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

EPS-HEP 2021, T01 parallel, 30th July 2021, contrib. #105585

paper: arXiv:2105.06384

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and the Virgo Collaboration

slides: https://dcc.ligo.org/G2100936-v3

Universitat de les Illes Balears

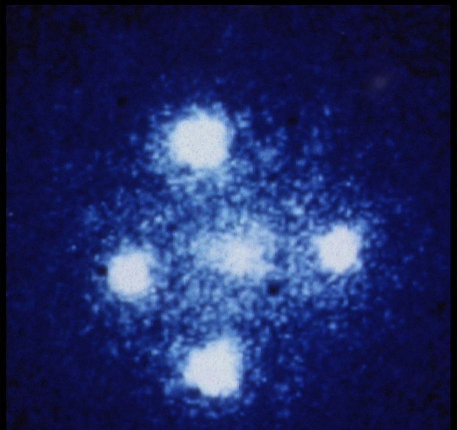
IAC3 Institute of Applied Computing & Community Code.

LSC LIGO Scientific Collaboration

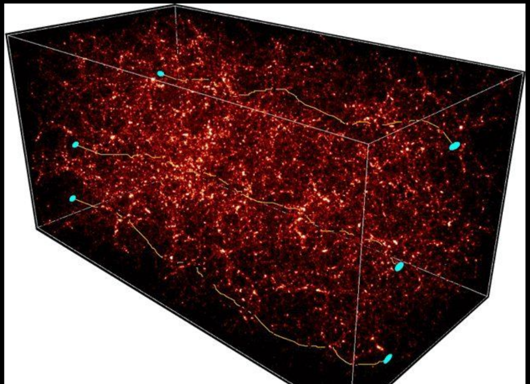
VIRGO

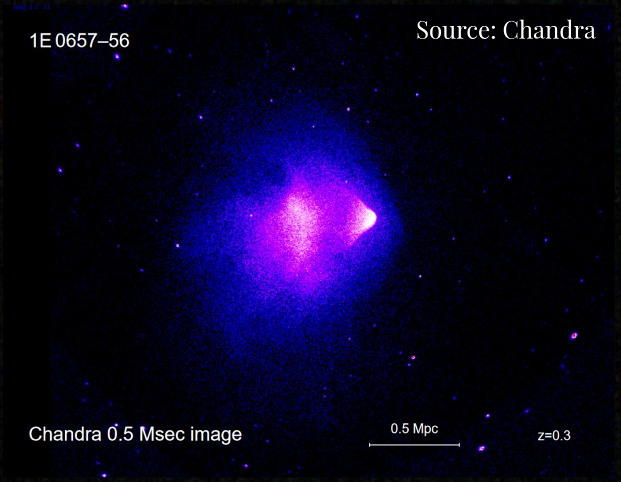
background image credits:
R. Buscicchio

Gravitational lensing of light


Source: NASA, ESA & STScI


Source: NASA

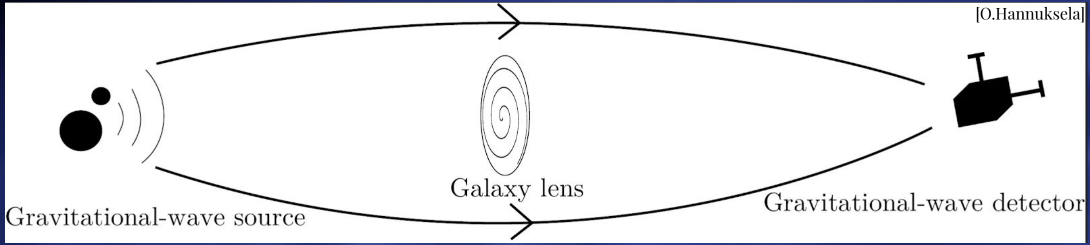

Source: Munshi et.al 2006

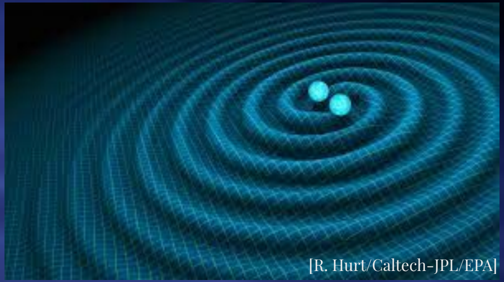


Source: Chandra

an exceptionally productive tool across many domains of astrophysics and cosmology

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

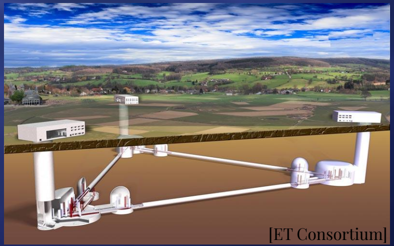
[references at the end]

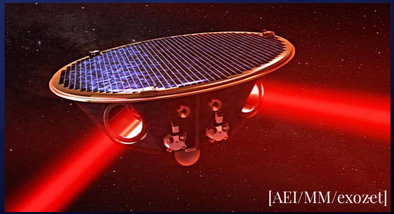
example science cases in the literature:

- 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]

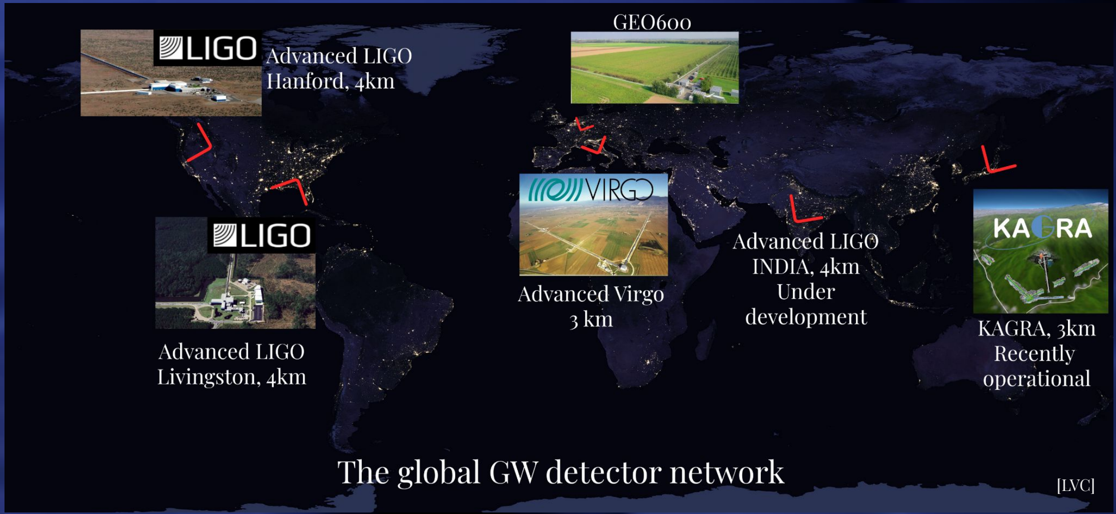
- large expected lensed event rates
- potential for precision cosmography

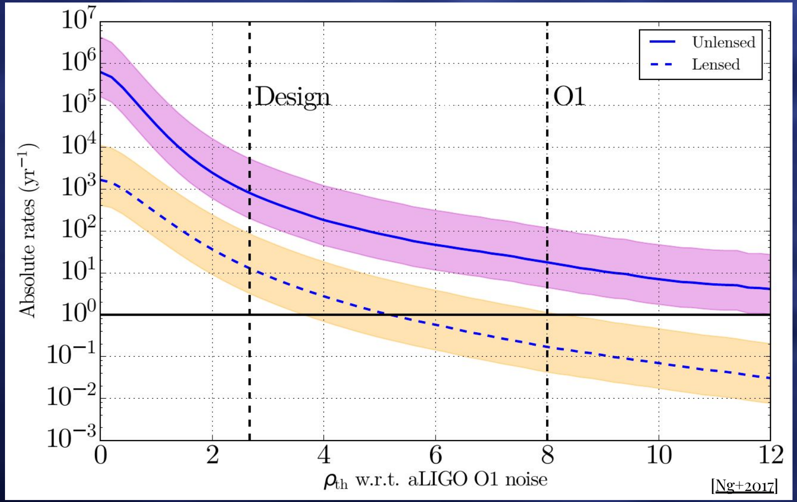




Why is GW lensing exciting (*now*)?

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

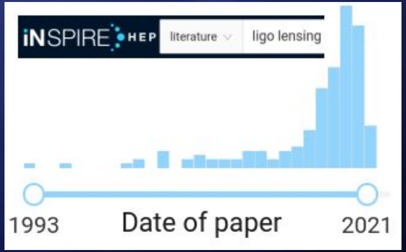




Some recent forecasts in the literature predict strong lensing at a reasonable rate at design sensitivity.

[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]

recent paper: 1st LVC study on GW lensing

arXiv.org > gr-qc > arXiv:2105.06384

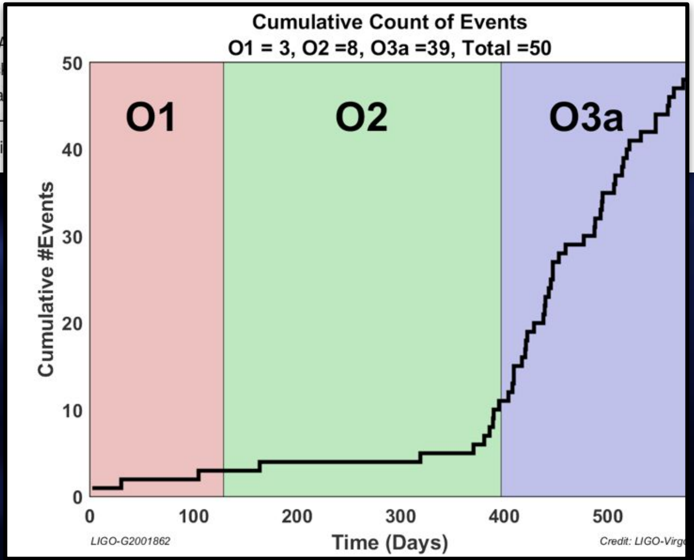
General Relativity and Quantum Cosmology

[Submitted on 13 May 2021]

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

The LIGO Scientific Collaboration, the Virgo Collaboration: R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, A. Adams, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, D. Agarwal, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, K. M. Aleman, G. Allen, A. Allocca, P. A. Altin, A. Amato, S. Anand, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Ansoldi, J. M. Antelis, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Arène, N. Arnaud, S. M. Aronson, K. G. Arun, Y. Asali, G. Ashton, S. M. Aston, P. Astone, F. Aubin, P. Aufmuth, K. AultONeal, C. Austin, S. Babak, F. Badaracco, M. K. M. Bader, S. Bae, A. M. Baer, S. Bagnasco, Y. Bai, J. Baird, M. Ball, G. Ballardin, S. W. Ballmer, M. Bals, A. Balsamo, G. Baltus, S. Banagiri, D. Bankar, R. S. Bankar, J. C. Barayoga, C. Barbieri, B. C. Barish, D. Barker, P. Barneo, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, M. A. Barton, I. Bartos, R. Bassiri, A. Basti, M. Bawaj, J. C. Bayley, A. C. Baylor, M. Bazzan, B. Bécsy, V. M. Bedakihale, M. Bejger, I. Belahcene, V. Benedetto, D. Beniwal, M. G. Benjamin, T. F. Bennett, J. D. Bentley, M. BenYaala, F. Bergamin, B. K. Berger, S. Bernuzzi, C. P. L. Berry, D. Bersanetti et al. (1279 additional authors not shown)

We search for signatures of gravitational lensing in the gravitational-wave signals from compact binary coalescences detected by Advanced LIGO and A
expected rate of lensing at current detector sensitivity and the implications of a non-observation of strong lensing or a stochastic gravitational-wave bac
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 gala
pairs of signals in the multiple-image analysis show similar parameters and, in this sense, are nominally consistent with the strong lensing hypothesis. H
against lensing, these events do not provide sufficient evidence for lensing. Overall, we find no compelling evidence for lensing in the observed gravitati



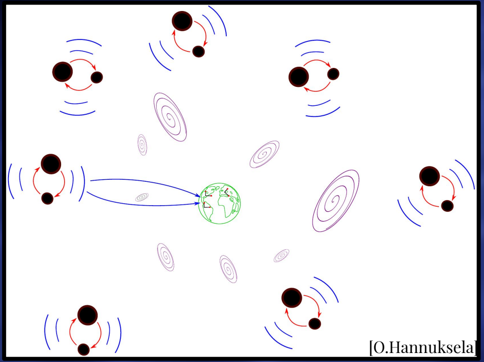
arxiv.org/abs/2105.06384

data release:
dcc.ligo.org/P2100173/public

outreach summary:
www.ligo.org/science/Publication-O3aLensing

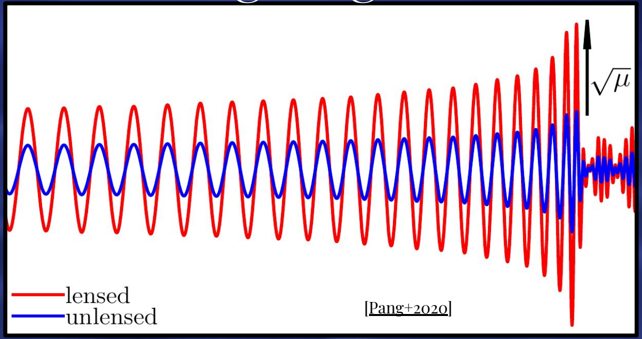
paper focuses on the ***39 events from O3a*** included in GWTC-2

1st LVC study on GW lensing

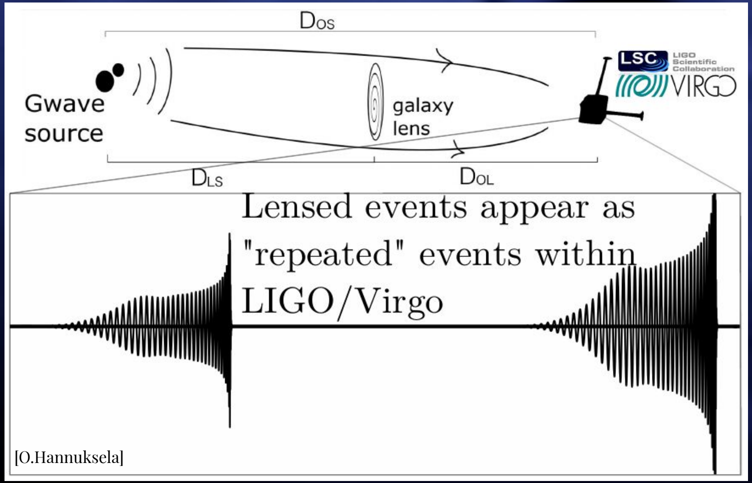


I. lensing statistics

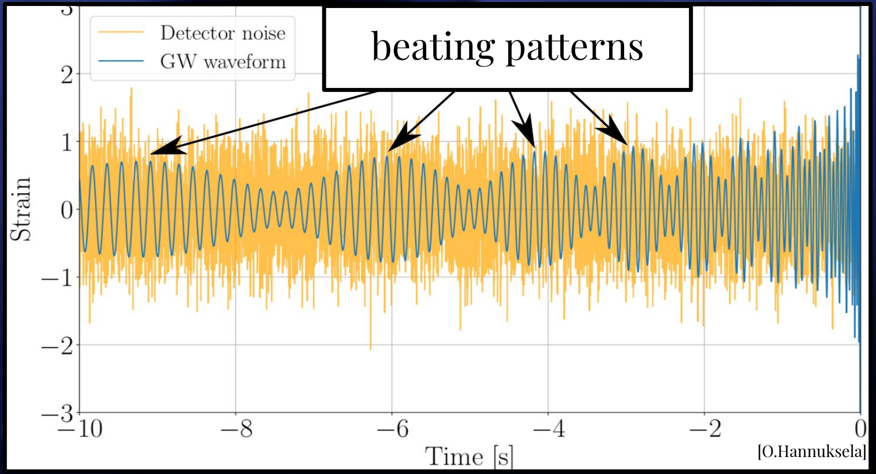
II. lensing magnification



III. strong lensing: multiple images

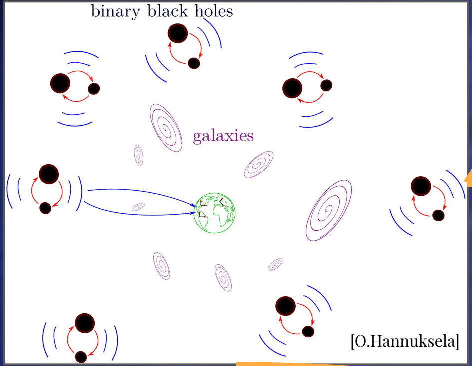


IV. microlensing distortions



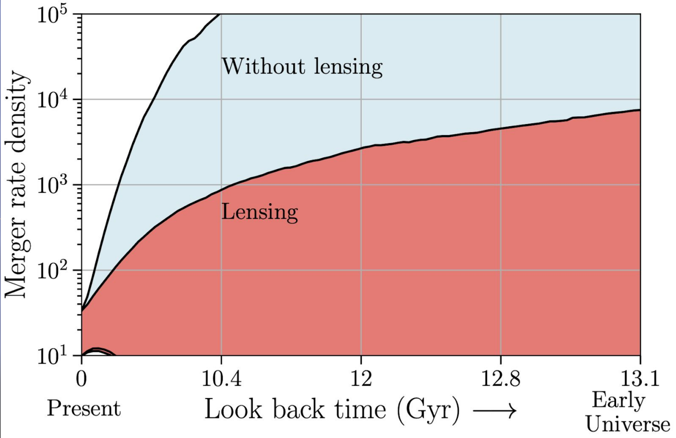
I. lensing statistics

given our understanding of
- BBH population
- lens populations



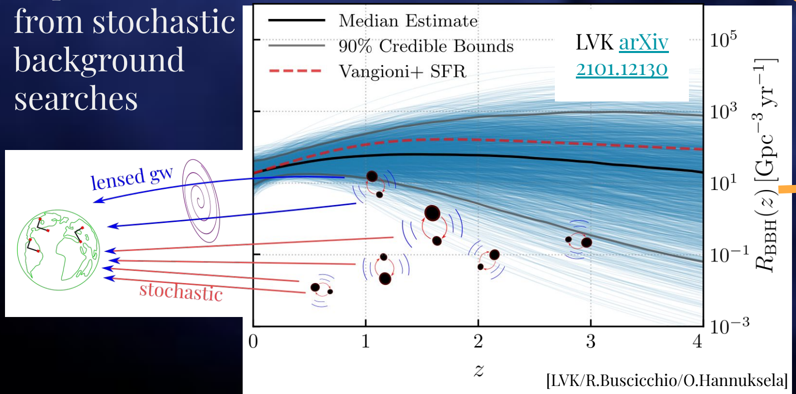
predicted rate of strong lensing:
$1{:}10^{3-4}$ events

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

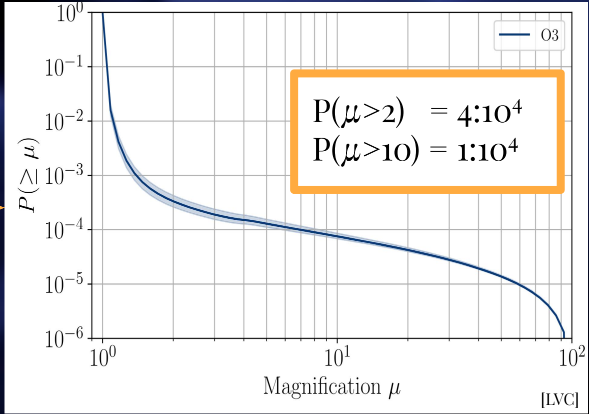


[LVC]

implications on unresolvable CBCs from stochastic background searches

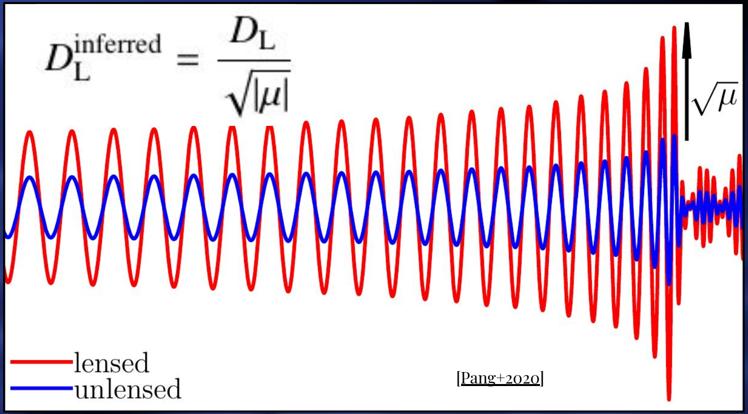


- magnification model from Dai+2017
- parametric fit to weak (Takahashi+2011) and strong regime (Hilbert+2008)
- based on method in (Buscicchio+2020)

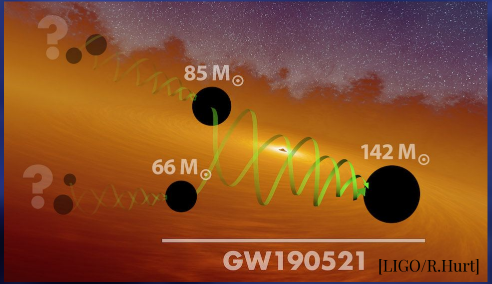


II. lensing magnification

- Lensing magnifies GWs, but maintains their frequency evolution.
  ↣ Sources appear closer and more massive than they really are!



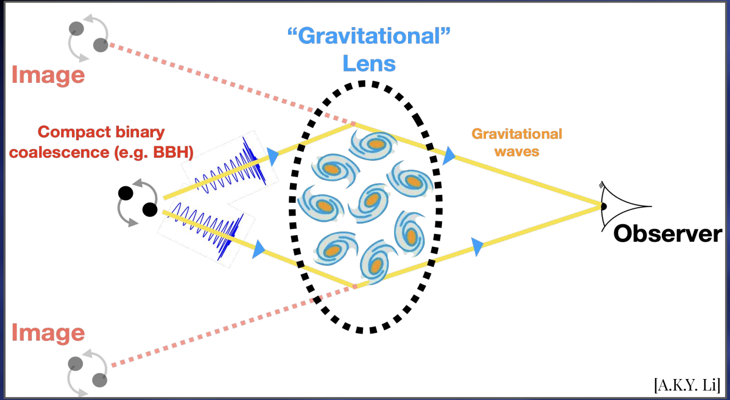
- re-analyzed events under the lensed hypothesis of origin from lower-mass source populations:
  - heavy BBHs (GW190521, GW190602_175927, GW190706_222641): from below PISN mass gap (at 50/65 $M_\odot$)?
    ↣ would require moderate magnifications ~O(10), originate from z~1-2



  - Neutron stars in GW190425 and GW190426_152155: from Galactic population?
    ↣ would require high magnifications ~O(100) or more

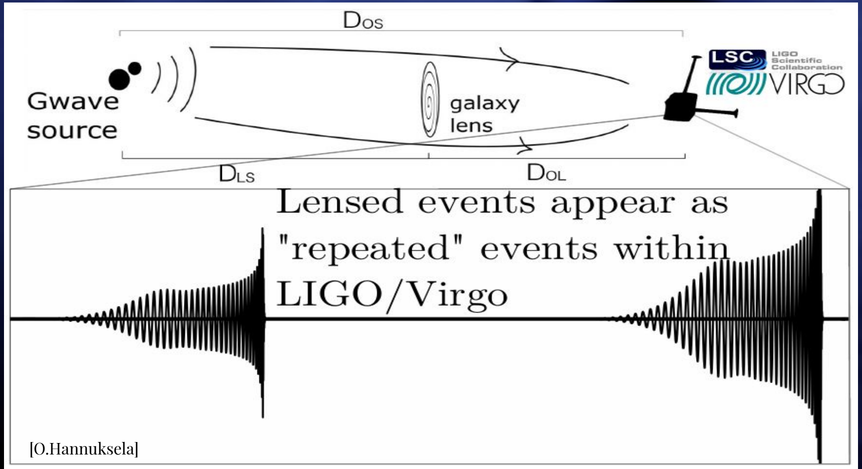
- no compelling evidence of lensing, given Occam's razor
- follow-up studies may allow us to better constrain hypothesis together with multi-image / microlensing signatures

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. joint parameter estimation

Event 1	Event 2	$\log_{10} \mathcal{R}^{\rm gal}$	$\log_{10}(\mathcal{C}^{\rm L}_{\rm U})$ LALINFERENCE ($\Delta\phi$: 0, $\pi/2$, π, $3\pi/2$)	$\log_{10}(\mathcal{C}^{\rm L}_{\rm U}\|_{\rm pop})$ HANABI	$\log_{10}(\mathcal{B}^{\rm L}_{\rm U})$ 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 $C^{\rm L}_{\rm U}$: overlap information

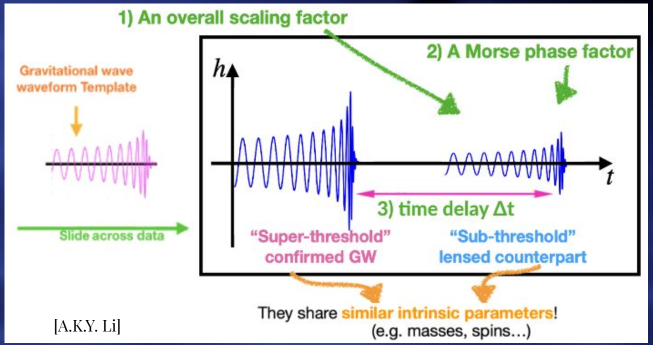
Population-weighted $C^{\rm L}_{\rm U}|_{\rm pop}$: overlap + priors on BBH and lens populations

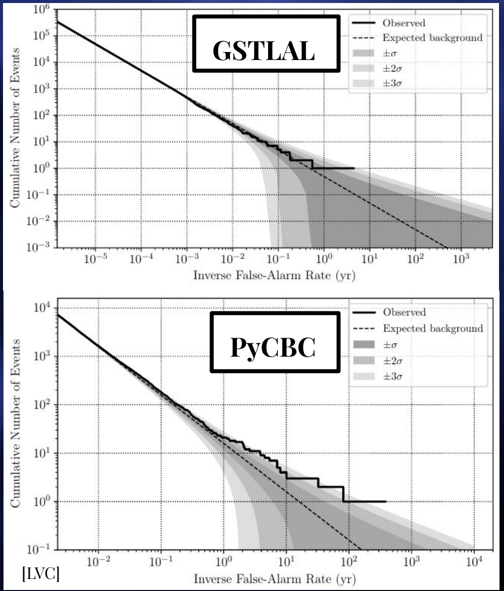
Bayes factor $B^{\rm L}_{\rm U}$: overlap + pop. prior + selection effects

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

III. 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)

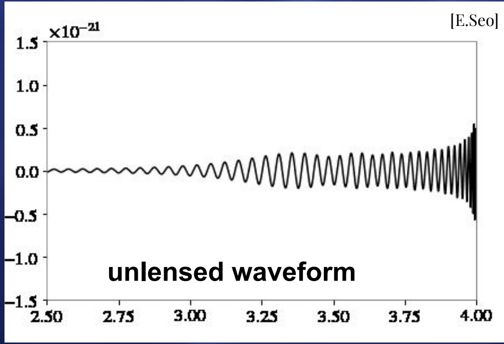
[*] also found in 3-OGC [Nitz+, arXiv:2105.09151]   [†] also found in GWTC-2.1 [Abbott+, LIGO-P2100063]

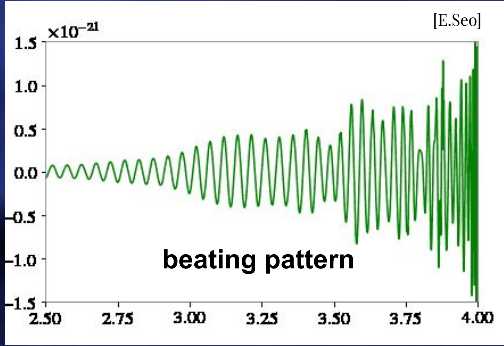
IV. microlensing search

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

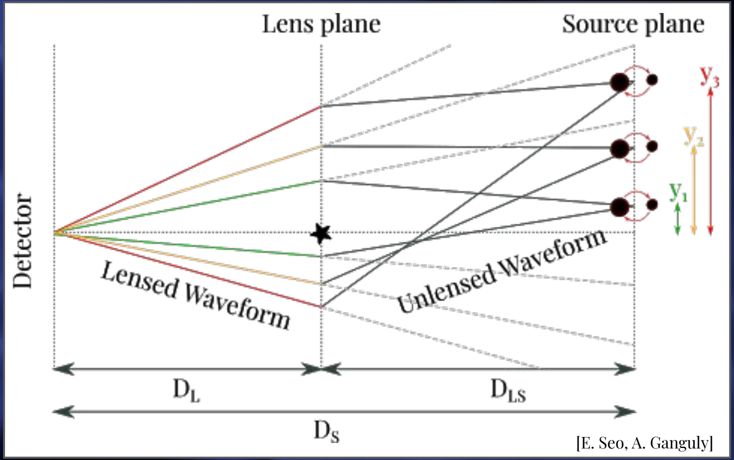
$$h^{ML}(f;\theta_{ML}) = h^{U}(f;\theta)\,F(f;M_L^z,y)$$

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

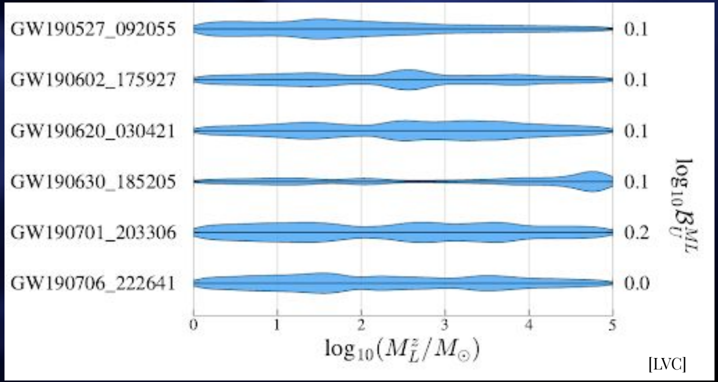




- for 36 O3a events (clear BBHs): Bayes factors for lensed (by point-mass lens) vs. unlensed hypotheses, posteriors over lens mass M^z_L
- no well-recovered posteriors, all Bayes factors within the statistical fluctuations expected for unlensed events
- **No microlensing effect observed.**



results snippet; see paper for full results on 36 events



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).

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

GW lensing: future outlook

arXiv:1304.0670v11 [LVK]

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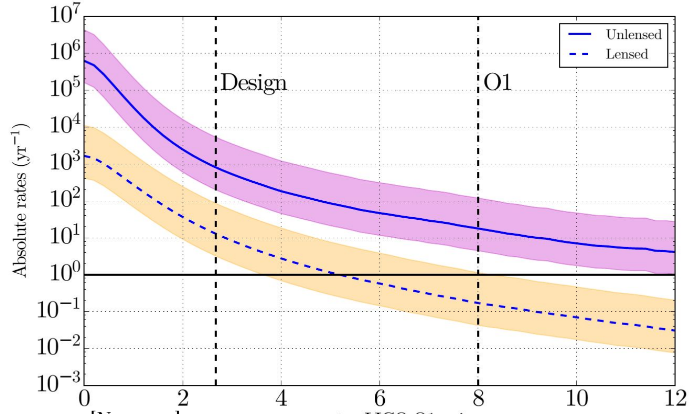
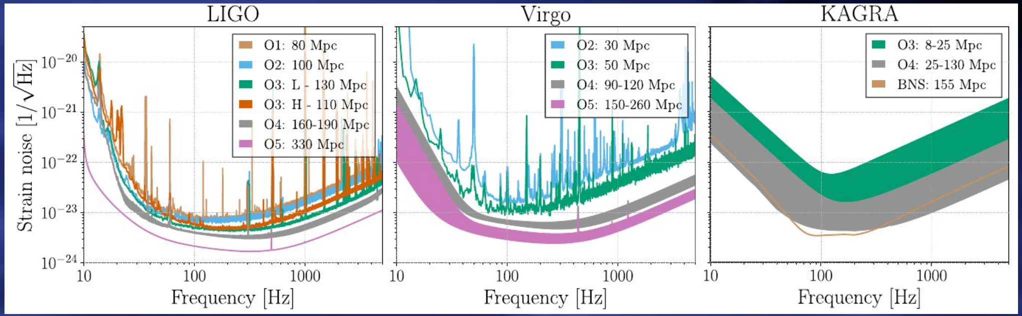
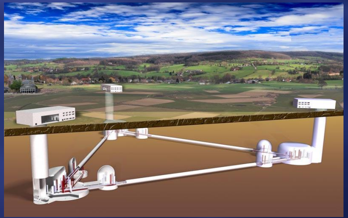
our chances to detect lensing will improve!

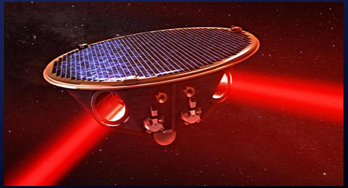


[Ng+2017]



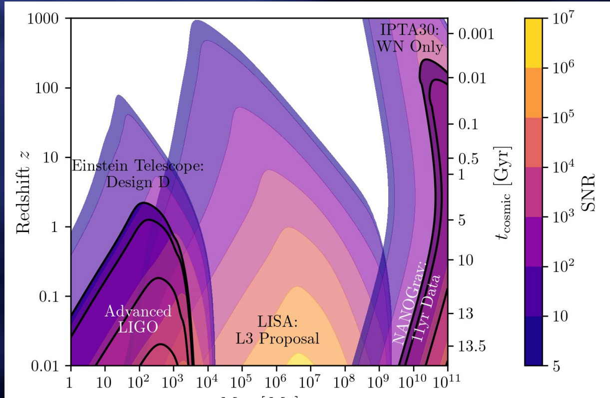
future detectors (Einstein Telescope, Cosmic Explorer, LISA): truly cosmological reach, new regime of large lensed event rates, better constraints from SGWB





detecting lensed GWs can enable:

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



[Kaiser&McWilliams2020]

Thank you!

I hope I left some time for questions…

acknowledgments [for the LVC: dcc.ligo.org/P2100218-v2/public]

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background image credits: R. Buscicchio

references (not exhaustive)
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, GW polarizations): Collett&Bacon 1602.05882, Fan+ 1612.04095, Minazzoli 1912.06891, Goyal+ 2008.07060 …
3. localization of merging black holes: Smith+ 1805.07370, Hannuksela+ 2004.13811, Yu+ 2007.00828
4. precision cosmology from lensing time delays: Sereno+ 1104.1977, Baker&Trodden 1612.02004, Liao 1904.01744, Cremonese&Salzano 1911.11786, Hou+ 1911.02798, Hannuksela+ 2004.13811, …
5. microlens population studies (e.g. primordial BHs?): Jung&Shin 1712.01396, Dai+1810.00003, Diego 1911.05736, Pagano+ 2006.12879, Oguri&Takahashi 2007.01936, Cheung+ 2012.07800, …
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, Xu+ 2105.14390, Wierda+2106.06303…

BACKUP SLIDES

Image credits: Riccardo Buscicchio

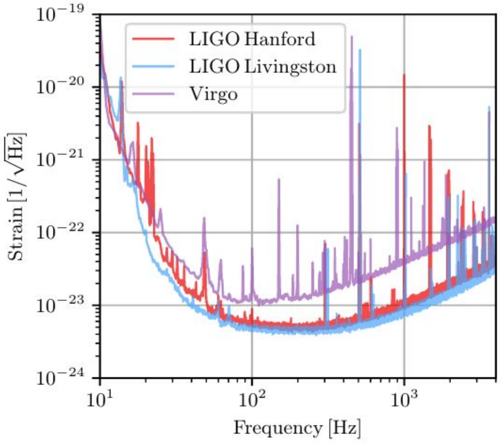
Previous searches for GW lensing

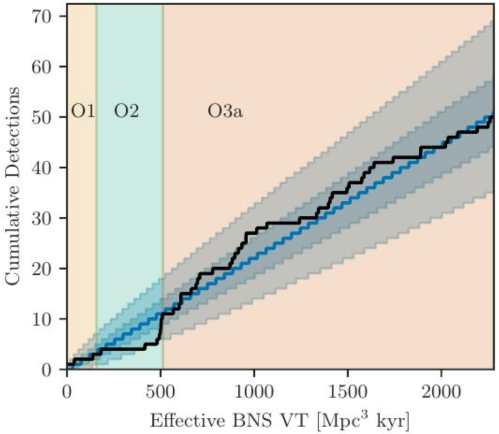
- interest in GW lensing for 2nd generation ground-based detectors grew with discoveries of heavy binary black hole (BBH) mergers [e.g. Smith+2018, Broadhurst+2018]
- Hannuksela+2019 studied magnification, multiple images, and microlensing in O1&O2 events (GWTC-1).
- lensing scenario also considered for various events/pairs in O1&O2, and low-latency candidates from O3a [Broadhurst+2019, Dai+2020, Liu+2020, LVC2020, Pang+2020, Singer+2019, Broadhurst+2020]
- searches for faint sub-threshold counterpart images in O1&O2 [Li+2019, McIsaac+2019, Dai+2020]
- no generally recognized evidence for any lensed GW events so far, consistent with expected rates
- most promising pair candidate from O1&O2: GW170104–GW170814 [Hannuksela+2019, Dai+2020, Liu+2020], but would require unusual required lensing geometry; together with low expected lensing rate ↣ unlikely to be lensed

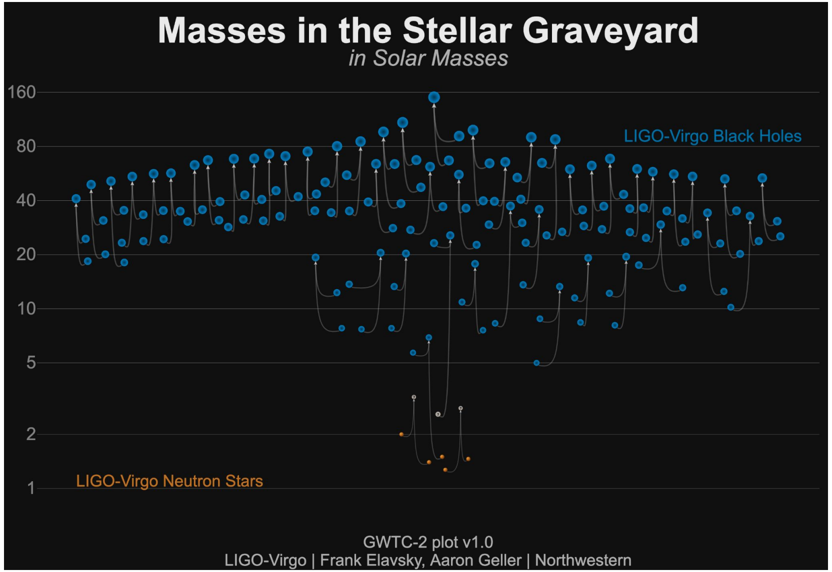
LVC O3a results - where we are now

- second GW transient catalogue GWTC-2 [arxiv:2010.14527] includes 50 CBC events:
  - 3 from O1
  - 8 from O2
  - **39** from O3a
  (first half of 3rd observing run, 1 Apr 2019 – 1 Oct 2019)

- increased event rate enabled by unprecedented detector sensitivity thanks to instrumental upgrades and thorough commissioning at all 3 sites





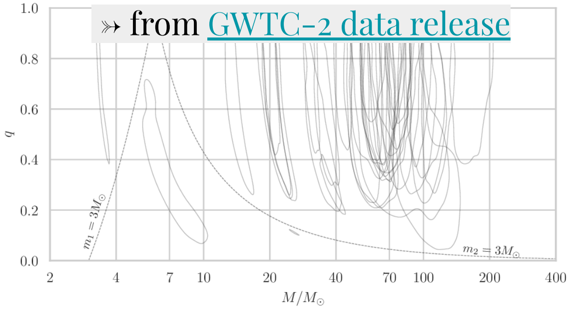


- Stay tuned for more results from O3b! (Nov 2019 – Mar 2020)

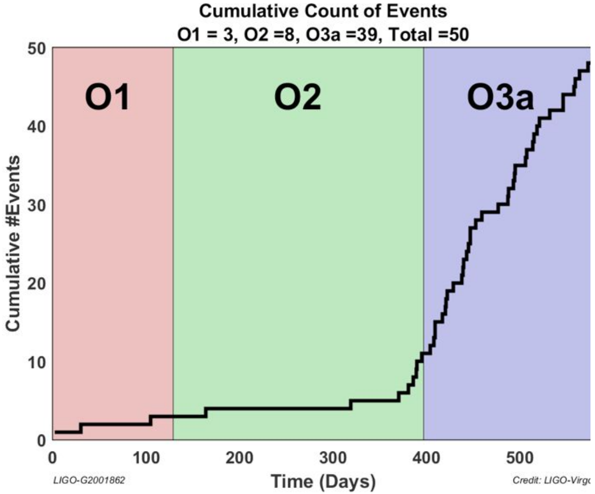
Data and events considered

- paper focuses on the ***39 events from O3a*** included in GWTC-2

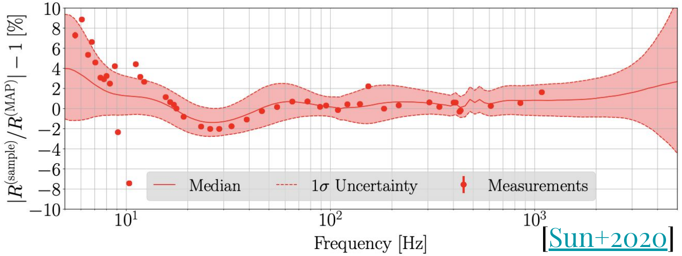
- some analyses use posterior samples from Bayesian inference of the source parameters



↣ from GWTC-2 data release



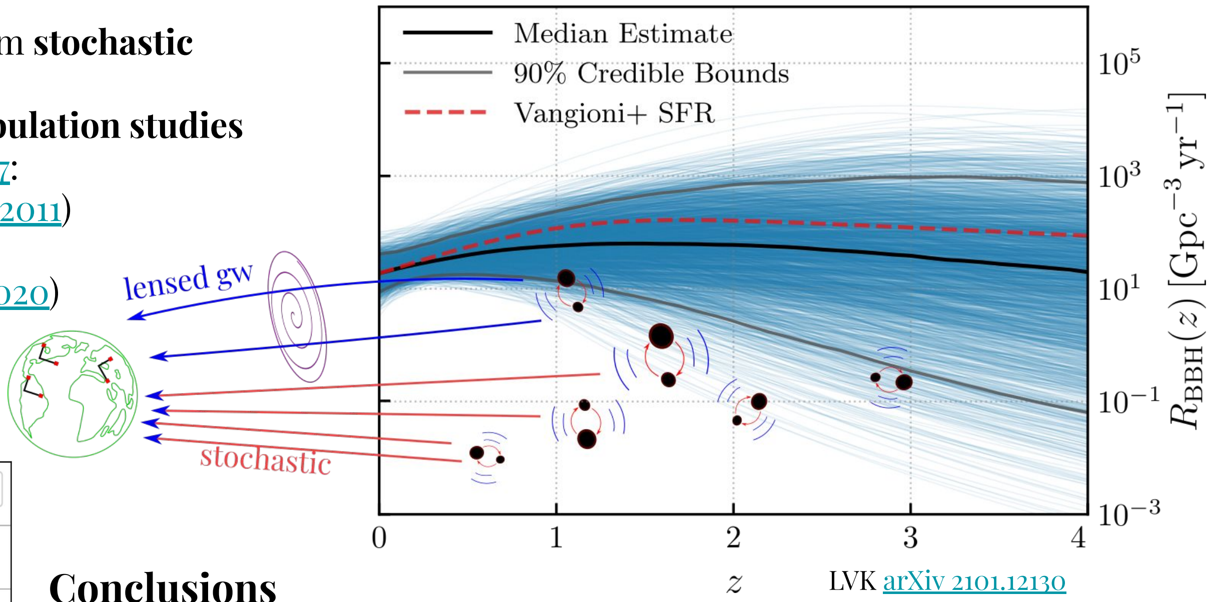
- interferometer strain data directly used in:
  - **strong-lensing joint-PE analysis** and **microlensing** analysis: short snippets of data with same calibration version, PSDs, and data quality mitigation strategies as in GWTC-2
  - **subthreshold counterpart searches**: full O3a strain data set, calibration as in PE analyses, and same data quality vetoes as in GWTC-2 searches
  - data available from https://www.gw-openscience.org/O3/O3a/



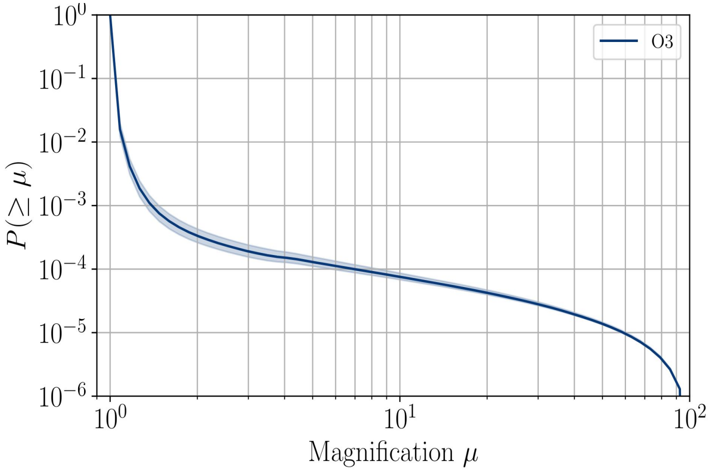
[Sun+2020]

I. Lensing statistics (stochastic)

- Implications on unresolvable CBCs from **stochastic background searches**
- Knowledge on detected CBCs from **population studies**
- Magnification model from Dai et al 2017: parametric fit to weak (Takahashi et al 2011) and strong regime (Hilbert et al 2008)
- Based on method in (Buscicchio et al 2020)



LVK arXiv 2101.12130



Conclusions

- Expected rate
  - $P(\mu>2) = 4{:}10^4$
  - $P(\mu>10) = 1{:}10^4$
- Merger rate rate uncertainties in blue shading

III. Search for multiple images

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

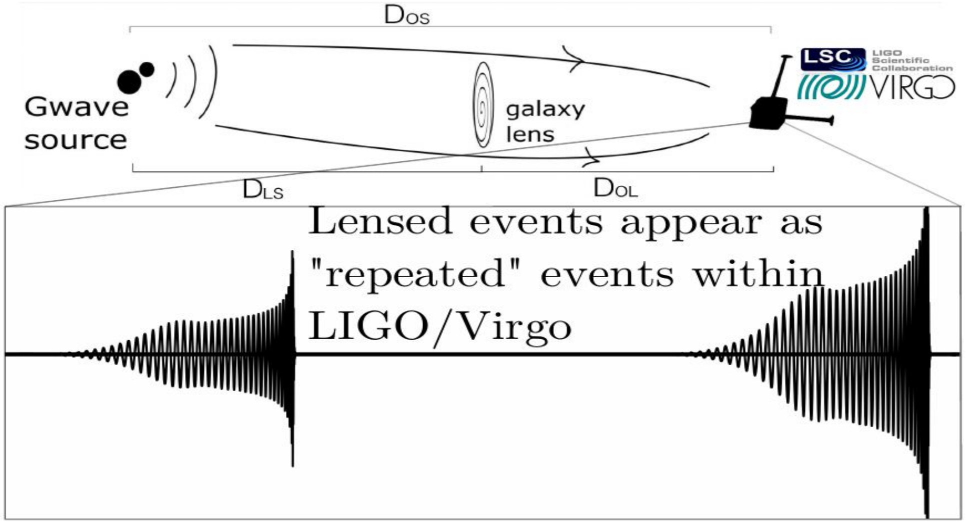
Magnification | Time delay | Morse phase

Image types:

Type I: minima $\Delta\phi_j = 0$

Type II: saddle point $\Delta\phi_j = \pi/2$

Type III: maxima $\Delta\phi_j = \pi$



- The inferred luminosity distance and coalescence time would be different for lensed images of an event.
- While intrinsic parameters such as masses and spins are expected to be the same.

III.A posterior-overlap multi-image analysis

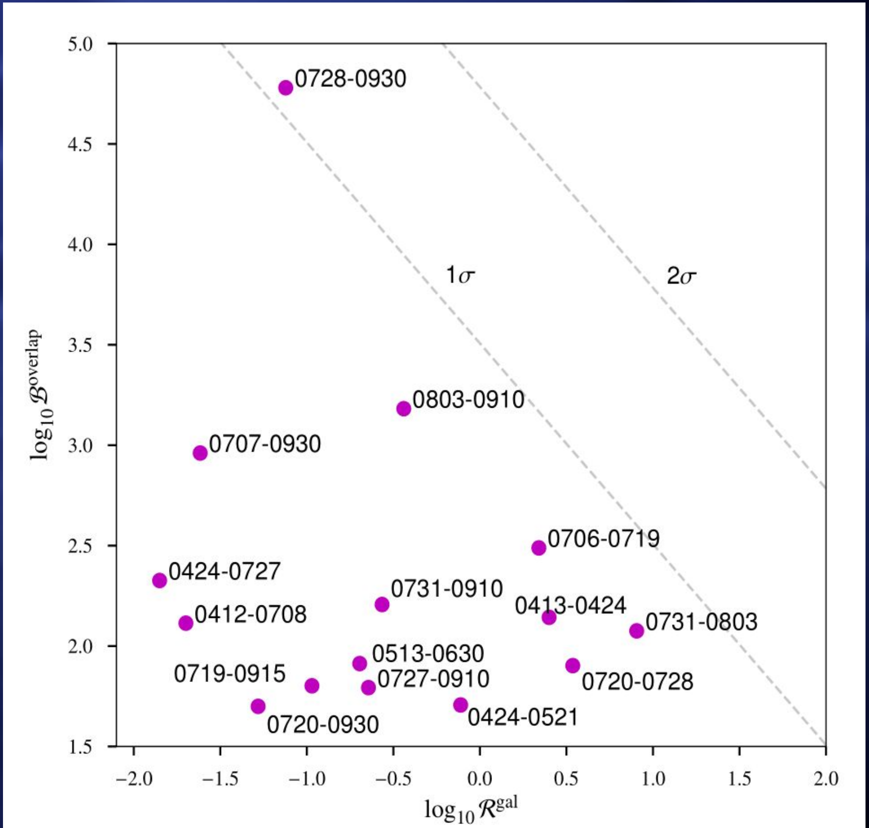
- identify most promising pair candidates (by parameter consistency) using **fast** posterior-overlap method
- **lensed vs. unlensed hypothesis** for a selected pair of signals:

$$\mathcal{B}^{\text{overlap}} = \int \mathrm{d}\Theta \, \frac{p(\Theta|d_1)\, p(\Theta|d_2)}{p(\Theta)}$$

- also considering time delay for (galaxy-)lensed pairs vs. random coincidences:

$$\mathcal{R}^{\text{gal}} = \frac{p(\Delta t|\mathcal{H}_{\text{SL}})}{p(\Delta t|\mathcal{H}_{\text{U}})}$$

- no significant candidates by these two stats combined
- identified the **19 most promising** candidate pairs by B^{overlap} to follow up with more complete joint parameter estimation



III.B joint parameter estimation

- for 19 events with high posterior overlap
- joint Bayesian parameter estimation of the combined data sets with matching intrinsic parameters and sampling in the magnification, time delay and Morse phase
- compared against individual per-event runs with independent intrinsic parameters

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

magnification time delay Morse phase

LALInference-based pipeline [Liu+2020]

- aligned-spin quadrupole waveform (IMRPhenomD, 11 parameters)
- Morse phase equivalent to shift in coalescence phase
- one run per possible phase shift (image type)
- also applied to O1+O2 events

bilby-based *hanabi* pipeline [Lo&Magaña2021]

- higher modes + precession included (IMRPhenomXPHM waveform, 15 parameters)
- Morse phase added in frequency domain
- sampling over image types
- includes source and lens population priors
- includes selection effects

III.C search for sub-threshold lensed images

- strongly lensed events could have **fainter counterparts** not yet identified in wide parameter space searches
- targeted searches can **reduce the noise background** thanks to a smaller trials factor
  when only looking for lensed waveforms that are identical up to the 3 points discussed before:

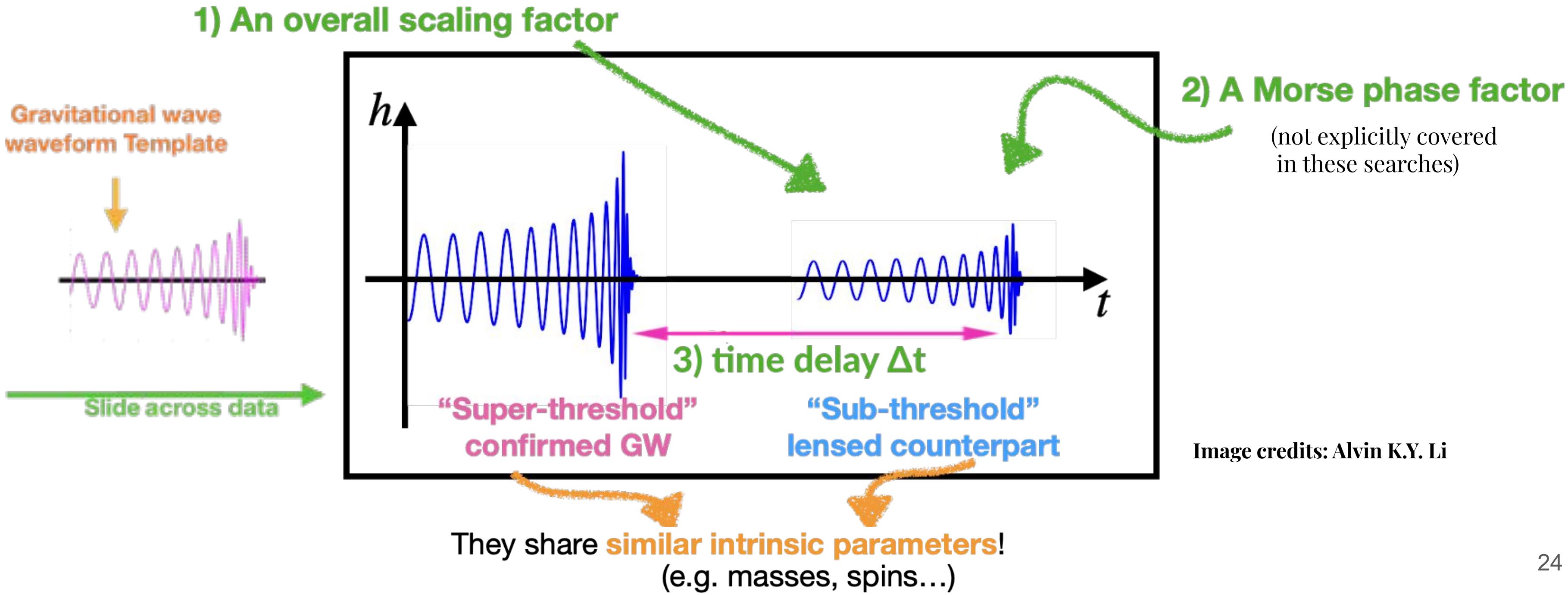
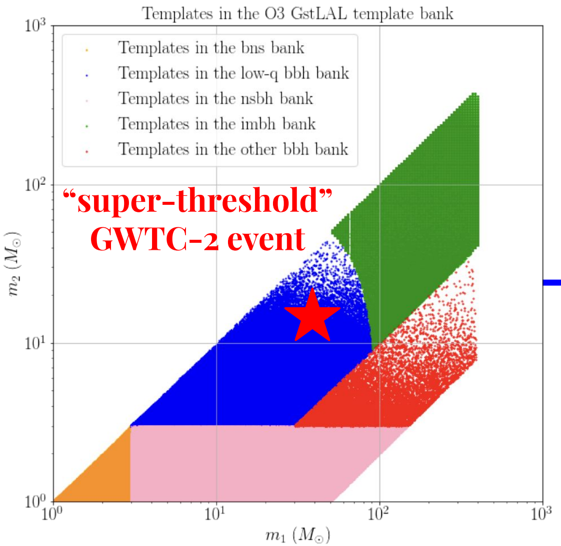


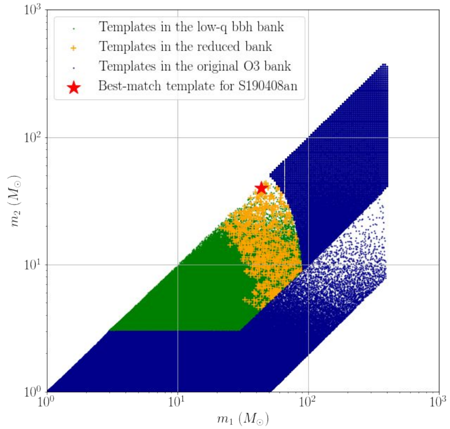
Image credits: Alvin K.Y. Li

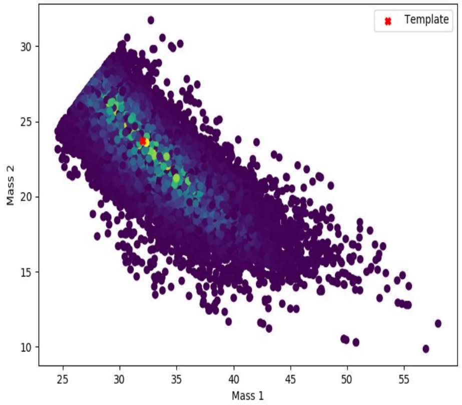
III.C search for sub-threshold lensed images

two matched-filter pipelines based on those already used in GWTC-2, two different targeted search strategies



created based on Table II of GWTC-2





1) GSTLAL lensing search

- based on GSTLAL pipeline [Sachdev+2019; Hanna+2020; Messick+2017]
- lensing adaptation following Li+2019
- **targeted template banks** based on recovery of injections with parameters drawn from GWTC-2 posterior samples

2) PyCBC lensing search

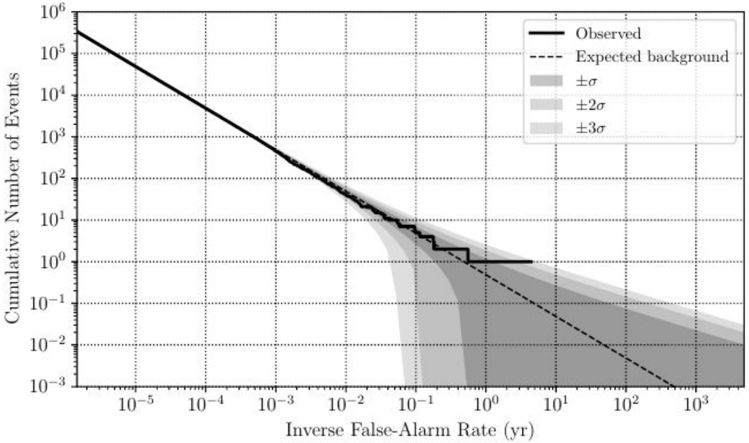
- based on PyCBC pipeline [Allen+2012; Allen+2005; DalCanton+2014; Usman+2016; Nitz+2017]
- lensing adaptation following McIsaac+2019
- **a single template** per target (max-posterior of GWTC-2 samples)

figures for illustrative purposes only

III.C Search for sub-threshold lensed images

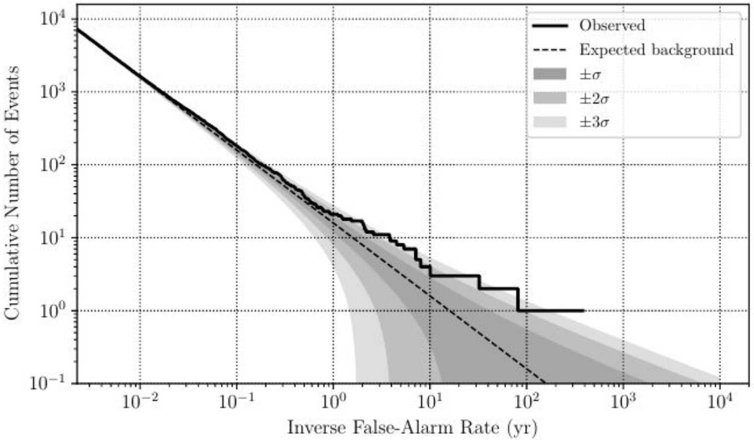
- each pipeline: 39 searches targeted at each of the GWTC-2 events
- combined search results for each pipeline:
  - excluding triggers corresponding to known GWTC-2 events
  - estimated background accounts for trials factor from analysing the data set multiple times

1) GSTLAL results



- FARs from search using combined version of the 39 template banks
- background from non-coincident noise triggers

2) PyCBC results



- FARs from the individual searches
- for repeated triggers: inverse FARs summed
- background from time-shifted data

- from both pipelines: ***slight observed excess at low FARs*** (high inverse FARs)

III.C Search for sub-threshold lensed images

- pure noise: ~2 events expected at FAR < 1/16 yr from combining 39 searches of 2 pipelines
- ***8 new triggers found with FAR < 1/16 yr*** (6 of them unique)
- 6 candidate pairs followed up with LALInference joint PE ***assuming the triggers are astrophysical*** (we did not calculate a p_{astro} here for whether they are!)
- some pairs *consistent* with shared parameters, but compared with results shown before for GWTC-2 pairs, the obtained C^{L}_{U} give ***no evidence*** for lensed pairs

UTC time	GWTC-2 targeted event	$\|\Delta t\|$ [d]	$(1+z)\mathcal{M}$ $[M_\odot]$	FAR $[\mathrm{yr}^{-1}]$ PyCBC	FAR $[\mathrm{yr}^{-1}]$ GstLAL	$O_{90\%\mathrm{CR}}$ [%]	$\log_{10} C^{L}_{U}$ (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)

- last pair (highest C^{L}_{U}) has $\log_{10}(\mathcal{B}^{L}_{U}) = -3.2$ from Hanabi

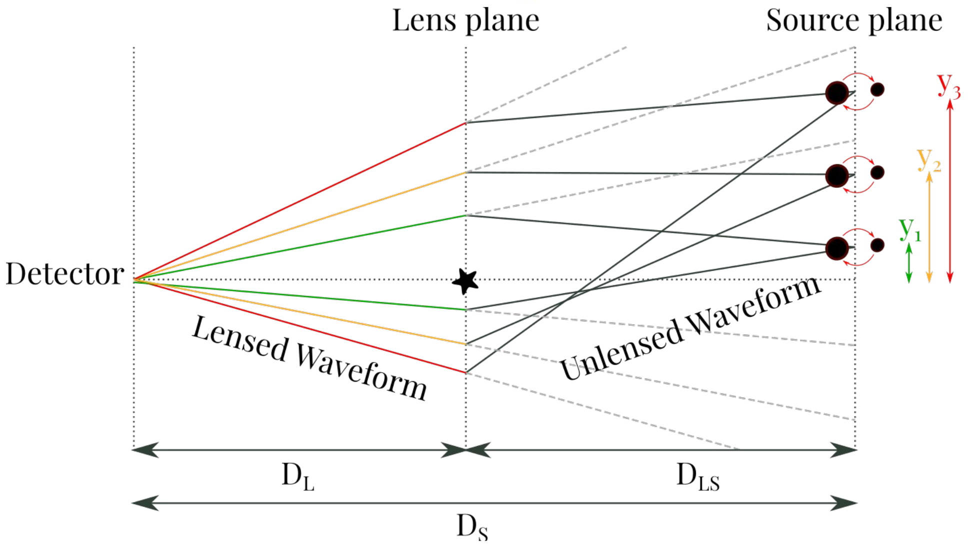
IV. Microlensing search

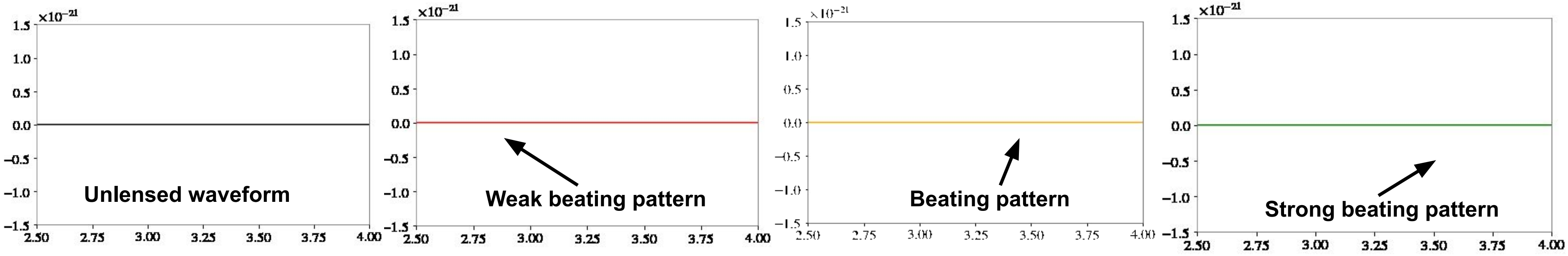
- Microlenses which are comparable to the GW wavelength can modulate the waveforms by ***frequency-dependent amplification factors*** which are a function of redshifted lens mass and source position:

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

- Lensed images with time delays shorter than the chirp time of the signal superpose to create ***beating patterns*** which are more significant when the GW passes closer to the lens (ie. smaller ***y***).

3 microlens systems with same M_L^z and different source positions





IV. Microlensing search

- Investigate lensing signatures due to **isolated point mass lens** on O3a events by calculating Bayes' factors between the two (lensed & unlensed) hypotheses.

Results:

- For none of the events are the M_L^z posteriors well recovered, no high Bayes' factors.
- Bayes factors for all events within the statistical fluctuations expected for unlensed events.
- **No microlensing effect observed.**