Gravitational-wave lensing within ground-based gravitational-wave detectors

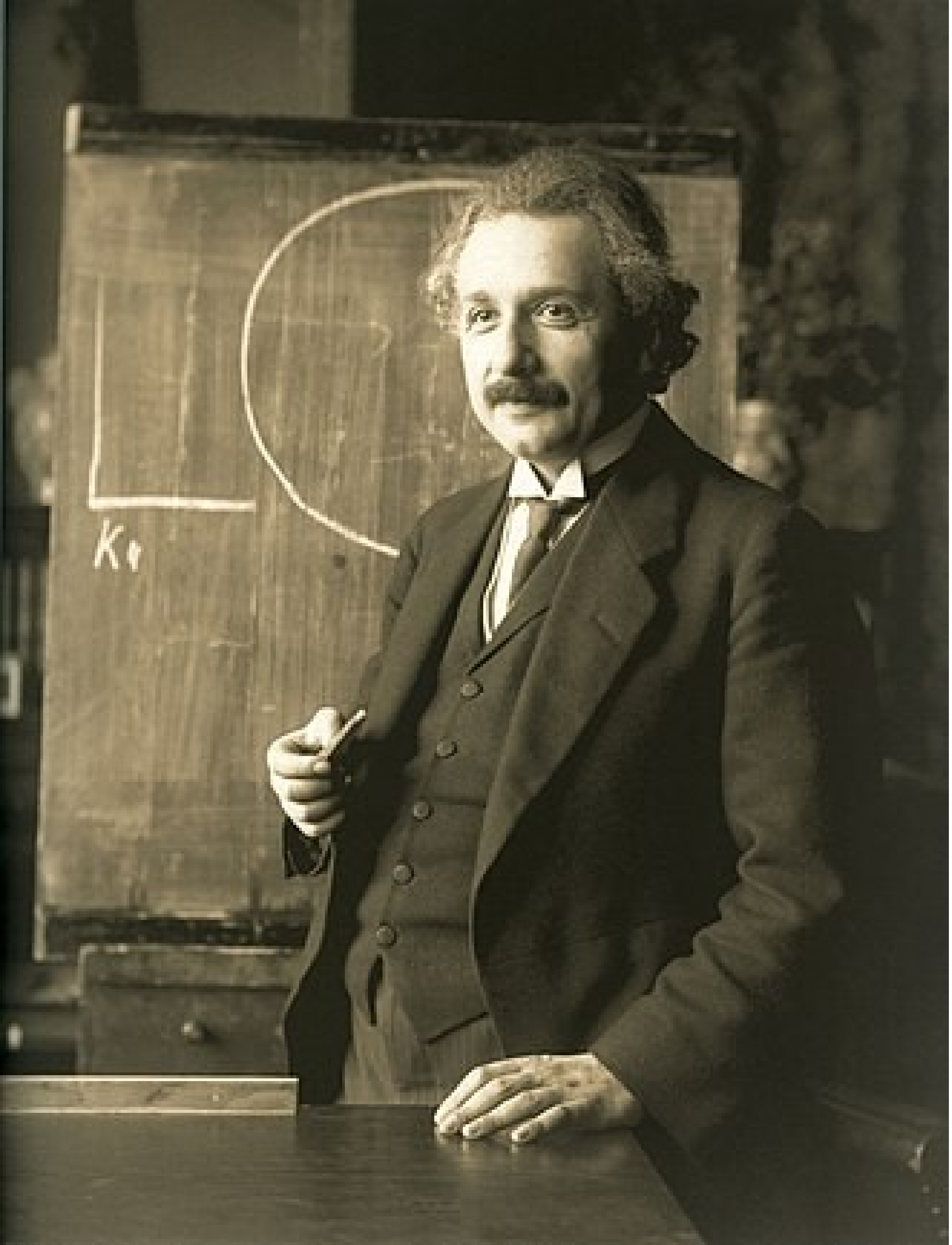
Otto Akseli Hannuksela

P. Ajith, T. Broadhurst, J.M. Diego, K. Haris, D. Keitel, K. Kim,
S. Kumar, K.H. Lai, T.G.F. Li, K.K.Y Ng,
P.L. Kelly A.K. Mehta, G. Pagano, G.F. Smoot III,
I. Wong, Peter T. H. Pang, Tim Dietrich, Ian Harry

Virtual Seminar at Institut d'astrophysique de Paris

Nikhef

Utrecht University



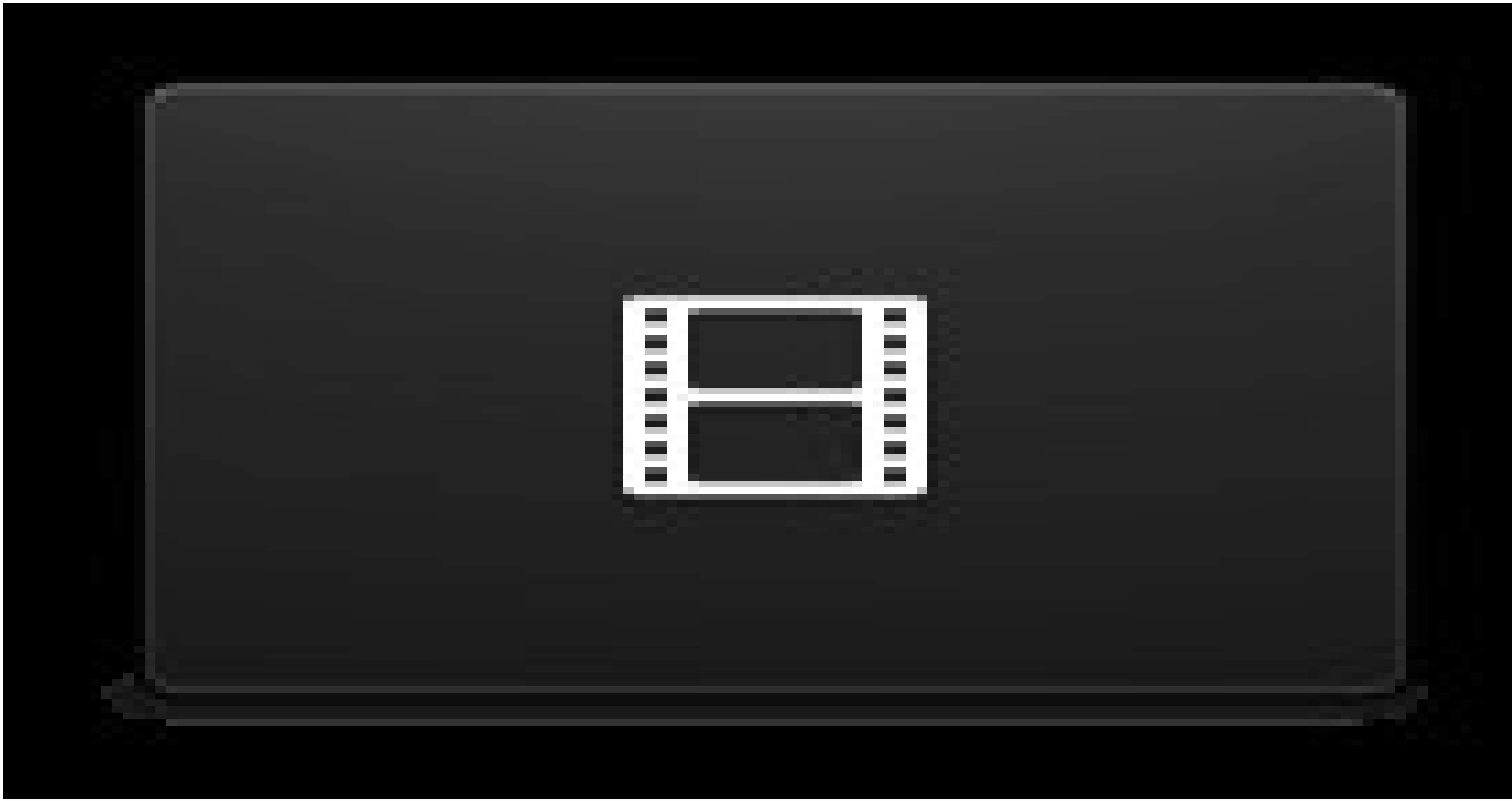
Gravitational Waves

- Predicted by Einstein in 1916

Properties:
- Travels at the speed of light
- Two polarizations
- Passes through matter unimpeded

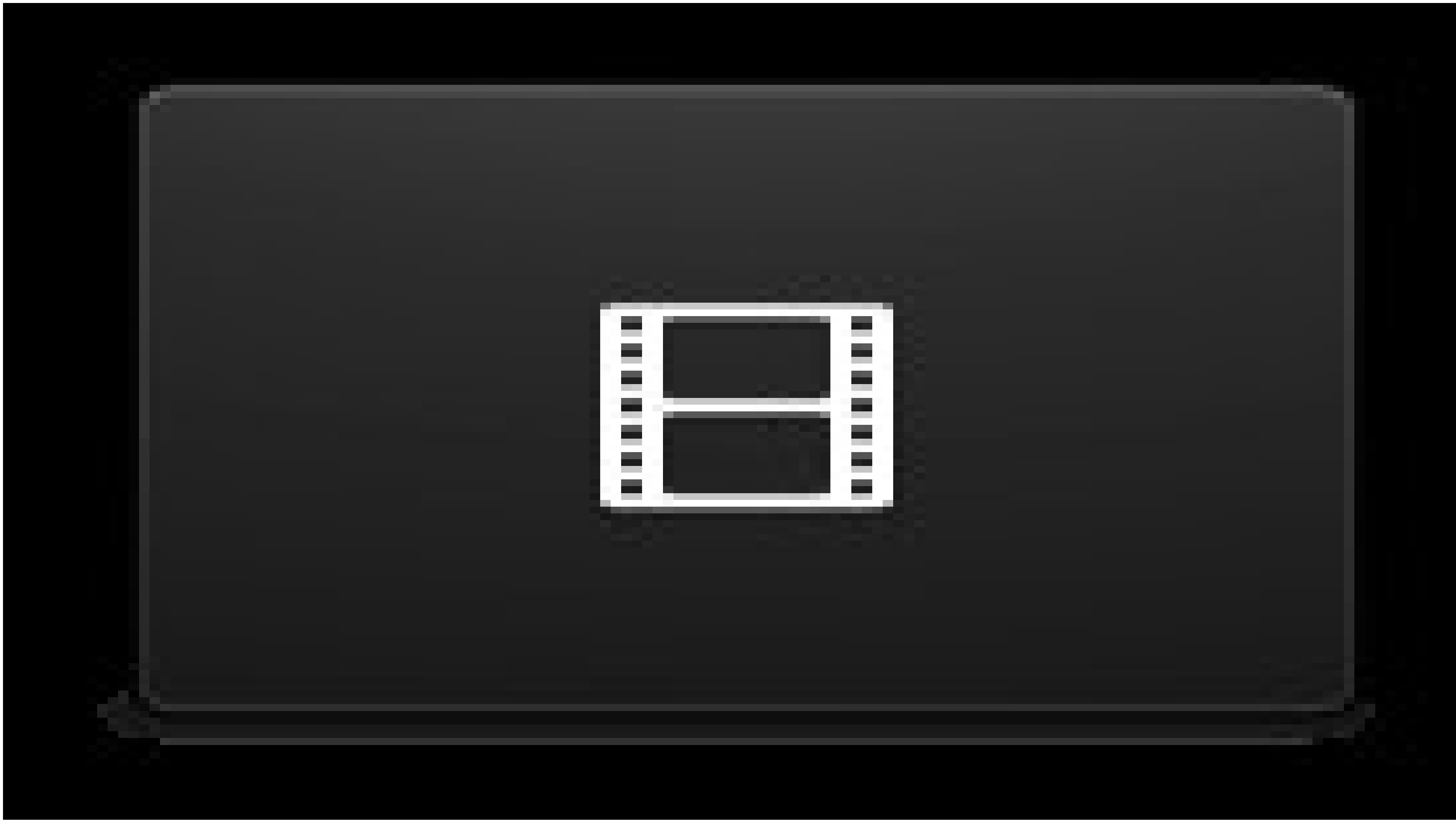
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Gravitational-Wave Generation



Credits: LIGO/Virgo, SXS

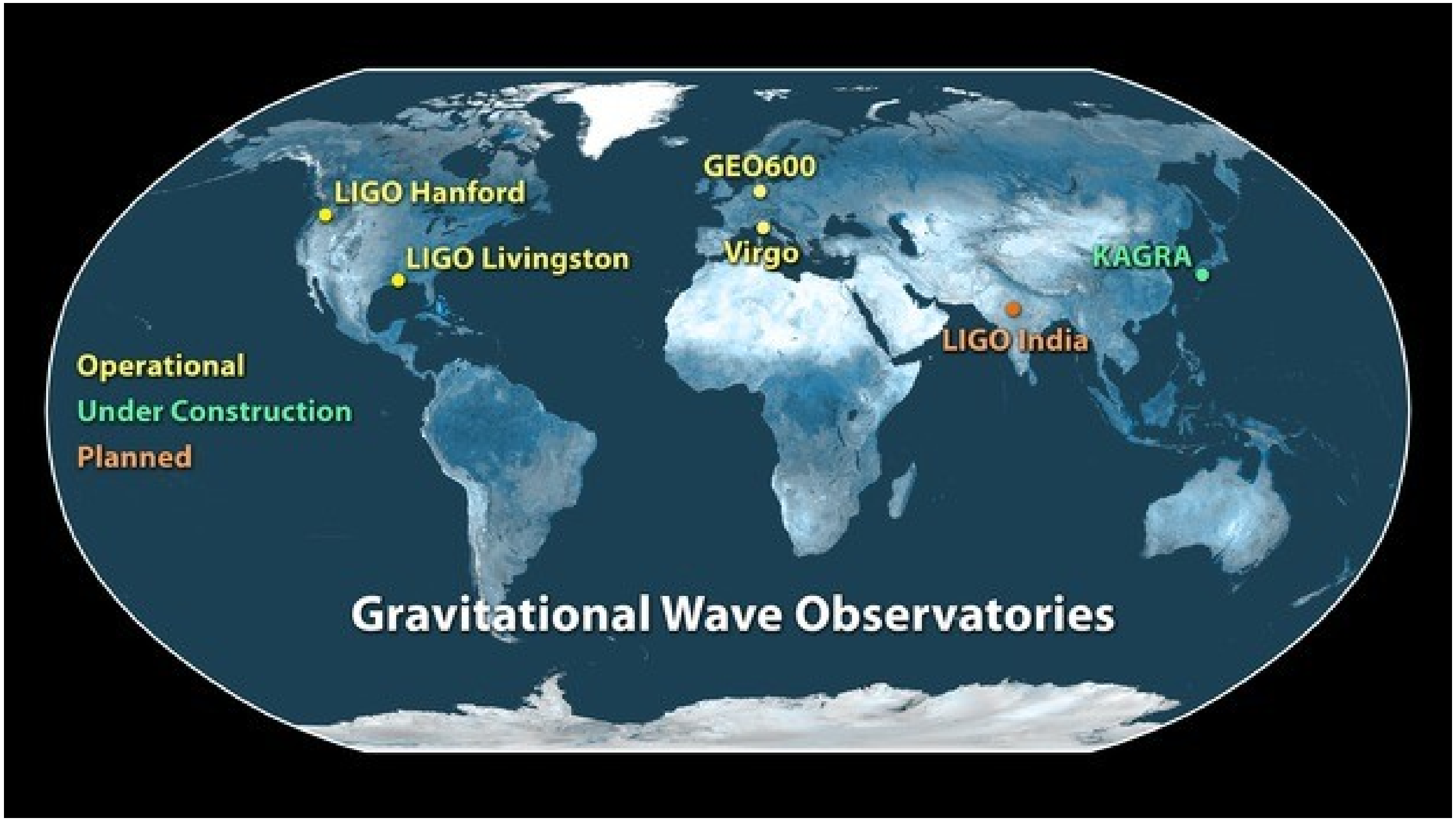
Gravitational-Wave Detection



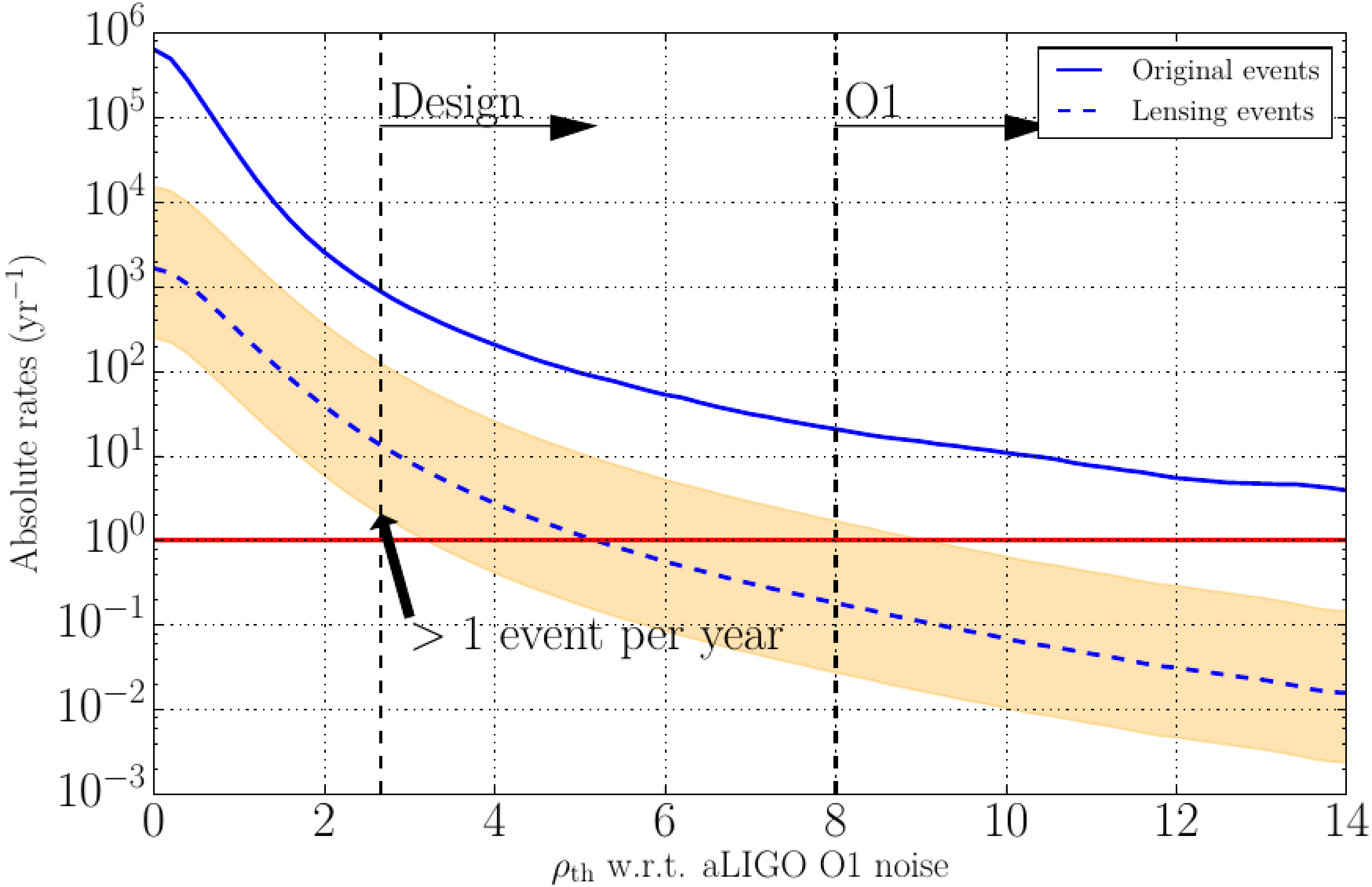
Credits: LIGO/Virgo, SXS

O1/O2 detections

		FAR [y^{-1}]			Network SNR		
Event	UTC Time	PyCBC	GstLAL	cWB	PyCBC	GstLAL	cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
GW170823	13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

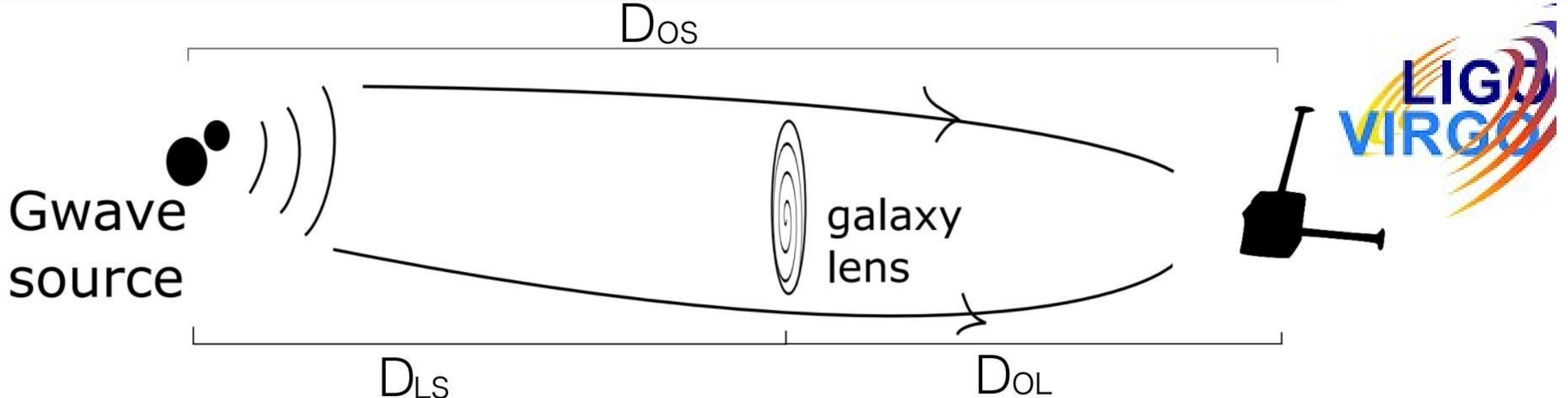


Rate of Lensing

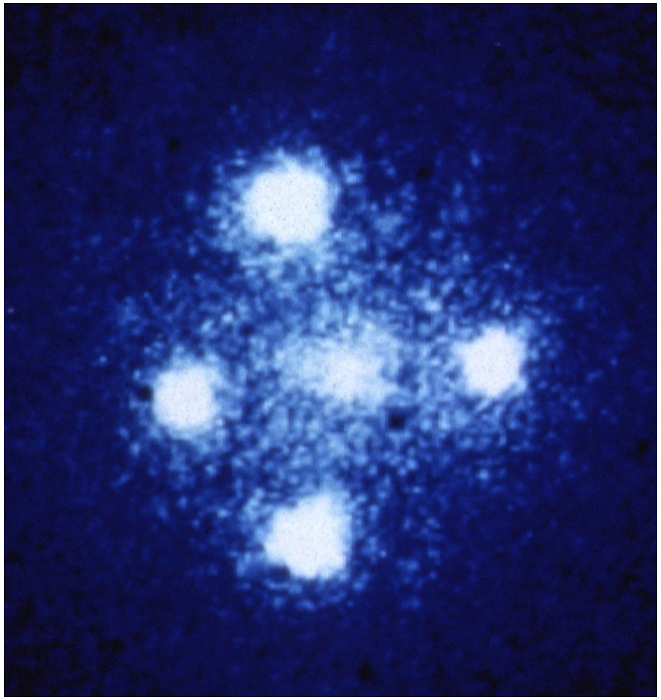


Ng et al., Physical Review D 97.2 (2018): 023012.; see also Li et al., MNRAS 476.2 (2018): 2220-2229; Oguri, MNRAS 480.3 (2018): 3842-3855.

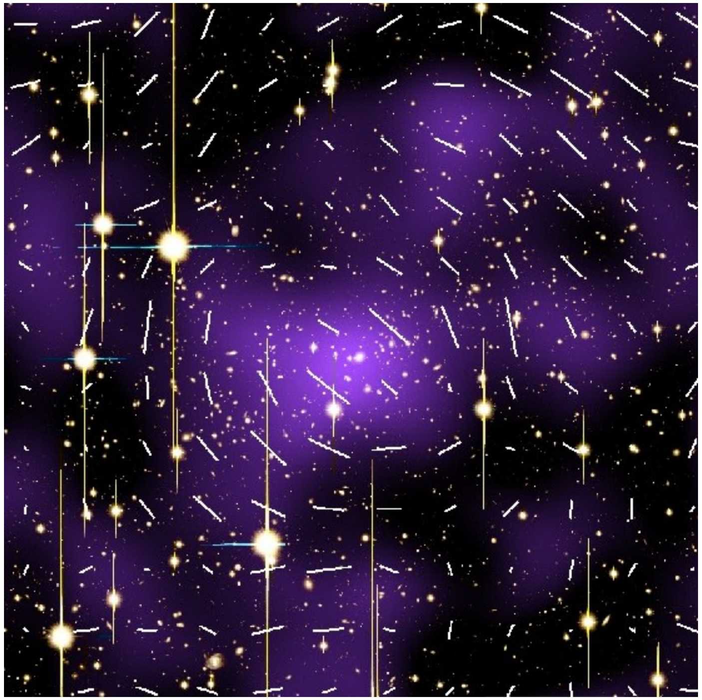
Gravitational Lensing



ESA/Hubble & NASA

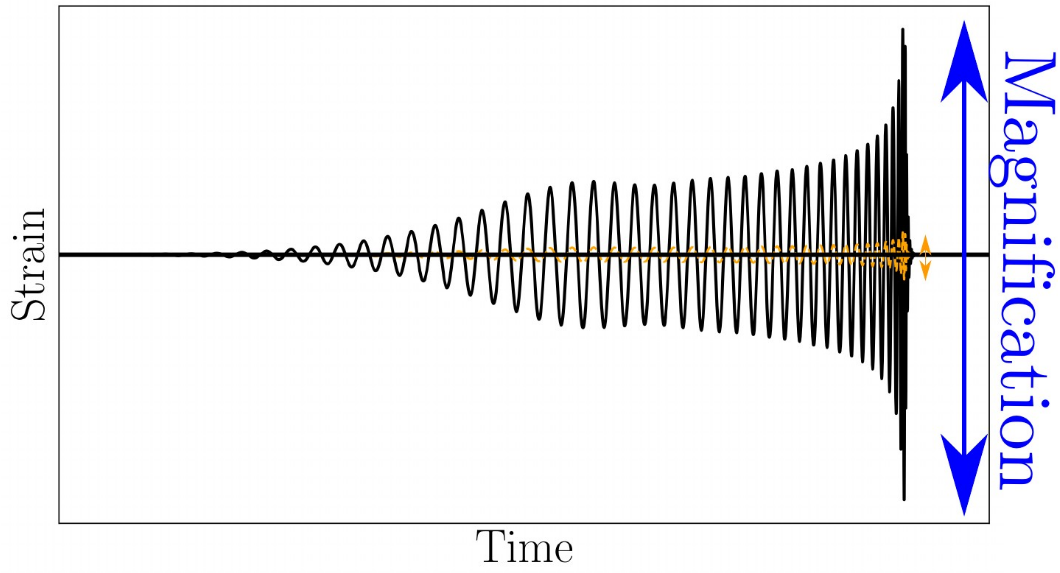


NASA, ESA & STScI



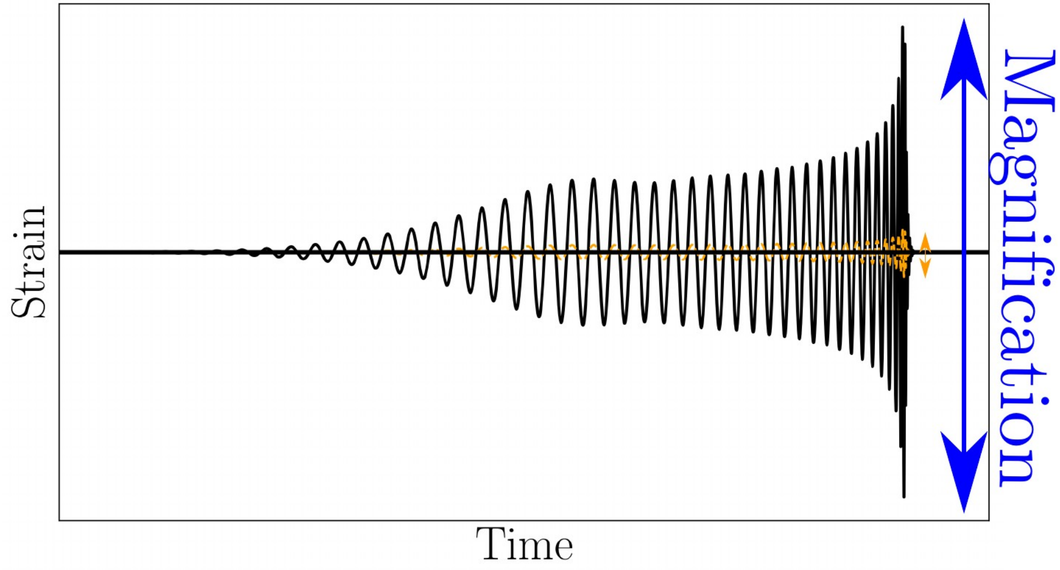
Oguri et al.

Strong Lensing Magnification



$$(1+z)m_i = (1+z_L)m_i^L,$$
$$D_L = D/\sqrt{\mu}$$

Strong Lensing Magnification



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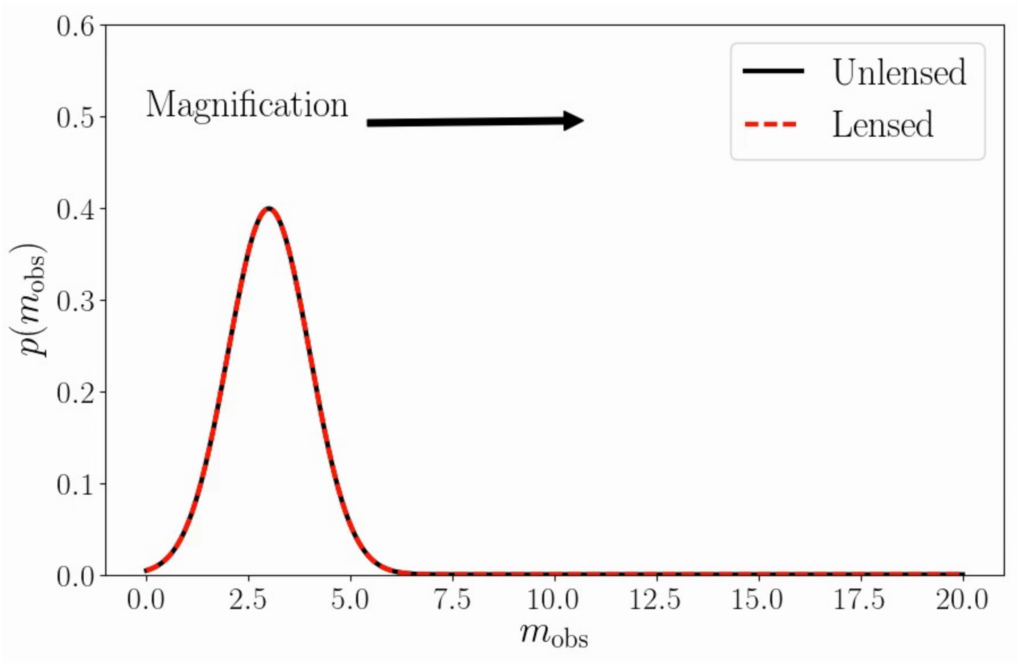

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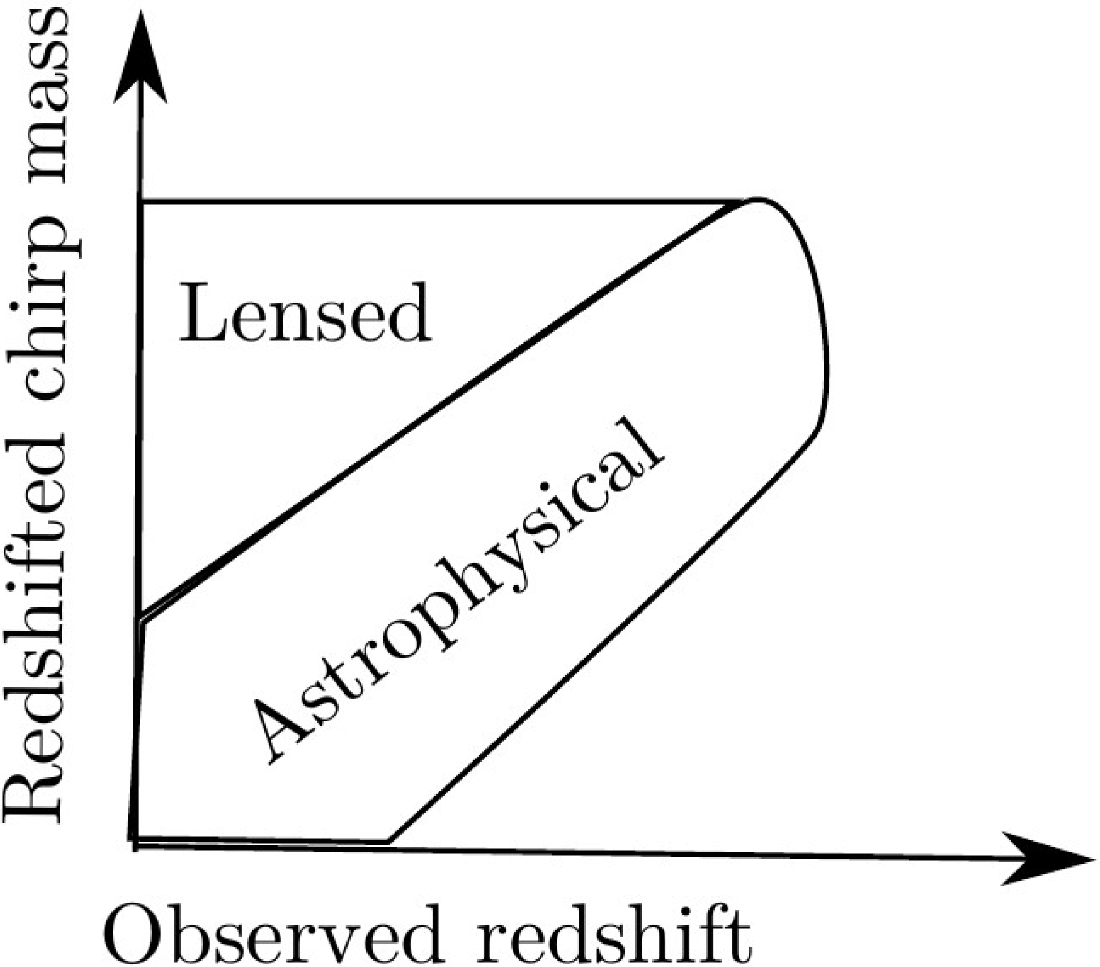
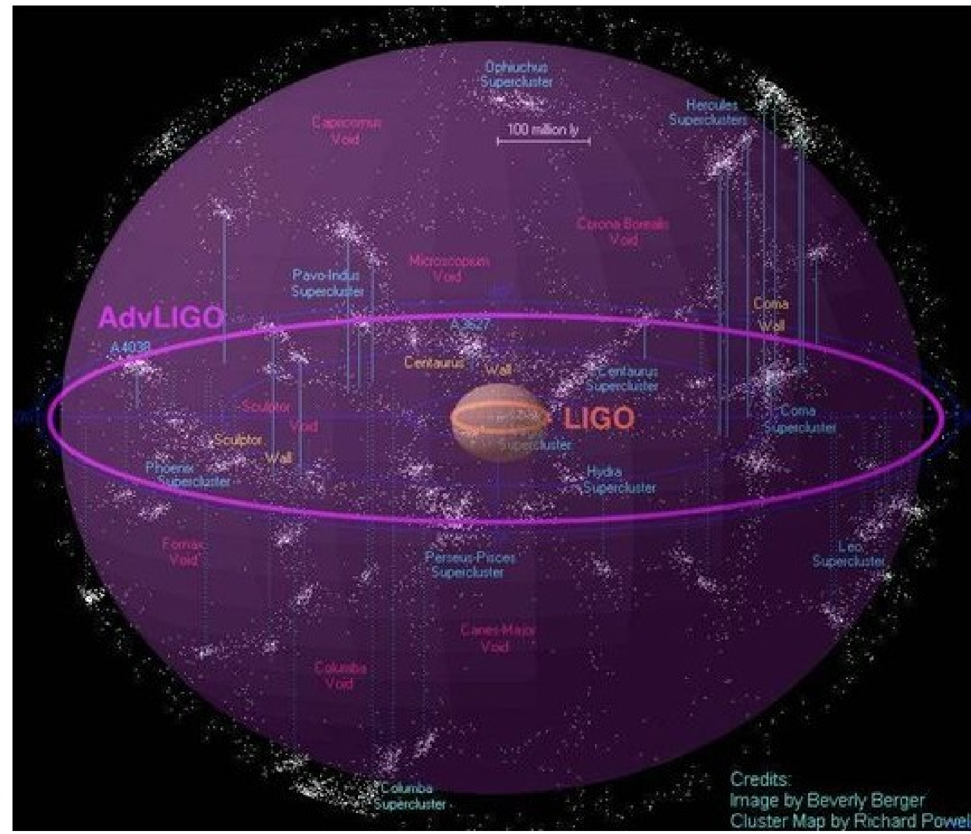
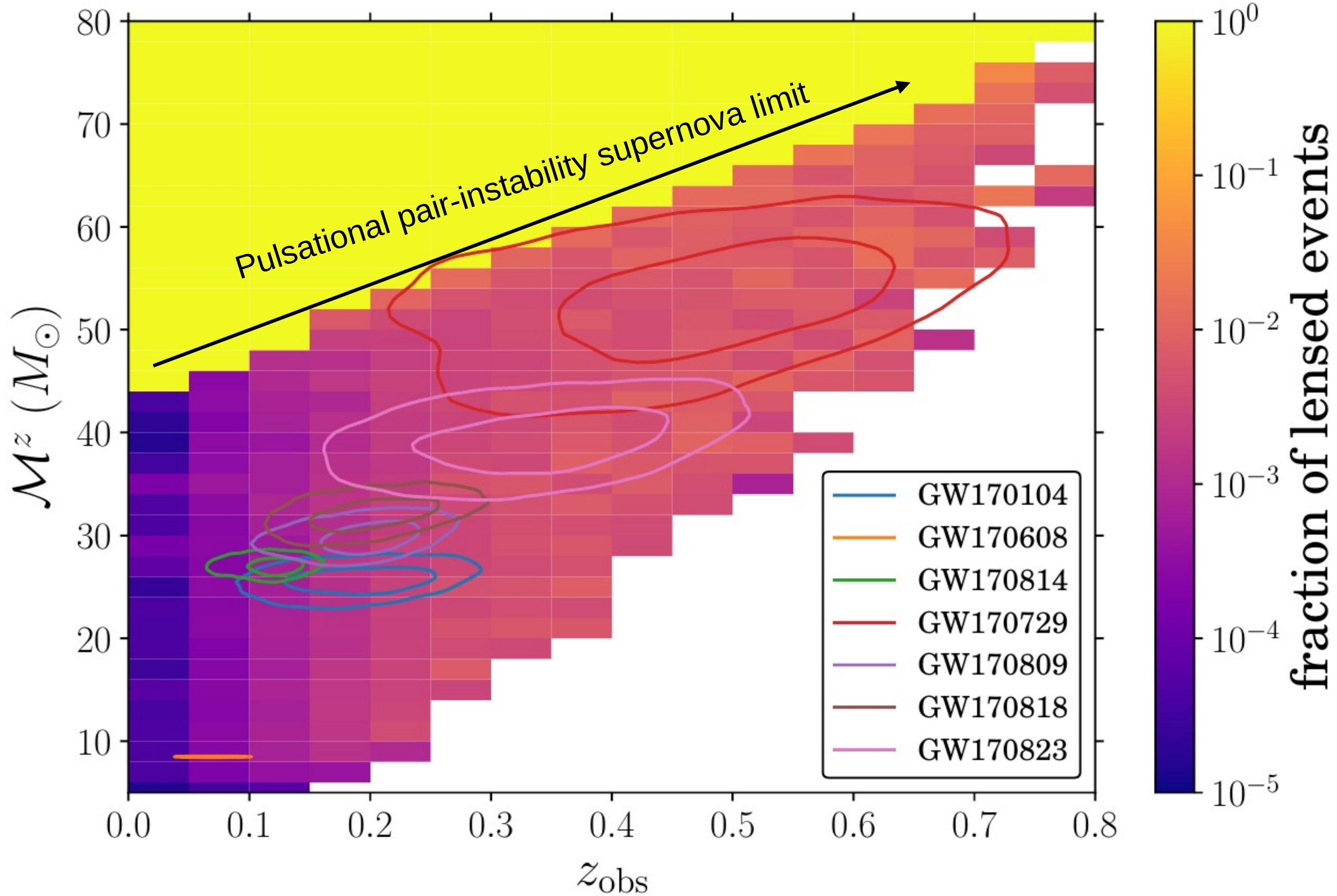




Credits: LIGO/Virgo

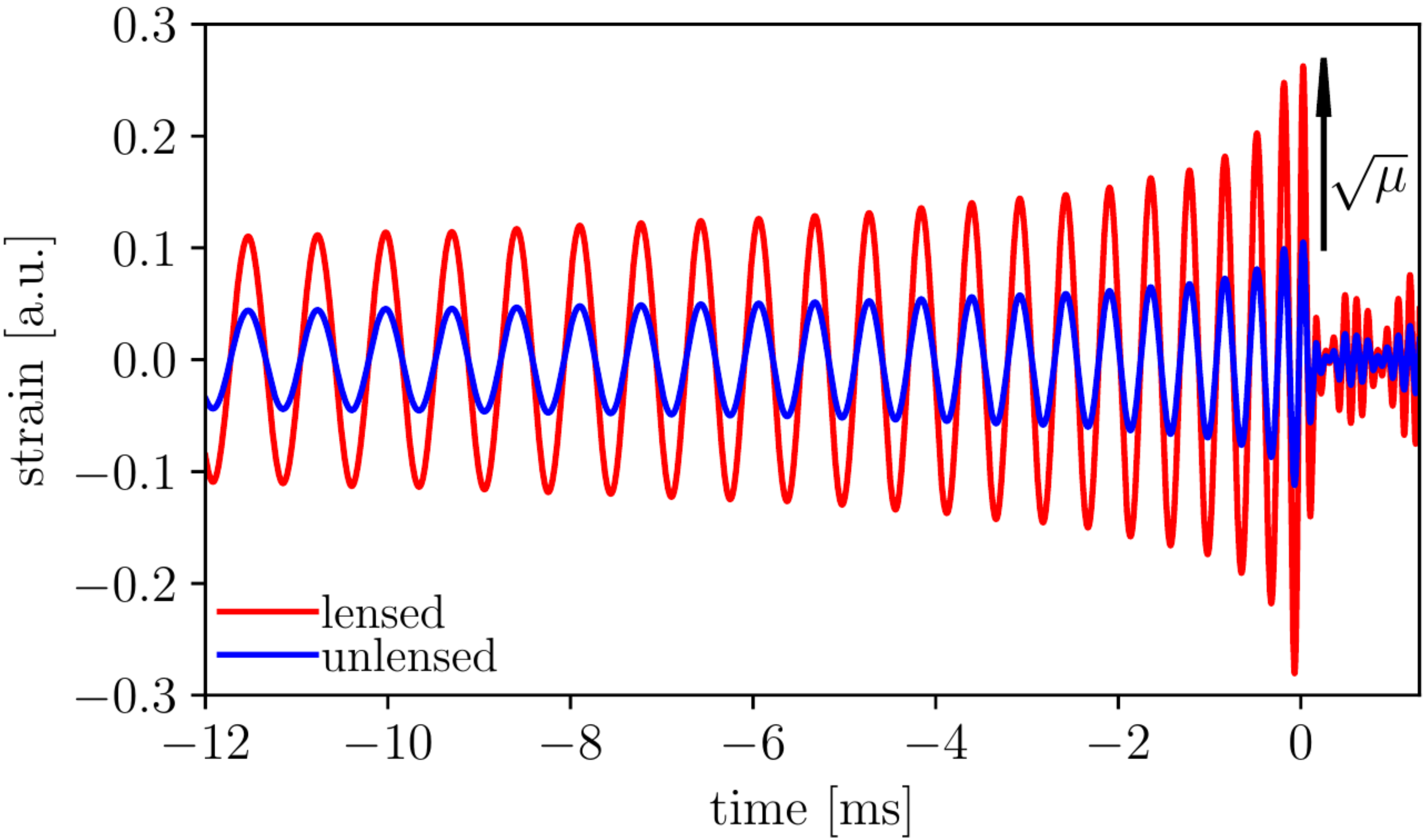
Ng, et al., Physical Review D 97.2 (2018): 023012. Dai, et al., Physical Review D 95.4 (2017): 044011.

GWTC-1: Strong Lensing Magnification



Hannuksela, et al., The Astrophysical Journ
al Letters 874.1 (2019): L2.

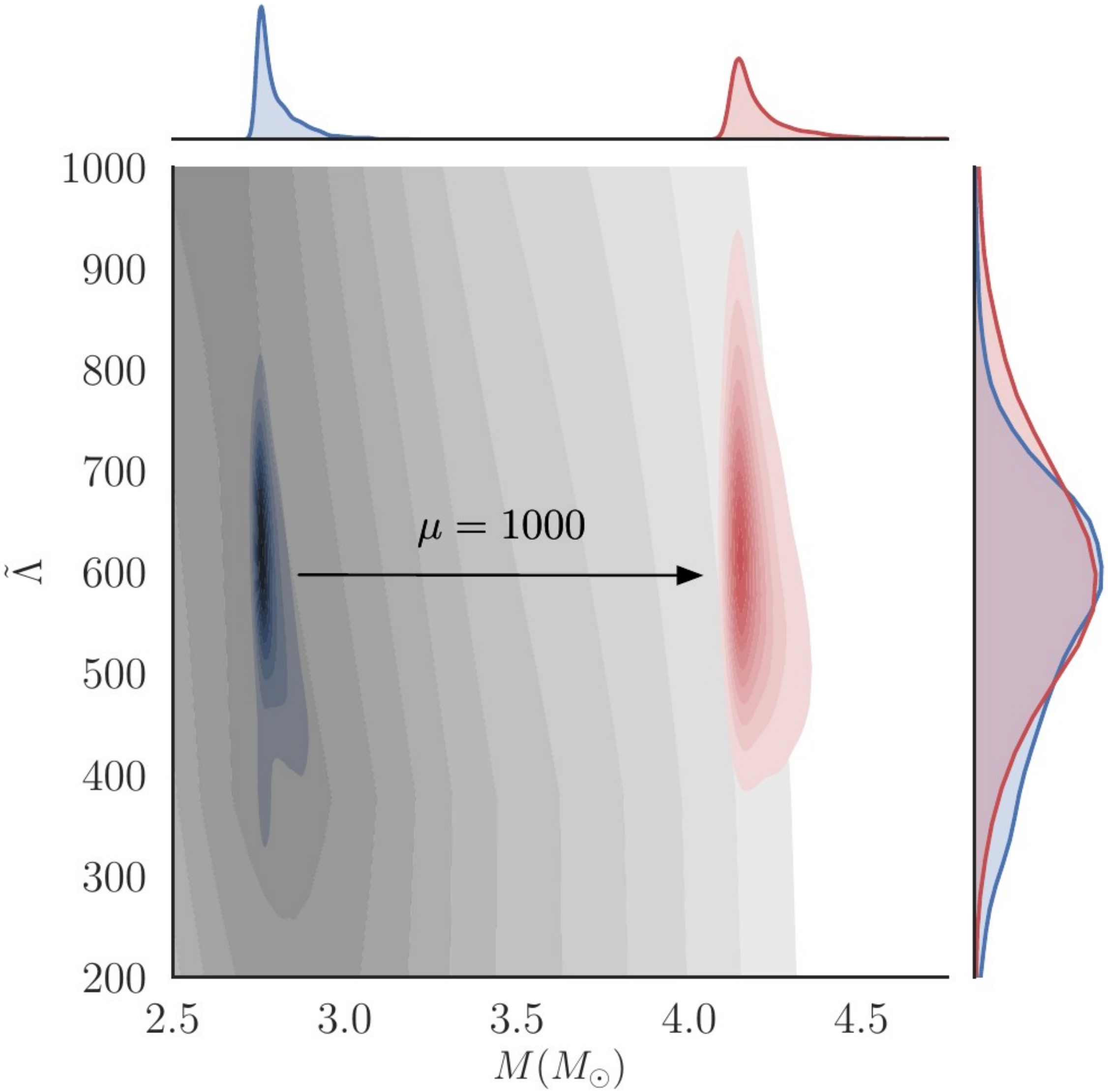
Heavy neutron stars (e.g. GW190425)



Pang, et al., arXiv:2002.04893 (2020)

Heavy neutron stars (e.g. GW190425)

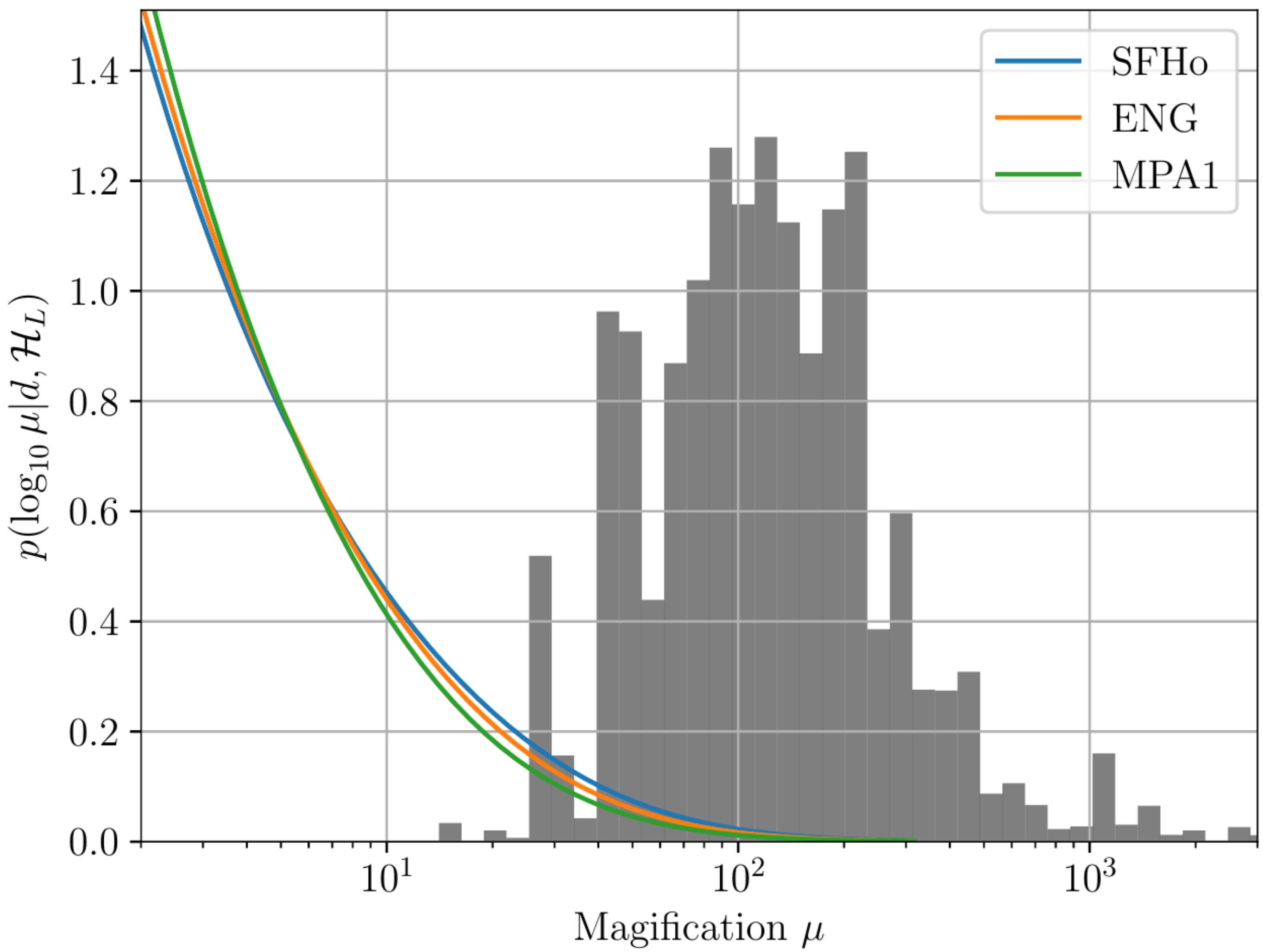
- Binary neutron stars (BNSs) offer tidal measurements that would not be biased by lensing magnification
- Thus, a lensed BNS would appear as a massive BNS with a tidal deformability of a lower-mass BNS.
- Given an equation of state, we might rule out/confirm lensing for BNSs.



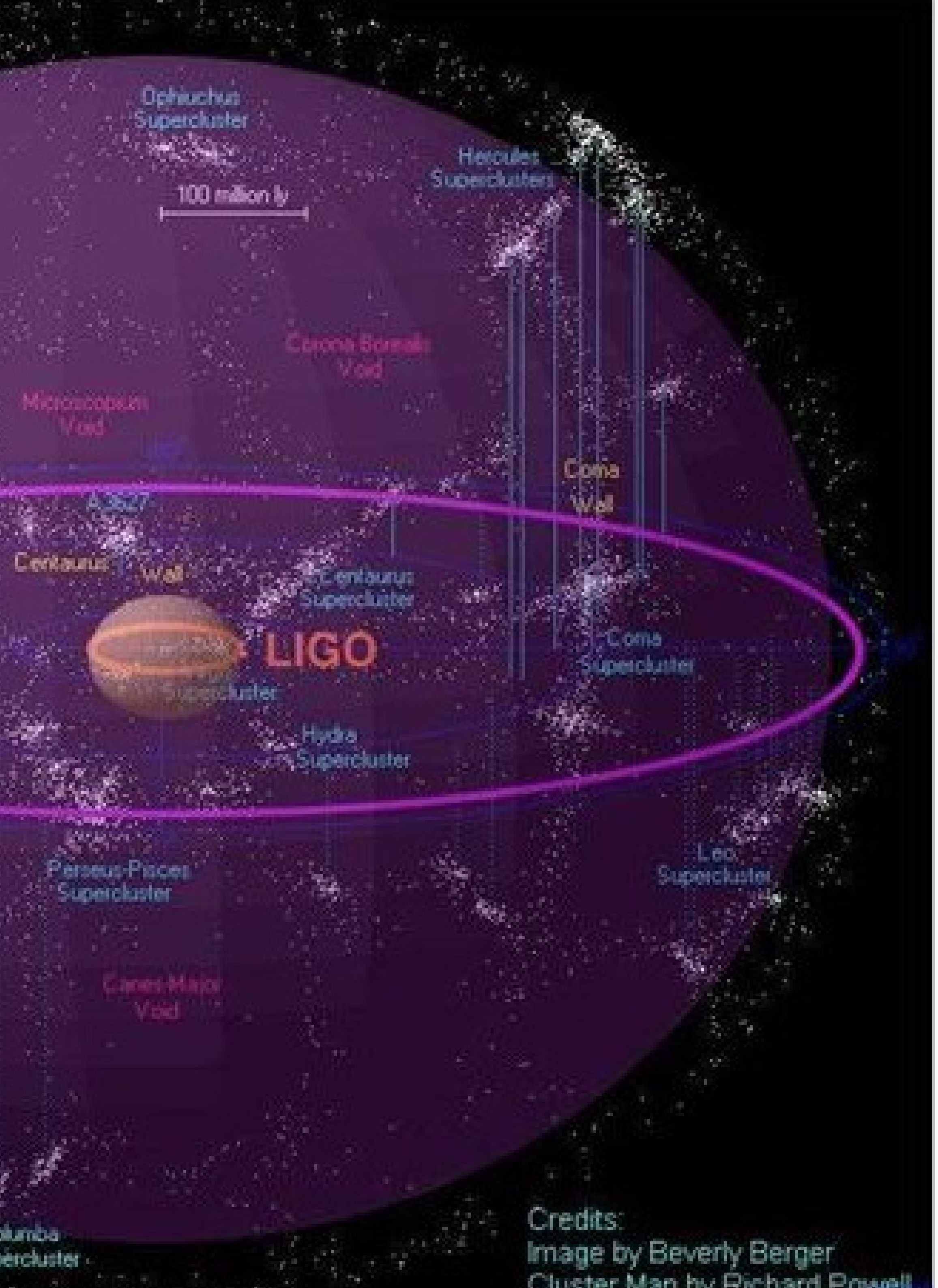
Pang, et al., arXiv:2002.04893 (2020)

Heavy neutron stars (e.g. GW190425)

- Methodology could be used to confirm/rule out lensing.
- No evidence of GW lensing magnification for GW190425
- Future detections with better tidal measurements will likely yield better constraints



Pang, et al., arXiv:2002.04893 (2020)



Why study magnification?

Example work:

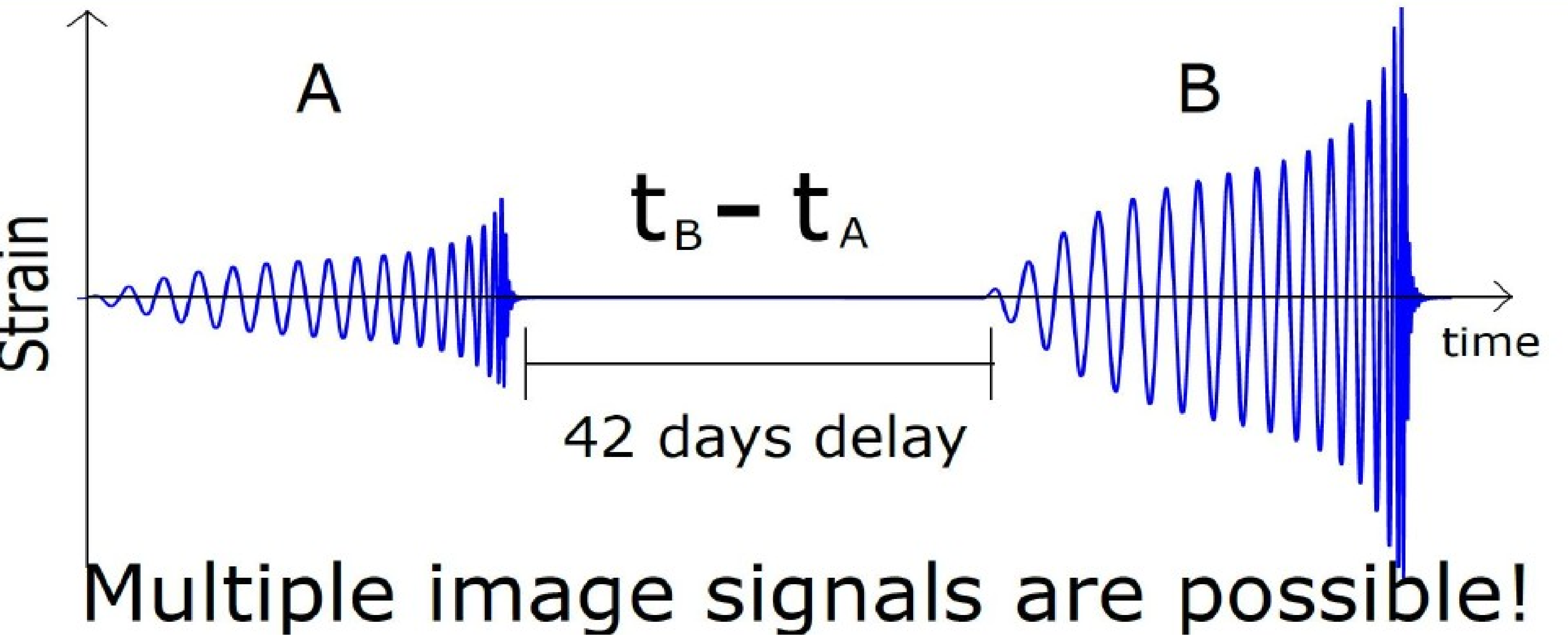
- High-redshift BBH probes (Dai et al. 2017)

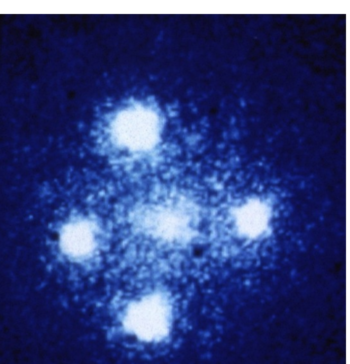
- Primordial black hole probes (Dai et al. 2017)

- Wave effects (Diego et al. 2019)

- Combined with tidal measurements, could allow for evidence of lensing for binaries with EM counterparts (Pang et al. 2020)

Strong Lensing Multi-Images





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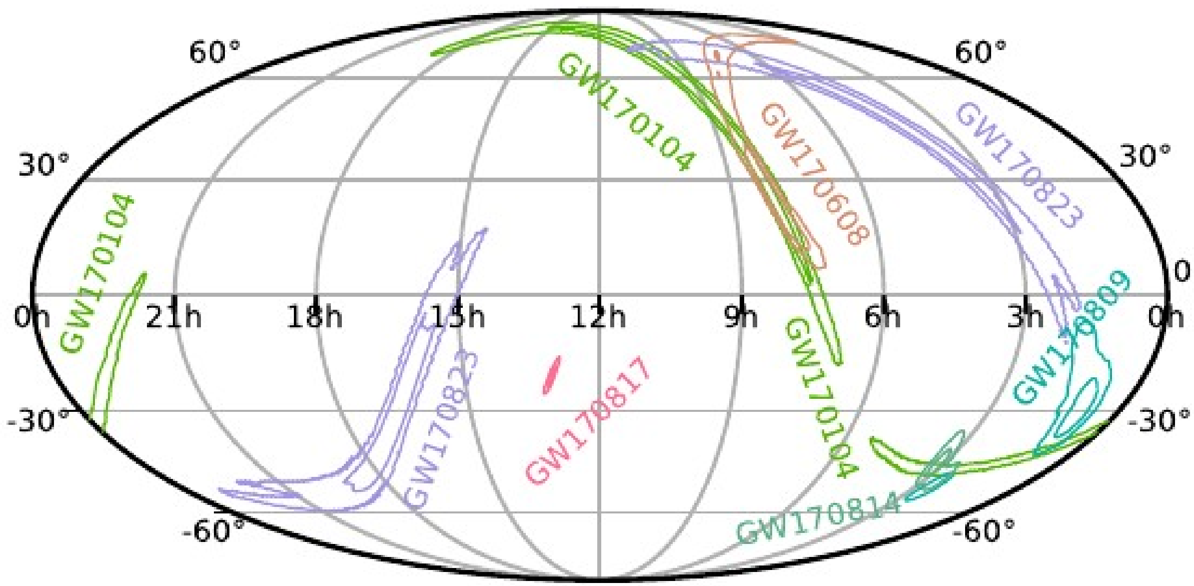
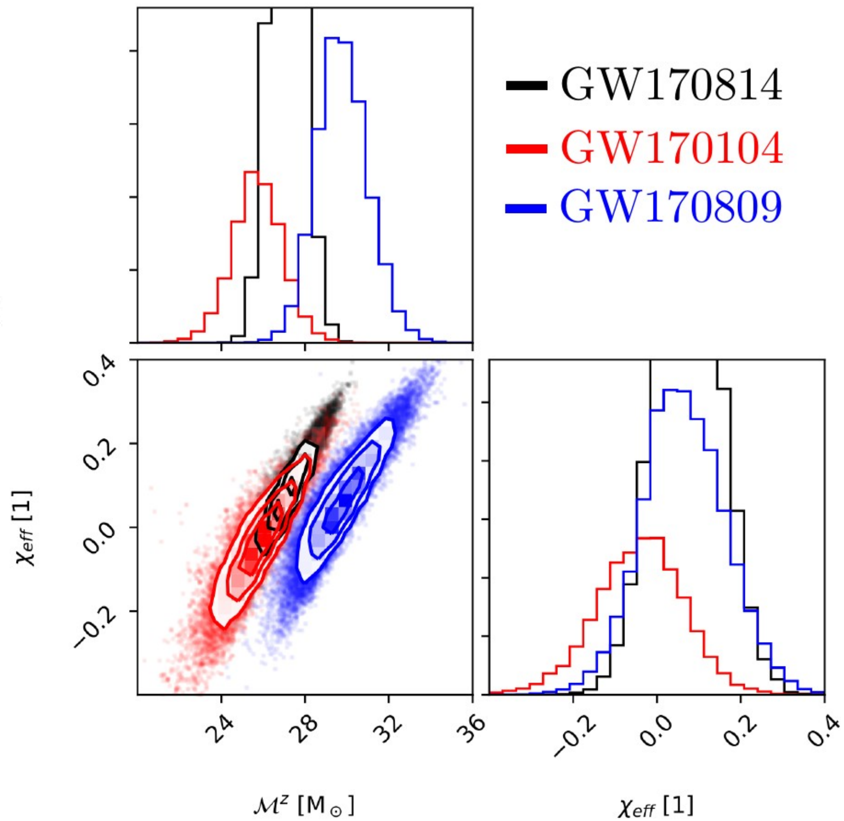
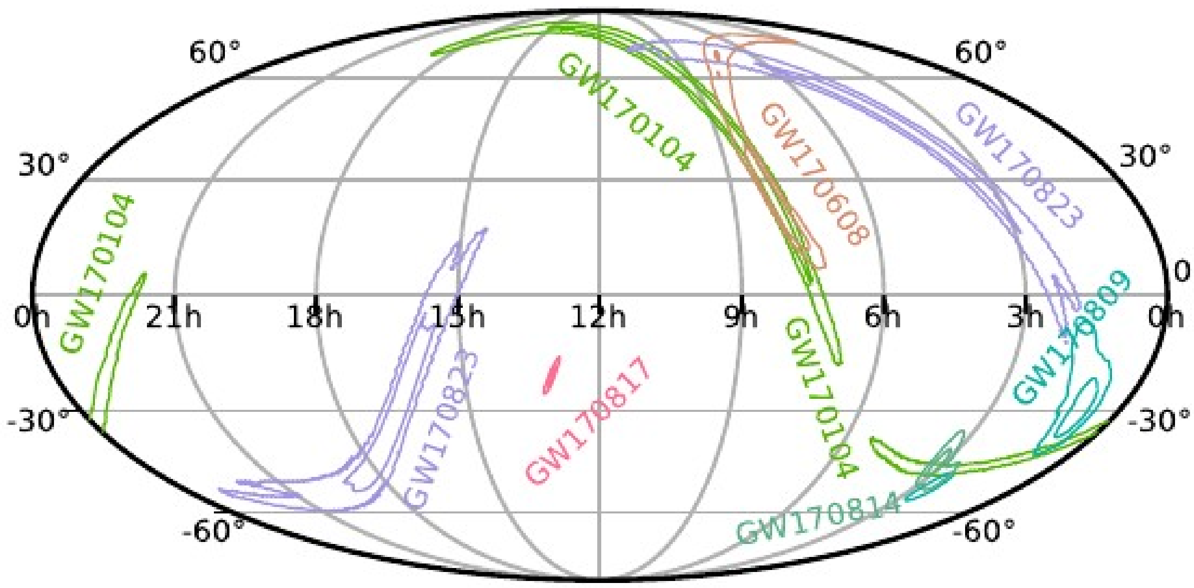
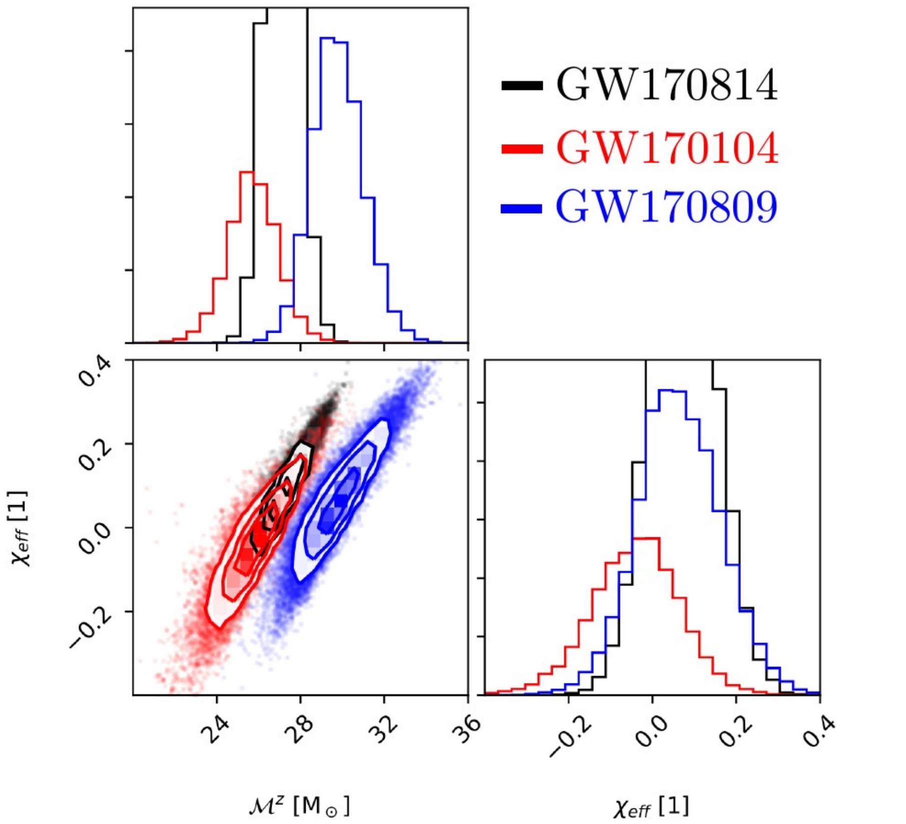




Haris, K., et al., arXiv preprint arXiv:1807.0
7062 (2018). Lo et al. (in prep)

Strong Lensing Multi-Images





$$\mathcal{B}^{\mathrm{L}}_{\mathrm{U}} := \frac{\mathcal{Z}_{\mathrm{L}}}{\mathcal{Z}_{\mathrm{U}}} = \int d\boldsymbol{\theta}\, \frac{P(\boldsymbol{\theta}|d_1)\ P(\boldsymbol{\theta}|d_2)}{P(\boldsymbol{\theta})}$$

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

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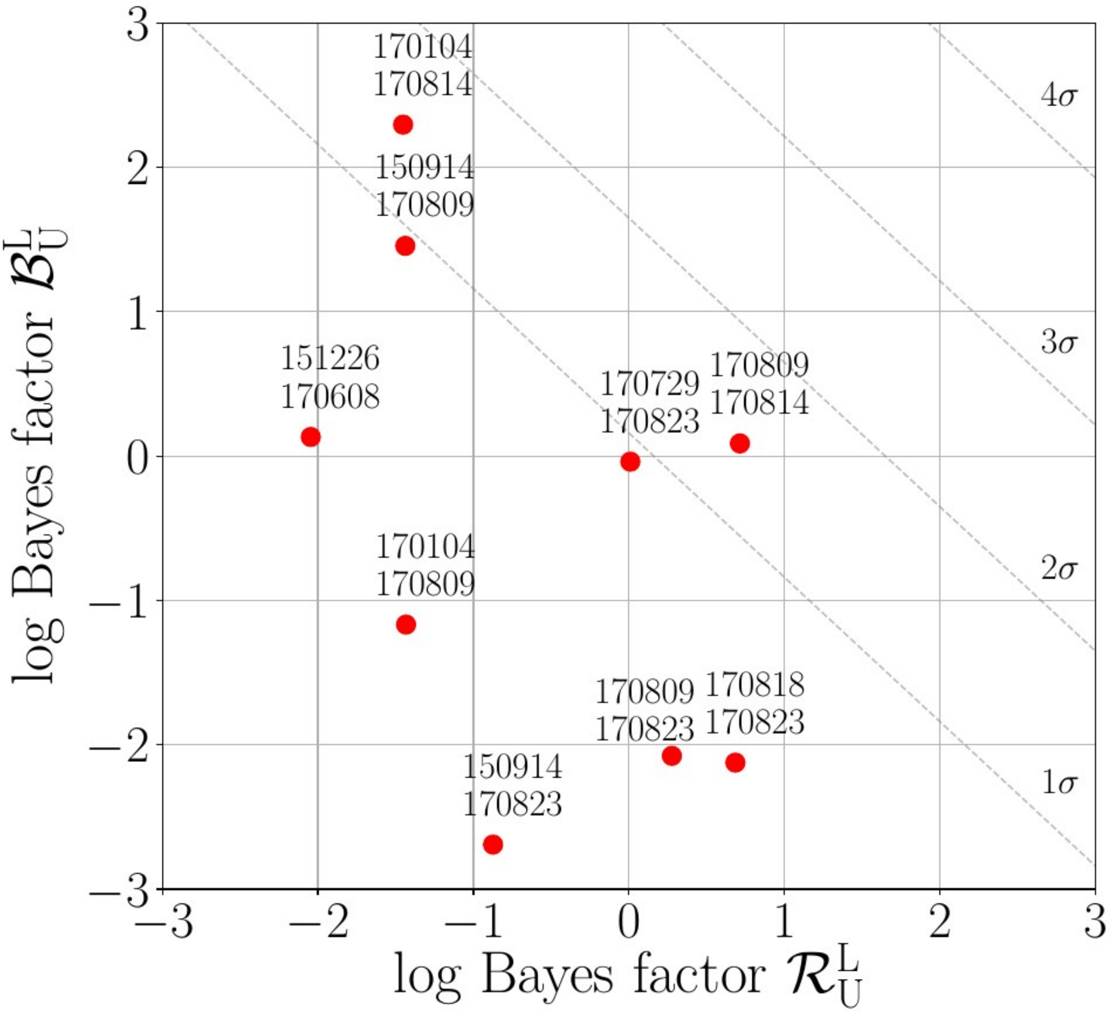
GWTC-1: Strong Lensing Multi-Images



$$\mathcal{B}_{\rm U}^{\rm L} := \frac{\mathcal{Z}_{\rm L}}{\mathcal{Z}_{\rm U}} = \int d\boldsymbol{\theta} \, \frac{P(\boldsymbol{\theta}|d_1)\, P(\boldsymbol{\theta}|d_2)}{P(\boldsymbol{\theta})}$$

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Hannuksela, et al., The Astrophysical Journ
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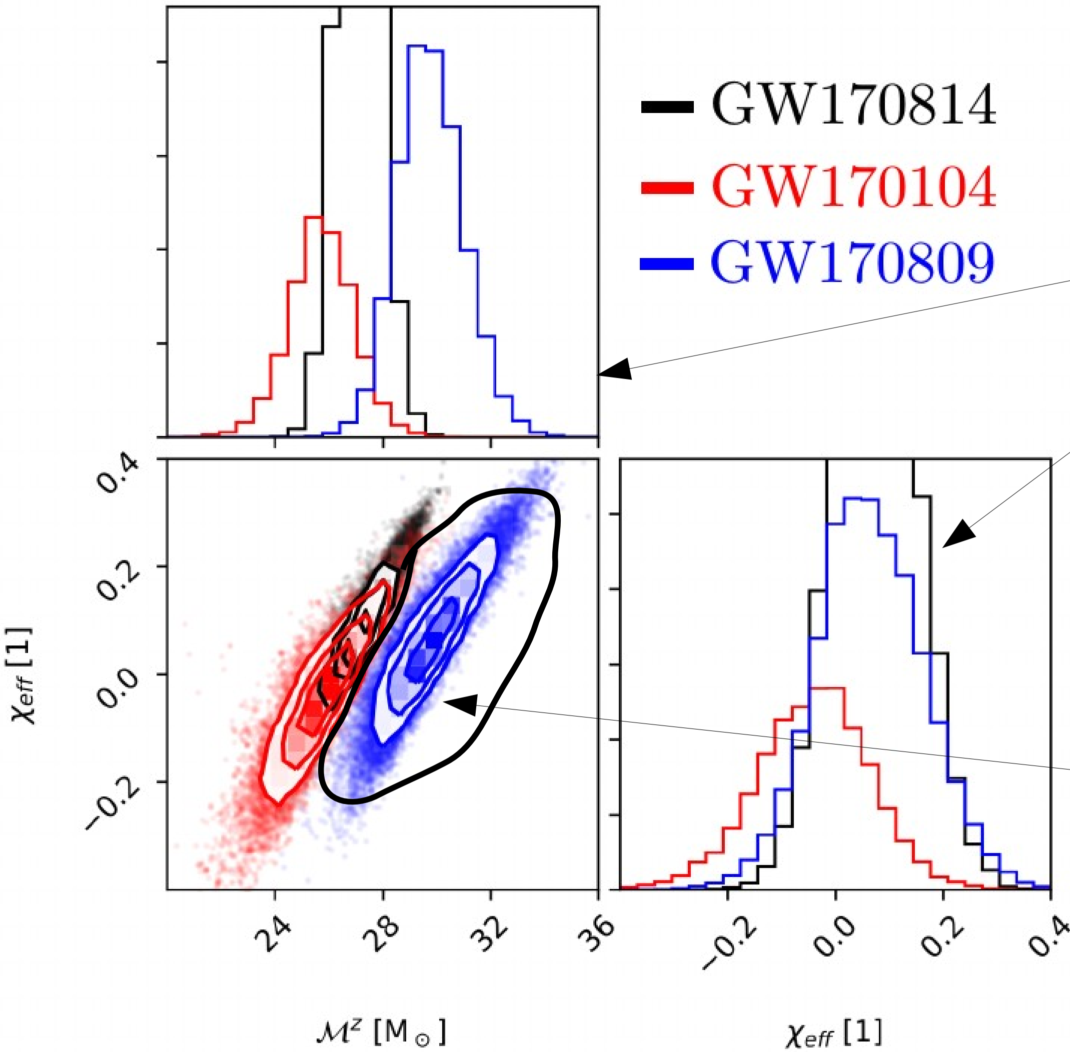
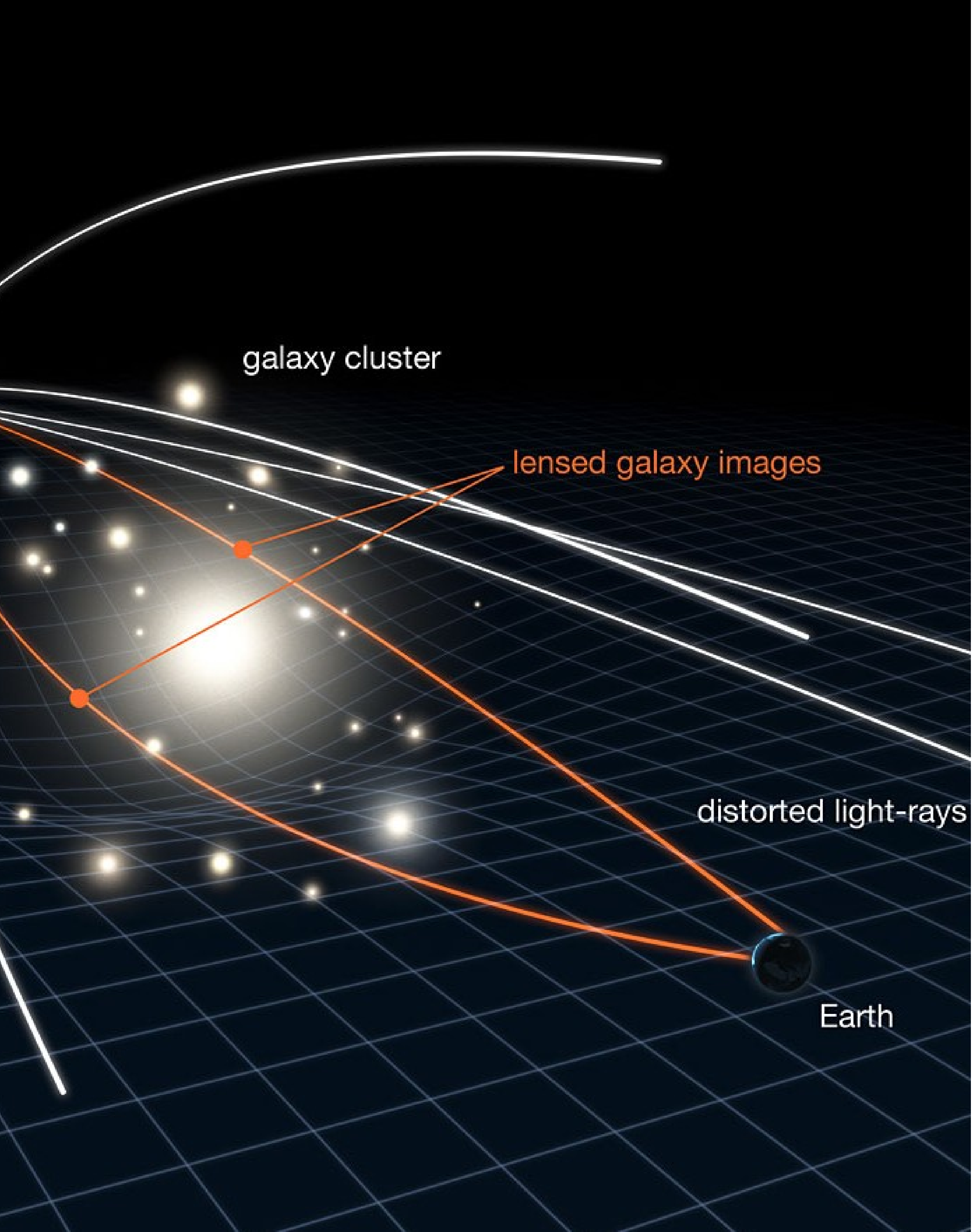


GW170814-GW170809:
- Apparent overlap in chirp masses, spins

However, likely caused by correlations between parameters

Hannuksela, et al., The Astrophysical Journal Letters 874.1 (2019): L2.



Why study multi-images

Example work:

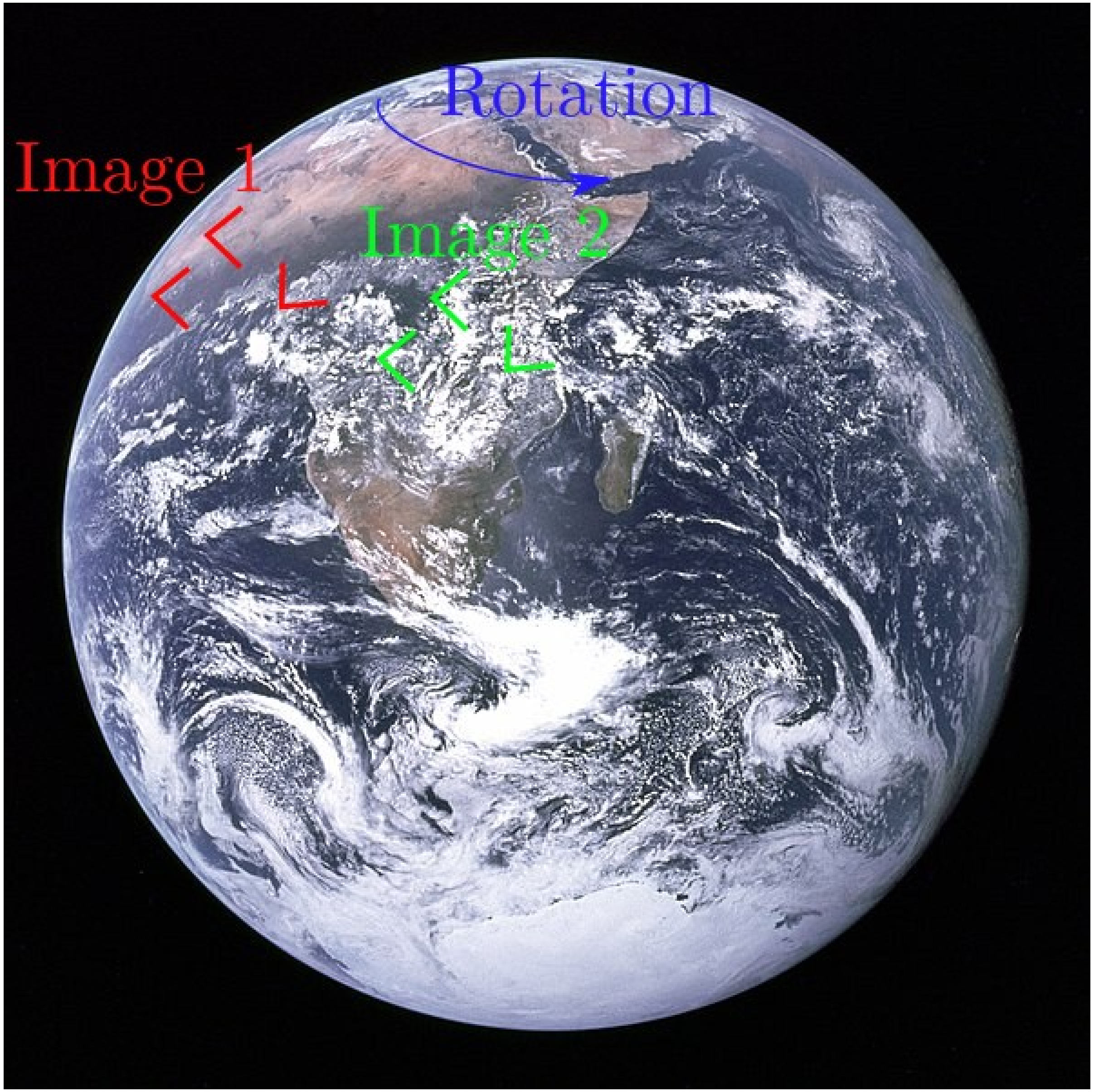
- Tests of speed of gravity (Collett &Bacon 2017, Fan et al. 2017)

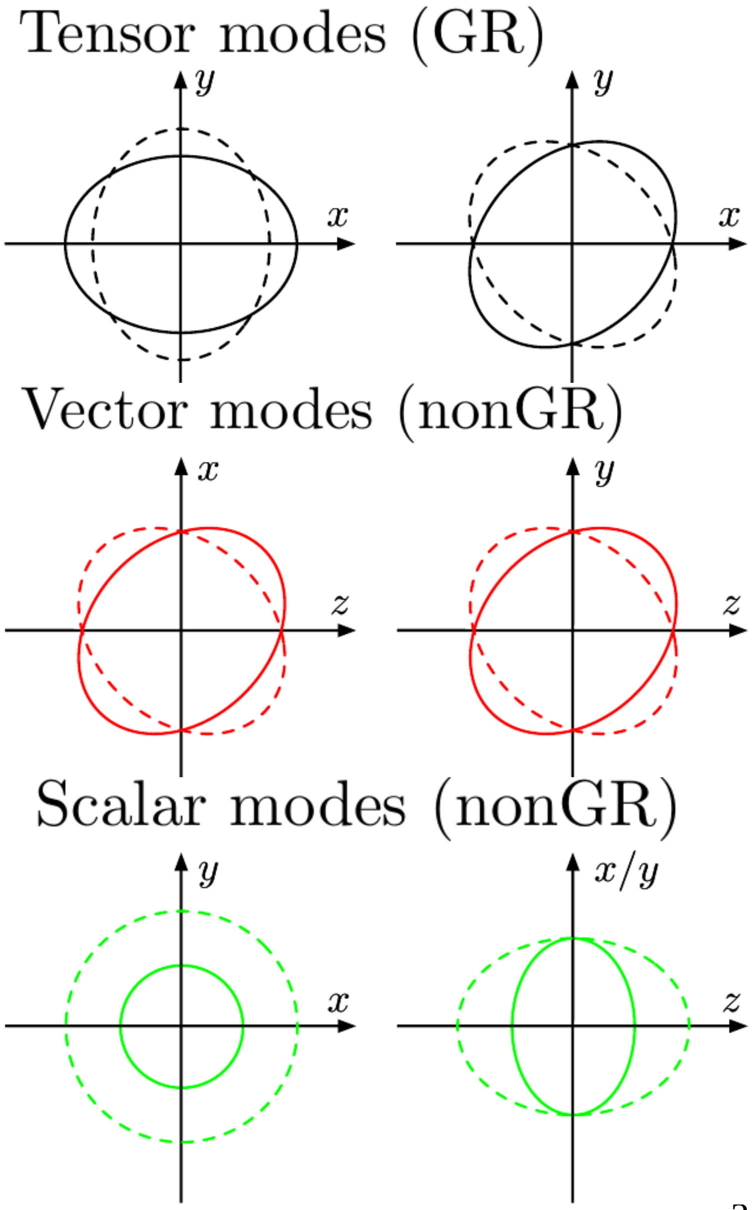
- Strong lensing cosmography (Baker & Trodden 2017, Liao et al. 2017)

- Hubble constant measurements (Liao et al. 2017)

- Polarization tests (Wong et al., in prep)

Polarization tests (preliminary)

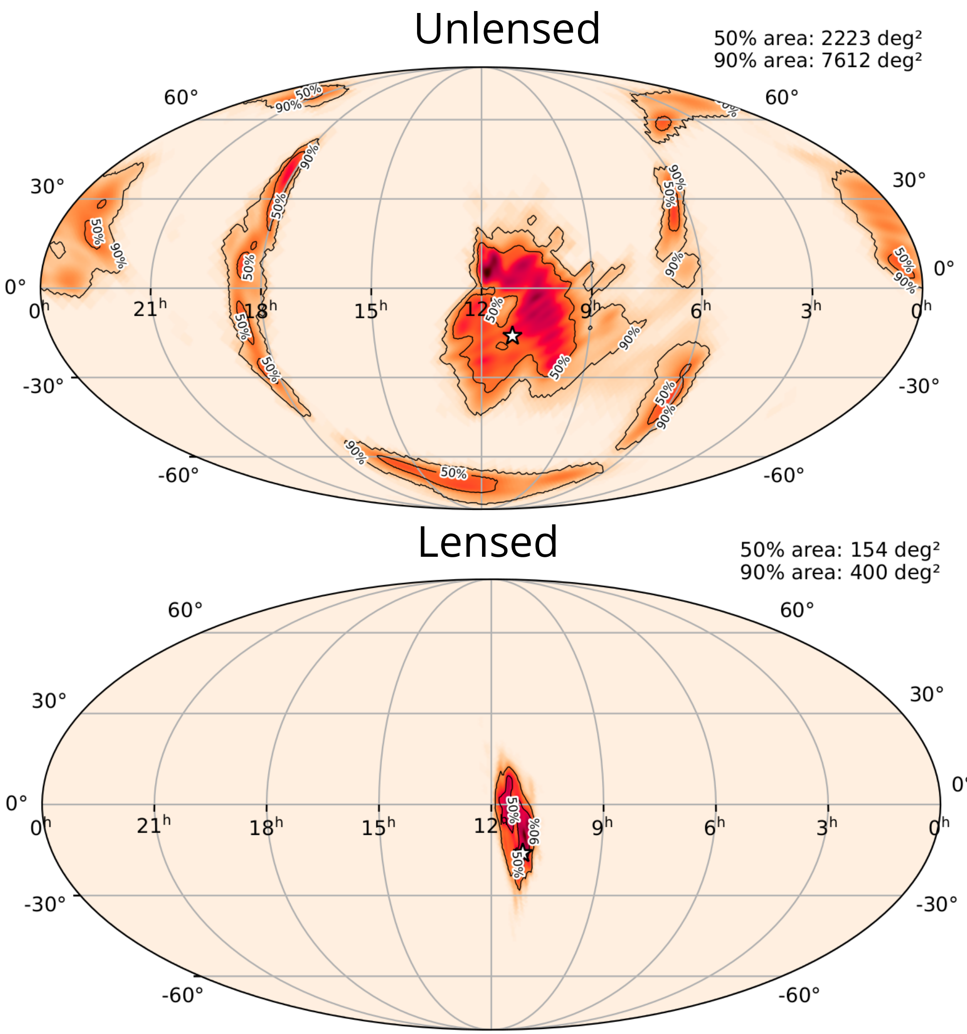


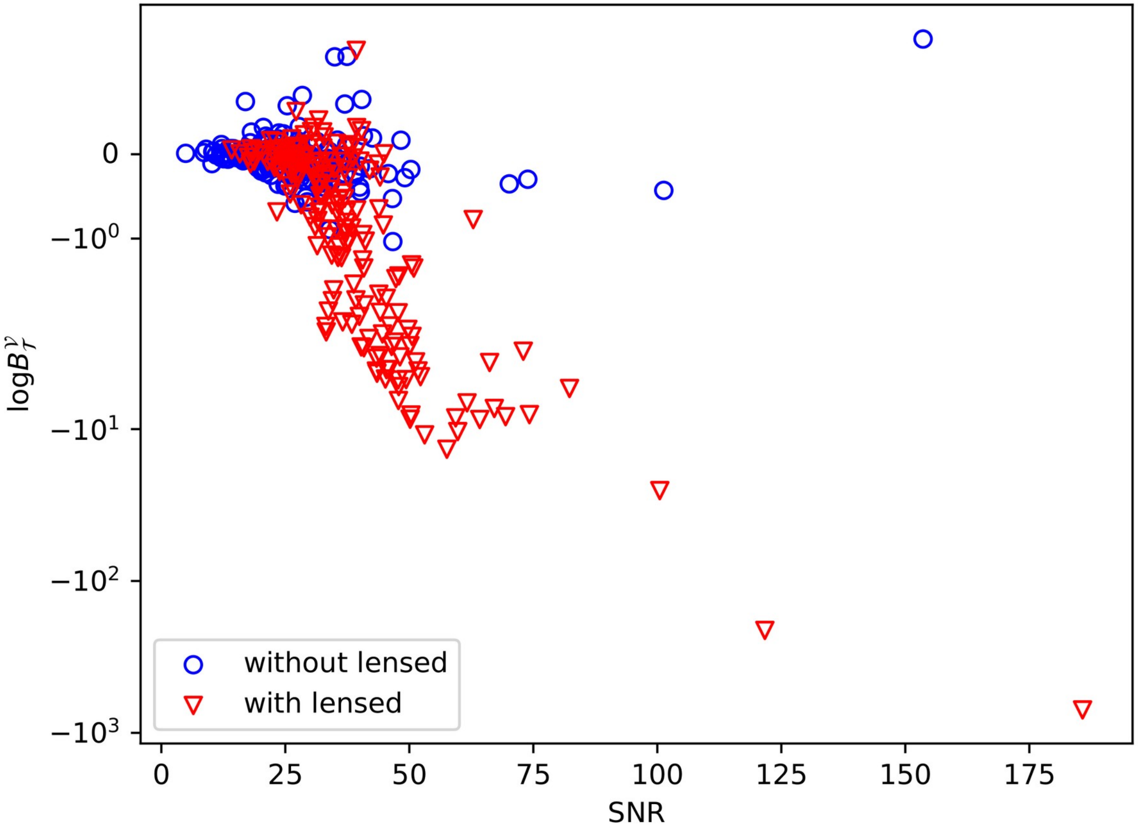


Credits: Apollo 17

Wong et al. (in prep)

Polarization tests (preliminary)

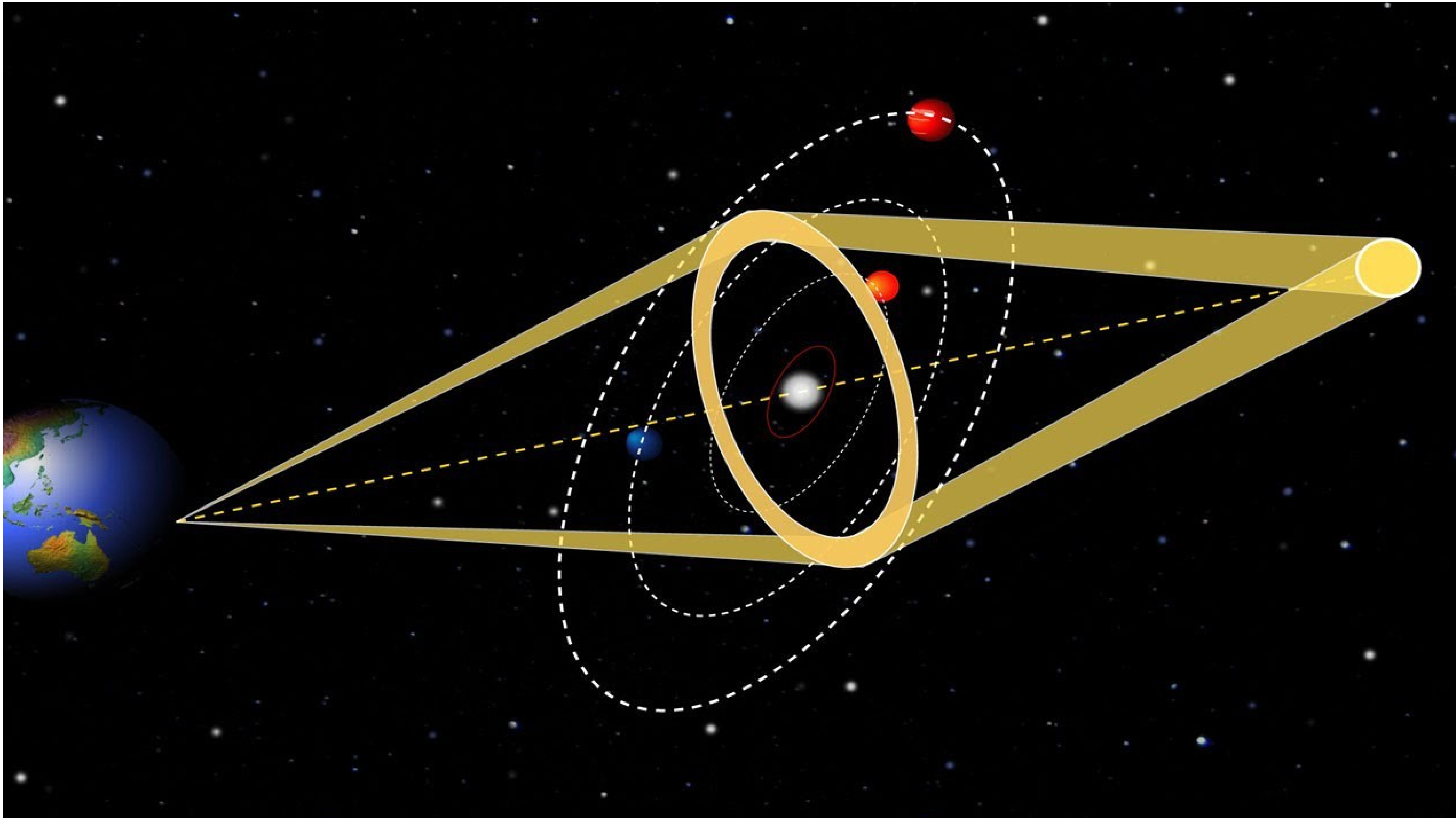




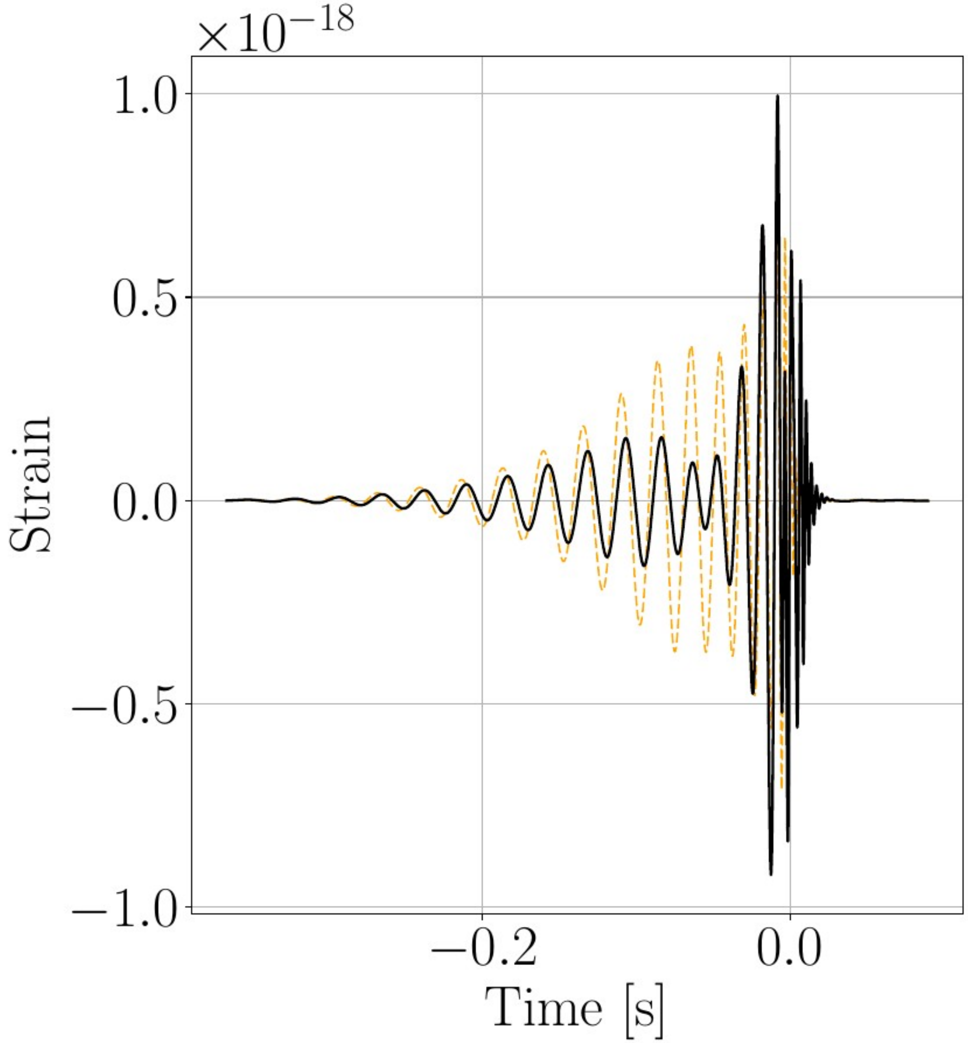
- Because multiple images arrive at a time-delay and thus different detector orientation, it allows for tests with effectively larger number of detectors

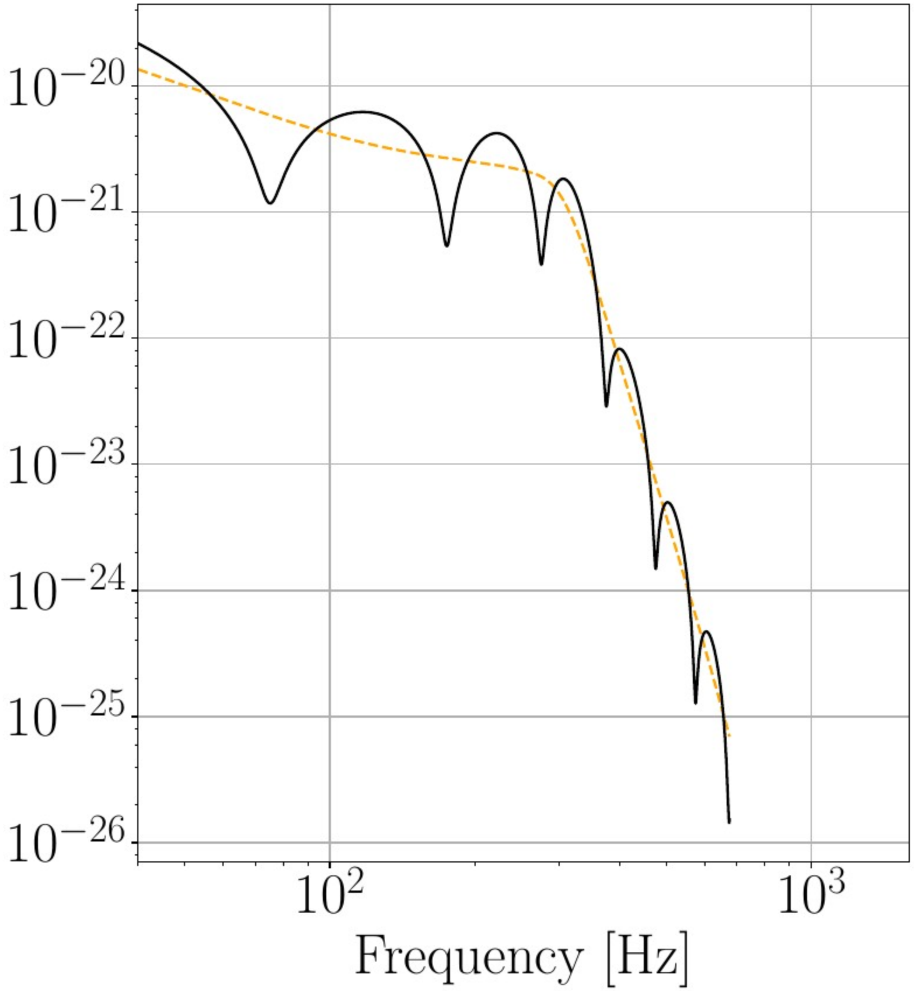
Wong et al. (in prep)

Microlensing



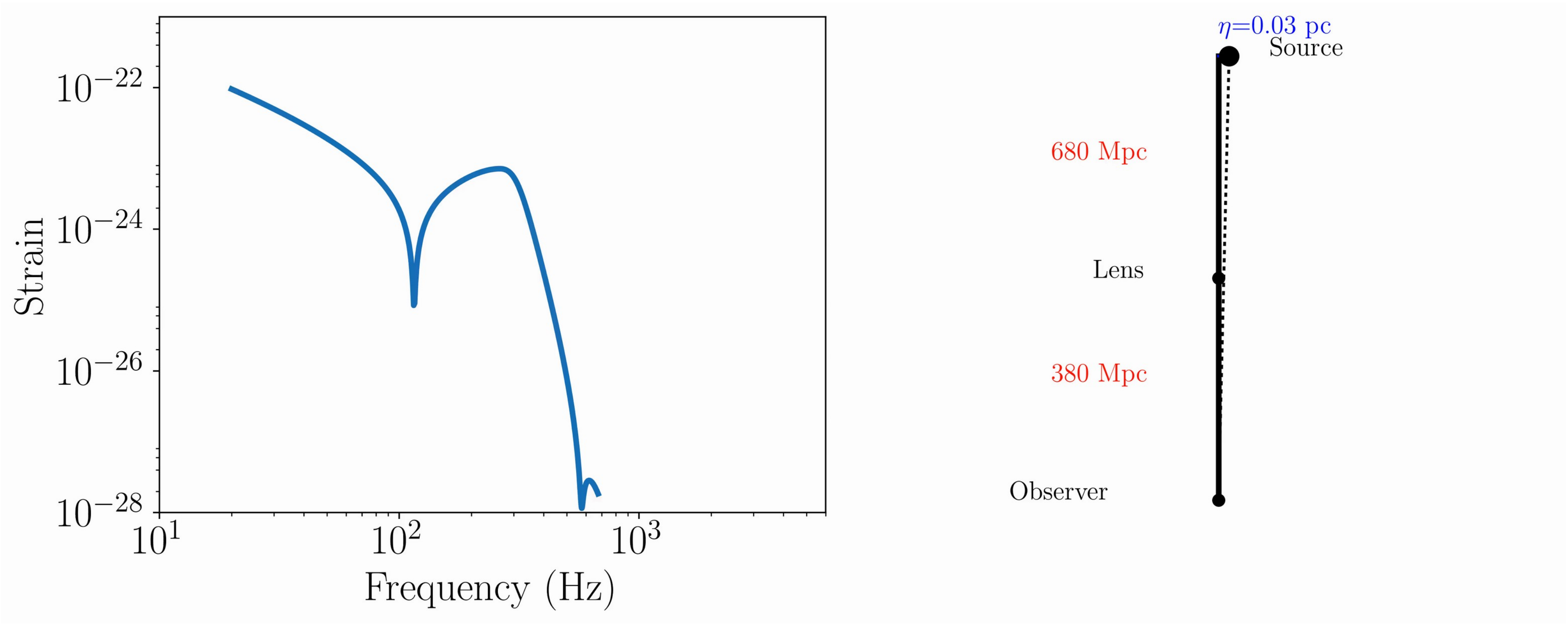
Microlensing





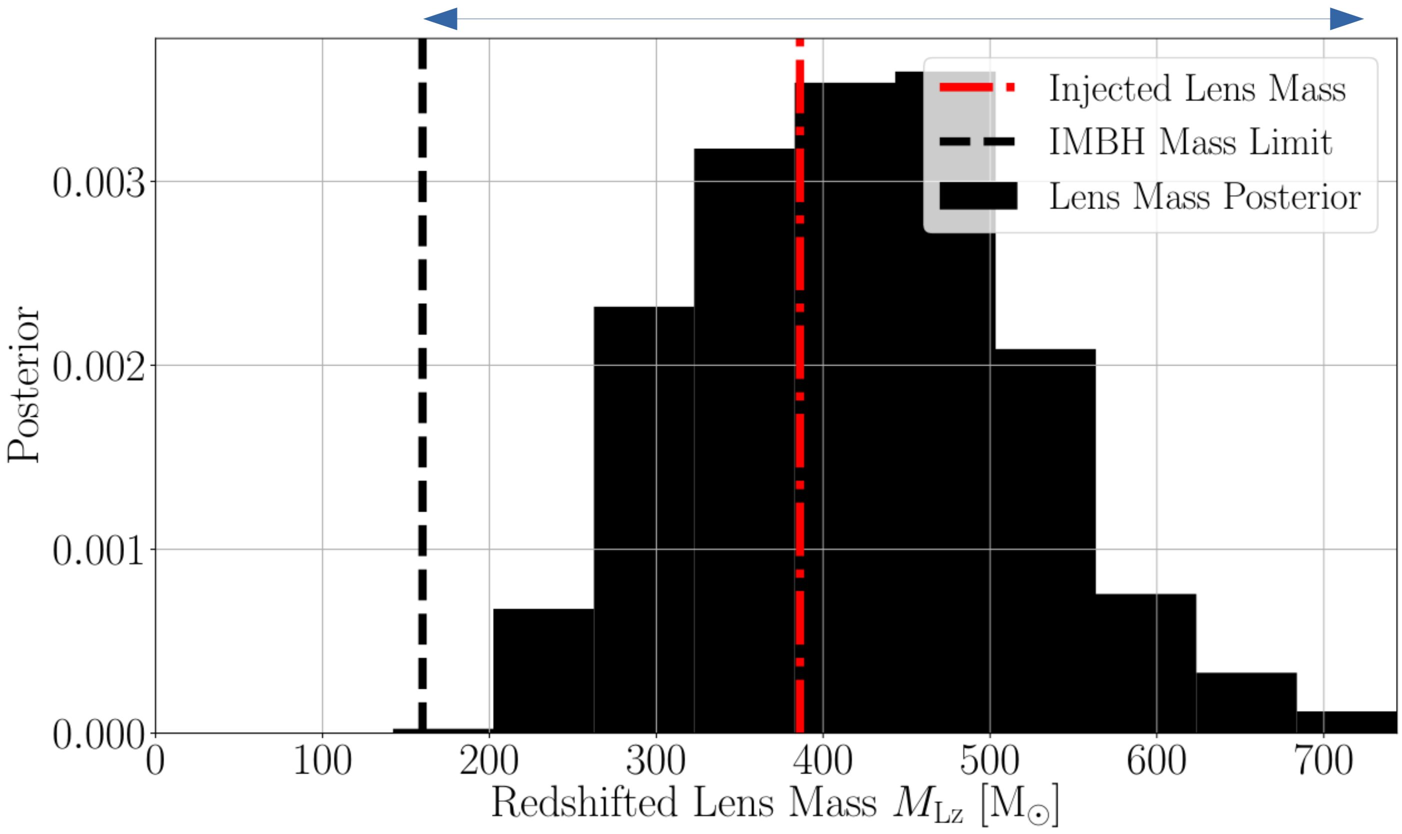
Microlensing

Point mass lens



Microlensing: intermediate-mass black holes

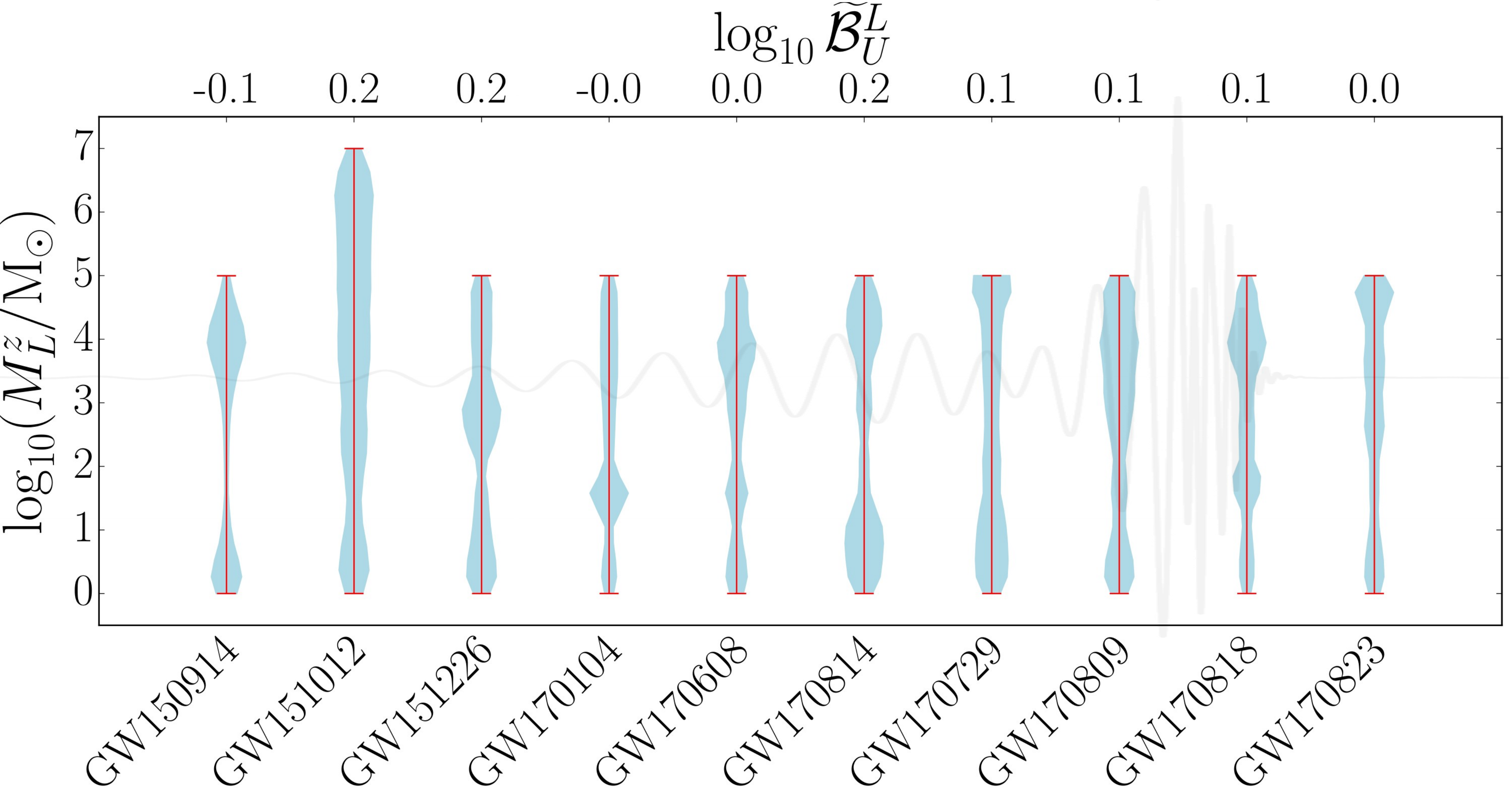
Above 100 solar masses



Implementation within LSC-developed LALSuite

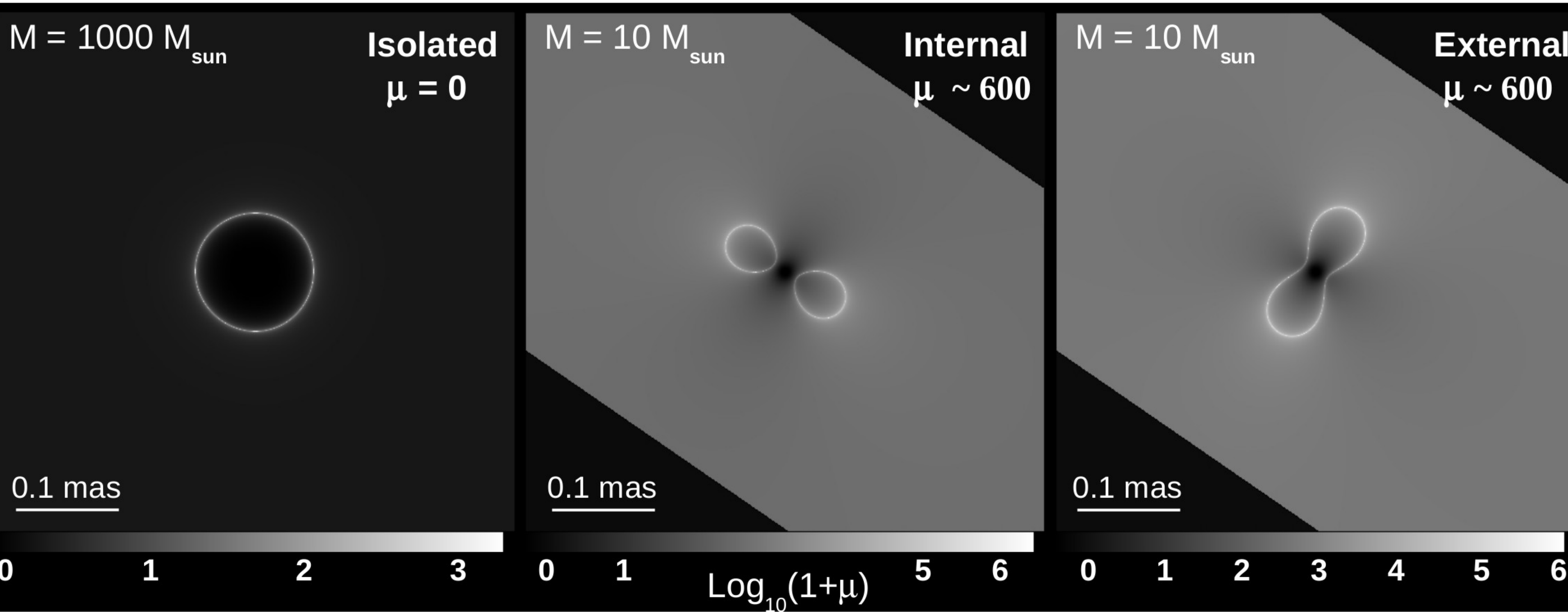
Lai, et al., Physical Review D 98.8 (2018): 083005.

GWTC-1: Microlensing



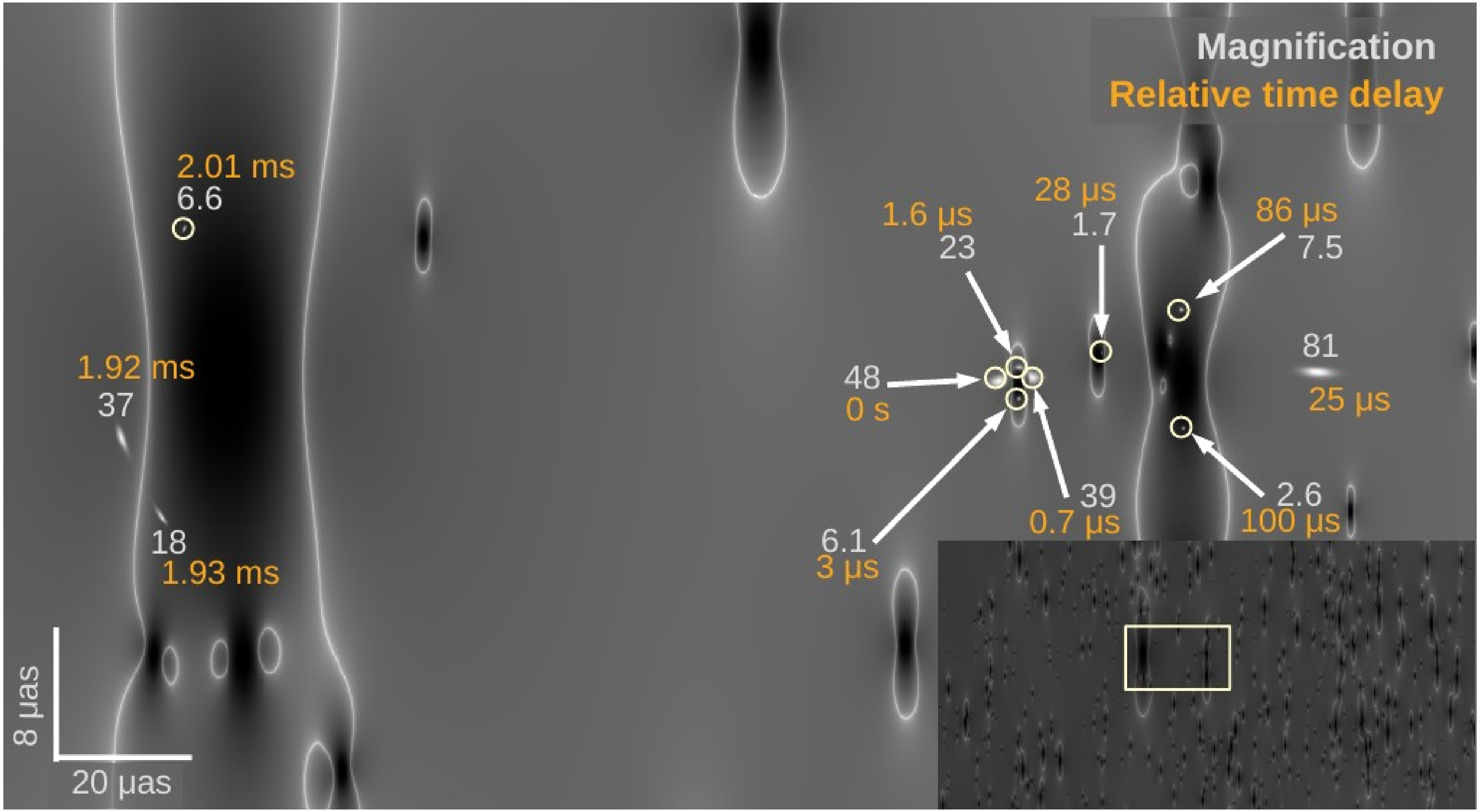
Hannuksela, et al., The Astrophysical Journal Letters 874.1 (2019): L2.

Microlensing: Macromodels



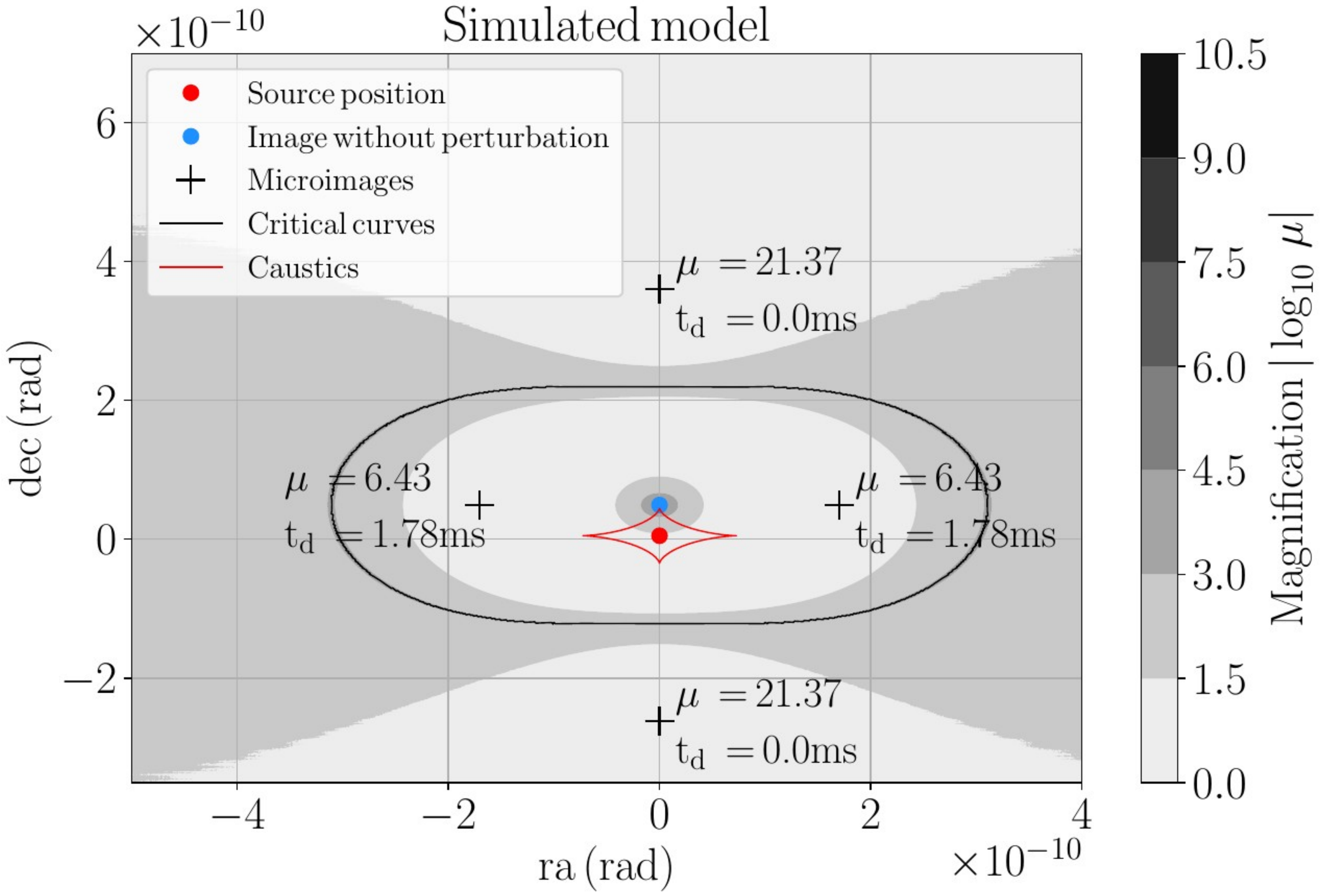
Diego, et al., A&A 627, A130 (2019)

Microlensing: Macromodels



Diego, et al., A&A 627, A130 (2019)

Microlensing: Outlook

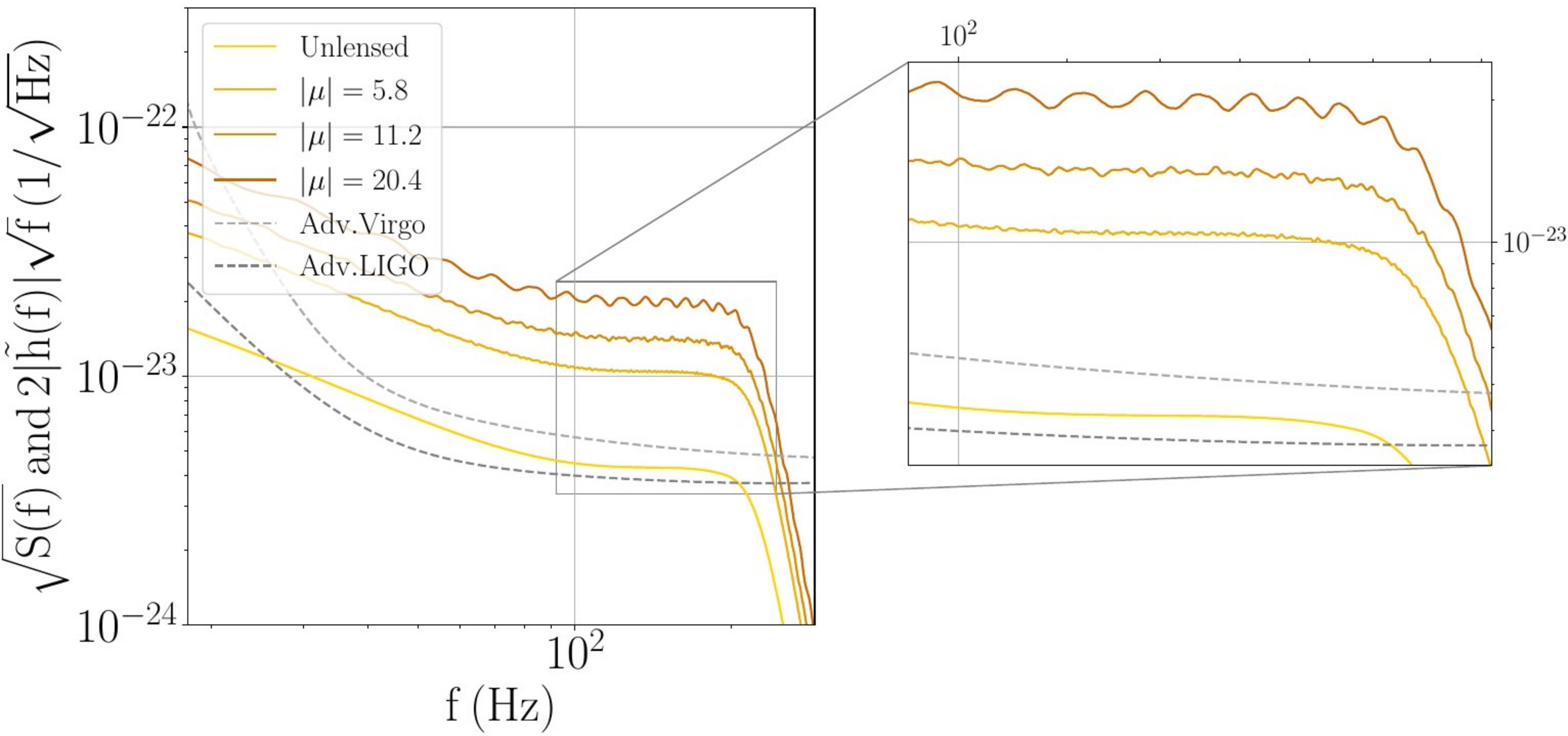


- Framework for generic microlensing configurations

Pagano et al., in prep.

- Waveform generation and analysis by lensingGW

Microlensing: Outlook



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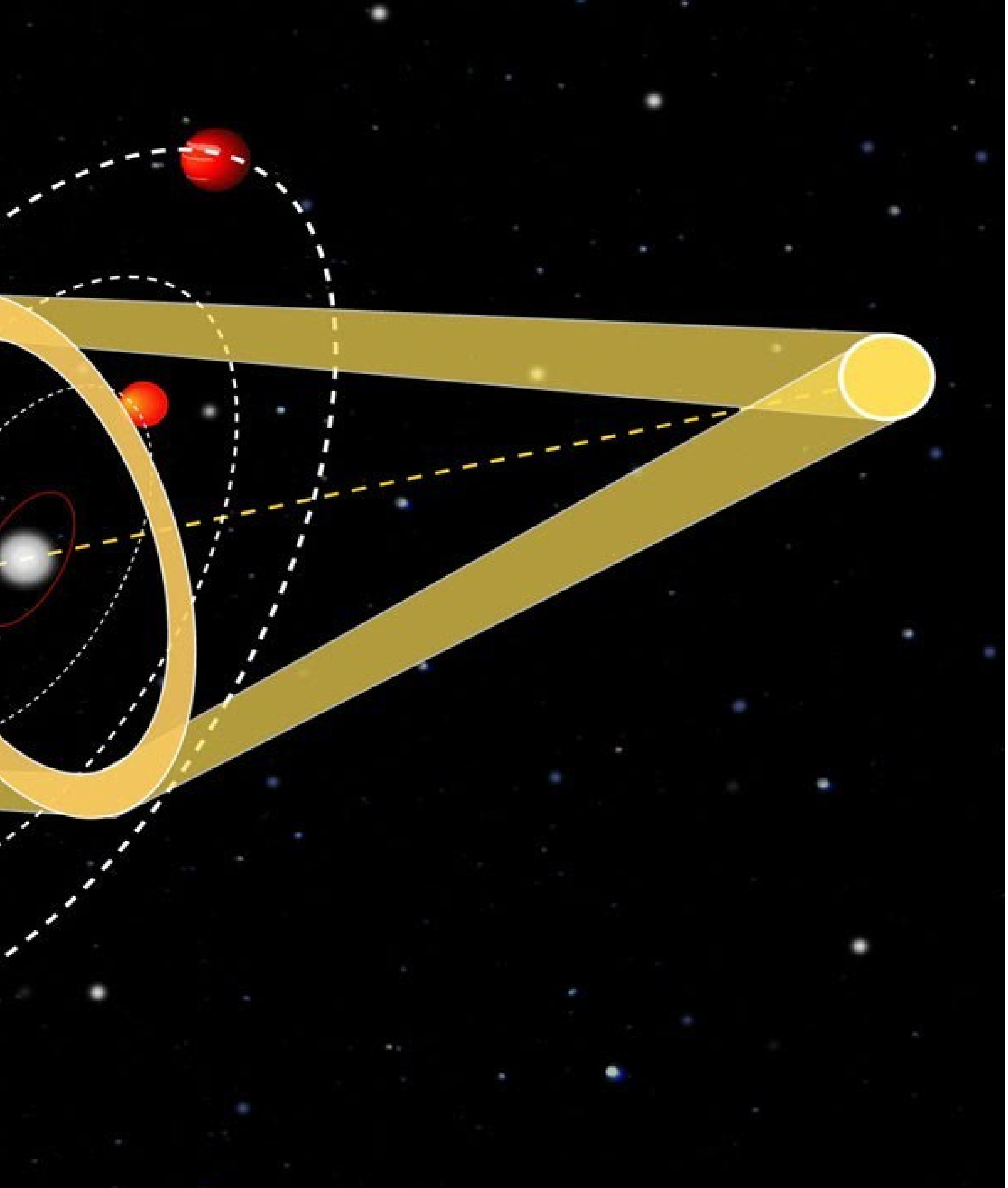


Why study microlensing?

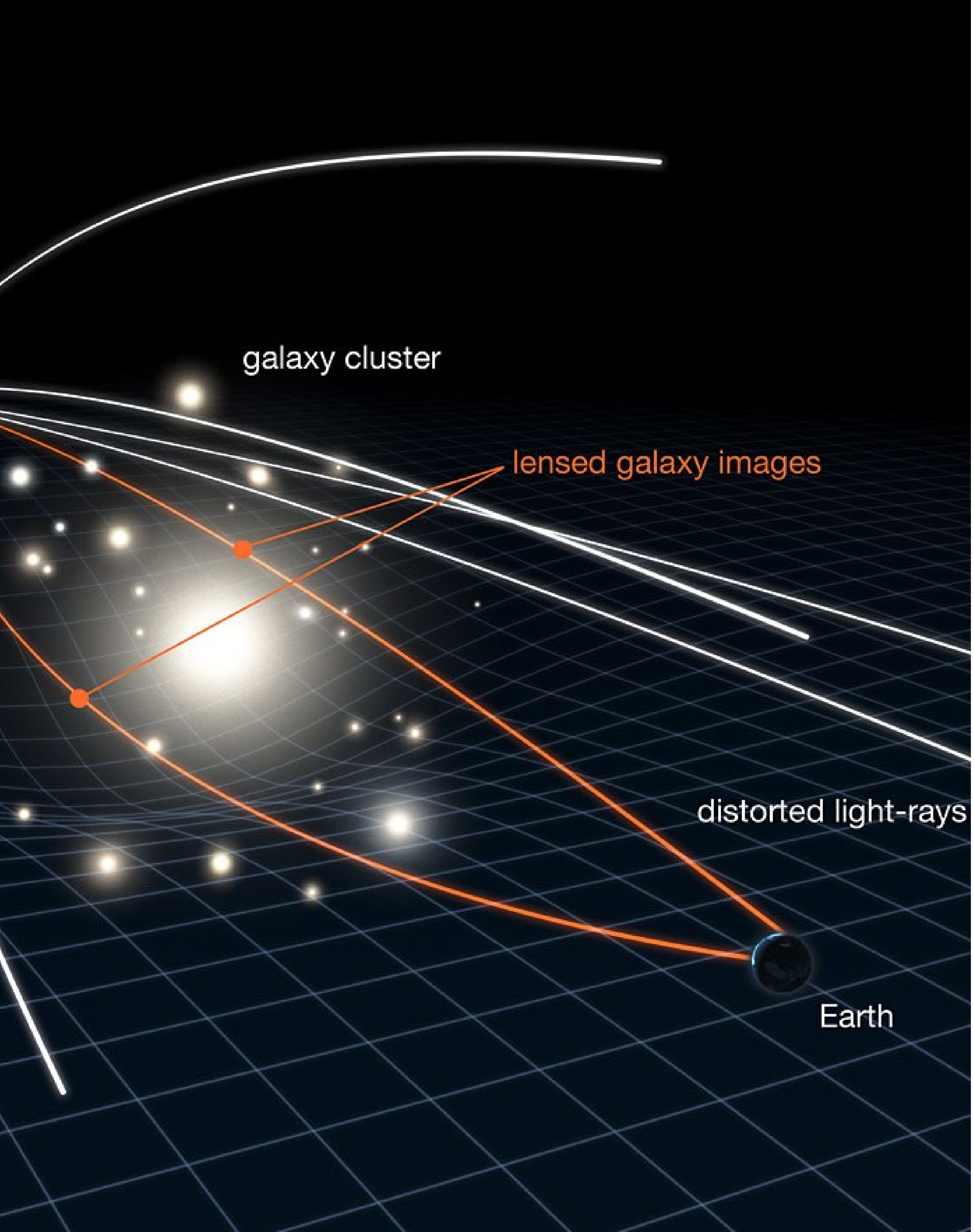
Example work:

- Study primordial black hole dark matter (Jung et al., 2019)

- Search for intermediate-mass black holes (Lai et al., 2017)

- Possibly smoking-giun evidence of strong lensing (Diego et al., 2019)

- Gravitational waves could allow for study of wave diffraction effects



Gravitational-wave lensing

- Gravitational waves, like light, can be gravitationally lensed

- Strong lensing would cause the signal to be magnified and split into multiple images

- If the wave travels through substructures, it could experience microlensing

- Thus far, we have not found compelling evidence of Gravitational-wave lensing

- However, future analyses and detector upgrades allow for better sensitivity and improved searches