LIGO Scientific Collaboration

VIRGO

UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run

2nd European Physics Society Conference on Gravitation

05/07/2021 - preprint: 2105.06384 - webinar

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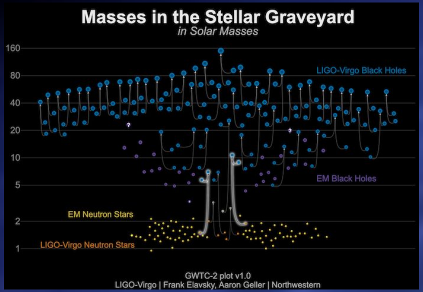
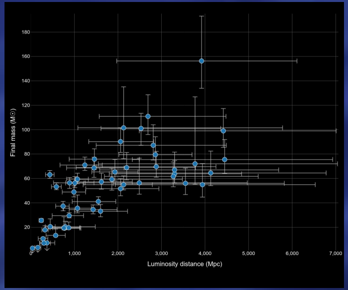
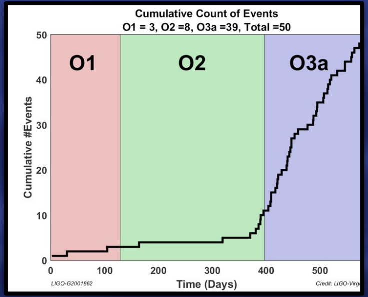
for the LIGO Scientific Collaboration
and the Virgo Collaboration

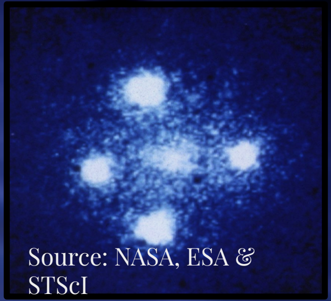
Image credits: Riccardo Buscicchio

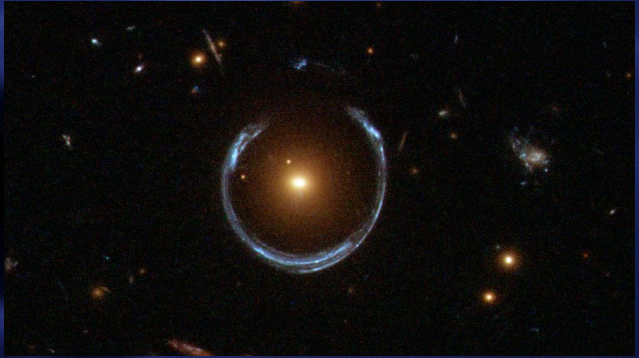
Eyes and Ears onto the Universe

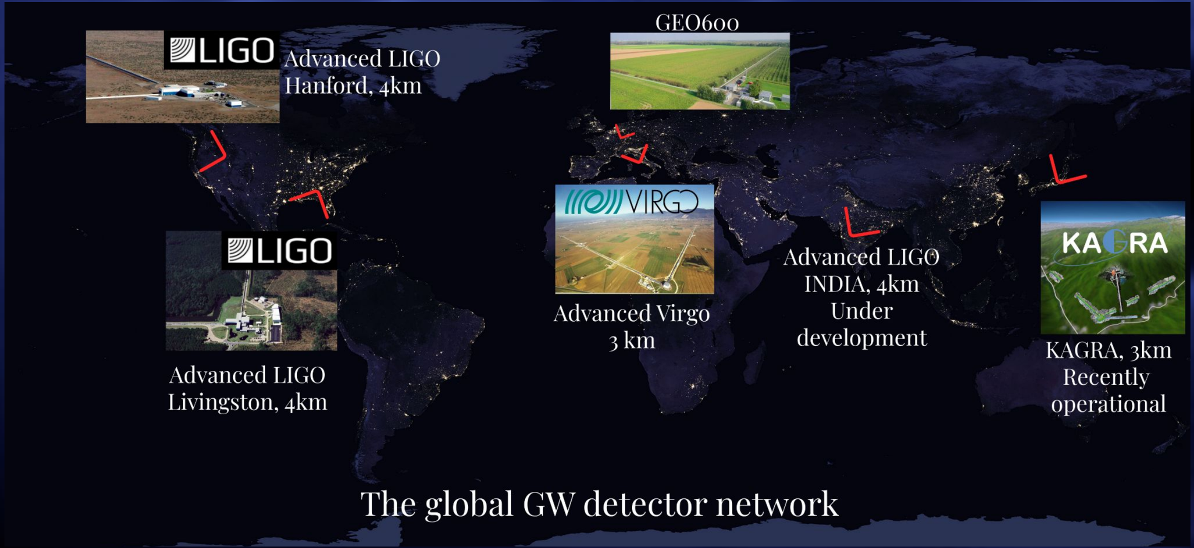






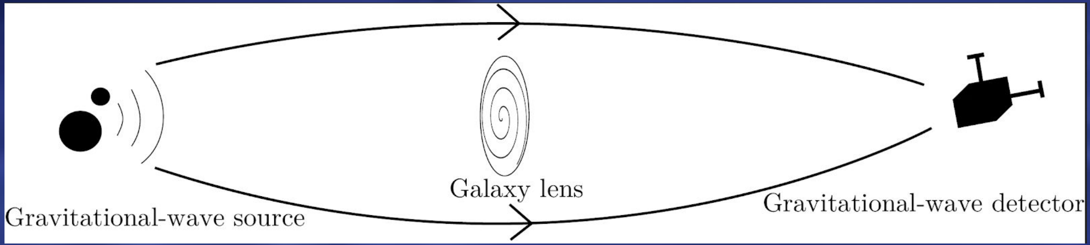


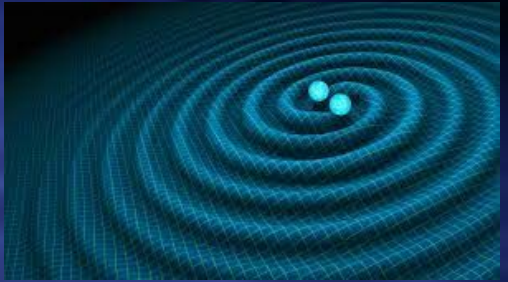




Both Exceptionally rich tools to explore the Universe

Gravitational lensing of gravitational waves





- GWs can be gravitationally lensed just like light [1]
- detection methods and science cases very different than for EM lensing
- GWs experience
  - lensing magnification
  - multiple images
  - frequency-dependent deformations

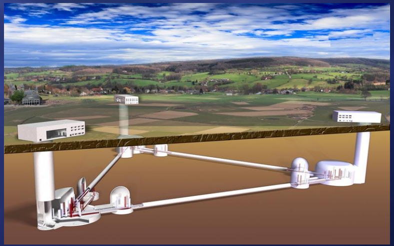
[references at the end]

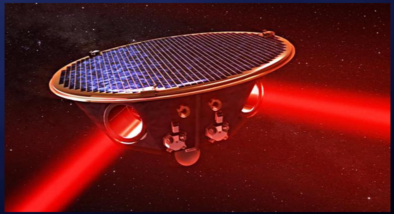
example science cases in the literature:

- tests of fundamental physics (e.g. speed of light vs speed of GWs [2])
- localization of merging black holes [3]
- precision cosmology studies from lensing time delays [4]
- microlens population studies [5] (e.g. primordial BHs?)

for future detectors (Einstein Telescope, LISA) [6]

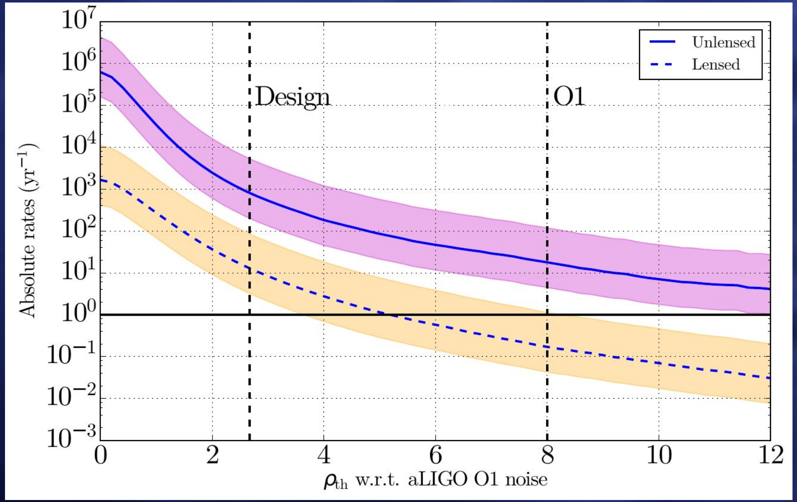
- large expected lensed event rates
- potential for precision cosmography





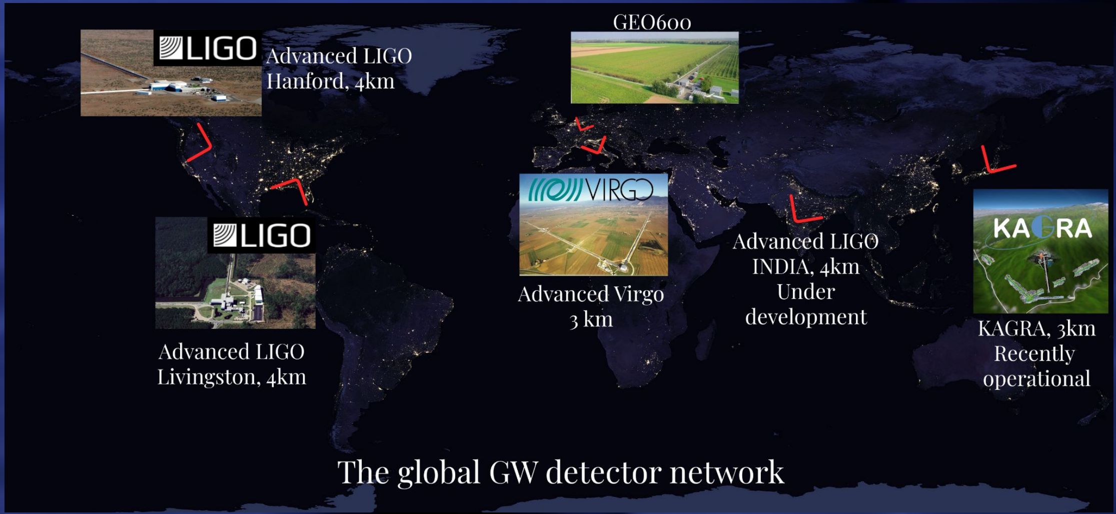
Why is GW lensing exciting (now)?

Sensitivity of **current global GW detector network** rapidly increasing and more sites are getting added.



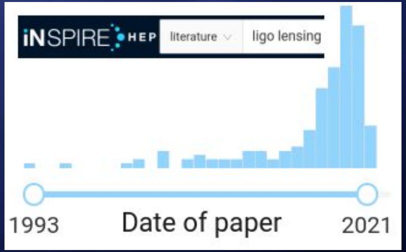
Some recent forecasts in the literature predict strong lensing at a reasonable rate at design sensitivity.

[plot: Ng+2017; see also Li+2018, Oguri+2018, Wierda+2021]



Interest in the community has grown rapidly.

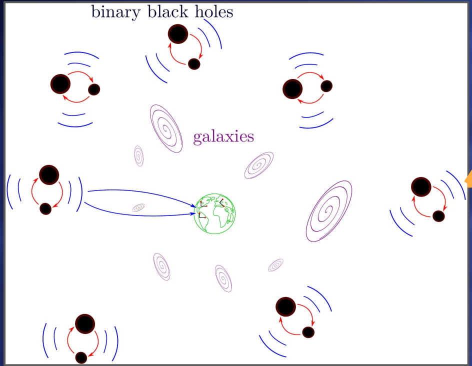
Searches of O1–O2 data found some intriguing candidates, but no generally recognized evidence for any lensed GWs.



[e.g. Broadhurst+2018/2019/2020, Hannuksela+2019, Li+2019, McIsaac+2019, Dai+2020, Liu+2020]

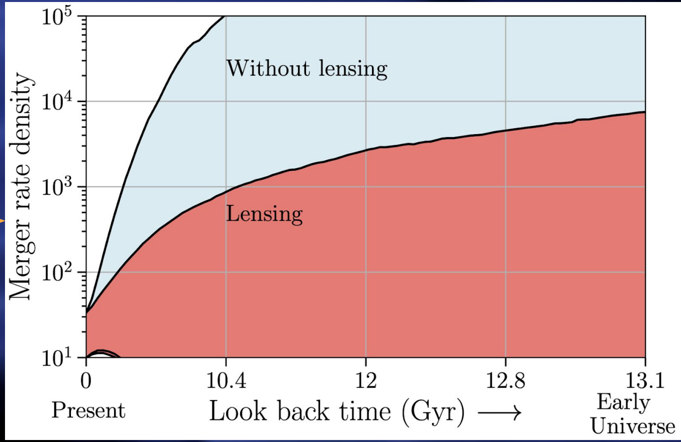
I. lensing statistics

given our understanding of
- BBH population
- lens populations

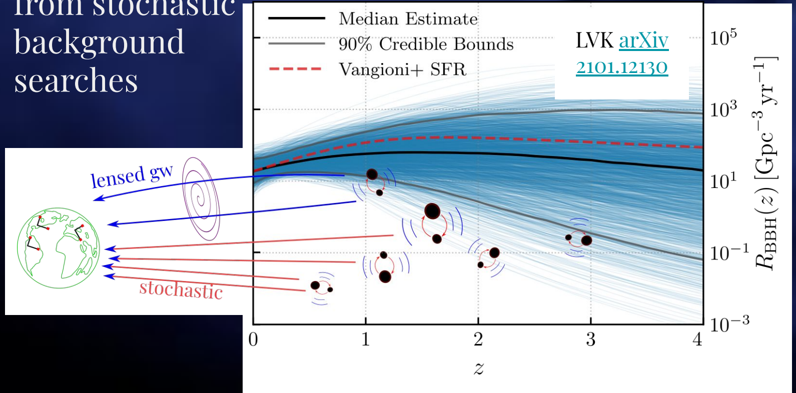


predicted rate of strong lensing:
1:10^{3-4} events

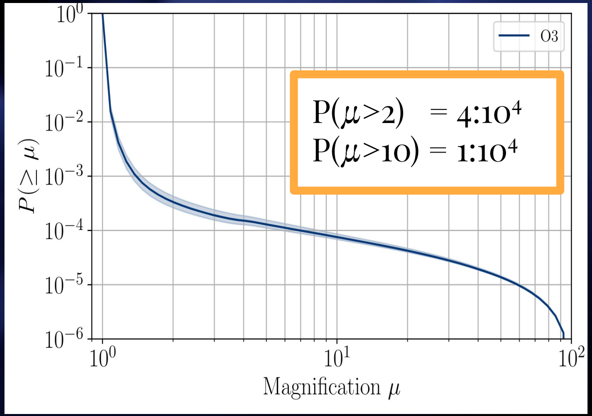
non-detection of lensed events can constrain high-redshift merger rate density



implications on unresolvable CBCs from stochastic background searches



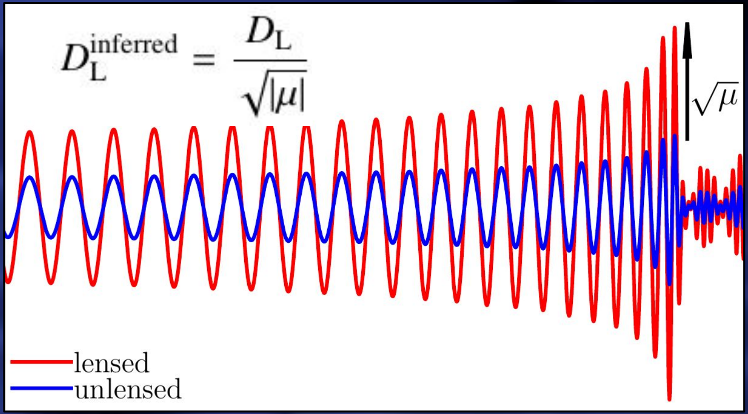
- magnification model from Dai+2017
- parametric fit to weak (Takahashi+2011) and strong regime (Hilbert+2008)
- based on method in (Buscicchio+2020)



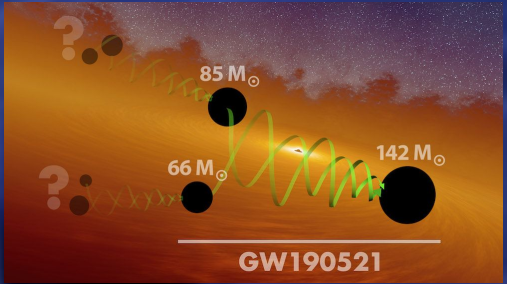
$P(\mu>2) = 4:10^4$
$P(\mu>10) = 1:10^4$

II. lensing magnification

- lensing magnifies GWs but maintains their frequency evolution
  ⤜ sources appear closer and more massive than they really are



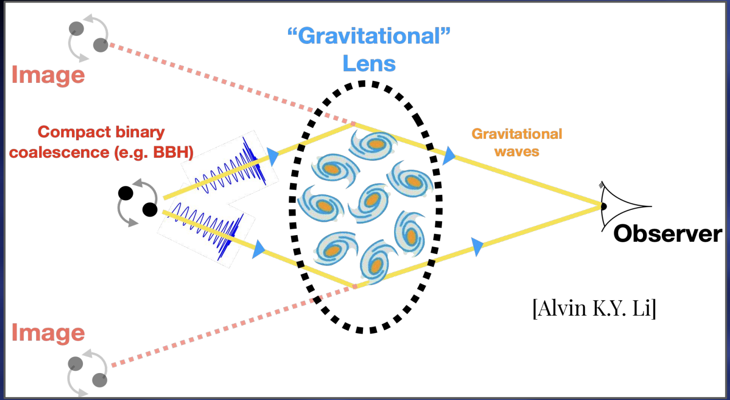
- re-analyzed events under lensed hypothesis of origin from lower-mass source populations:
  - heavy BBHs GW190521, GW190602_175927, GW190706_222641: from below PISN mass gap at 50/65 $M_\odot$?
    ⤜ would require moderate magnifications ~O(10), originate from z~1-2

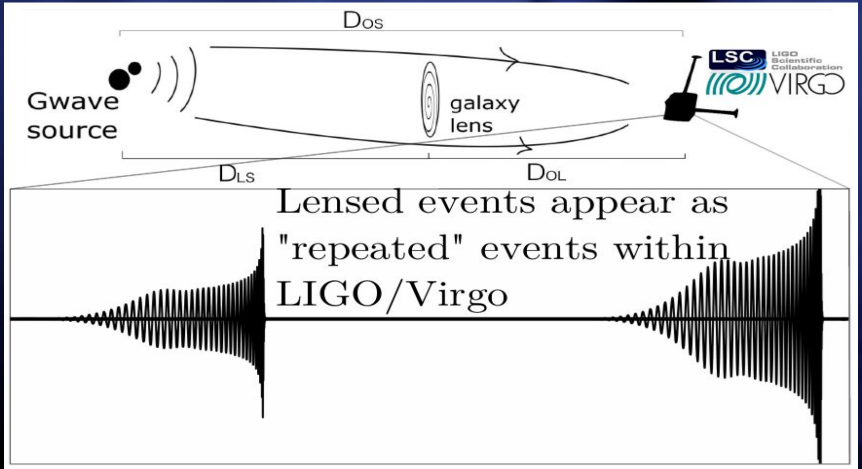


  - NSs in GW190425 and GW190426_152155 from Galactic population
    ⤜ would require high magnifications ~O(100) or more

- no compelling evidence of lensing, given Occam's razor
- follow-up studies may allow us to better constrain hypothesis together with multi-image / microlensing signatures

III. strong lensing: multiple images





$$\tilde{h}_j^L(f;\theta,\mu_j,\Delta t_j,\Delta\phi_j) = \sqrt{|\mu_j|}h(f;\theta,\Delta t_j)e^{i\Delta\phi_j \mathrm{sign}(f)}$$

magnification time delay Morse phase

- inferred luminosity distance and coalescence time different for lensed images of same event
- intrinsic parameters (masses, spins) should be the same
- Morse phase depends on type I/II/III images
- identify promising pair candidates using fast posterior-overlap method [Haris+2018]
- 19 pairs passed to joint Bayesian parameter estimation of the combined data sets with matching intrinsic parameters and sampling in the magnification, time delay and Morse phase [Liu+2020, Lo&Magaña2021]; evidence compared against single-event runs

III.B joint parameter estimation

Event 1	Event 2	$\log_{10} \mathcal{R}^{\mathrm{gal}}$	$\log_{10}(\mathcal{C}^{\mathrm{L}}_{\mathrm{U}})$ LALInference ($\Delta\phi$: 0, $\pi/2$, π, $3\pi/2$)	$\log_{10}(\mathcal{C}^{\mathrm{L}}_{\mathrm{U}}\|_{\mathrm{pop}})$ HANABI	$\log_{10}(\mathcal{B}^{\mathrm{L}}_{\mathrm{U}})$ HANABI
GW190412	GW190708_232457	-1.7	(+1.0, -9.7, -22.8, -4.4)	-5.6	-8.0
GW190421_213856	**GW190910_112807**	–	(**+4.5**, +2.5, -1.5, -0.0)	0.67	**-1.8**
GW190424_180648	**GW190727_060333**	-1.9	(**+4.9**, +0.0, +1.1, **+4.0**)	0.96	**-1.5**
GW190424_180648	**GW190910_112807**	–	(+2.5, **+4.7**, **+4.3**, +1.6)	0.62	-1.8
GW190513_205428	**GW190630_185205**	-0.7	(+0.8, **+4.3**, -1.9, -6.5)	-0.39	-2.8
GW190706_222641	GW190719_215514	0.34	(+2.4, +2.4, -0.0, -0.5)	0.81	**-1.7**
GW190707_093326	GW190930_133541	-1.6	(-4.6, -4.3, -3.5, -4.1)	-8.2	-11.
GW190719_215514	**GW190915_235702**	-1.	(+3.5, -2.1, -0.1, **+4.1**)	1.4	**-1.1**
GW190720_000836	GW190728_064510	0.54	(-1.4, -0.9, -4.5, -5.4)	-6.0	-8.5
GW190720_000836	GW190930_133541	-1.3	(-3.5, -2.8, -3.9, -3.9)	-8.2	-11.
GW190728_064510	GW190930_133541	-1.1	(-3.6, -2.5, -3.1, -2.9)	-7.	-9.8
GW190413_052954	GW190424_180648	0.4	(+0.6, -0.9, +0.4, -0.0)	0.35	-2.1
GW190421_213856	**GW190731_140936**	-2.1	(+3.1, -1.9, +2.5, **+5.2**)	1.7	**-0.79**
GW190424_180648	**GW190521_074359**	-0.1	(+1.3, +3.8, +3.7, **+4.4**)	-0.64	**-3.1**
GW190424_180648	**GW190803_022701**	-2.1	(**+4.2**, +1.9, +2.6, +3.1)	0.81	**-1.7**
GW190727_060333	GW190910_112807	-0.6	(+1.8, +3.3, +3.7, +3.4)	0.12	-2.3
GW190731_140936	**GW190803_022701**	0.9	(**+4.1**, +3.2, +2.2, +3.4)	1.1	**-1.3**
GW190731_140936	**GW190910_112807**	-0.6	(+0.1, **+4.5**, +0.8, -7.2)	0.92	**-2.1**
GW190803_022701	**GW190910_112807**	-0.4	(**+4.0**, **+5.5**, **+4.7**, +2.6)	1.5	**-0.98**

Coherence ratio C^{L}_{U}: overlap information

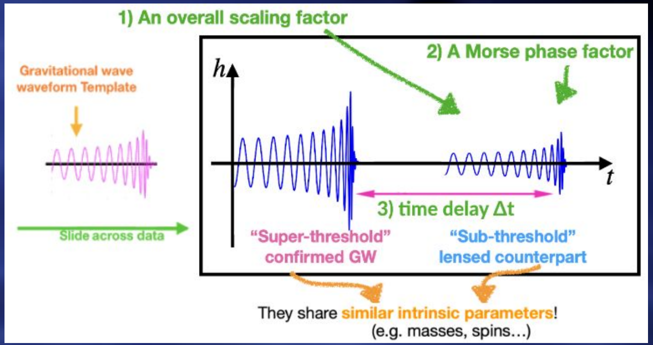
Population-weighted $C^{L}_{U}|_{pop}$: overlap + priors on BBH and lens populations

Bayes factor B^{L}_{U}: overlap + pop. prior + selection effects

no evidence of strongly lensed super-threshold pairs in GWTC-2

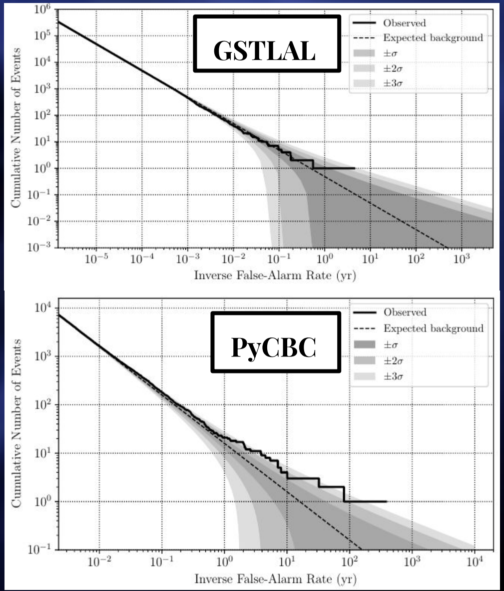
III.C search for sub-threshold lensed images

- events could have **faint lensed counterparts** not found in previous searches
- two matched-filter pipelines [Li+2019, McIsaac+2019] with targeted template banks based on GWTC-2 events to reduce noise background
- ***slight observed excess*** of search results at low false alarm rates (FARs)
  - pure noise: ~2 events expected at FAR < 1/16 yr from 2*39 searches
  - ***8 new triggers found with FAR < 1/16 yr*** (6 of them unique)
- joint-PE follow-up *assuming the triggers are astrophysical* [*]
  - some pairs *consistent* with shared parameters
  - but compared with results for GWTC-2 pairs: ***no evidence*** for lensing



UTC time	GWTC-2 targeted event	$\lvert\Delta t\rvert$ [d]	$(1+z)\mathcal{M}$ [$M_\odot$]	FAR $[\mathrm{yr}^{-1}]$ PyCBC	FAR $[\mathrm{yr}^{-1}]$ GstLAL	$O_{90\%\mathrm{CR}}$ [%]	$\log_{10} C^{\mathrm{L}}_{\mathrm{U}}$ (LALInference) ($\Delta\phi$: 0, $\pi/2$, π, $3\pi/2$)
2019 Sep 25 23:28:45 *	GW190828_065509	28.69	17.3	0.003	98.681	0.0%	–
2019 Apr 26 19:06:42	GW190424_180648	2.04	65.5	–	0.017	63.8%	(−5.8, −5.8, −5.9, −5.6)
2019 Jul 11 03:07:56	GW190421_213856	80.23	47.7	0.032	0.341	1.2%	(+2.3, +1.1, +1.1, +2.6)
2019 Jul 25 17:47:28 *	GW190728_064510	2.54	9.0	–	0.038	0.0%	–
2019 Jul 11 03:07:56	GW190731_140936	20.46	47.4	0.045	0.944	2.9%	(+2.6, −1.2, −1.6, +0.9)
2019 Aug 05 21:11:37	GW190424_180648	103.13	68.8	–	0.051	26.9%	(−1.1, +0.6, −0.3, −0.7)
2019 Jul 11 03:07:56	GW190909_114149	60.36	49.0	0.053	1.196	12.6%	(+3.5, +2.2, +3.4, +2.9)
2019 Sep 16 20:06:58 *	GW190620_030421	88.71	53.3	0.055	1.389	49.5%	(+1.7, +3.6, +2.1, −3.2)

[*] also found independently in 3-OGC [Nitz+, arXiv:2105.09151]

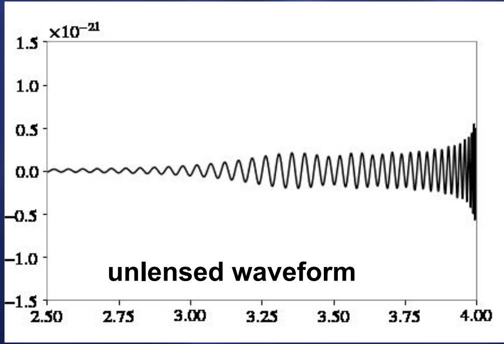


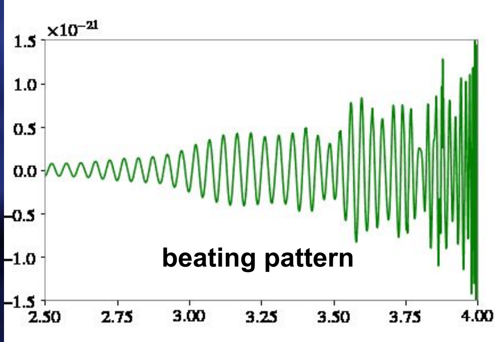
IV. microlensing search

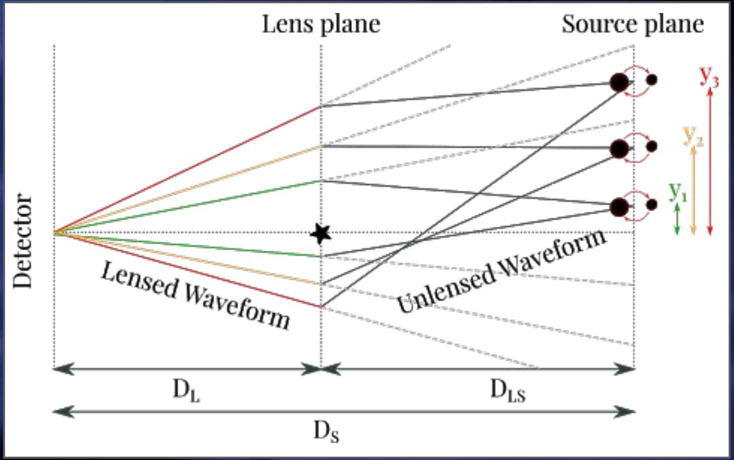
- microlenses (size ~ GW wavelength) » ***frequency-dependent amplification***

$$h^{ML}(f;\theta_{ML}) = h^U(f;\theta)\,F(f;M_L^z,y)$$

lensed images with time delays < chirp time superpose » ***beating patterns*** (more significant when GW passes closer to the lens / smaller ***y***)

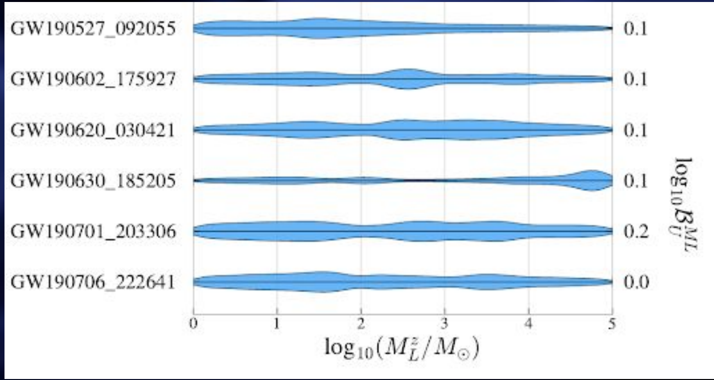






[Eungwang Seo, Apratim Ganguly]

results snippet; see paper for full results on 36 events



- for 36 O3a events (clear BBHs): Bayes factors for lensed (by point-mass lens) vs. unlensed hypotheses, posteriors over lens mass M^z_L
- no well-recovered posteriors, all Bayes factors within the statistical fluctuations expected for unlensed events
- **No microlensing effect observed.**

O3a search for lensed GWs: conclusions

https://arxiv.org/abs/2105.06384

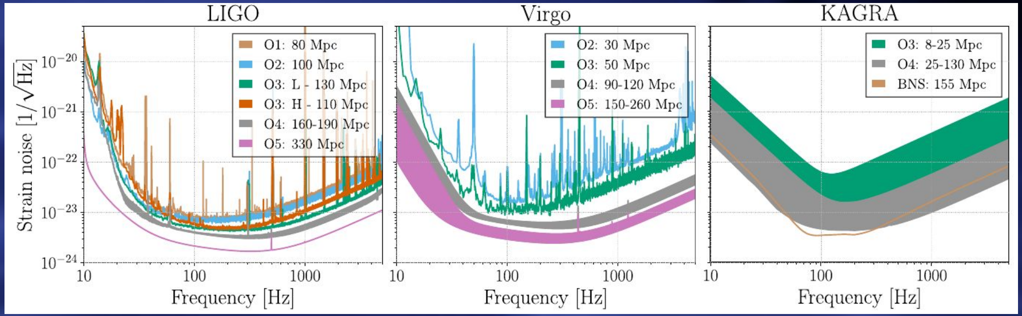
Four gravitational-wave analyses on O3a data:

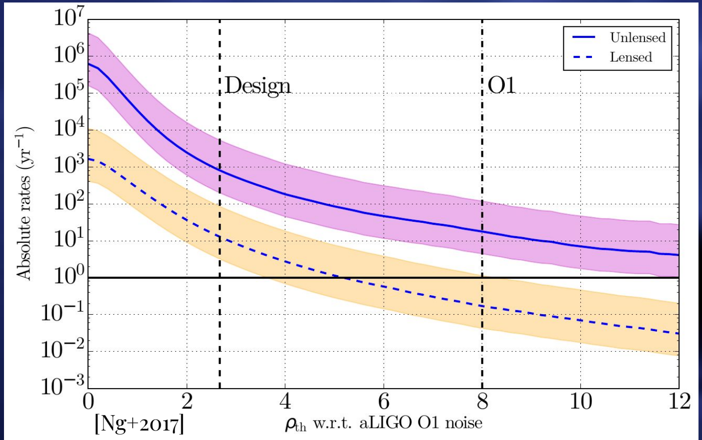
- statistical forecasts, constraining the rate of lensing and mergers
- analysis of high-mass events under the hypothesis that they might be lensed
- three searches for multiple images from strong lensing
- search for microlensing-induced beating patterns

- First LVC analysis on a topic that is expected to be pursued further with new data (see the LVK white paper).

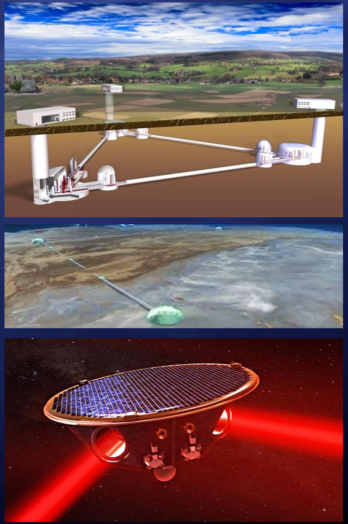
GW lensing: future outlook

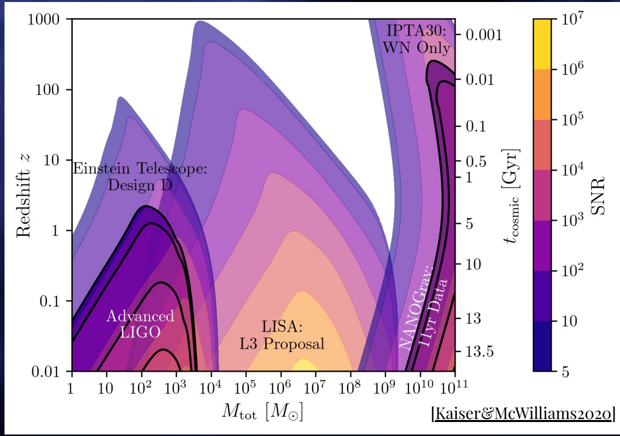
As the current GW detector network expands and its sensitivity increases, our chances to detect lensing will improve!





future detectors (Einstein Telescope, Cosmic Explorer, LISA): truly cosmological reach, new regime of large lensed event rates, better constraints from SGWB





detecting lensed GWs can enable:

- tests of fundamental physics
- localization of merging black holes
- precision cosmology studies from lensing time delays
- microlens population studies

The science case tree...

1. classical works and general reviews: Deguchi&Watson 1986, Wang&Stebbins astro-ph/9605140, Nakamura 1998, Takahashi&Nakamura astro-ph/0305055, Oguri 1907.06830
2. tests of fundamental physics (e.g. speed of light vs speed of GWs): Collett&Bacon 1602.05882, Fan+ 1612.04095, Minazzoli 1912.06891, ...
3. localization of merging black holes: Smith+ 1805.07370, Hannuksela+ 2004.13811, Yu+ 2007.00828
4. precision cosmology studies from lensing time delays: Sereno+ 1104.1977, Baker&Trodden 1612.02004, Liao 1904.01744, Cremonese&Salzano 1911.11786, Hou+ 1911.02798, ...
5. microlens population studies (e.g. primordial BHs?): Jung&Shin 1712.01396, Dai+1810.00003, Diego 1911.05736, Oguri&Takahashi 2007.01936, ...
6. predictions for future detectors: Seto astro-ph/0305605, Sereno+ 1104.1977, Piorkowska+ 1309.5731, Biesiada+ 1409.8360, Ding+ 1508.05000, Liao+ 1703.04151, Cusin&Tamanini 2011.15109, Wang+ 2101.08264...

(and many other branches)

Thank you!

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