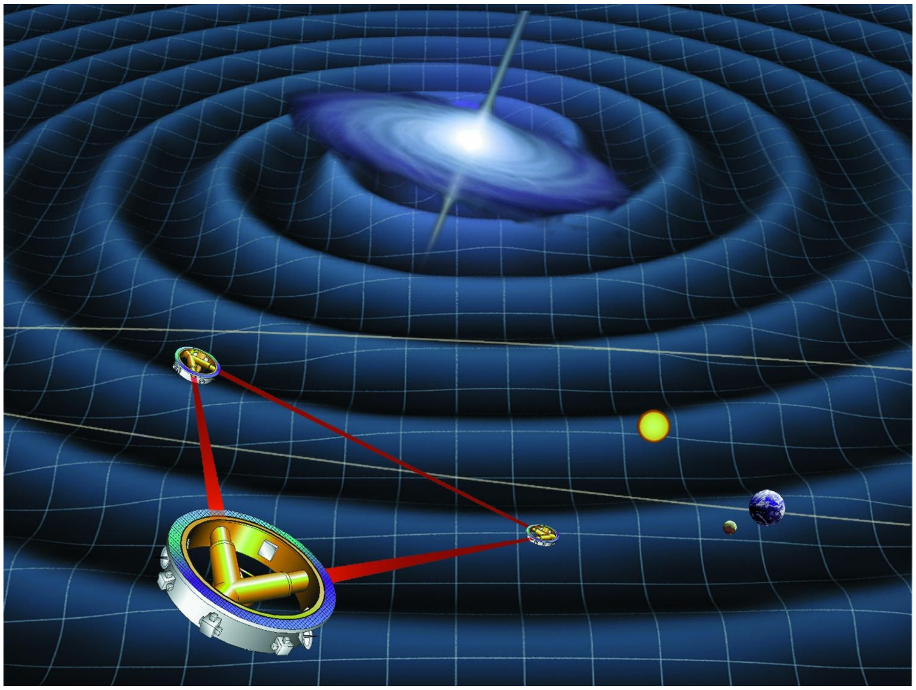
L I S A (2034)

Laser Interferometer Space Antenna

https://lisa.nasa.gov/



- Three space stations forming an equailateral triangle, each containing two test masses and two lasers, as well as two telescopes

- Each space station is then a Michaelson interferometer with arms of length

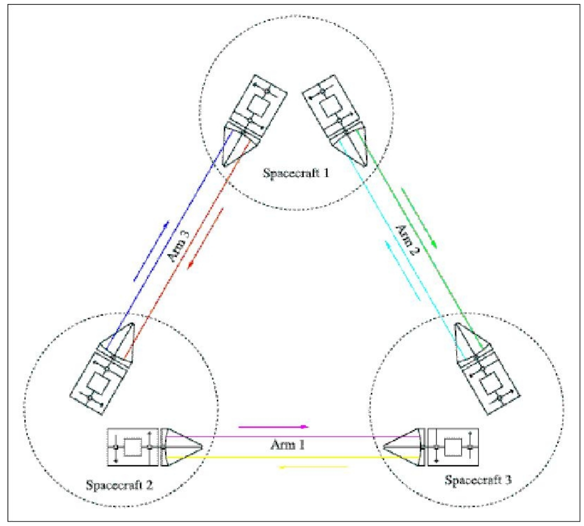
$$L = 2{,}500{,}000 \text{ km} \sim 400 \text{ Earth radii}$$

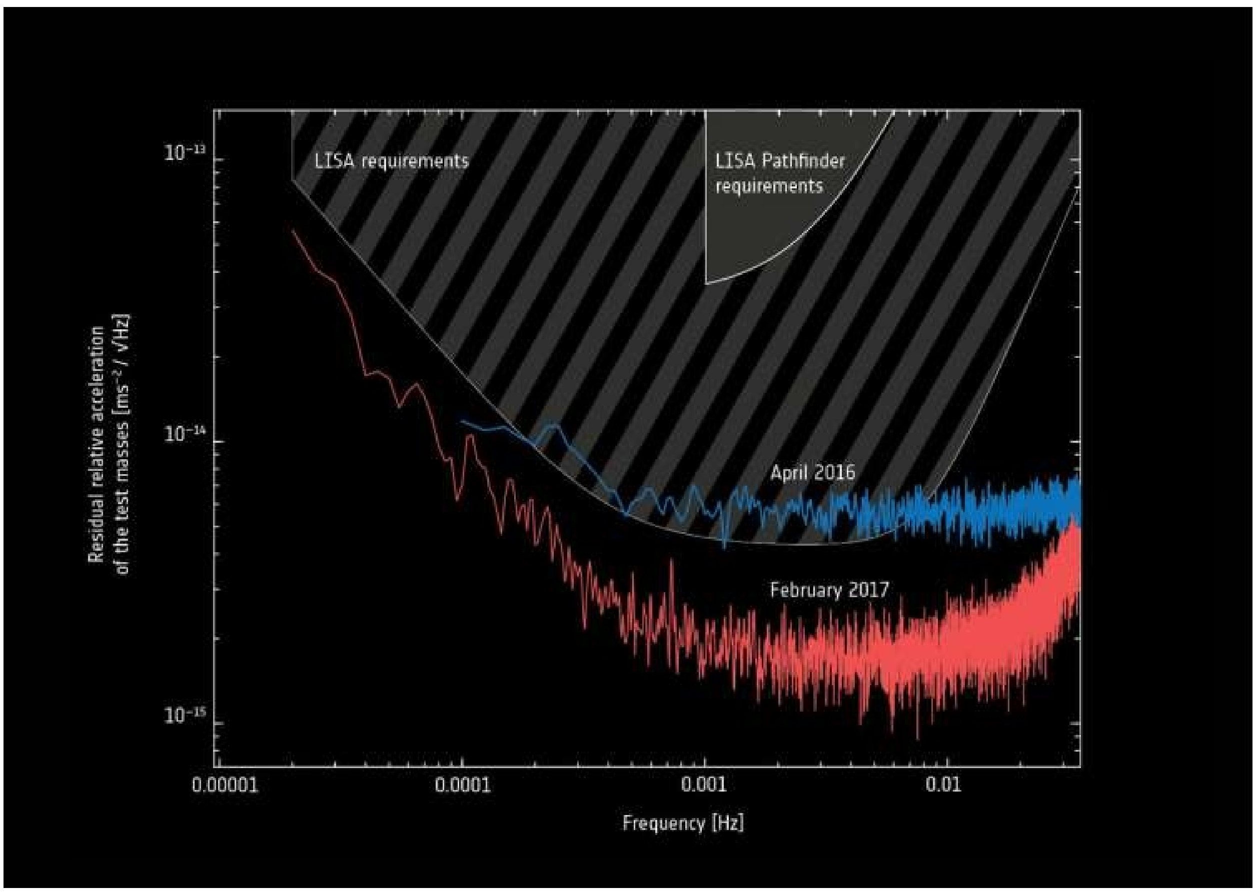
- Since arm position cannot remain fixed, need precise distance tracking and cannot use the Fabry-Perot resonant arm cavities or signal recycling, but with 1024 nm seed laser at ~40mW they can amplify to a stable power of ~3 W
https://www.sciencedaily.com/releases/2019/09/190918124529.htm

L I S A Pathfinder (2015)

https://arxiv.org/pdf/1903.08924.pdf

- Launched proof of concept mission in December 2015





https://phys.org/news/2018-02-results-lisa-pathfinder-satellite.html

- Tests hit all benchmarks by 2017, performing 100 times above its baseline requirements and 30 times better than existing ground-based detectors!

LISA SCIENCE OBJECTIVES

https://www.cosmos.esa.int/documents/678316/1700384/SciRD.pdf

SO 1 Study the formation and evolution of compact binary stars in the Milky Way Galaxy

SI 1.1 Elucidate the formation and evolution of Galactic Binaries by measuring their period, spatial and mass distributions

SI 1.2 Enable joint gravitational and electromagnetic observations of galactic binaries (GBs) to study the interplay between gravitational radiation and tidal dissipation in interacting stellar systems

SO 2 Trace the origin, growth and merger history of massive black holes across cosmic ages

SI 2.1 Search for seed black holes at cosmic dawn

SI 2.2 Study the growth mechanism of MBHs before the epoch of reionization

SI 2.3 Observation of EM counterparts to unveil the astrophysical environment around merging binaries

SI 2.4 Test the existence of intermediate-mass black holes (IMBHs)

SO 3 Probe the dynamics of dense nuclear clusters using extreme mass-ratio inspirals (EMRIs)

SI 3.1 Study the immediate environment of Milky Way like massive black holes (MBHs) at low redshift

SO 4 Understand the astrophysics of stellar origin black holes

SI 4.1 Study the close environment of Stellar Origin Black Holes (SOBHs) by enabling multi-band and multi-messenger observations at the time of coalescence

SI 4.2 Disentangle SOBHs binary formation channels

SO 5 Explore the fundamental nature of gravity and black holes

SI 5.1 Use ring-down characteristics observed in massive black hole binary (MBHB) coalescences to test whether the post-merger objects are the black holes predicted by General Theory of Relativity (GR)

SI 5.2 Use EMRIs to explore the multipolar structure of MBHs

SI 5.3 Testing for the presence of beyond-GR emission channels

SI 5.4 Test the propagation properties of gravitational waves (GWs)

SI 5.5 Test the presence of massive fields around massive black holes with masses larger than $10^3\ M_\odot$

SO 6 Probe the rate of expansion of the Universe

SI 6.1 Measure the dimensionless Hubble parameter by means of GW observations only

SI 6.2 Constrain cosmological parameters through joint GW and electro-magnetic (EM) observations

SO 7 Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

SI 7.1 Characterise the astrophysical stochastic GW background

SI7.2 Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

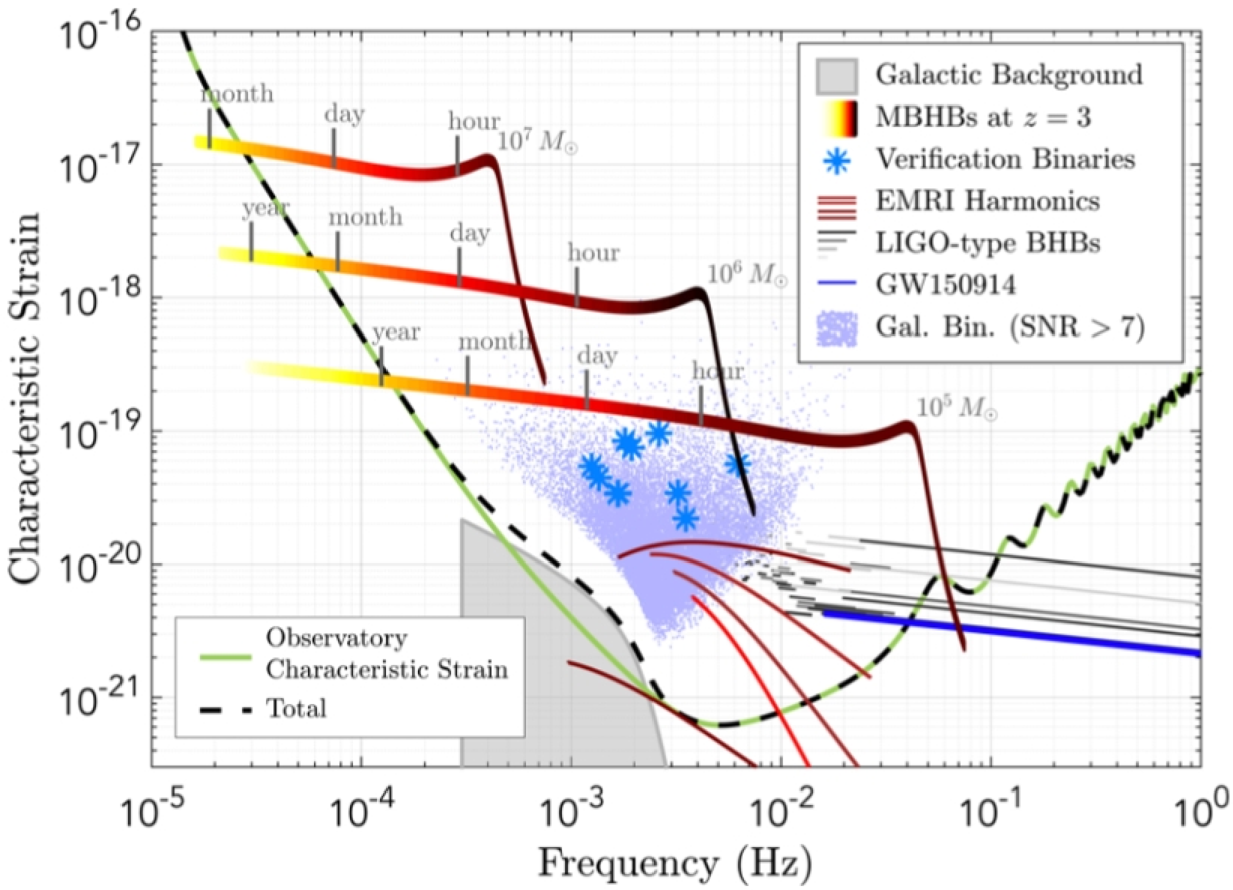
SO 8 Search for GW bursts and unforeseen sources

SI 8.1 Search for cusps and kinks of cosmic strings

SI 8.2 Search for unmodelled sources

→ What makes these goals possible?

Sensitivity from ~0.1 mHz to ~0.1 Hz



https://arxiv.org/pdf/1803.01944.pdf

$$L = 2.5 \text{ Gm}, \; f_* = 19.09 \text{ mHz}$$

$$S_n(f) = \frac{10}{3L^2}\left(P_{\rm OMS}(f) + \frac{4P_{\rm acc}(f)}{(2\pi f)^4}\right)\left(1 + \frac{6}{10}\left(\frac{f}{f_*}\right)^2\right) + S_c(f)$$

The current "official" model for the power spectral density of the LISA noise $P_n(f)$ is based on the Payload Description Document, and is referenced in the "LISA Strain Curves" document LISA-LCST-SGS-TN-001. The single-link optical metrology noise is quoted as

$$P_{\rm OMS} = (1.5 \times 10^{-11}\,\text{m})^2 \left(1 + \left(\frac{2\,\text{mHz}}{f}\right)^4\right) \text{Hz}^{-1}, \tag{10}$$

and the single test mass acceleration noise is quoted as

$$P_{\rm acc} = (3{\times}10^{-15}\,\text{m}\,\text{s}^{-2})^2 \left(1 + \left(\frac{0.4\,\text{mHz}}{f}\right)^2\right)\left(1 + \left(\frac{f}{8\,\text{mHz}}\right)^4\right) \text{Hz}^{-1}. \tag{11}$$

Estimates for the confusion noise using the new LISA design are given in Ref. [8], and are well fit by the function

$$S_c(f) = A\, f^{-7/3} e^{-f^\alpha + \beta f \sin(\kappa f)} \left[1 + \tanh(\gamma(f_k - f))\right] \text{Hz}^{-1} \tag{14}$$

What do we know about these unobserved sources?

SMBH Mergers: https://arxiv.org/pdf/1601.06156.pdf

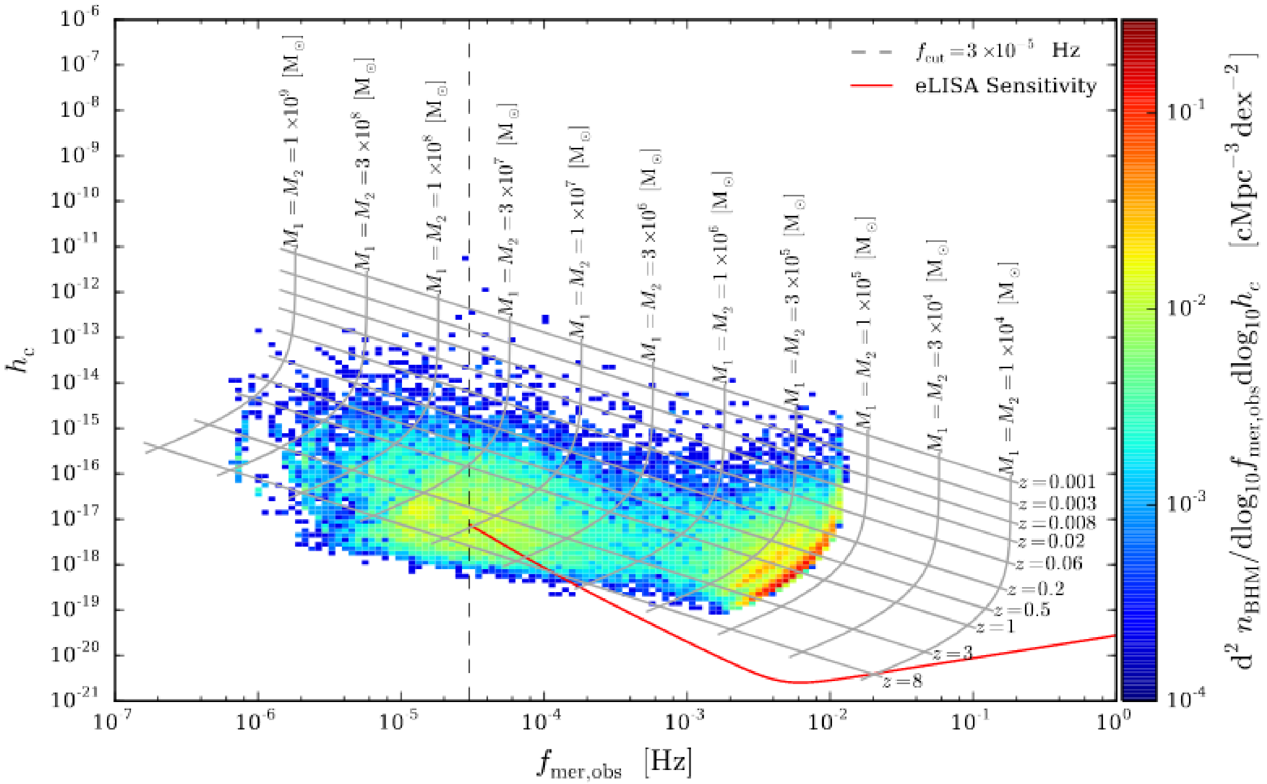


Figure 7. Characteristic strain amplitude h_c of the GW signals emitted by all SMBH coalescences in the EAGLE Ref-L100N1504 simulation as a function of the observed frequency at the transition between the inspiral phase and the merger phase of the SBMH coalescence process $f_{\rm mer,obs} = (0.018\, c^3/GM_{\rm total})/(1+z)$. Colour coding represents the co-moving number density of events per characteristic strain-observed merger frequency bin. Grey contour lines indicate the characteristic strain and observed merger frequency for equal mass BH binaries ($M_1 = M_2$) coalescing at different redshifts z. The sensitivity curve of eLISA calculated from the analytic approximation in Eq. (8) is shown in red. The black dashed line indicates the low-frequency cut-off of the sensitivity curve $f_{\rm cut} = 3 \times 10^{-5}$ Hz. GW signals above the sensitivity curve and to the right of the low-frequency cut-off can be resolved from the eLISA data stream.

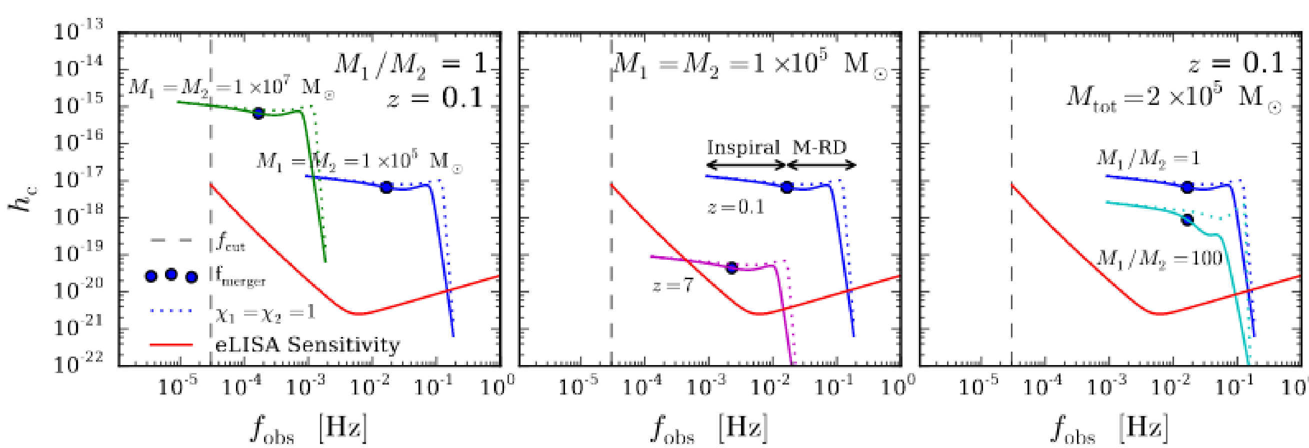


Figure 2. Example of the dimensionless characteristic strain amplitude, h_c, produced by non-spinning SMBH coalescence events ($\chi_i = 0$). Maximally spinning SMBHs aligned with the orbital angular momentum of the binary are shown in dotted lines ($\chi_i = 1$). In all panels the inspiral and merger-ringdown phases are shown for an equal mass BH binary (Mass ratio $M_1/M_2 = 1$, $M_1 = M_2 = 1 \times 10^5$ M$_\odot$) that merge at redshift $z = 0.1$ as reference (blue line). The frequency at the transition from the inspiral phase to the merger phase ($f_{\rm merger} = 0.018\, c^3/GM_{\rm total}$) is highlighted with a blue dot. The sensitivity curve of eLISA was calculated from the analytic approximation provided by Amaro-Seoane et al. (2013). The black dashed line indicates the low-frequency cut-off of the sensitivity curve $f_{\rm cut} = 3 \times 10^{-5}$ Hz. GW signals above the sensitivity curve and to the right of the low-frequency cut-off can be resolved from the eLISA data stream. *LEFT PANEL:* The effect of increasing the total mass of the SMBH binary. An equal mass SMBH binary (Mass ratio $M_1/M_2 = 1$) with $M_1 = M_2 = 1 \times 10^7$ M$_\odot$ that merges at redshift $z = 0.1$ is shown in green. *MIDDLE PANEL*: The effect of redshift. An equal mass SMBH binary (Mass ratio $M_1/M_2 = 1$, $M_1 = M_2 = 1 \times 10^5$ M$_\odot$) merging at redshift $z = 7$ is shown in magenta. *RIGHT PANEL*: The effect of mass ratio. A BH binary with total mass $M_{\rm total} = 2 \times 10^5$ M$_\odot$ and mass ratio $M_1/M_2 = 100$ merging at redshift $z = 0.1$ is shown in cyan.

What can we do by combining precision measurements of (IMR) INSPIRAL, MERGER, and RINGDOWN ?

LIGO could achieve the SNR: https://arxiv.org/pdf/gr-qc/9701039.pdf
Testing framework: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.73.064030

GW150914: https://arxiv.org/pdf/1602.03841.pdf

Testing consistency between GR prediction of BBH merger remnant and observed IMR signal (no hair → all information in MASS, SPIN, CHARGE~0):

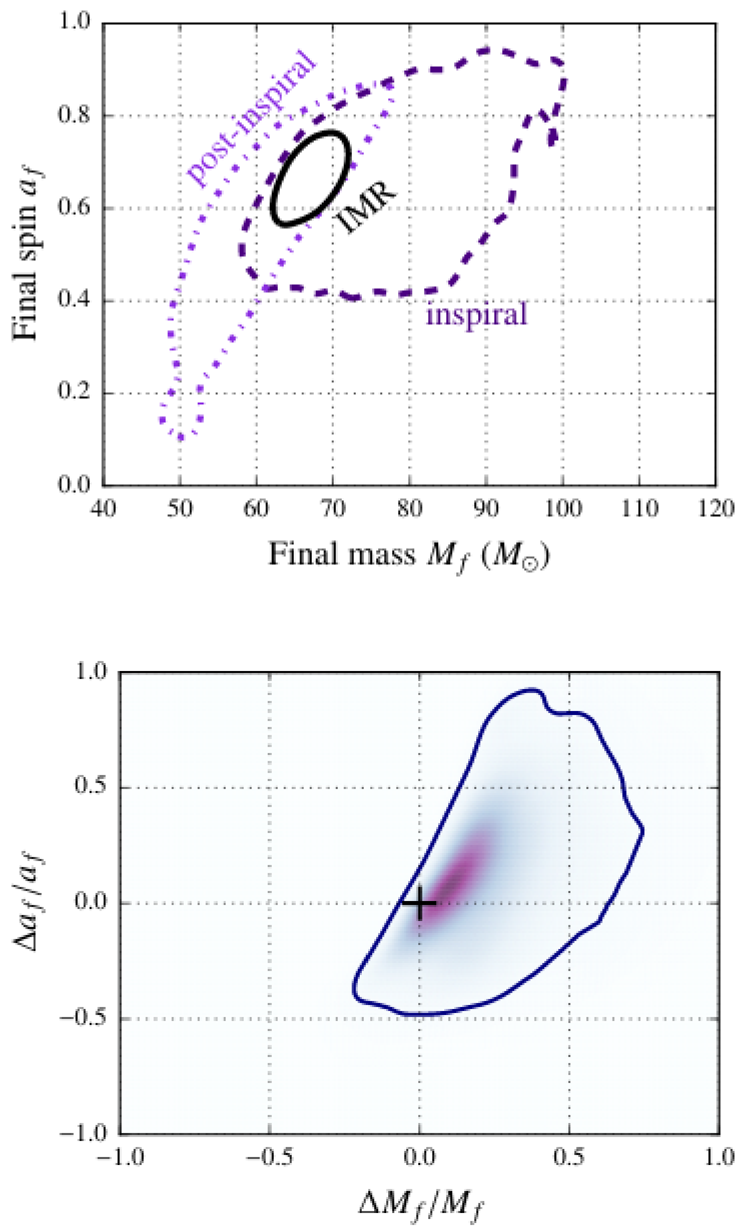


FIG. 4. *Top panel*: 90% credible regions in the joint posterior distributions for the mass M_f and dimensionless spin a_f of the final compact object as determined from the inspiral (dark violet, dashed) and post-inspiral (violet, dot-dashed) signals, and from a full inspiral–merger–ringdown analysis (black). *Bottom panel*: Posterior distributions for the parameters $\Delta M_f/M_f$ and $\Delta a_f/a_f$ that describe the fractional difference in the estimates of the final mass and spin from inspiral and post-inspiral signals. The contour shows the 90% confidence region. The plus symbol indicates the expected GR value (0, 0).

Testing GR prediction of quasinormal modes in ringdown (central frequency and samping time):

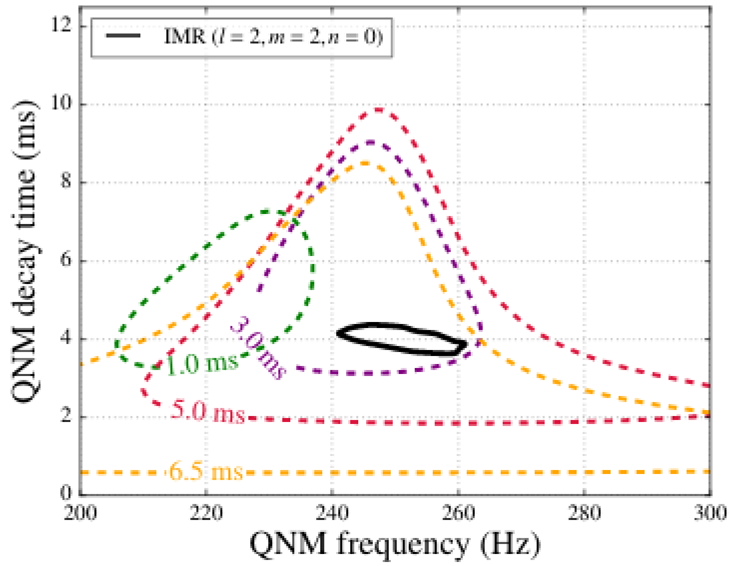


FIG. 5. 90% credible regions in the joint posterior distributions for the damped-sinusoid parameters f_0 and τ (see main text), assuming start times $t_0 = t_M + 1, 3, 5, 6.5$ ms, where t_M is the merger time of the MAP waveform for GW150914. The black solid line shows the 90% credible region for the frequency and decay time of the $\ell = 2$, $m = 2$, $n = 0$ (i.e., the least damped) QNM, as derived from the posterior distributions of the remnant mass and spin parameters.

Testing parameterized deviations (here to ≤ 3.5PN):

TABLE I. Summary of results for the gIMR parameterized-deviation analysis of GW150914. For each parameter in the gIMR model, we report its frequency dependence, its median and 90% credible intervals, the quantile of the GR value of 0 in the 1D posterior probability density function. Finally, the last two columns show $\log_{10}$ Bayes factors between GR and the gIMR model. The uncertainties on the log Bayes factors are 2σ. The a and b coefficients shown for $\delta\hat{\alpha}_4$ are functions of the component masses and spins (see Ref. [41]). For each field, we report the corresponding quantities for both the single-parameter and multiple-parameter analyses.

waveform regime			median		GR quantile		$\log_{10} B^{\rm GR}_{\rm model}$	
	parameter	f−dependence	single	multiple	single	multiple	single	multiple
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	$-0.1^{+0.1}_{-0.1}$	$1.4^{+3.3}_{-3.0}$	0.94	0.21	1.9 ± 0.1	2.1 ± 0.6
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	$-0.4^{+0.0}_{-0.9}$	$-0.6^{+17.7}_{-18.0}$	0.94	0.52	1.3 ± 0.3	
	$\delta\hat{\varphi}_2$	f^{-1}	$-0.35^{+0.3}_{-0.35}$	$-3.2^{+19.3}_{-15.2}$	0.97	0.60	1.2 ± 0.2	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	$0.2^{+0.2}_{-0.2}$	$2.6^{+13.8}_{-15.7}$	0.04	0.41	1.2 ± 0.1	
	$\delta\hat{\varphi}_4$	$f^{-1/3}$	$-2.0^{+1.6}_{-1.8}$	$0.5^{+17.3}_{-18.2}$	0.98	0.49	0.3 ± 0.1	
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	$0.8^{+0.6}_{-0.55}$	$-1.5^{+19.1}_{-16.3}$	0.02	0.55	0.7 ± 0.1	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	$-1.5^{+1.1}_{-1.1}$	$-0.6^{+18.2}_{-17.2}$	0.99	0.53	0.4 ± 0.1	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	$8.9^{+6.8}_{-6.8}$	$-2.4^{+18.7}_{-15.2}$	0.02	0.57	-0.2 ± 0.1	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	$3.7^{+2.6}_{-2.75}$	$-3.4^{+19.3}_{-14.8}$	0.02	0.59	-0.0 ± 0.2	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	$0.1^{+0.4}_{-0.3}$	$0.15^{+0.6}_{-0.5}$	0.29	0.35	1.2 ± 0.1	2.2 ± 0.1
	$\delta\hat{\beta}_3$	f^{-3}	$0.1^{+0.5}_{-0.3}$	$-0.0^{+0.8}_{-0.6}$	0.38	0.56	0.6 ± 0.1	
merger–ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}	$-0.1^{+0.4}_{-0.4}$	$-0.0^{+1.0}_{-1.15}$	0.68	0.51	1.1 ± 0.1	2.1 ± 0.1
	$\delta\hat{\alpha}_3$	$f^{3/4}$	$-0.5^{+2.0}_{-1.5}$	$-0.0^{+4.4}_{-4.4}$	0.67	0.50	1.3 ± 0.1	
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af + b)$	$-0.1^{+0.5}_{-0.6}$	$-0.0^{+1.2}_{-1.1}$	0.61	0.55	1.2 ± 0.1	

Methods for computing constraints: https://arxiv.org/pdf/1704.06784.pdf

Extreme Mass Ratio Inspiral (EMRI):

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.75.042003

For quadrupole moment Q of the primary mass M,
an inspiral of SNR ~100 would allow us to measure the dimensionless quadrupole Q / M^3 at a precision of 10^{-4} - 10^{-2}
→ test for deviations from the GR prediction for a Kerr BH

...Looks hopeful!

Quantum Gravity Probe?

https://iopscience.iop.org/article/10.1088/1742-6596/154/1/012042/pdf

Hawking radiation from SMBH would peak in LISA band, but strain would be orders of magnitude too small

Quasi-normal mode overtones will be detectable, but even with SNR strong enough to include up to the 70th overtone, but the degeneracy between the overtones will prevent us from distinguishing individual overtone power beyond the n=0 and n=1 modes, so it will be difficult to gain much beyond the central frequency and decay time

...Not as hopeful.

SMBH merger rates? Highly dependent on unknown priors, but that doesn't stop us from guessing!
https://arxiv.org/abs/astro-ph/0503210
https://arxiv.org/abs/astro-ph/0604281
https://arxiv.org/pdf/1908.05779.pdf