candidates

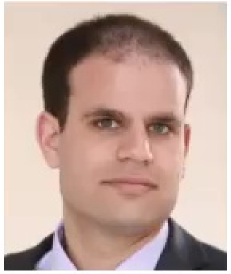
Dai++ 2007.12709

Pitfalls with the Bayes evidence ratio:

- Unknown mass and spin prior distributions
- Anisotropic (sidereal-hour averaged) detector antenna pattern
- Accuracy of evidence evaluation in high dimensional parameter space

Our strategy:

Separately quantify coincidence in **intrinsic** and **extrinsic** parameters



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Javier Roulet (Princeton)

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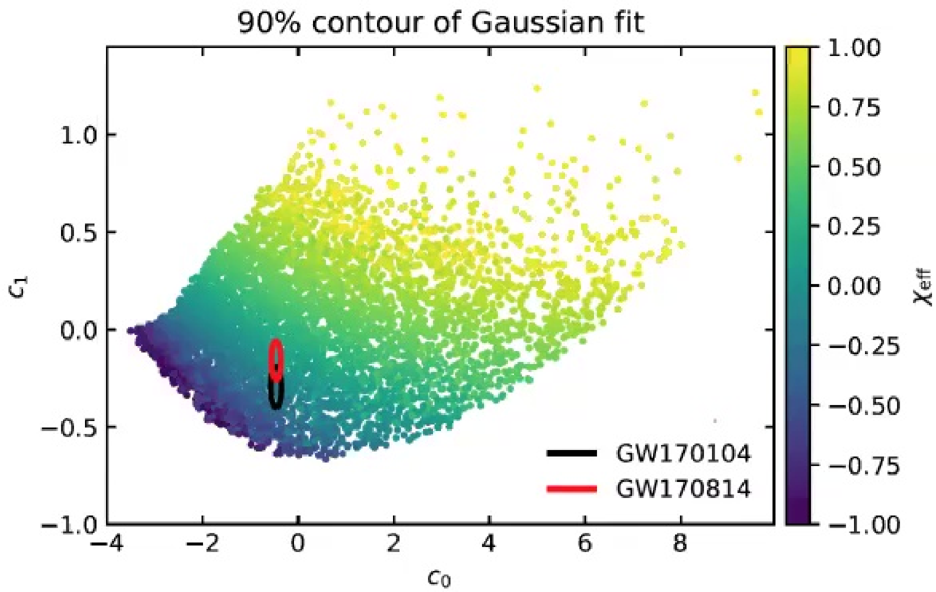
Coincidence of Intrinsic Parameters

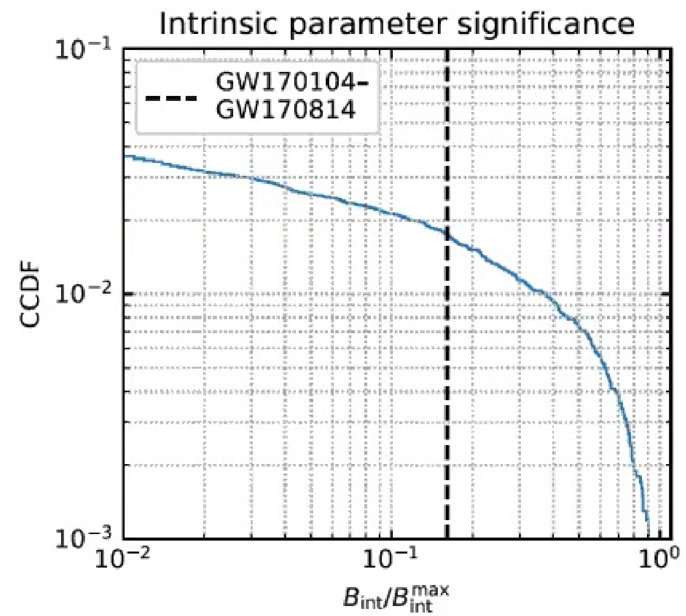
Most significant pair: **GW170814** and **GW170104**

"Geometric" coordinates in the space of GW phasing

Roulet++ (2019)



$$B_{\rm int} = \frac{A_{\rm eff} \int \mathrm{d}^2 c\, G_1(c)\, G_2(c)}{\left(\int \mathrm{d}^2 c\, G_1(c)\right)\, \left(\int \mathrm{d}^2 c\, G_2(c)\right)}$$



Prior for injections: Mc uniform in [20, 40], q uniform in [0.7, 1], isotropic spins

Coincidence of Extrinsic Parameters

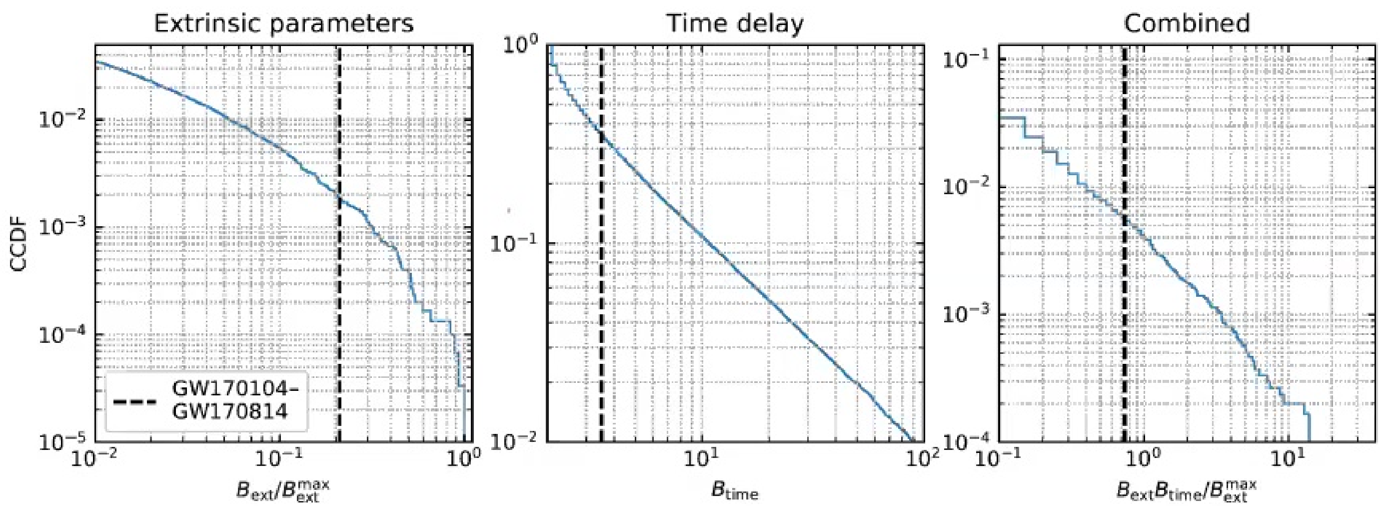
Fix intrinsic parameters to be the best-fit of **GW170814**
Coincident parameters: RA, DEC, inclination, polarization angle, orbital phase (accounting for discrete Morse phase shifts)

$$B_{\rm ext} = \frac{\sum_{\rm post} \sum_{\rm ph} \sum_{\rm time} L|_{\rm max\ x_0}}{N_{\rm post} N_{\rm ph} \int {\rm d}\theta_{\rm ext} L}$$

Time delay: log-flat delay distribution versus random time of arrival

$$B_{\rm time} = \frac{T^2}{2\,\delta t\,(T - \delta t)},$$

Injections: effect of antenna pattern



Single-template search

If lensing if true, there are possibly additional lensed images.

Use the **best-fit waveform** informed from GW170814 and GW170104 for a single-template search. Use extrinsic parameters informed from GW170814 and GW170104 (especially RA, DEC); this is implemented as a coherent score:

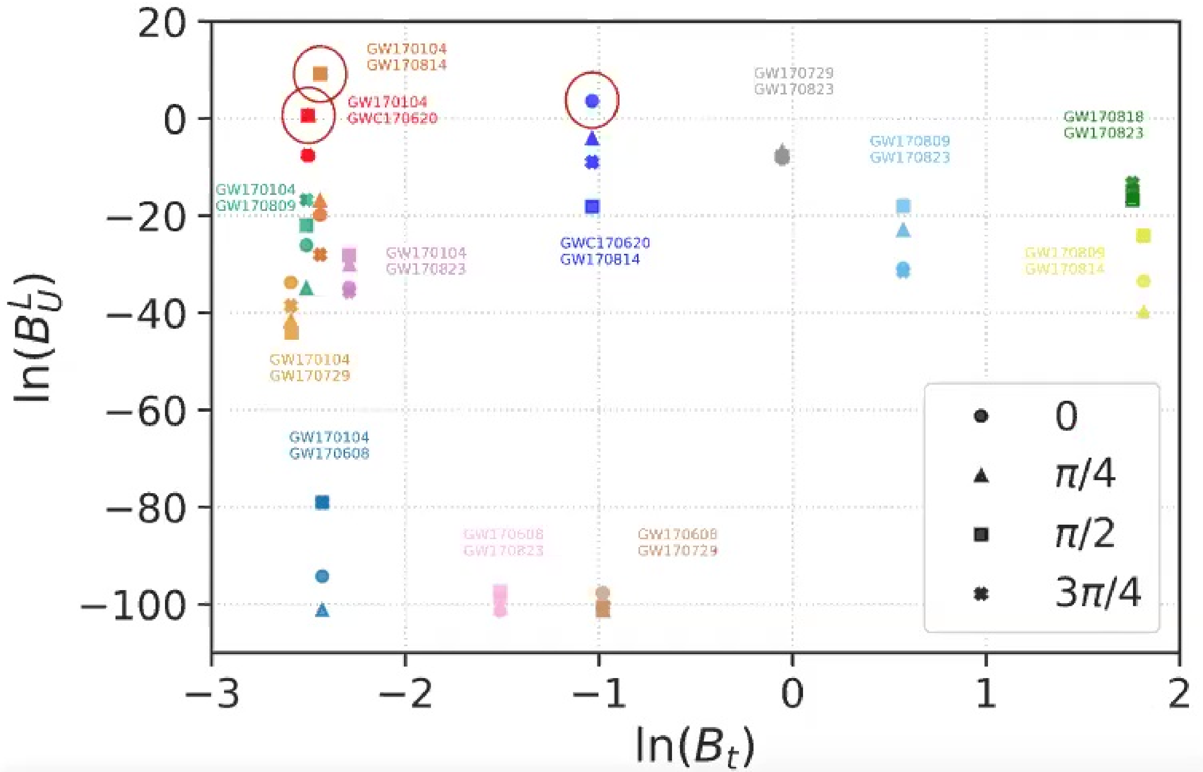
$$S \propto \sum_{s \in \Pi_{\mathrm{pair}}} \sum_{\phi_M, t_0} \int \mathrm{d}D_L \, \mathcal{L}(s, \phi_M, t_0, D_L) \; P(D_L).$$

Overall **~ 10⁴** reduction in look-elsewhere effect and **~ 20%** more sensitive in strain amplitude.

Somewhat surprisingly, we found one sub-threshold signal, GWC170620, with a false alarm probability 1.3% determined empirically from time slides

GW170814, GW170104 and GWC170620

Liu, Hernandez & Creighton 2009.06539



Confirmed significant coincidence in intrinsic + extrinsic parameters + Morse phases

Relative Morse phases

Morse phase manifests itself as a change in the orbital phase $\Delta\varphi = \frac{1}{2}\,\Delta\phi_M$

$$h = F_+(\alpha,\,\delta,\,\psi)\,h_+ + F_\times(\alpha,\,\delta,\,\psi)\,h_\times$$

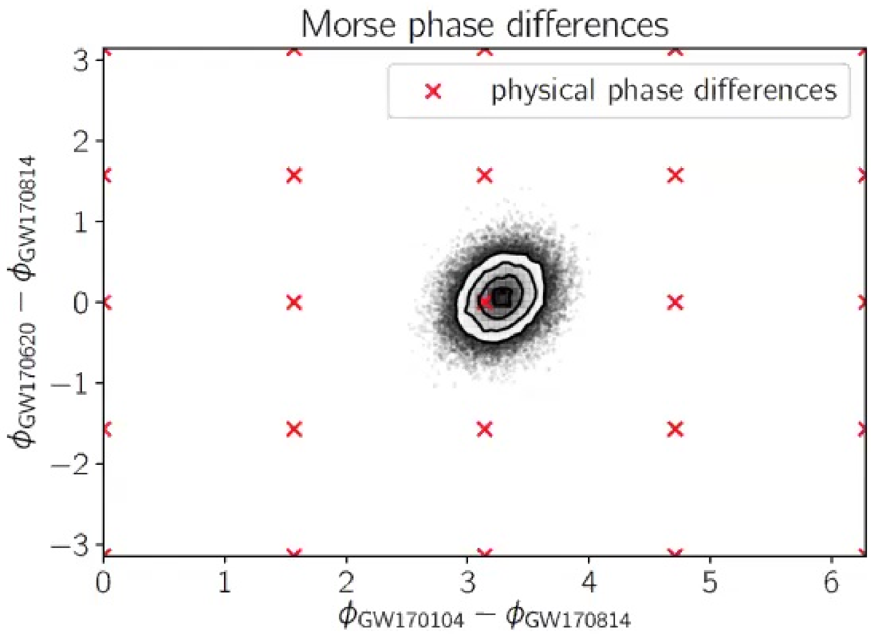
$$h_+ \propto \frac{1}{2}\,(1+\cos^2\iota)\,e^{2\,i\,\varphi}$$

$$h_\times \propto -i\,\cos\iota\,e^{2\,i\,\varphi}$$

Orbital phase for any individual event poorly constrained due to **degeneracy with other extrinsic parameters**.

Under lensing hypothesis, multiple events share the same extrinsic parameters, hence relative Morse phases can manifest as **apparent orbital phases differing by discrete amounts**.

Perform joint parameter estimation !



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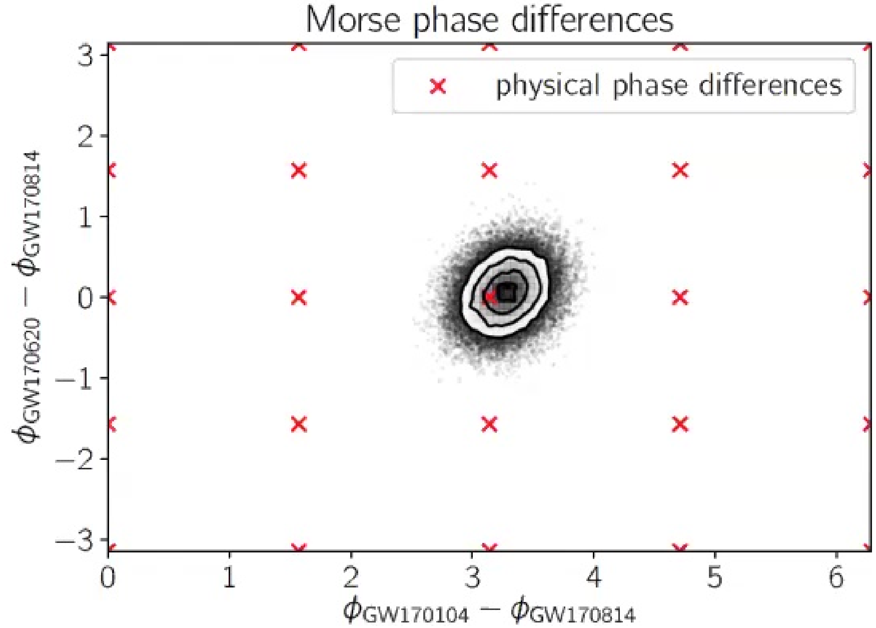


Magnification Ratios

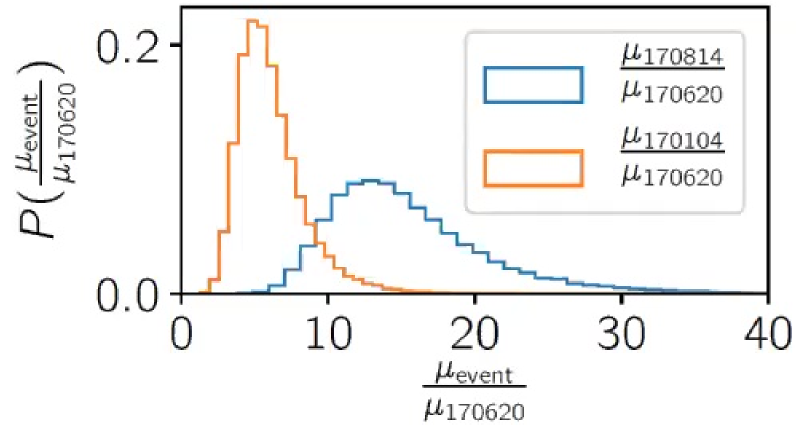
GW170814, GW170104 and GWC170620 have network SNRs ~18, ~14, 7.8

strain amplification ratios ~ 1 : 0.4 : 0.25

flux magnification ratios ~ 1 : 1/6 : 1/15

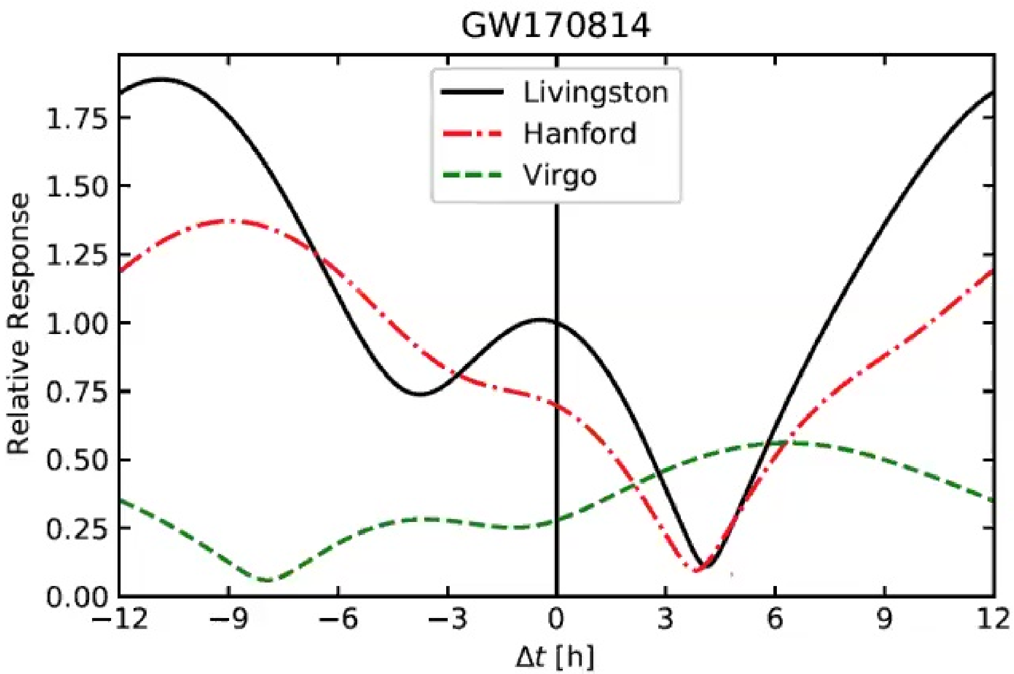
Very large magnification ratios still detectable!

Absolute magnifications undetermined!



Item	Value
Catalog FAP (GW170104, GW170814)	1.1×10^{-2}
Existence of GWC170620 (GPS time: 1181956460)	1.3×10^{-2}
Time delays (relative to GW170104)	0, 166.63 days, 222.01 days
Morse phase differences (relative to GW170104)	$0, \pi, \pi$
Magnification ratios (relative to GW170814)	$0.401 \pm 0.08,\ 0.0719 \pm 0.0024,\ 1$
Apparent luminosity distance of GW170814	$D_L^{\mathrm{GW170814}}/\sqrt{\mu_{\mathrm{GW170814}}} = 577^{+159}_{-216}$ Mpc
Expected number of lensed events in O2	10^{-2}–10^{-3}

Detector responses play tricks



Strain amplitude response

About 4—5 hrs after GW170814, LIGO detectors became almost blind toward that direction on the sky, and Virgo was more sensitive !

Broadhurst, Diego & Smoot 1901.03190

Lesson learned:
an image equally loud as GW170814 could have hidden in the Gaussian noise.

Constraints on Image Configuration

Three types of images:
minimum (L), saddle point (S), maximum (H)

GW170104, GWC170620, GW170814 must be either **L, H, H** or **H, L, L**

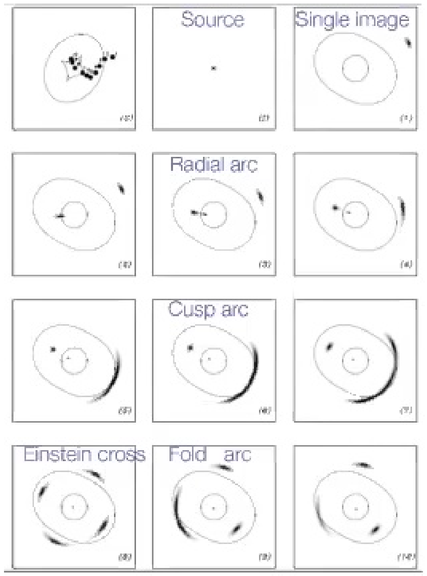
S images must have been missed from n(L) + n(H) - n(S) = 1. This however is not too strange given the fraction of Hanford-Livingston coincident times

L images have (absolute) magnification factors > 1, so **at least one H image is significantly magnified** (?!) (GW170814 for **L, H, H**, or GW170104 for **H, L, L**). This is peculiar!

$$z_S^{\mathrm{HLL}} > 0.26$$

$$z_S^{\mathrm{LHH}} > 0.13$$

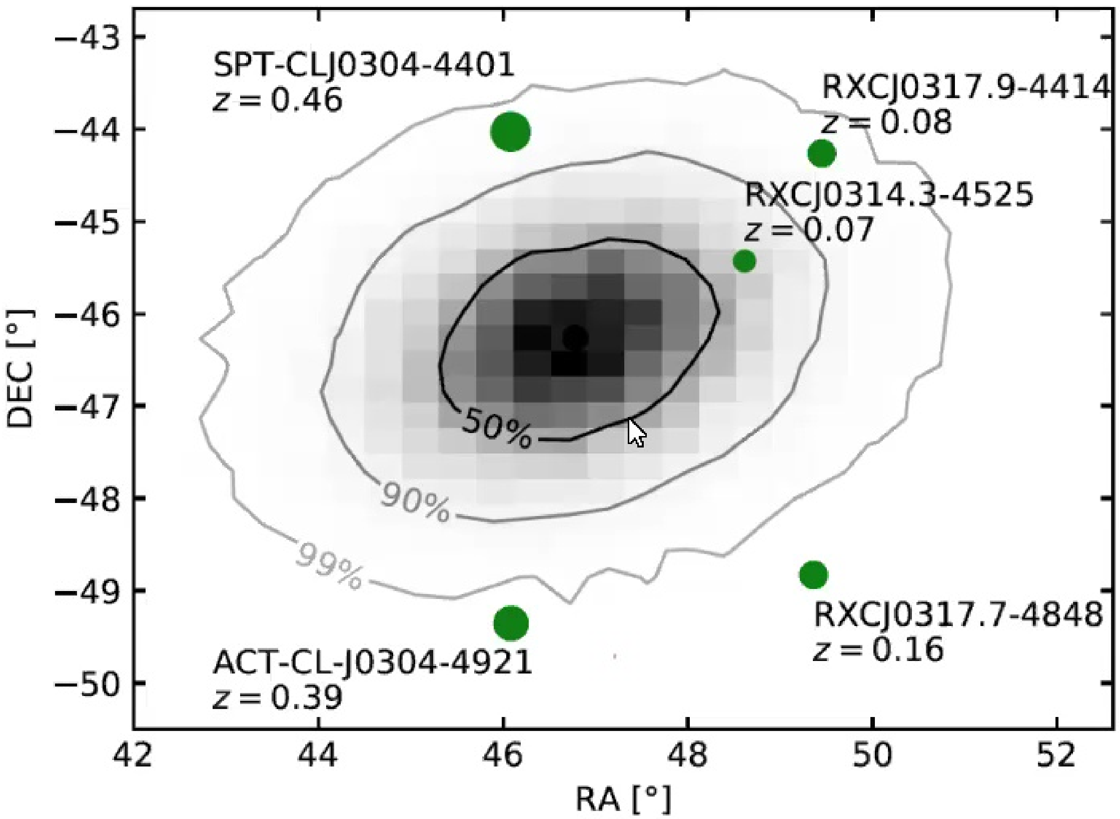
Likely **zs < 0.7** because no counter image within 1 hr of GW170814.



Kneib (1993)

Einstein quad: central de-magnified H image
Radial arc: counter S image with short delay

Localization From Joint PE



localized to ~ 16 deg^2

Time delays ~ months require a DM halo of galaxy group or galaxy cluster scale

Galaxy group or cluster lenses can have more complicated structure.

Perhaps the peculiar image configuration not completely out of the question.

(non-)Conclusion about the triplet

- Anomalous: extrinsic parameter coincidence ~ **10^{-2}** between GW170814 and GW170104, and the unlikely third signal, GWC170620, just below the detection threshold ~ **10^{-2}**. This is conservatively NOT including intrinsic parameter coincidence.

- As a theorist, the combination of relative Morse phases, small apparent source distance (~ 600 Mpc for GW170814), and long time delays make us doubt. Level of tuning in the lens countervails the low false alarm probability.

- Since source is unlikely to be too far (zs < 0.7), if the BBH host is a major galaxy, the optical lens might be easier to find than average. Image configuration, time delays and magnification ratios need to work out.

- If not lensing, we have no better explanation :(

Lesson learned

- **Relative Morse phases are measurable!** The combination of time delays, magnification ratios, and Morse phases proves very powerful at constraining any viable lens.

- Due to detector antenna patterns, even very loud lensed images can hide in noise. Conversely, very faint lensed images can get lucky to be detectable.

- **If the triplet is a statistical fluke, we are already limited by false alarms.** Getting more events at current measurement quality won't help. Need better measurement!
  - (1) better sky localization from at least 3 detectors
  - (2) smaller error bars on intrinsic parameters and extrinsic parameters from better sensitivity at low frequencies
  - (3) detection of distant lower-mass BBH events (much better chirp mass measurement)