Astrophysics with GW detections
Warsaw, 2019-09-06

LIGO-G1901486-v3

Could gravitational lensing impact the observed BBH population?

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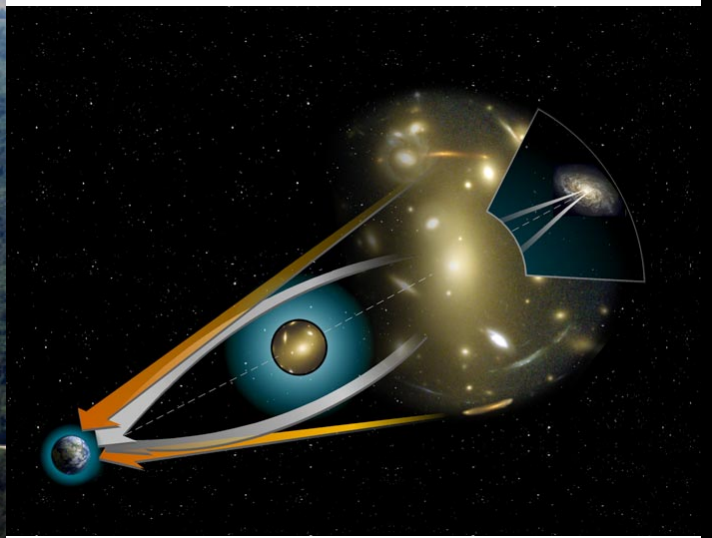
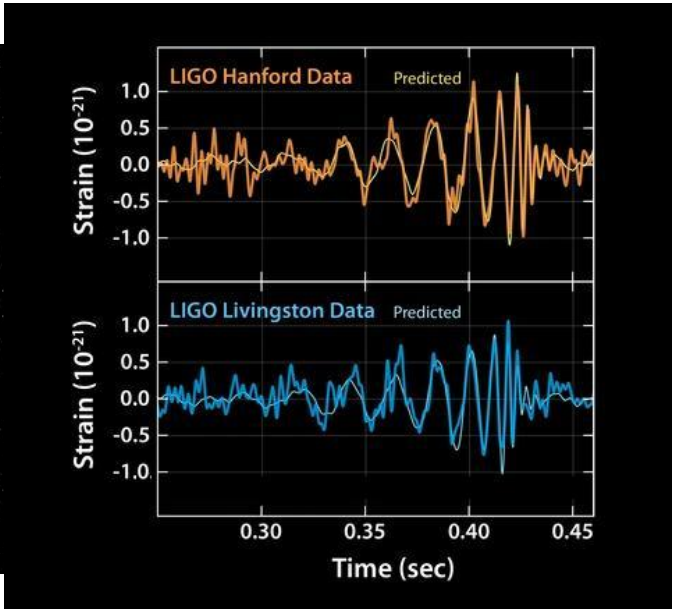
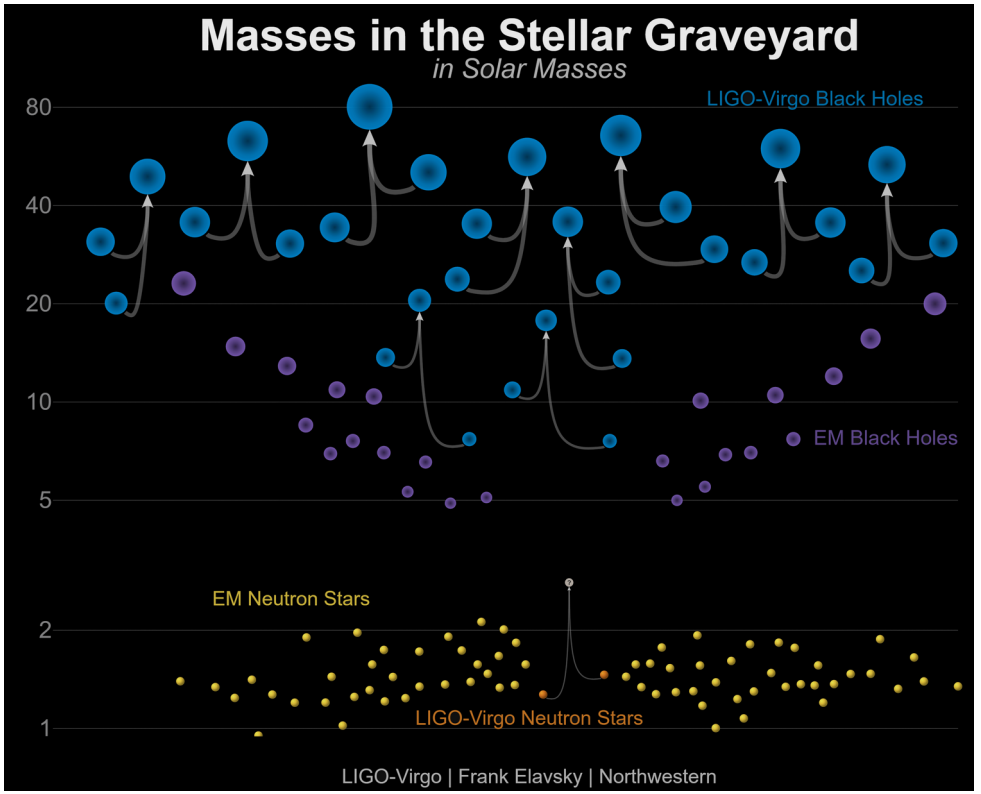
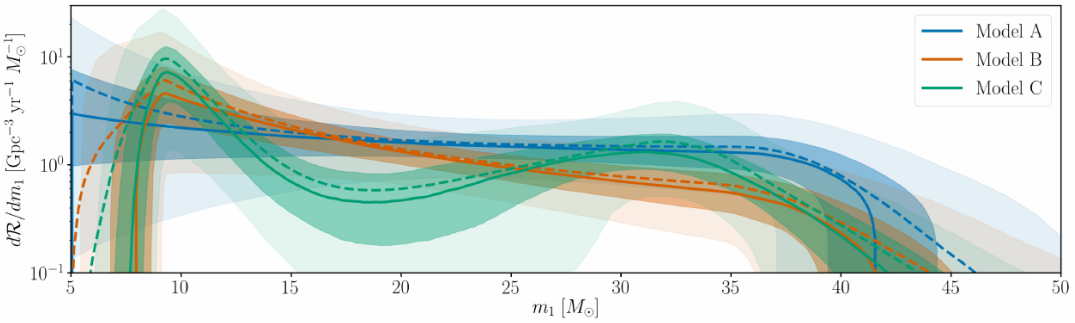


[NASA/STScI]

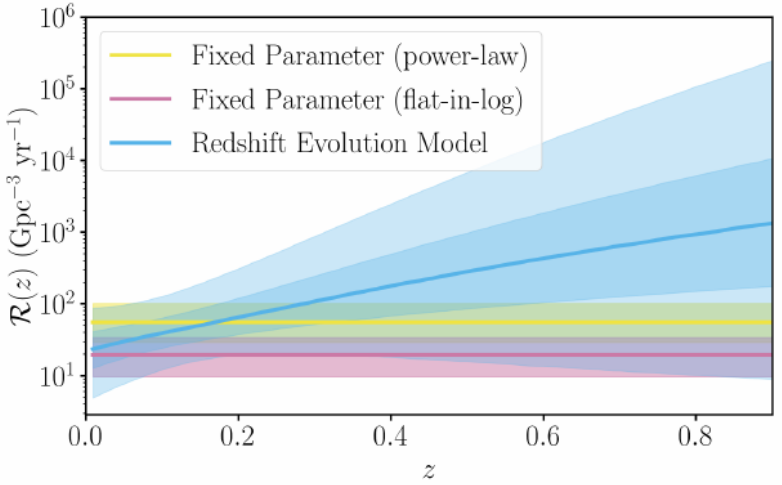


The merging BBH population so far





[arXiv:1811.12940]

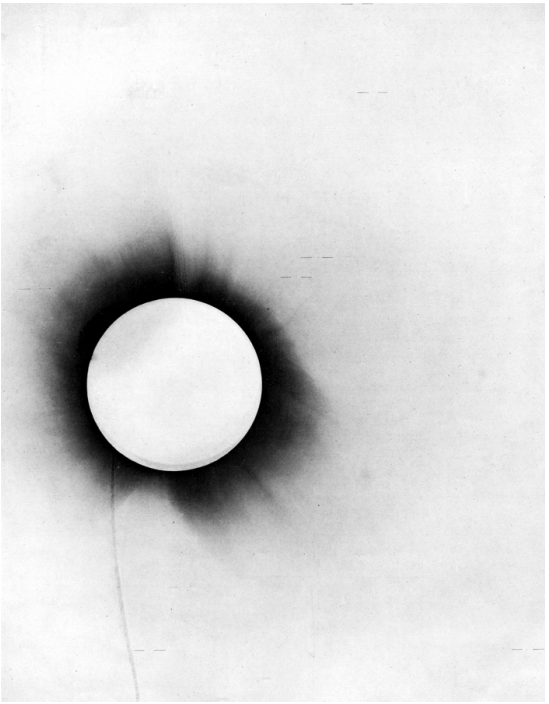


- LIGO-Virgo GWTC-1: ten BBHs from O1+O2 [arXiv:1811.12907]
- Venumadhav et al: 7 more (?) [arXiv:1904.07214]
- masses ~ 7 – 50 Msun
- distances ~ 300 Mpc – 3 Gpc (z ~ 0.05 – 0.6)
- O3 so far: > 2 dozen alerts for candidate binaries (of mysterious properties)

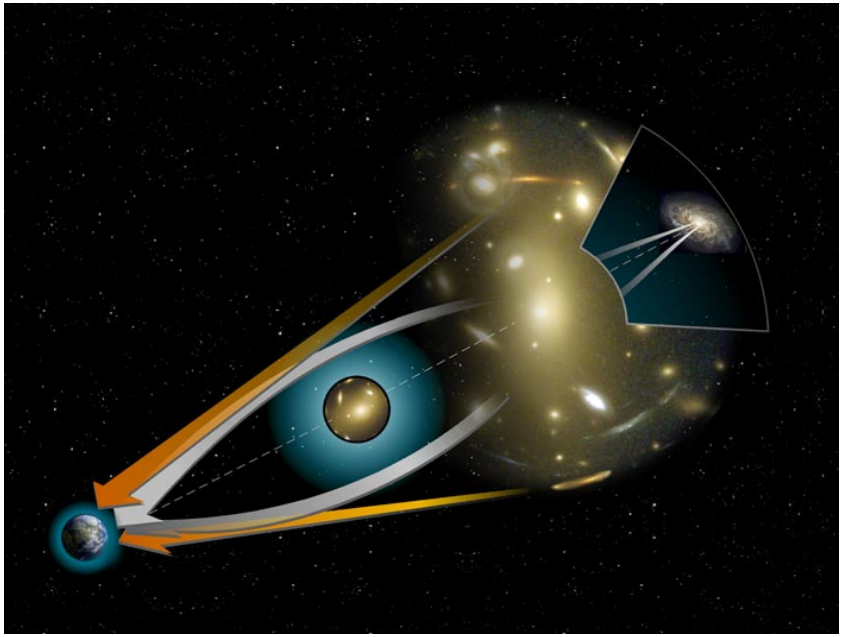
[https://gracedb.ligo.org/search/?query=public&query_type=S]

Gravitational Lensing

(of light)



- first experimental test of Einstein's GR (1919): gravitational light deflection by the sun
- Lensing of light sources at cosmological distances has become a crucial tool in observational astrophysics.
- strong lensing regime:
  - high magnifications
  - multiple images
  - significant time delays
- use as 'natural telescopes' for high-redshift sources
- Almost always: geometric optics, no frequency-dependent distortions.



Gravitational Lensing of GWs

- J.A. Wheeler: “Spacetime tells matter how to move,
  and matter tells spacetime how to curve.”

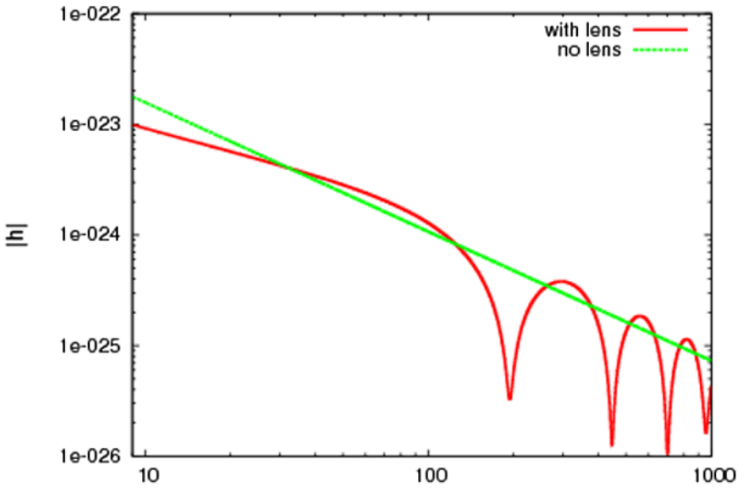
  ➔ corollary: “Matter tells gravity how to move.”

[SXS]

- GWs = propagating gravitational field excitations.
  Can be deflected by heavy masses, just like light.
- early work: e.g. Vishveshwara 1970, Lawrence 1971/73,
  Peters 1974, Ohanian 1973/74
- much focus on future detectors (Einstein Telescope, LISA)

  e.g. Takahashi&Nakamura 2003,
  Sereno+ 2010, Biesiada+2014

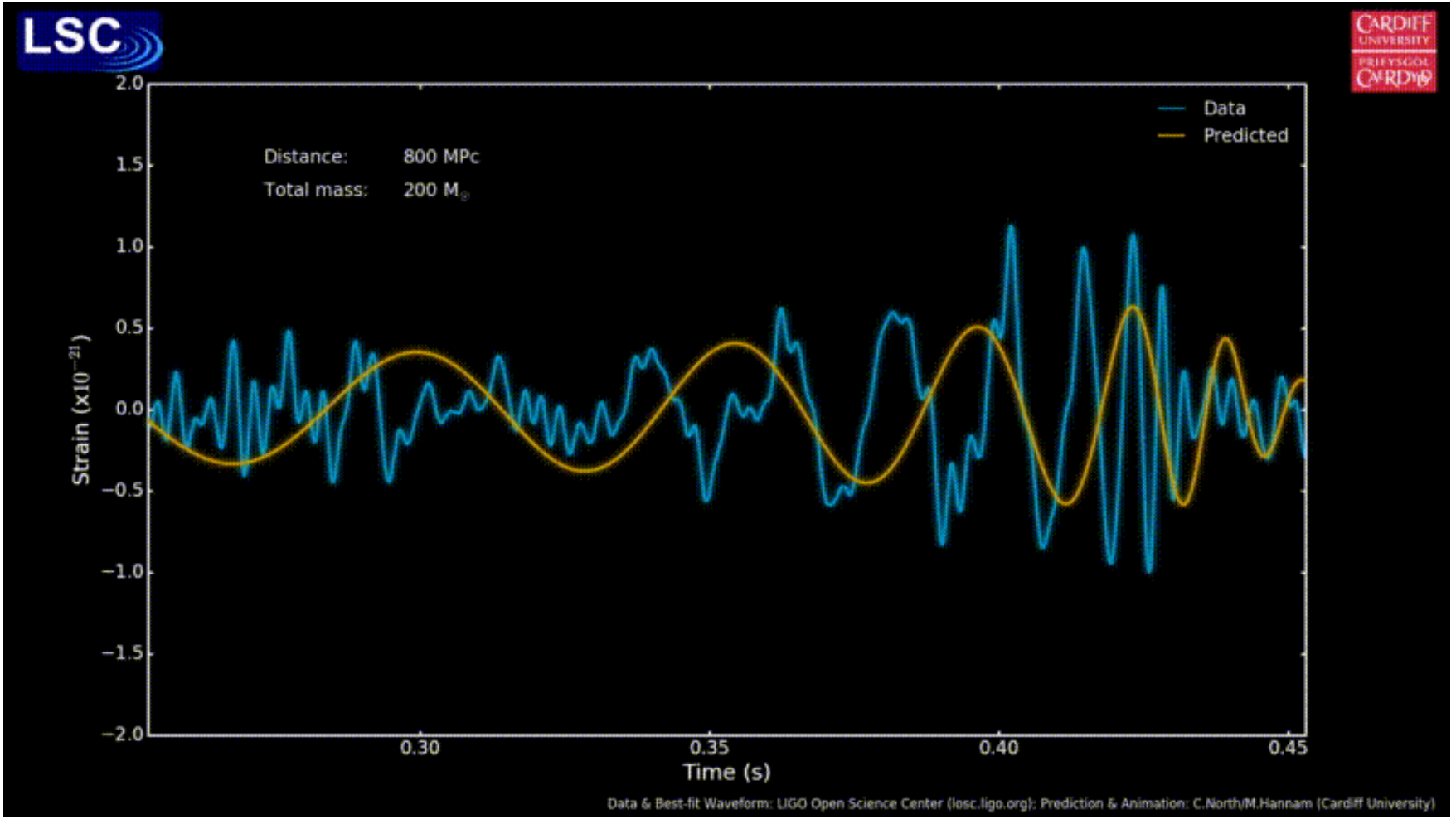
- Wave optics effects can be important!
  [e.g. Nakamura 1998]
  (IMBHs as lenses, substructure in galaxy lenses)



[Cao, Li & Wang 2014
PRD90,062003]

strong lensing of BBHs
(in the geometric limit)

- BBH parameter estimation in a nutshell:
  - phasing → chirp mass
  - amplitude at known mass → luminosity distance



strong lensing of BBHs
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- BBH parameter estimation in a nutshell:
  - phasing → chirp mass
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- if lensed: GW amplitude ~ sqrt(magnification)

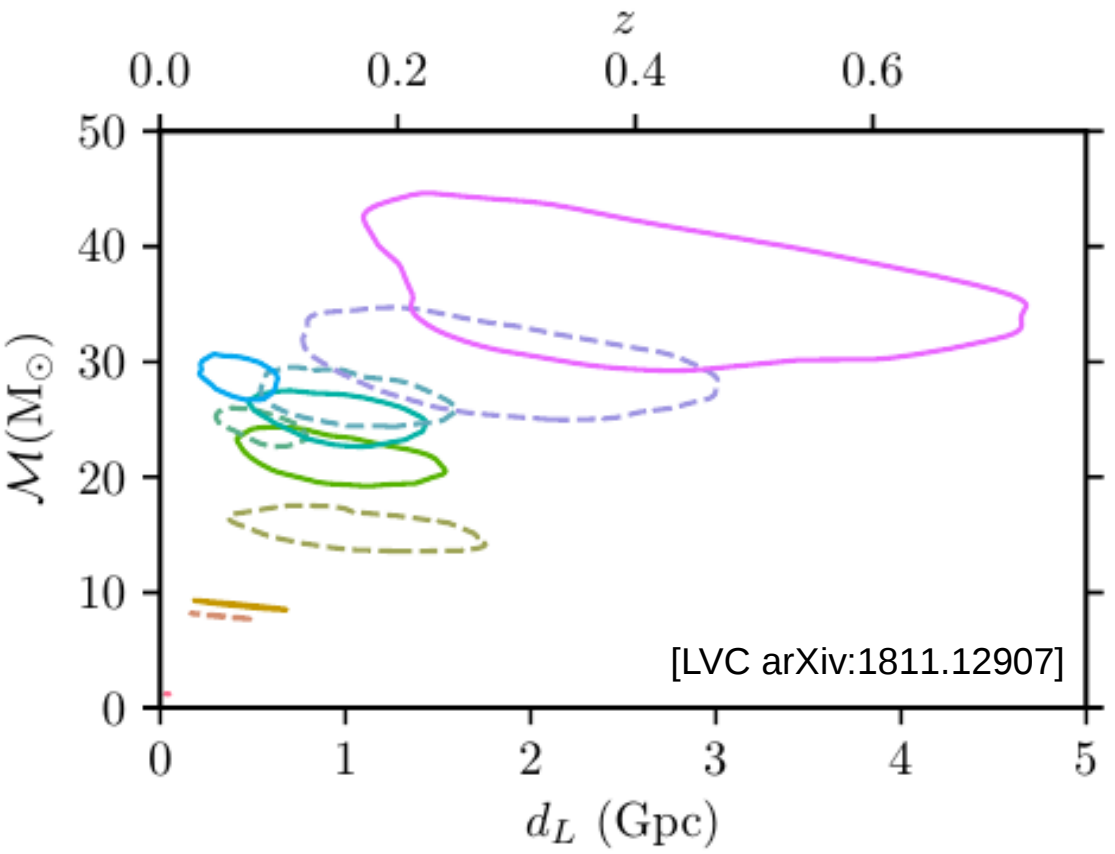
  ➔ real distance higher by sqrt(mag)
  ➔ stronger cosmological redshift

- But we have still measured the same redshifted chirp mass!

  ➔ Intrinsic BH masses would have been lower.

strong lensing of aLIGO detections?

- rich crop of LIGO-Virgo BBHs reaching up to cosmological distances



→ growing interest in lensing scenario

e.g.:

- Smith+ 2018: *"What if LIGO's gravitational wave detections are strongly lensed by massive galaxy clusters?"*
- Oguri 2018: *"Effect of gravitational lensing on the distribution of gravitational waves from distant binary black hole mergers"*

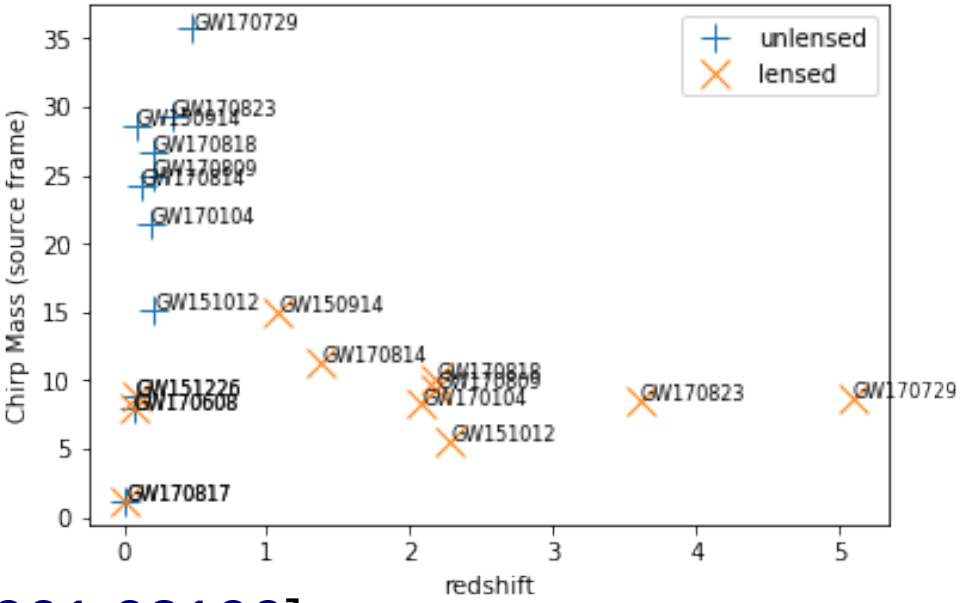
strong lensing of aLIGO detections?

- Broadhurst, Diego & Smoot [arXiv:1802.05273]:
  "Reinterpreting Low Frequency LIGO/Virgo Events as Magnified Stellar-Mass Black Holes at Cosmological Distances"

  ➔ black holes > 20 $M_\odot$ considered "puzzling"

  ➔ A lensed, more distant and lighter BBH population could produce the same detections.

  ➔ We'd have only found 1 image of each event, missing the possible counterparts.



- Broadhurst, Diego & Smoot [arXiv:1901.03190]:

  "Twin LIGO/Virgo Detections of a Viable Gravitationally-Lensed Black Hole Merger"

  ➔ claim that GW170809 and GW170814 are so similar that they could be lensed images of a single event (with intrinsic M_{chirp}~15 $M_\odot$ instead of measured ~30 $M_\odot$)

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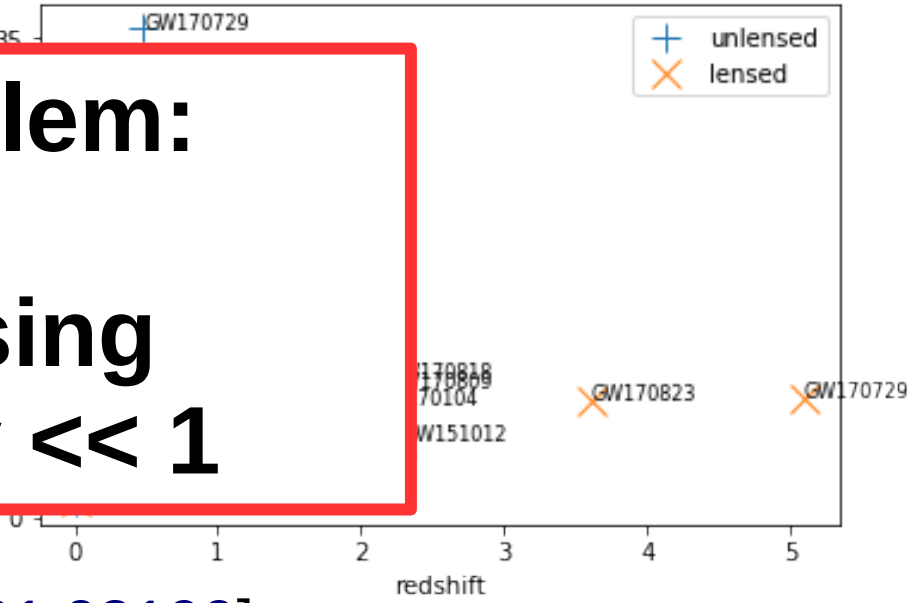
main problem:

prior lensing probability << 1



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Lensing tests on O2

- testing the Broadhurst+ claims & more generally searching for signatures of lensing in O1+O2 BBH events

arXiv.org > gr-qc > arXiv:1901.02674

General Relativity and Quantum Cosmology

Search for gravitational lensing signatures in LIGO-Virgo binary black hole events

O.A. Hannuksela, K. Haris, K.K.Y. Ng, S. Kumar, A.K. Mehta, D. Keitel, T.G.F. Li, P. Ajith

→ ApJL 874:L2

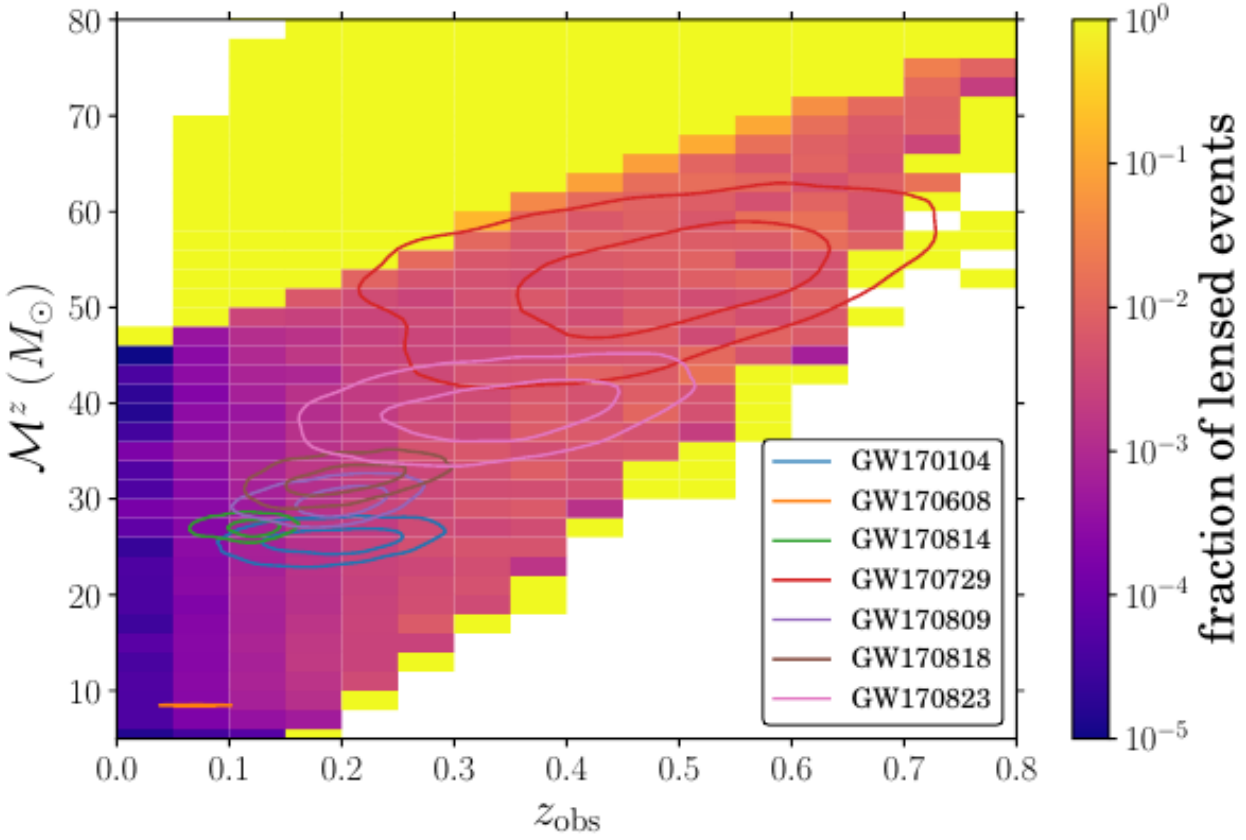
- three tests:

1) test of the observed chirp mass – redshift distribution
2) test for multiple images based on parameter overlaps
3) test for frequency-dependent wave-optics effects

Lensing tests on O2

Test 1: observed chirp mass – redshift distribution

- expected lensing rate from massive galaxies depends on BBH masses and redshifts [Oguri 2018, Ng+ 2018]
- can be compared with observed distribution



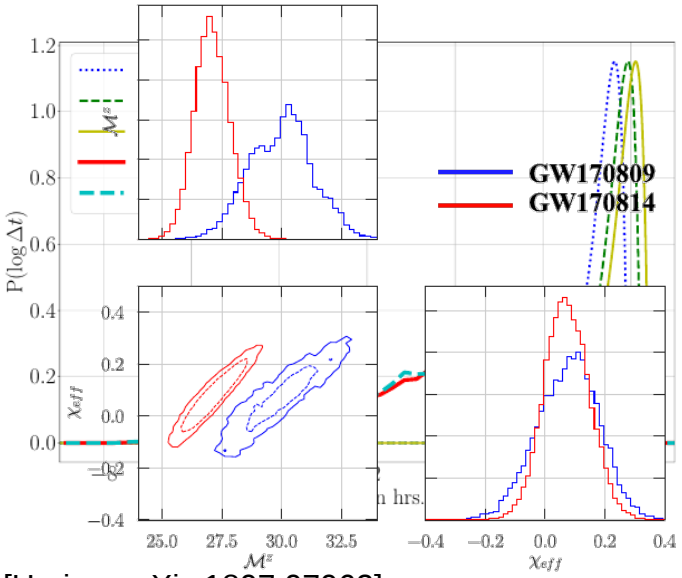
[ApJL 874:L2]

- all observed events in region of low (≤10^{-2}) lensing probability

Lensing tests on O2

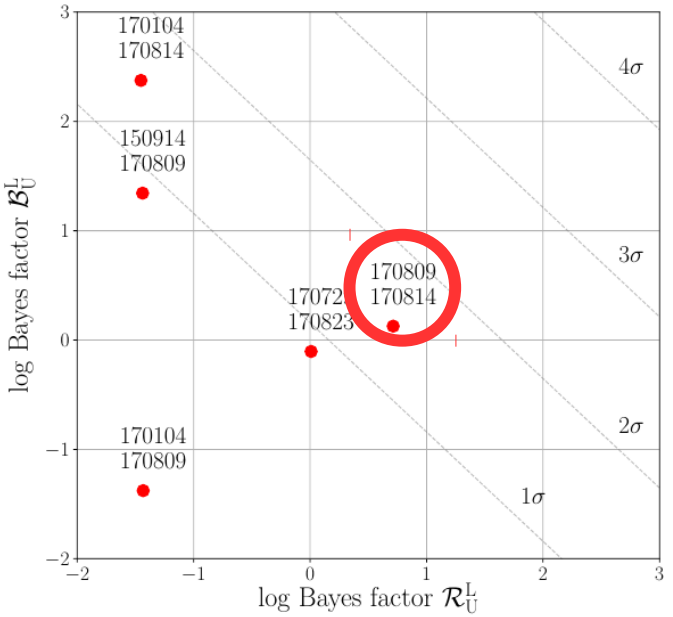
Test 2: multiple images?

- geometric limit: lensing only magnifies, no waveform distortion
  → should measure same masses & spins for each image
- deflection angles much smaller than sky resolution
- test statistic: posterior overlap over mass, spin, sky parameters
  - ➔ Bayes factor $\mathcal{B}^{\mathrm{L}}_{\mathrm{U}} := \frac{\mathcal{Z}_{\mathrm{L}}}{\mathcal{Z}_{\mathrm{U}}} = \int d\boldsymbol{\theta}\, \frac{P(\boldsymbol{\theta}|d_1)\, P(\boldsymbol{\theta}|d_2)}{P(\boldsymbol{\theta})}$ [Haris+, arXiv:1807.07062]
- extra info from time delays: more clustered for galaxy-mass lenses than unlensed (purely Poisson) events



[Haris+, arXiv:1807.07062]

result:
no evidence for lensed pairs



[ApJL 874:L2]

Lensing tests on O2

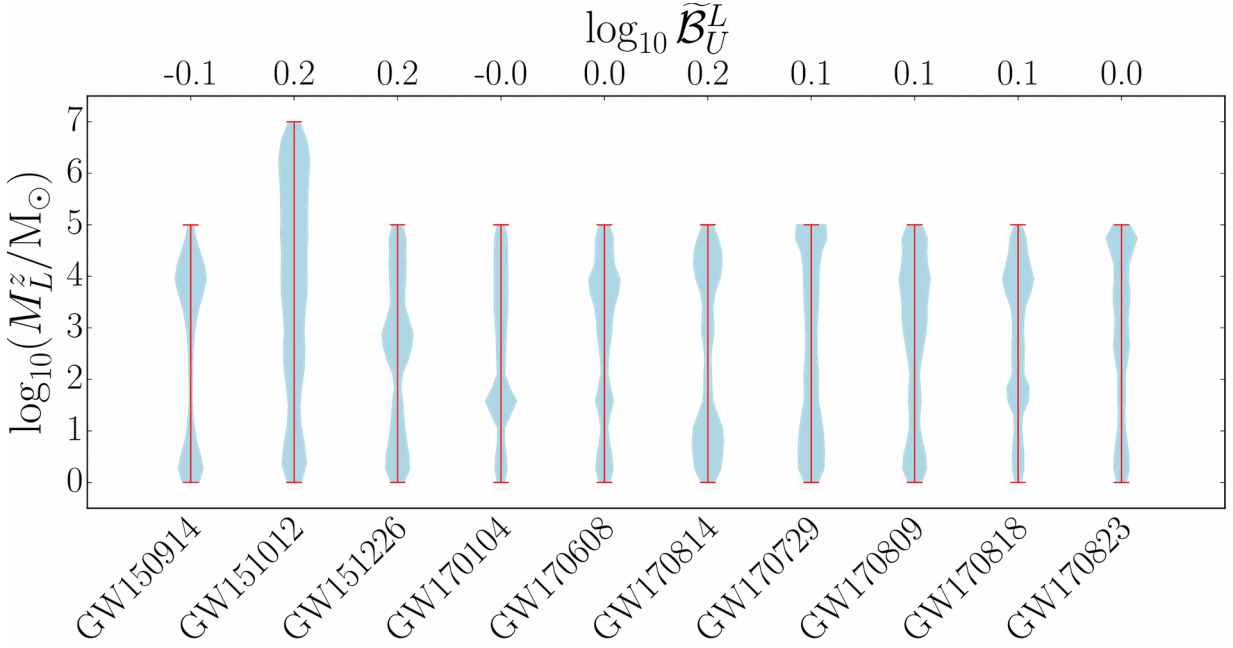
Test 3: wave optics effects?

- geometric limit breaks down for lens size ~ wavelength

  ➔ for stellar-mass BBH signals: lenses $<10^5\ M_\odot$

- search for frequency-dependent magnification from point-mass lenses

  (modified PhenomPv2 waveforms following Lai+2018)

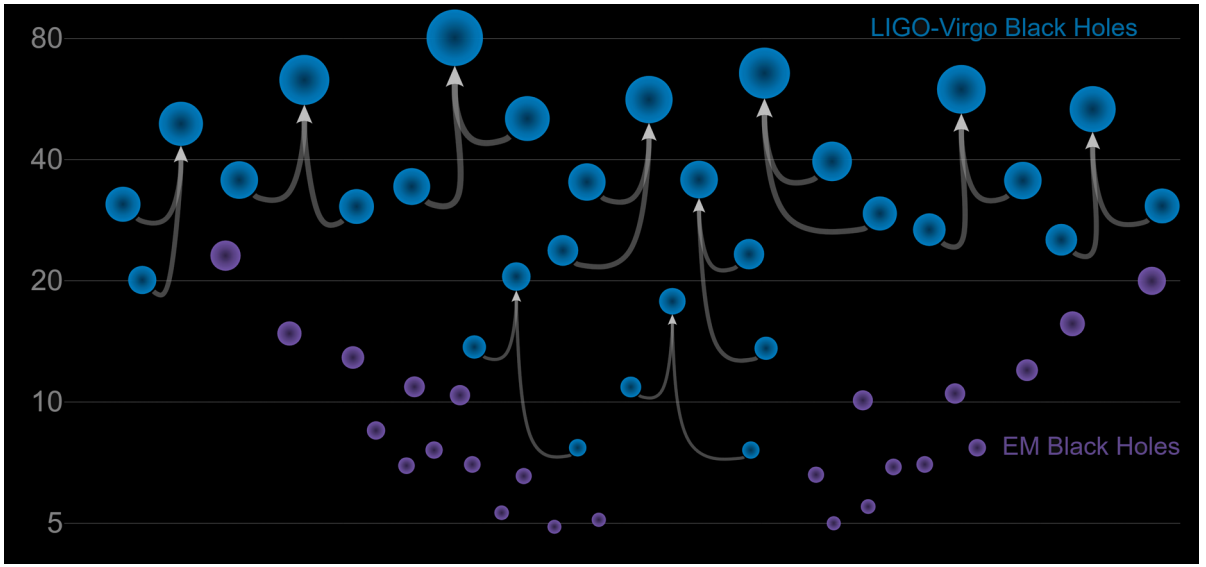


[ApJL 874:L2]

- no evidence for such distortions in any O1+O2 event

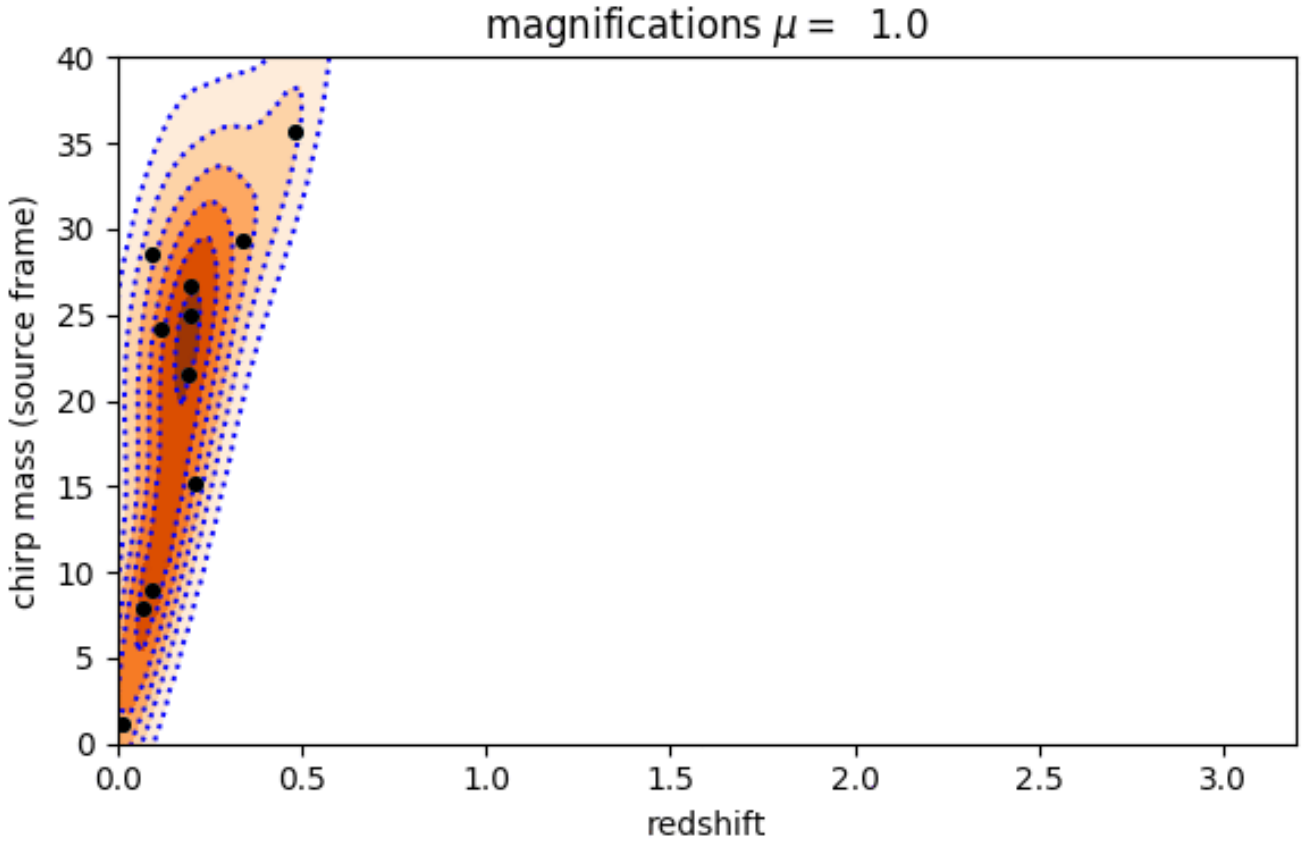
and now, actually about the title of this talk...

Could gravitational lensing impact the observed BBH population?



- We generally can’t tell if an individual GW is lensed.
- But even less extreme lensing hypotheses than Broadhurst+ can leave imprints in the observed BBH population.
- If our population modelling doesn’t include the lensing possibility, results may be biased.

Could gravitational lensing impact the observed BBH population?



silly assumption of fixed magnification for all GWTC-1 events

remember: GW amplitude ~ sqrt(magnification)

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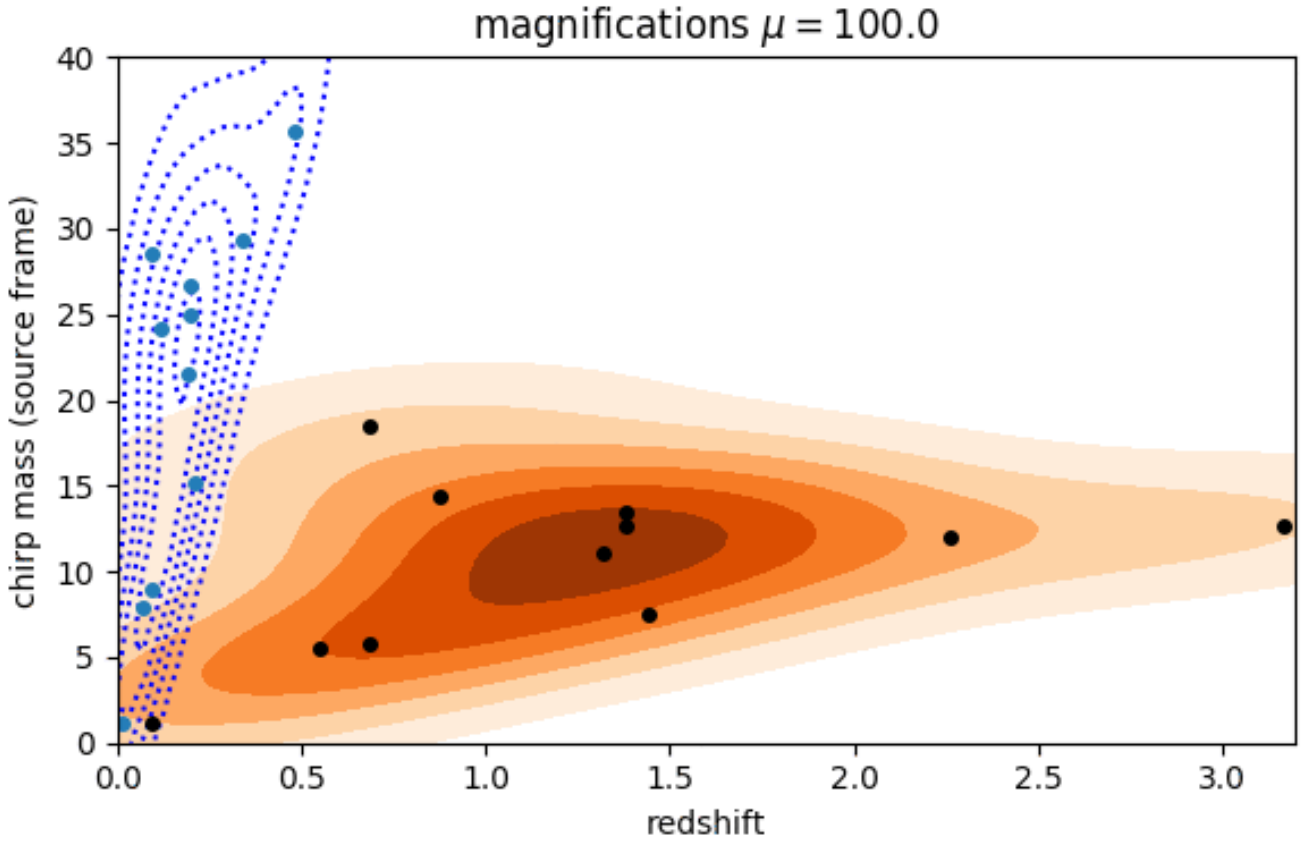

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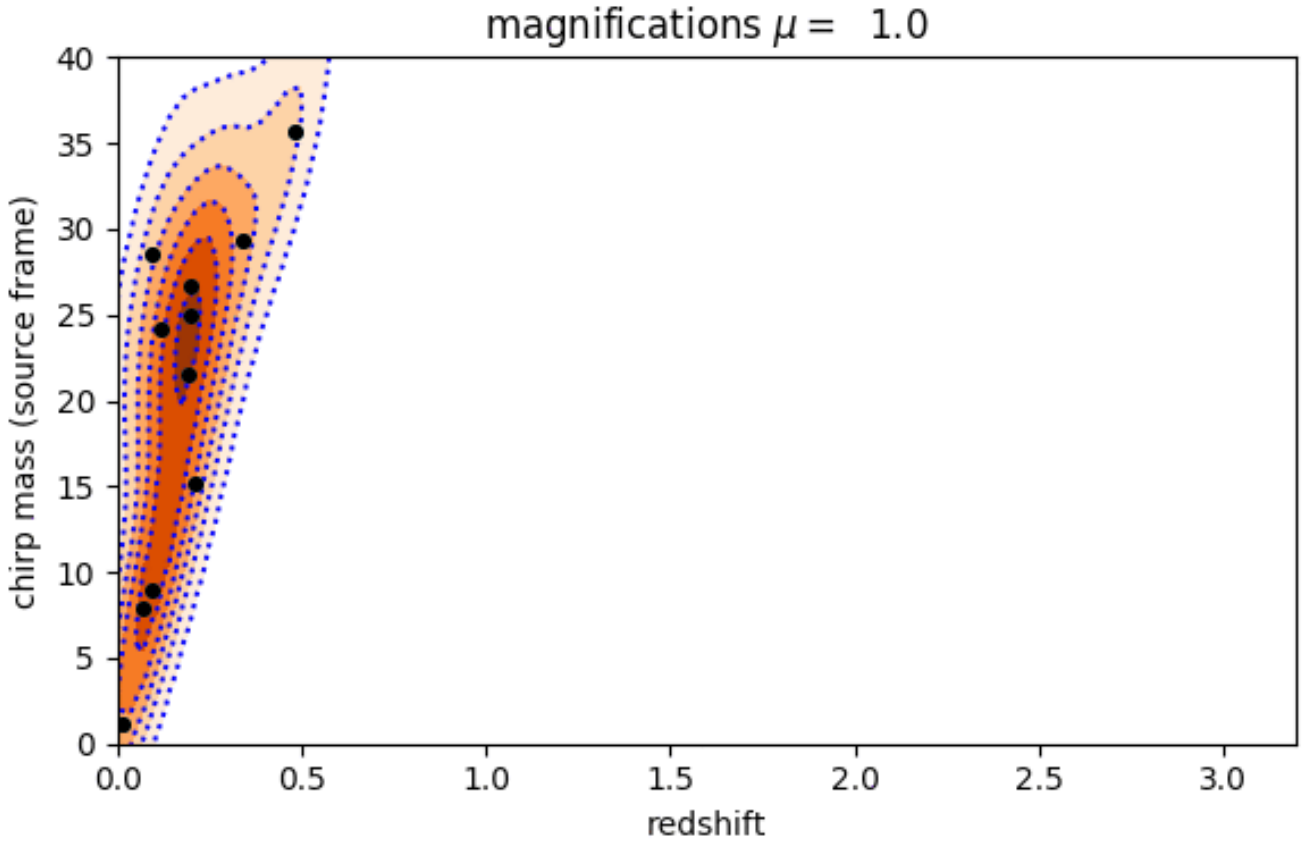
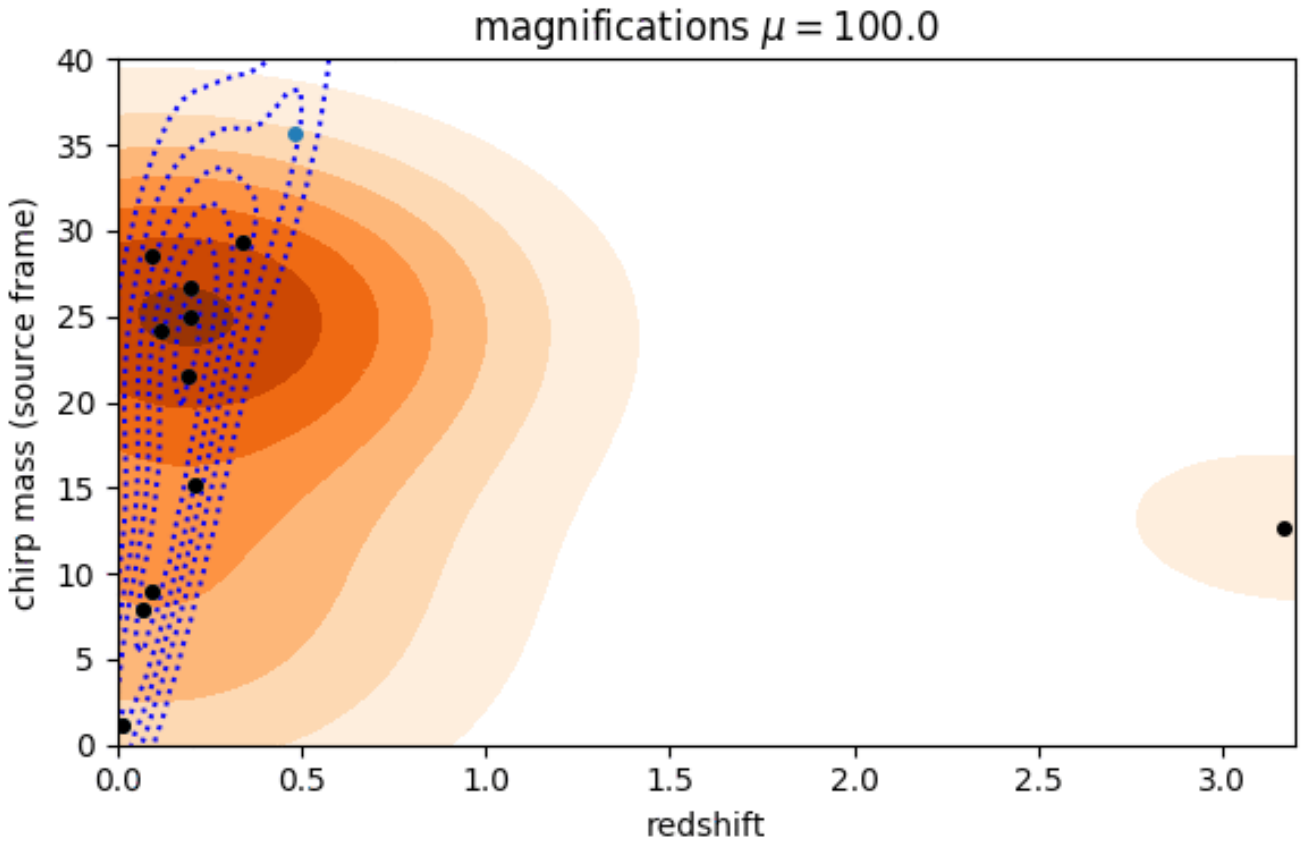


just one highly lensed event can distort pop inference
if the model is not flexible enough

remember: GW amplitude ~ sqrt(magnification)

Could gravitational lensing impact the observed BBH population?



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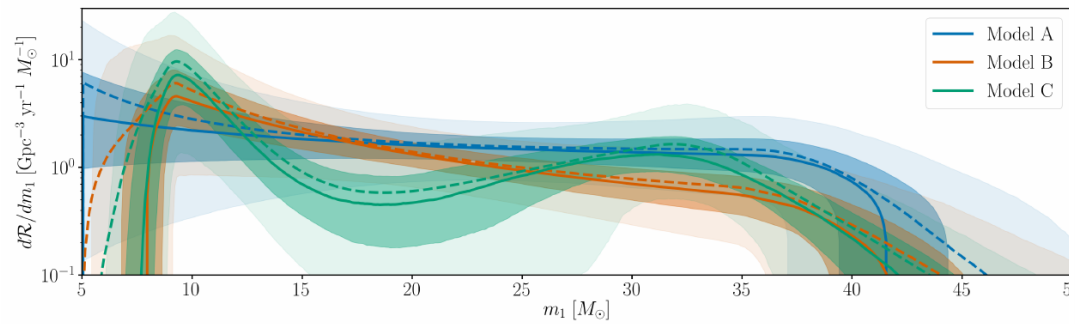
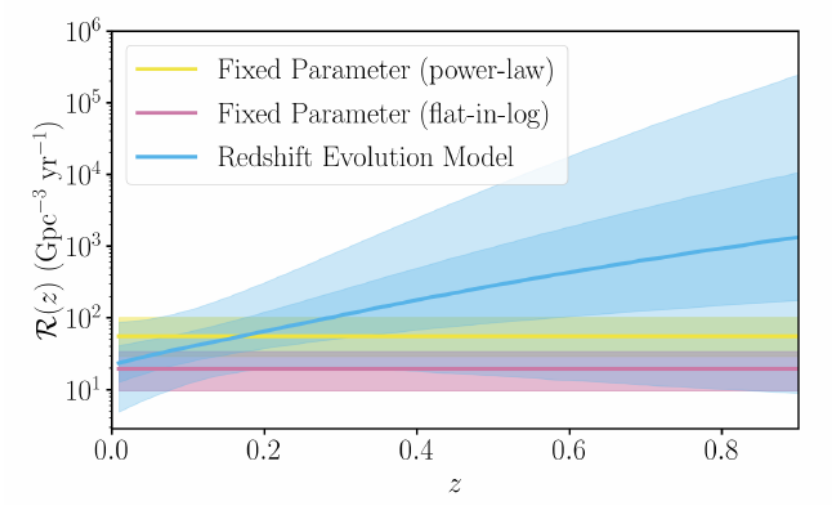
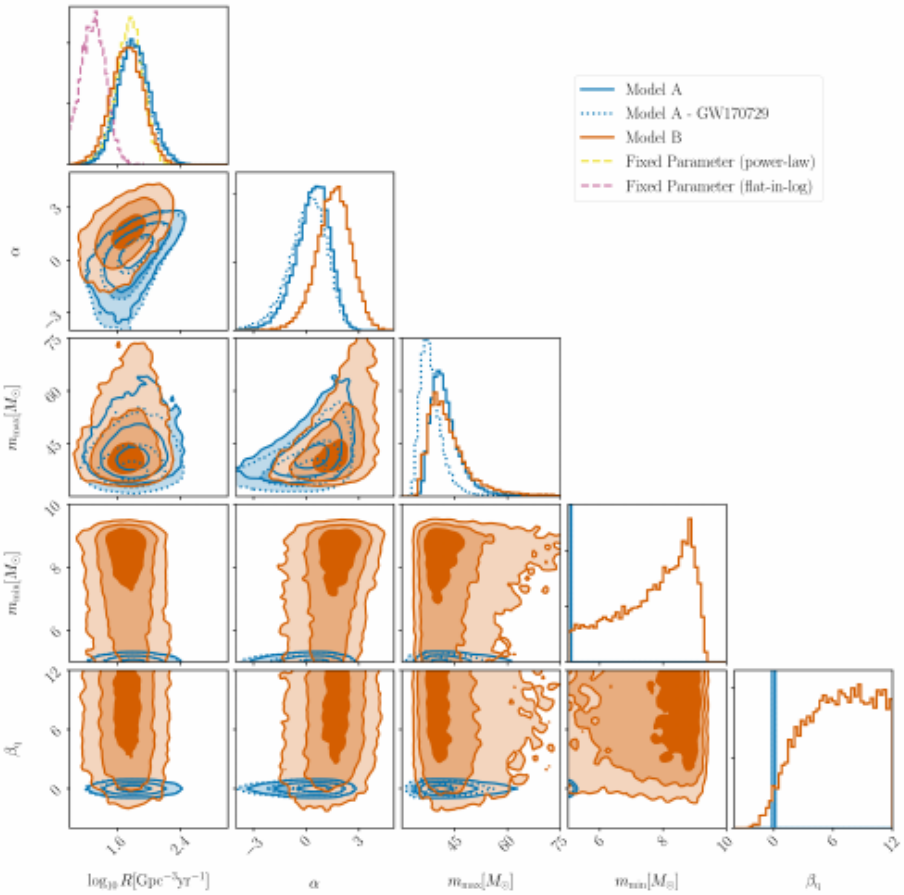
BBH population modelling

- admittedly, state-of-the art modelling
  is *quite a bit smarter* than matplotlib.contour()… ;-)
- key concepts: Hierarchical Bayes, hyperparameters



[LVC arXiv:1811.12940]





BBH population modelling + lensing?

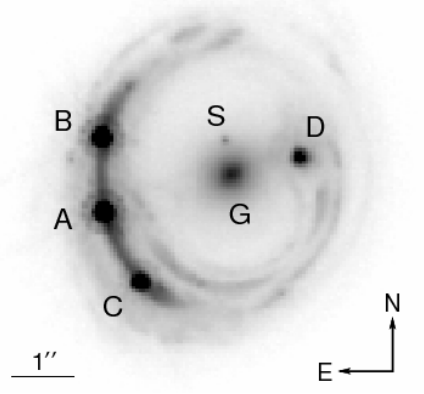
- Hierarchical Bayesian approach in 1811.12940 can be extended with arbitrary additional parameters.
- Sufficiently flexible generic M(z) models can in principle account for lensing already. [see e.g. Fishbach et al 2018, ApJL 863:L41]
- to *explicitly* include lensing:
  - free magnification parameter for each event
  - possibility of multiple images
  - new population hyperparameters:
    overall lensing rate, magnification distribution, time delay distribution
- Sounds like it should make the full model very underconstrained and full of degeneracies.
- But theory, EM observations and simulations should already significantly constrain the lensing sector!
- The prior is still that lensing should be rare overall, but in O3+ it could be worthwhile to explicitly include it in hierarchical population modelling to make sure our inferences are robust against it.

breakers of degeneracies

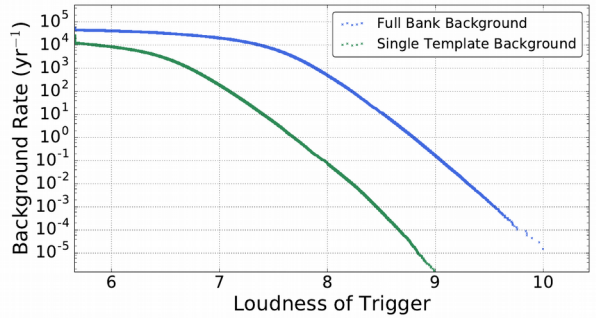
"we generally can't tell if an individual GW is lensed"

→ what would be smoking ~~guns~~ magnifying glasses to do so after all?

- identify a foreground object as the lens [Smith+ 2018]
  problem: often huge sky localisation uncertainties, incomplete surveys
- microlensing / wave optics imprints on the waveform [Lai+ 2018]
  problems: lens-model dependent, can look suspiciously like precession or eccentricity
- clearly lensed EM counterparts
  problem: rare – but *the jackpot*!
  - · measure H0 from time delay [Liao+2017], similar to standard quasar method [Refsdal 1964, Suyu+2013]
  - · test speed of gravity vs. light [Fan+2017, Collett & Bacon 2017]



- subthreshold searches: strongly lensed events should come with short-delay counterparts [Li et al 2019; McIsaac, Keitel, et al. in prep.]



Thanks for your attention!

Time for questions...

...and my thanks to collaborators
at Portsmouth and within the LVC

see you again before Christmas…?