What could machine learning do for finding gravitationally lensed GWs?

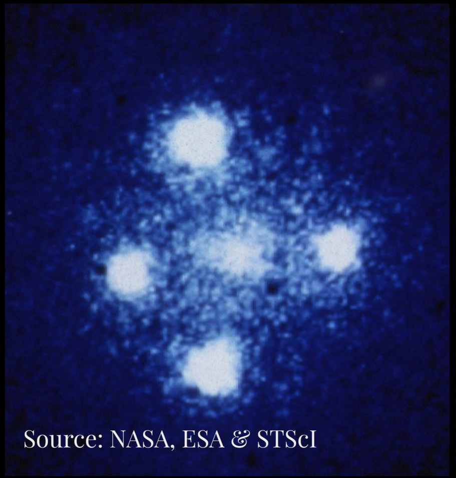
David Keitel
(Universitat de les Illes Balears / IAC3)

COST action CA17137 G2Net WG1 meeting,
Valencia, 2022/04/13

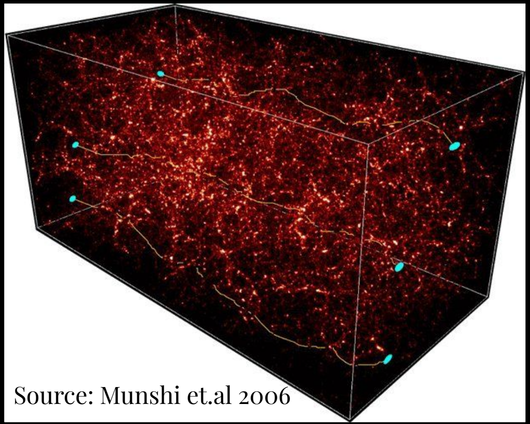
https://dcc.ligo.org/G2200631-v2

background image credits:
R. Buscicchio, LIGO/Virgo

Gravitational lensing of light



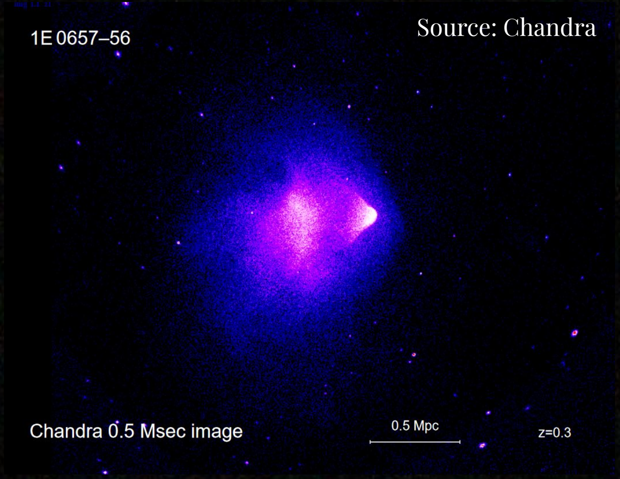
Source: NASA, ESA & STScI



Source: Munshi et.al 2006

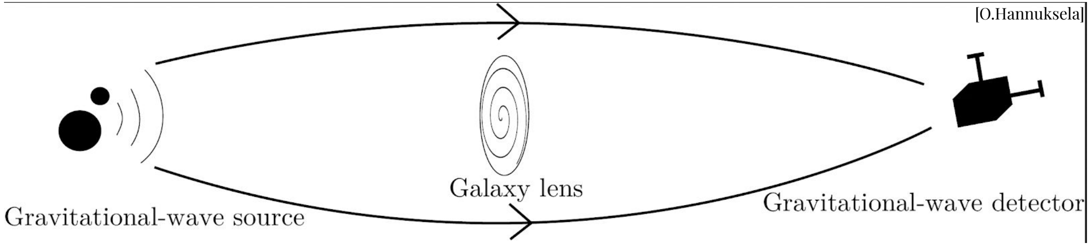
Source: NASA

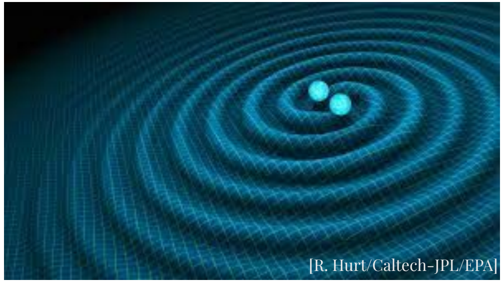
an exceptionally productive tool across many domains of astrophysics and cosmology



Source: Chandra

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

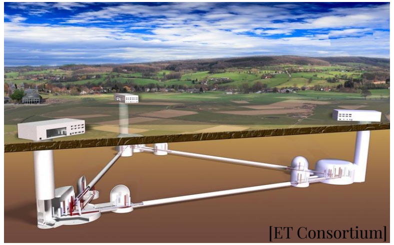
[references at the end]

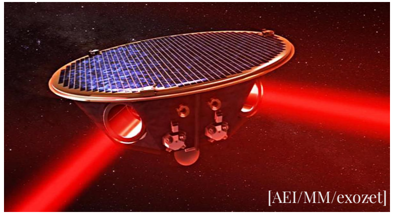
example science cases in the literature:

- 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]

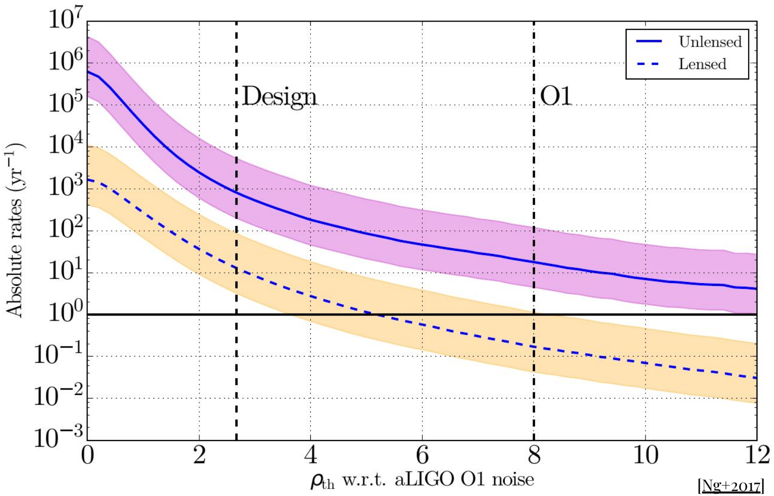
- large expected lensed event rates
- potential for precision cosmography

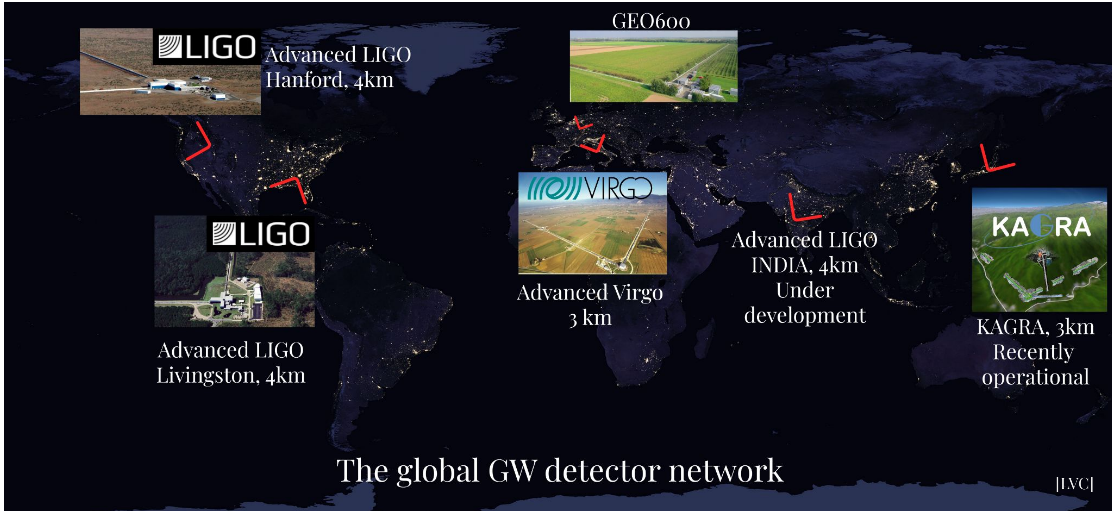




Why is GW lensing exciting (*now*)?

- sensitivity of global GW detector network increases rapidly
- more sites getting added





- recent forecasts predict strong lensing at a reasonable rate at LVK design sensitivity

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

- interest in the community has grown rapidly
- some intriguing candidates from O1-O2, but no generally recognised evidence

[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

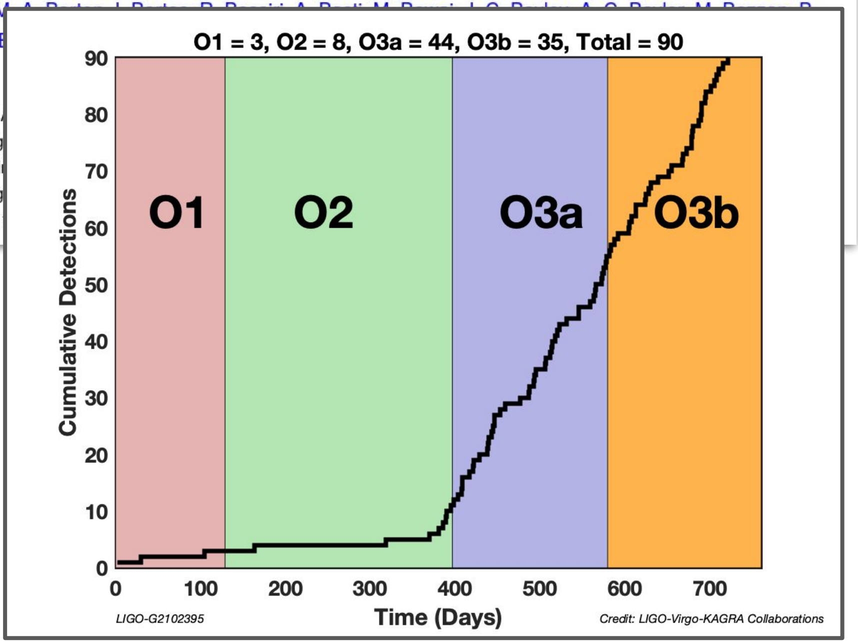
General Relativity and Quantum Cosmology

[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

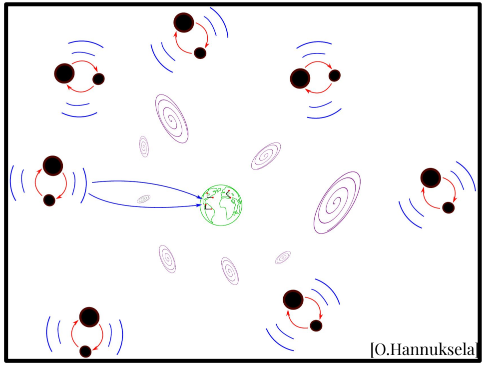
The LIGO Scientific Collaboration, the Virgo Collaboration: R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, A. Adams, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, D. Agarwal, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, K. M. Aleman, G. Allen, A. 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
Bécsy, V. M. Bedakihale, M. Bejger, I. Belahcene, V. Benedetto, D. Beniwal, M. G. Benjamin, T. F. Bennett, J. D. B
(1279 additional authors not shown)

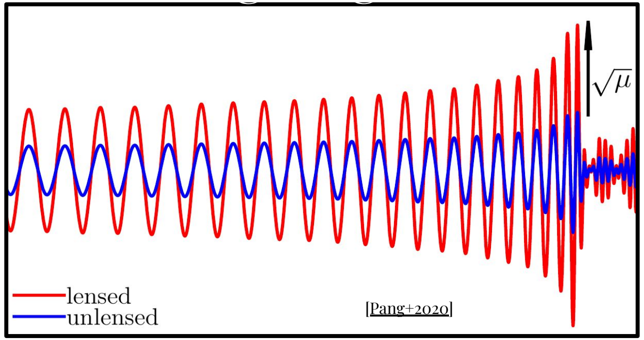
We search for signatures of gravitational lensing in the gravitational-wave signals from compact binary coalescences detected by
expected rate of lensing at current detector sensitivity and the implications of a non-observation of strong lensing or a stochastic g
individual high-mass events would change if they were found to be lensed; 3) the possibility of multiple images due to strong lensi
pairs of signals in the multiple-image analysis show similar parameters and, in this sense, are nominally consistent with the strong
against lensing, these events do not provide sufficient evidence for lensing. Overall, we find no compelling evidence for lensing in

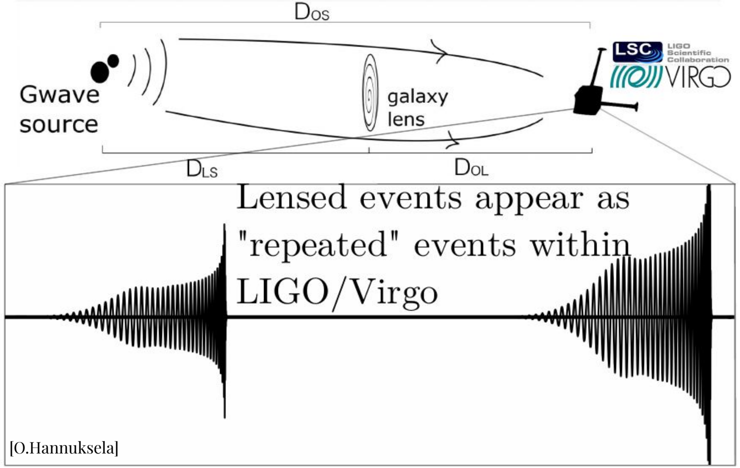


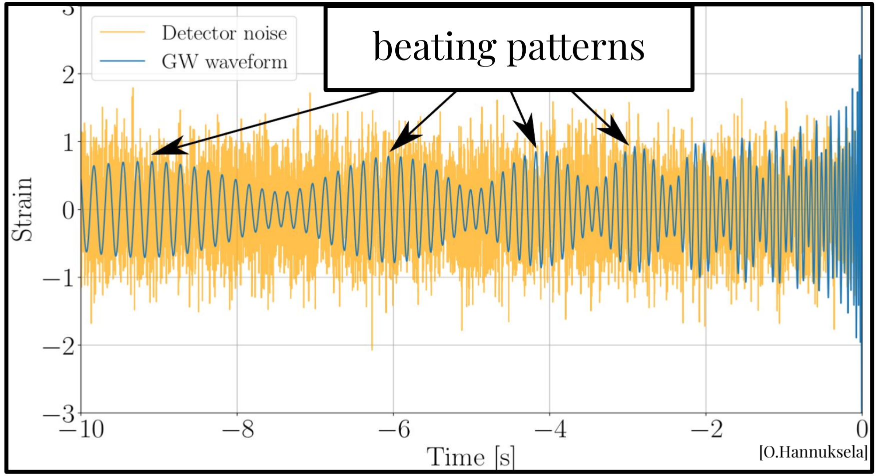
- arxiv.org/abs/2105.06384
- Astrophysical Journal 923:14 (2021)
- focuses on the ***39 events from O3a*** in GWTC-2
- O3b LVK analysis: coming!

1st LVC study on GW lensing









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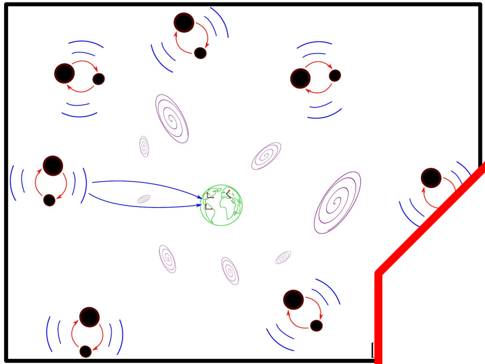
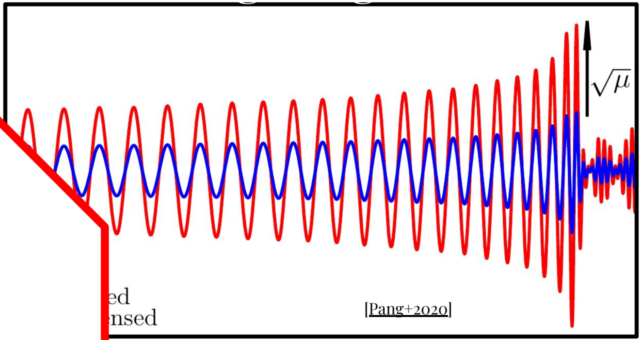
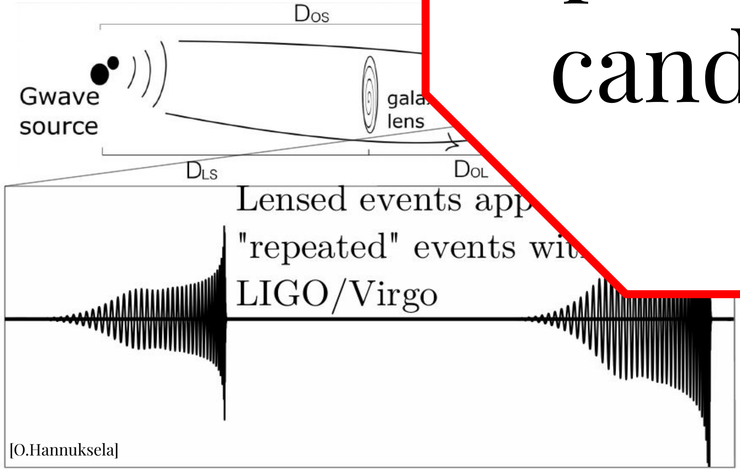
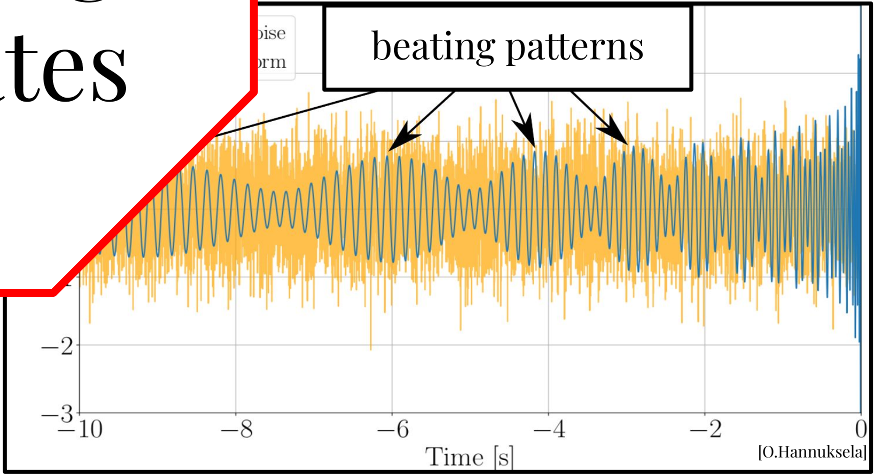


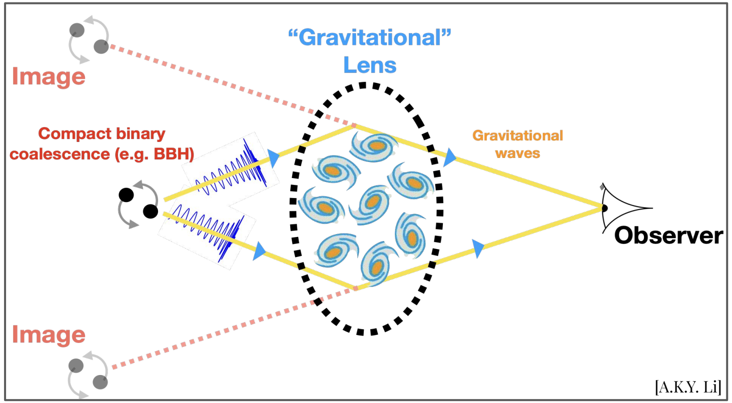


no promising candidates



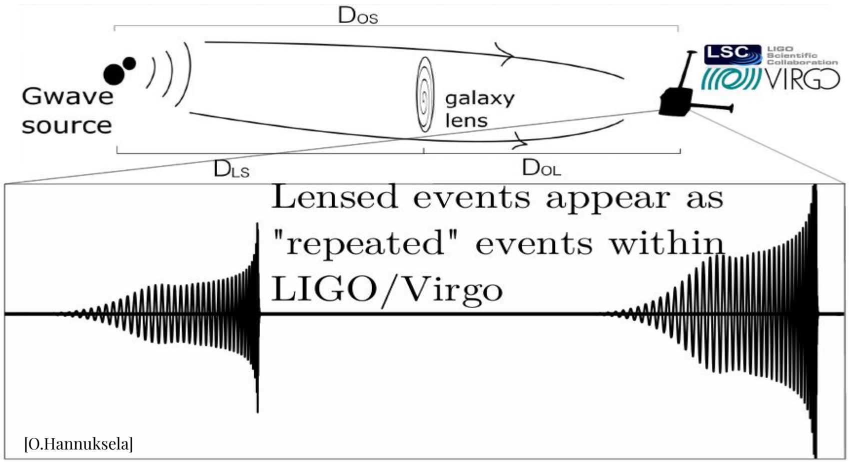


strong lensing: multiple images



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

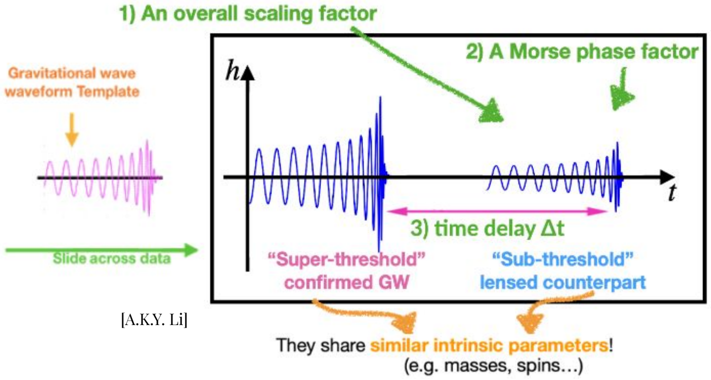
magnification time delay Morse phase



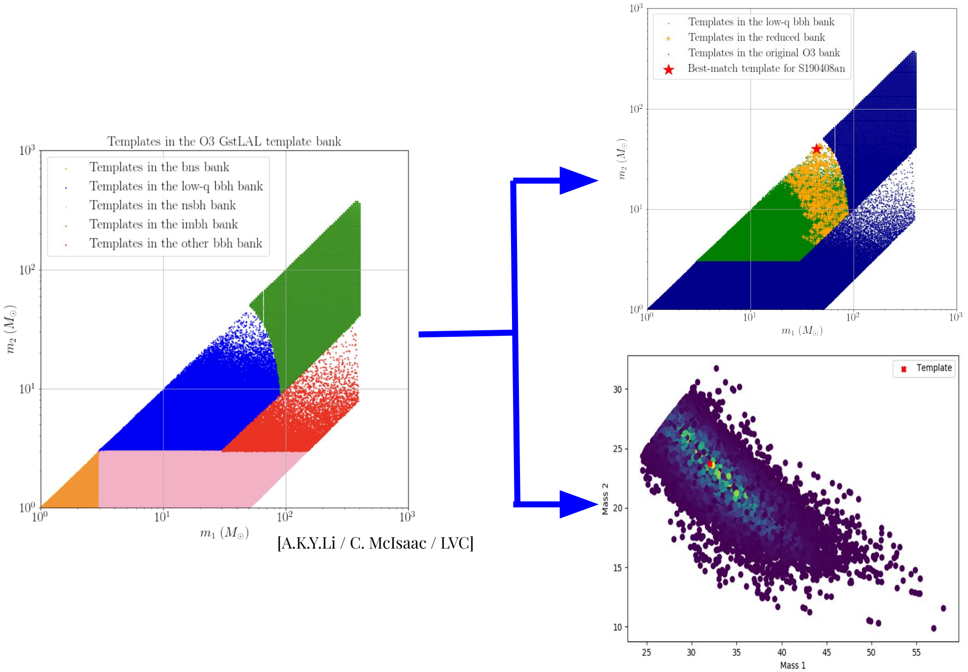
- inferred luminosity distance and coalescence time different for lensed images of same event
- intrinsic parameters (masses, spins) should be the same
- phase shift depends on type I/II/III images
- original method to identify promising pair candidates: KDE-based ***posterior-overlap method*** [Haris+2018]
- For N events in a catalog, have to check N(N-1)/2 pairs.
  ↠ ever bigger "needle in the haystack" problem!

search for sub-threshold lensed images

- GWTC events could have **faint lensed counterparts** not found before
- two LVK matched-filter pipelines [Li+ 1904.06020, McIsaac+1912.05389], using targeted template banks based on GWTC events
- independent approach by Dai+ 2007.12709



[A.K.Y. Li]

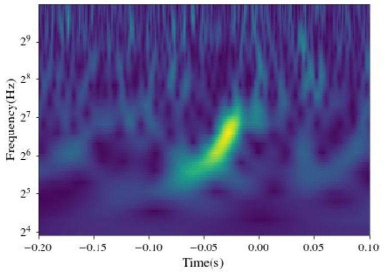


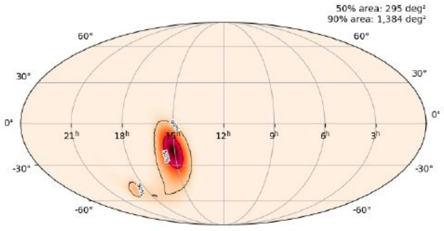
[A.K.Y.Li / C. McIsaac / LVC]

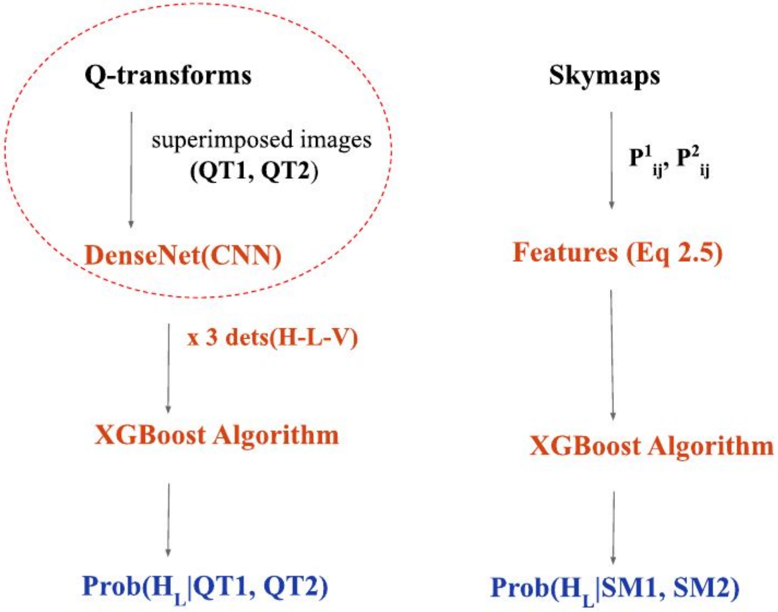
- **GSTLAL-based**: targeted template banks based on recovery of injections with parameters drawn from GWTC posterior samples
- **PyCBC-based**: single template per target (max-posterior of GWTC samples)
- Reasonably cheap, but with great catalogues comes great increase in cost.
- Original procedures don't consider actual lensing effects, template placement not optimised.

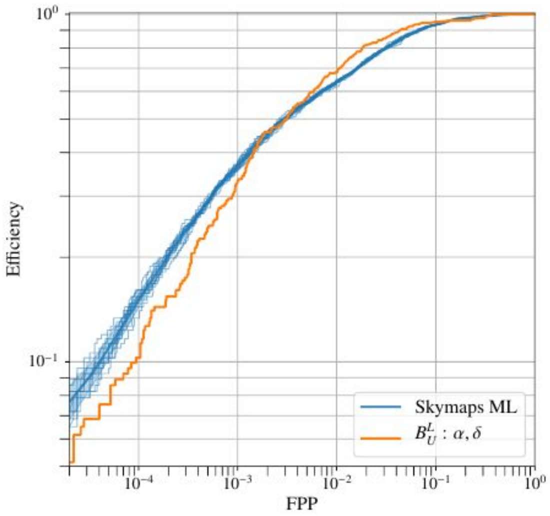
ML to identify multiple images

- need to address the N(N-1)/2 growth of the number of pair candidates
- pretrained ML classifiers can efficiently go through large sets, maybe even low latency (↣ enable EM followup)
- first proposed implementation: Goyal+ [2106.12466]









ML to identify multiple images

open challenges for pair candidate ranking:

- use full information available in original timeseries data
- robustness across parameter space
- ideal performance at different false alarm/dismissal working points
- low-latency implementations

ML for sub-threshold searches?

- "classical + ML" hybrid pipeline:
  ML-optimised ranking statistics trained on realistic GW and lens populations

- "pure ML" pipelines:
  trained on-the-fly on newly catalogued events?

strong lensing: joint parameter estimation

- Proper answer for "lensed copies of a single event?" requires analysing the two data sets *jointly*:

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

magnification time delay Morse phase

  - joint Bayesian PE with matching intrinsic parameters and sampling the magnification, time delay and Morse phase
  - Bayes factor against per-event runs with independent parameters

LALInference-based pipeline [Liu+ 2009.06539]

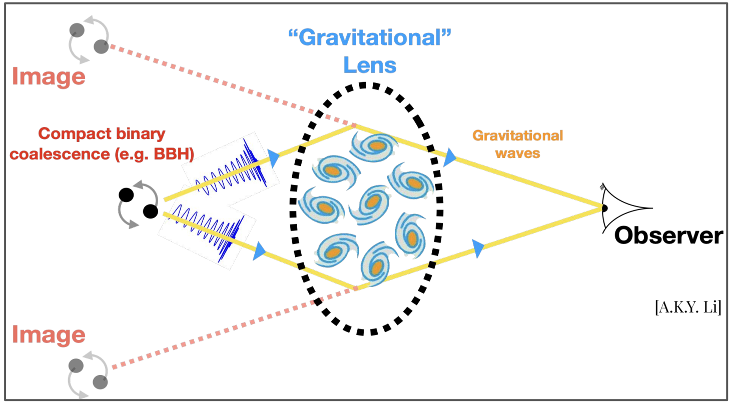
- aligned-spin quadrupole waveform (IMRPhenomD, 11 parameters)
- Morse phase = shift in coalescence phase
- one run per possible phase shift (image type)

bilby-based *hanabi* pipeline [Lo&Magaña 2104.09339]

- 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

- **THIS IS COMPUTATIONALLY VERY EXPENSIVE!** Runs can take weeks even with HPC parallelization.
- …though great progress with faster methods recently (e.g. Janquart+ 2105.04536)

strong lensing: waveform deformations



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

magnification   time delay   Morse phase

- 22-mode aligned-spin waveforms:
  Morse phase degenerate, no need to sample separately
- generic precessing HOM waveforms:
  deformations in the case of type-II images
  (Ezquiaga+ 2008.12814, Janquart+ 2110.06873)
- pipelines like hanabi (Lo&Magaña 2104.09339) and golum (Janquart+ 2105.04536) can take care of this

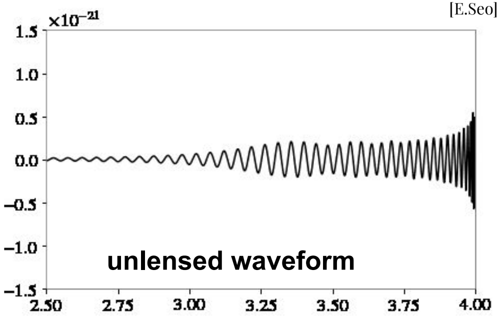
- When it gets really complicated: real world scenario of lenses with substructure…
  (e.g. Seo+ 2110.03308, Yeung+ 2112.07635)

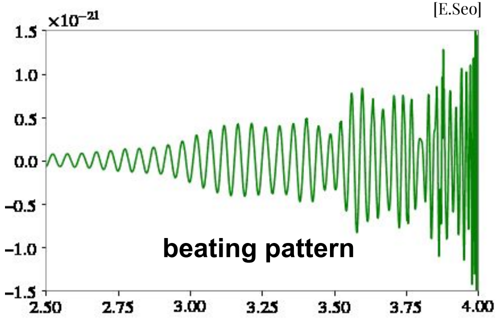
Microlensing: waveform deformations

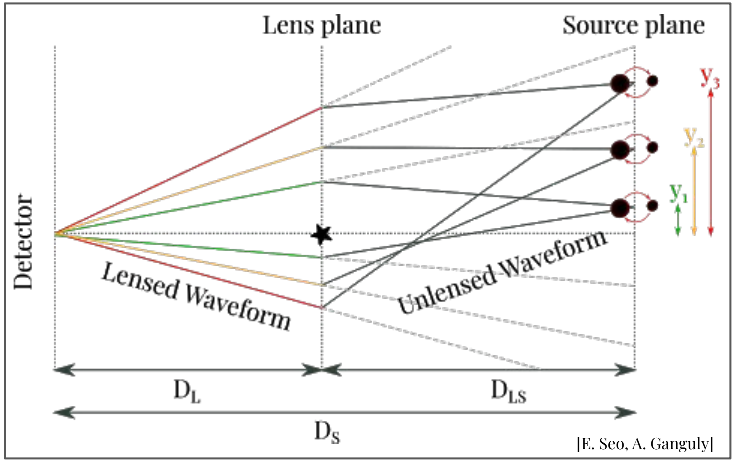
- microlenses (size ~ GW wavelength) ↠ ***frequency-dependent amplification***

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

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

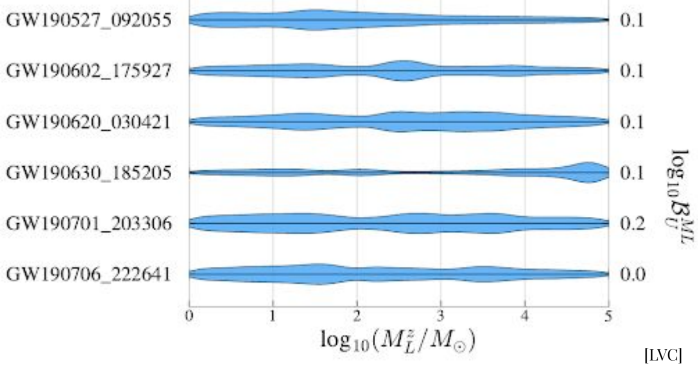






- Effects depend on density profile of the lens.
- Bayesian analysis more expensive and convergence more challenging than for unlicensed WFs (higher parameter space dimensionality).
- So far (including O3a): no microlensing effect observed.
- Really complicated: microlenses embedded in broader mass distribution.

results snippet from arXiv:2105.06384 (36 events total):



ML for lensed PE

- ML can potentially help with two interlinked challenges:
  - computational cost
  - nearly arbitrary model complexity

- “classical + ML” hybrids: ML-augmented Bayesian samplers
  - e.g. Nessai (Williams+ 2102.11056) or BilbyMCMC (Ashton+ 2106.08730)
  - challenge: adapt to high parameter space dimensionality for lensing

- “pure ML”: deep learning posterior emulation, autoecoders, simulation-based inference, and other approaches
  - e.g. Kim+ 2010.12093 for microlensing case
  - adapt Vitamin [J. Bayley talk at this meeting] and other candidates?

ML for lens modelling – learning from EM world

- ML is already huge in the EM lensing world, (survey data sets much larger than ours) ⤜ e.g.

arXiv > astro-ph > arXiv:2203.09536

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Astrophysics > Astrophysics of Galaxies

[Submitted on 17 Mar 2022]

Developing a Victorious Strategy to the Second Strong Gravitational Lensing Data Challenge

C. R. Bom, B. M. O. Fraga, L. O. Dias, P. Schubert, M. Blanco Valentin, C. Furlanetto, M. Makler, K. Teles, M. Portes de Albuquerque, R. Benton Metcalf

- *Search* and *PE* applications don't really translate to GWs, because fundamentally *we lack sky resolution*.
- But if we eventually want to extract the full physics from detected lensed events, we also require detailed *lens modelling* just like in the EM world (though again: we'll have less geometric information)
- With substructure, lens models can get almost arbitrarily complex ⤜ ML to the rescue!

arXiv > astro-ph > arXiv:2010.00602

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Astrophysics > Astrophysics of Galaxies

[Submitted on 1 Oct 2020 (v1), last revised 18 Dec 2020 (this version, v2)]

HOLISMOKES -- IV. Efficient mass modeling of strong lenses through deep learning

S. Schuldt, S. H. Suyu, T. Meinhardt, L. Leal-Taixé, R. Cañameras, S. Taubenberger, A. Halkola

arXiv > astro-ph > arXiv:2103.03257

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Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 4 Mar 2021 (v1), last revised 28 Jun 2021 (this version, v2)]

Strong lens modelling: comparing and combining Bayesian neural networks and parametric profile fitting

James Pearson, Jacob Maresca, Nan Li, Simon Dye

arXiv > astro-ph > arXiv:2012.00042

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Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 30 Nov 2020 (v1), last revised 12 Apr 2021 (this version, v2)]

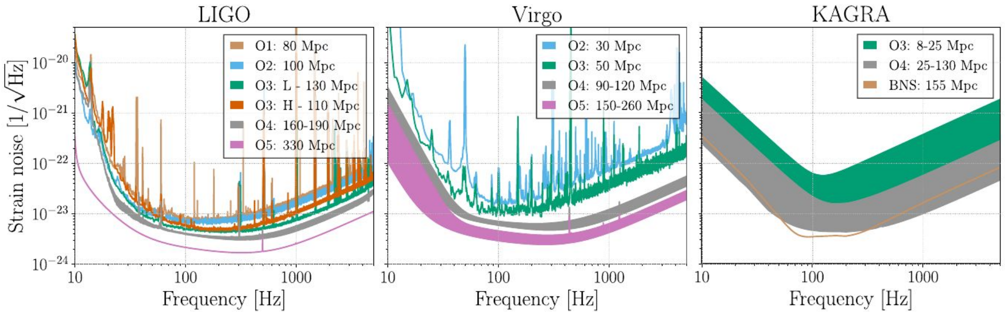
Large-Scale Gravitational Lens Modeling with Bayesian Neural Networks for Accurate and Precise Inference of the Hubble Constant

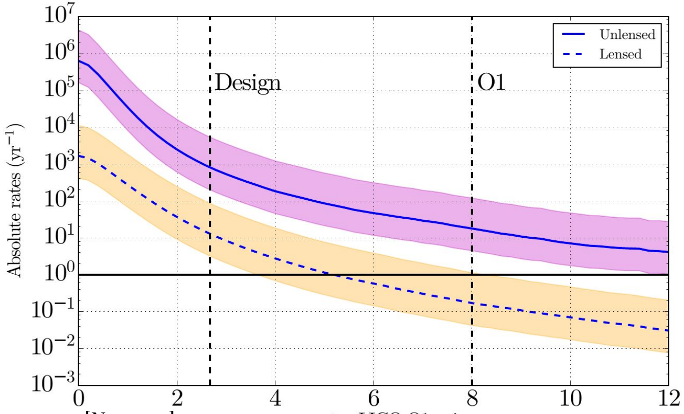
Ji Won Park, Sebastian Wagner-Carena, Simon Birrer, Philip J. Marshall, Joshua Yao-Yu Lin, Aaron Roodman (for the LSST

GW lensing: future outlook

arXiv:1304.0670v11 [LVK]

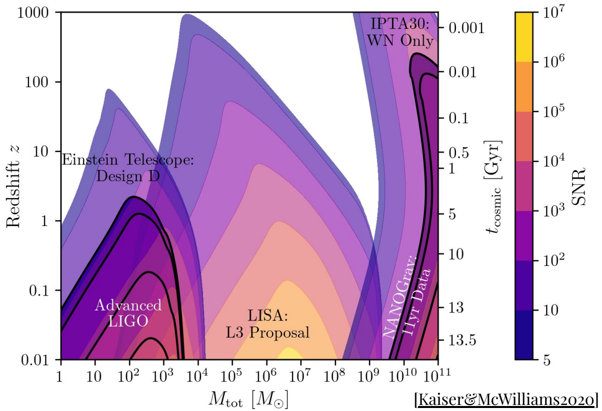
As the current GW detector network expands and its sensitivity increases, our chances to detect lensing will improve!



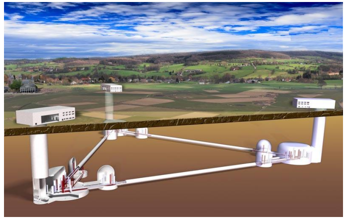


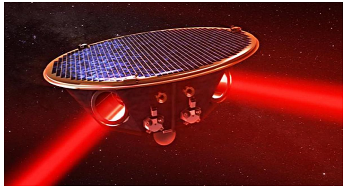
[Ng+2017]

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



[Kaiser&McWilliams2020]





detecting lensed GWs can enable:

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

GW lensing: future outlook

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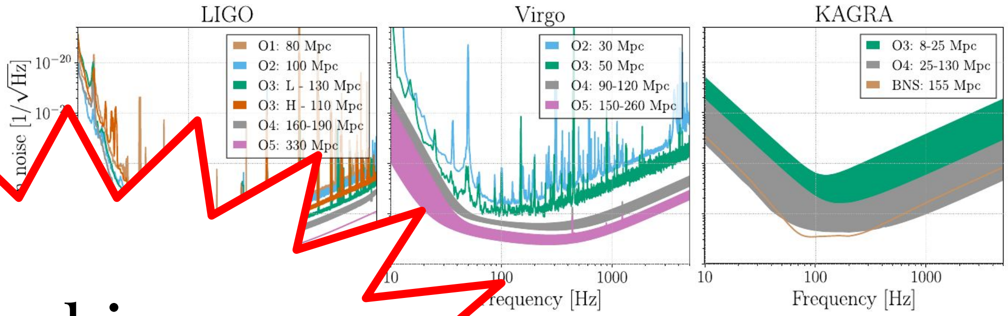
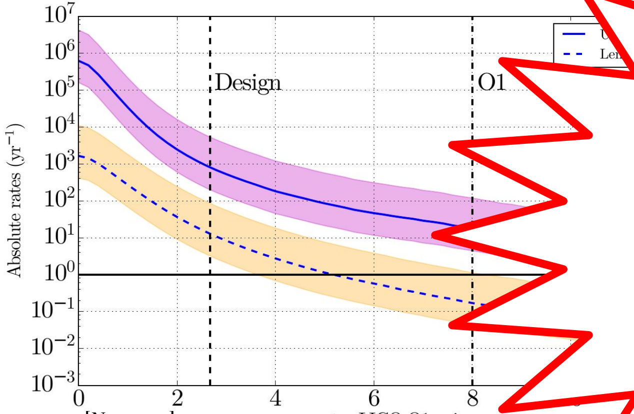
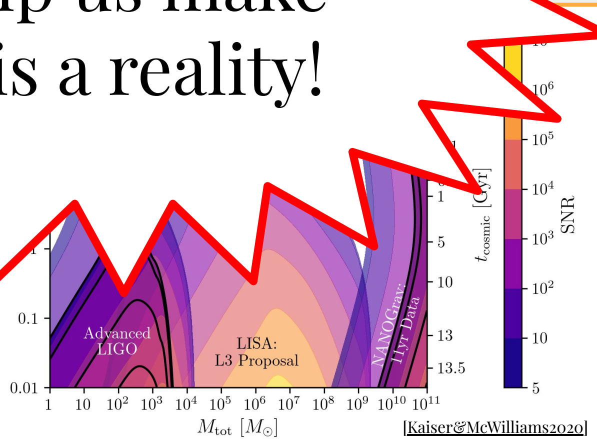


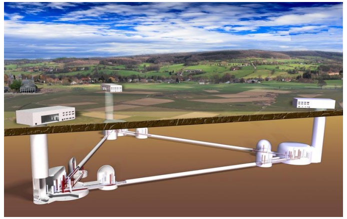


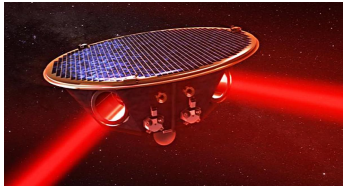
[Ng+2017]

Machine learning should help us make this a reality!



[Kaiser&McWilliams2020]





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Thank you!

I hope I left some time for questions...

acknowledgments [for the LVC: dcc.ligo.org/P21002182/public]

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