Echoes from the Abyss: Evidence for Planck-Scale Structure at Black Hole Horizons

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arXiv:1612.00266v1 [gr-qc] 1 Dec 2016

Echoes from the Abyss: Evidence for Planck-scale structure at black hole horizons

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In classical General Relativity (GR), an observer falling into an astrophysical black hole is not expected to experience anything dramatic as she crosses the event horizon. However, tentative resolutions to problems in quantum gravity, such as the cosmological constant problem, or the black hole information paradox, invoke significant departures from classicality in the vicinity of the horizon. It was recently pointed out that such near-horizon structures can lead to late-time echoes in the black hole merger gravitational wave signals that are otherwise indistinguishable from GR. We search for observational signatures of these echoes in the gravitational wave data released by advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), following the three black hole merger events GW150914, GW151226, and LVT151012. In particular, we look for repeating damped echoes with time-delays of $8M \log M$ (+spin corrections, in Planck units), corresponding to Planck-scale departures from GR near their respective horizons. Accounting for the "look elsewhere" effect due to uncertainty in the echo template, we find tentative evidence for Planck-scale structure near black hole horizons at 2.9σ significance level (corresponding to false detection probability of 1 in 270). Future data releases from LIGO collaboration, along with more physical echo templates, will definitively confirm (or rule out) this finding, providing possible empirical evidence for alternatives to classical black holes, such as in *firewall* or *fuzzball* paradigms.

arXiv:1701.03485v1 [gr-qc] 12 Jan 2017

Echoes from the Abyss: The Holiday Edition!

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In a recent paper [1], we reported the results of the first search for echoes from Planck-scale modifications of general relativity near black hole event horizons using the public data release by the Advanced LIGO gravitational wave observatory. While we found tentative evidence (at $\simeq 3\sigma$ level) for the presence of these echoes, our statistical methodology was challenged by Ashton, et al. [2], just in time for the holidays! In this short note, we briefly address these criticisms, arguing that they either do not affect our conclusion or change its significance by $\lesssim 0.3\sigma$. The real test will be whether our finding can be reproduced by independent groups using independent methodologies (and ultimately more data).

arXiv:1612.05625v1 [gr-qc] 16 Dec 2016

Comments on: "Echoes from the abyss: Evidence for Planck-scale structure at black hole horizons"

Gregory Ashton,[1,2] Ofek Birnholtz,[1,2,*] Miriam Cabero,[1,2] Collin Capano,[1,2] Thomas Dent,[1,2] Badri Krishnan,[1,2] Grant David Meadors,[1,2,3] Alex B. Nielsen,[1,2] Alex Nitz,[1,2] and Julian Westerweck[1,2]

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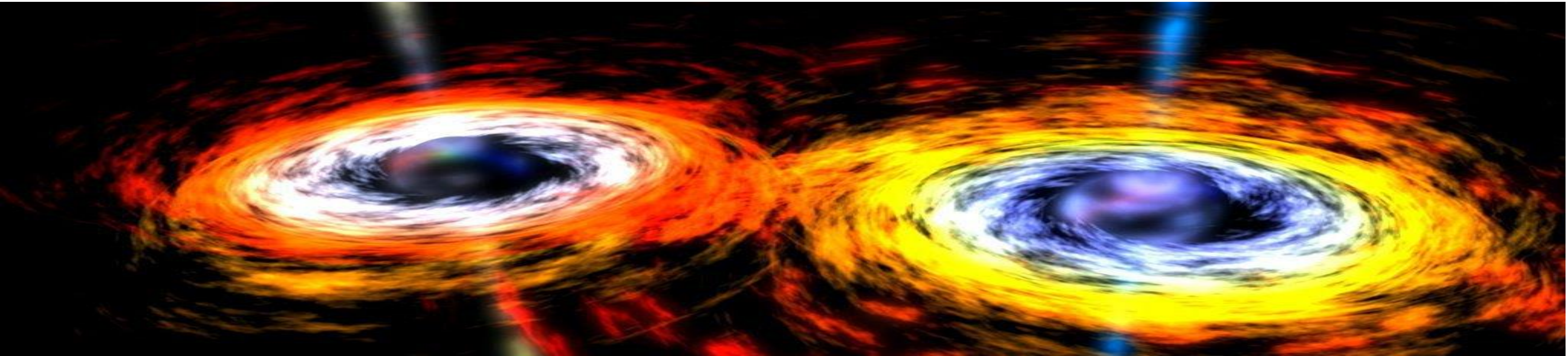
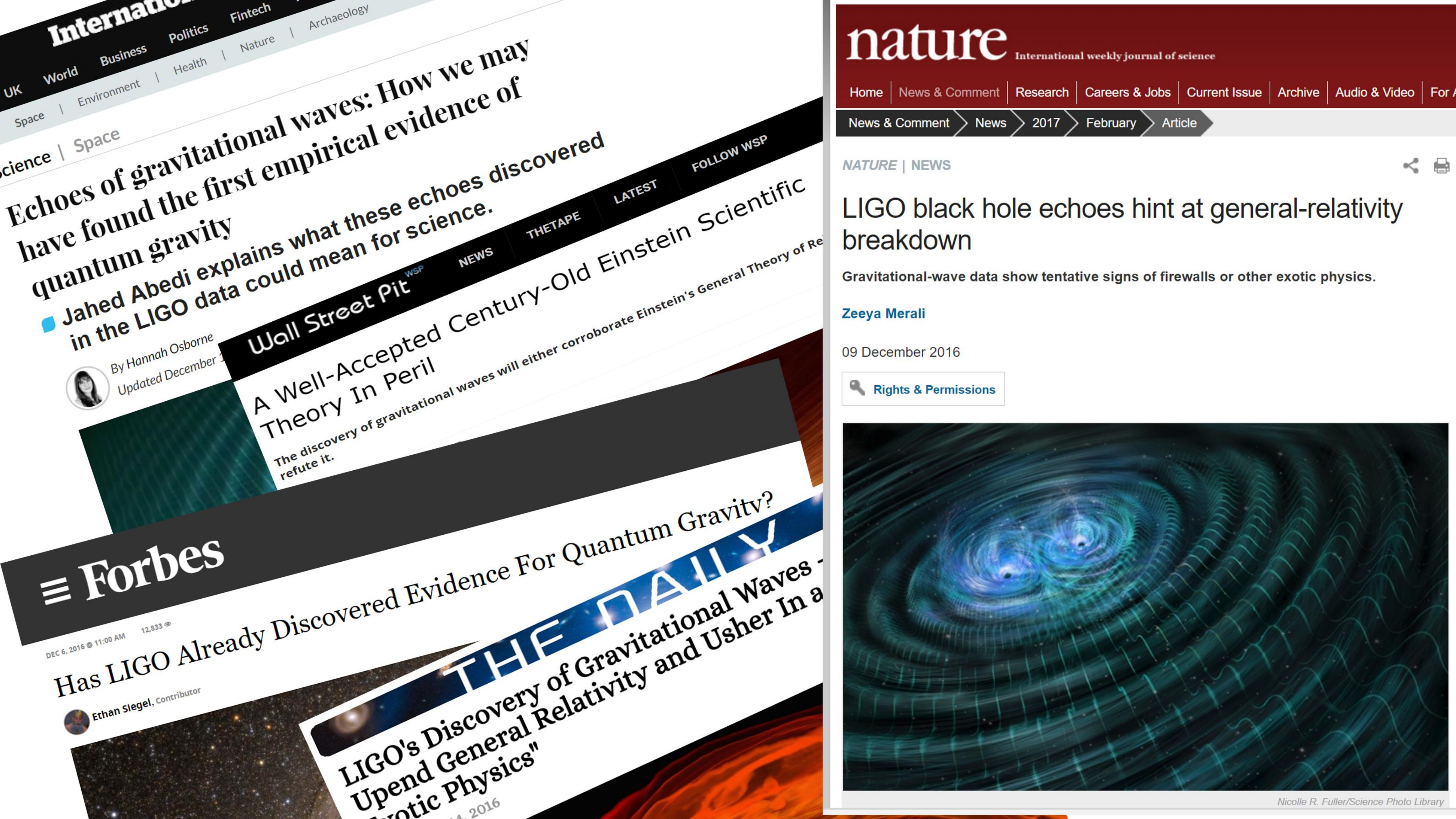
Recently, Abedi, Dykaar and Afshordi claimed evidence for a repeating damped echo signal following the binary black hole merger gravitational-wave events recorded in the first observational period of the Advanced LIGO interferometers. We discuss the methods of data analysis and significance estimation leading to this claim, and identify several important shortcomings. We conclude that their analysis does not provide significant observational evidence for the existence of Planck-scale structure at black hole horizons, and suggest renewed analysis correcting for these shortcomings.

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Echoes of gravitational waves: How we may have found the first empirical evidence of quantum gravity
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By Hannah Osborne
Updated December
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Forbes
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Ethan Siegel, Contributor
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Zeeya Merali
09 December 2016
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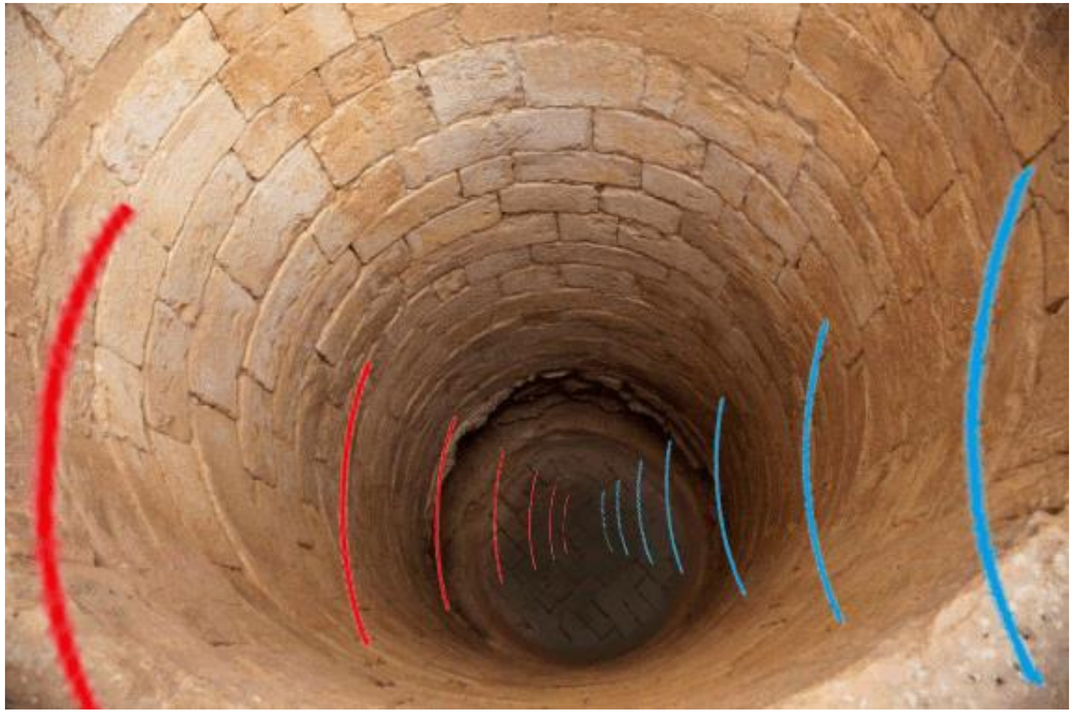


There is mounting, albeit controversial, theoretical evidence that quantum black holes might be significantly different from their classical counterparts[1,6].

In particular, modern versions of Hawking's black hole information paradox have led to exotic alternatives to classical black hole horizons, such as the fuzzball [2, 3] and firewall paradigms [1, 7].

Theory puts Planckian physics at horizon

- (Solving) Black Hole Information Paradox
  - *Hawking, Mathur … Almheiri, Marolf, Polchinski, & Sully*
- Black Hole (Fuzzball) Entropy in String Theory
  - *Mathur …*
- (Solving) Cosmological constant problem(s), Dark Energy
  - *Prescod-Weinstein et al., Afshordi*
- Gravitational Condensate Stars: An Alternative to Black Holes
  - Pawel O. Mazur, Emil Mottola

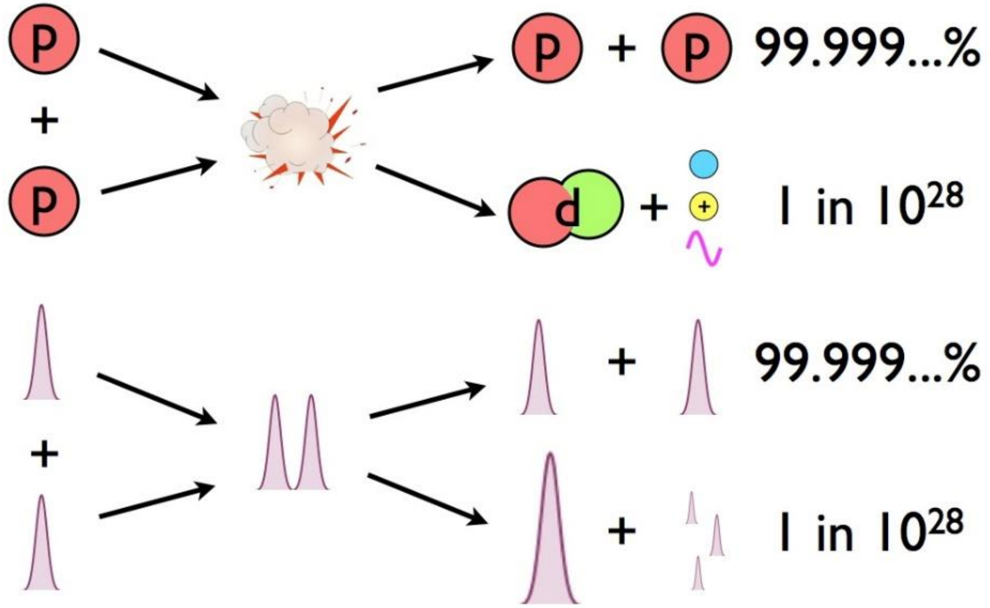
  …

Quantum Black Hole Tunneling (into Fuzzball)

$$e^{(entropy)} \times e^{-\alpha M^2} \sim 1$$

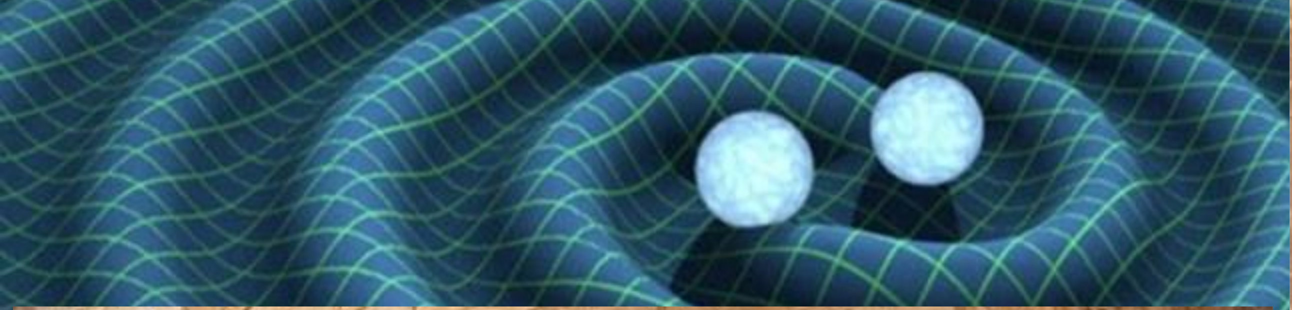
$$S_{BH\odot} = \frac{A_{BH\odot}}{4} = 4\pi M_{\odot}^2 = 2.66\times 10^{78}$$ Kraus, and Mathur 2016

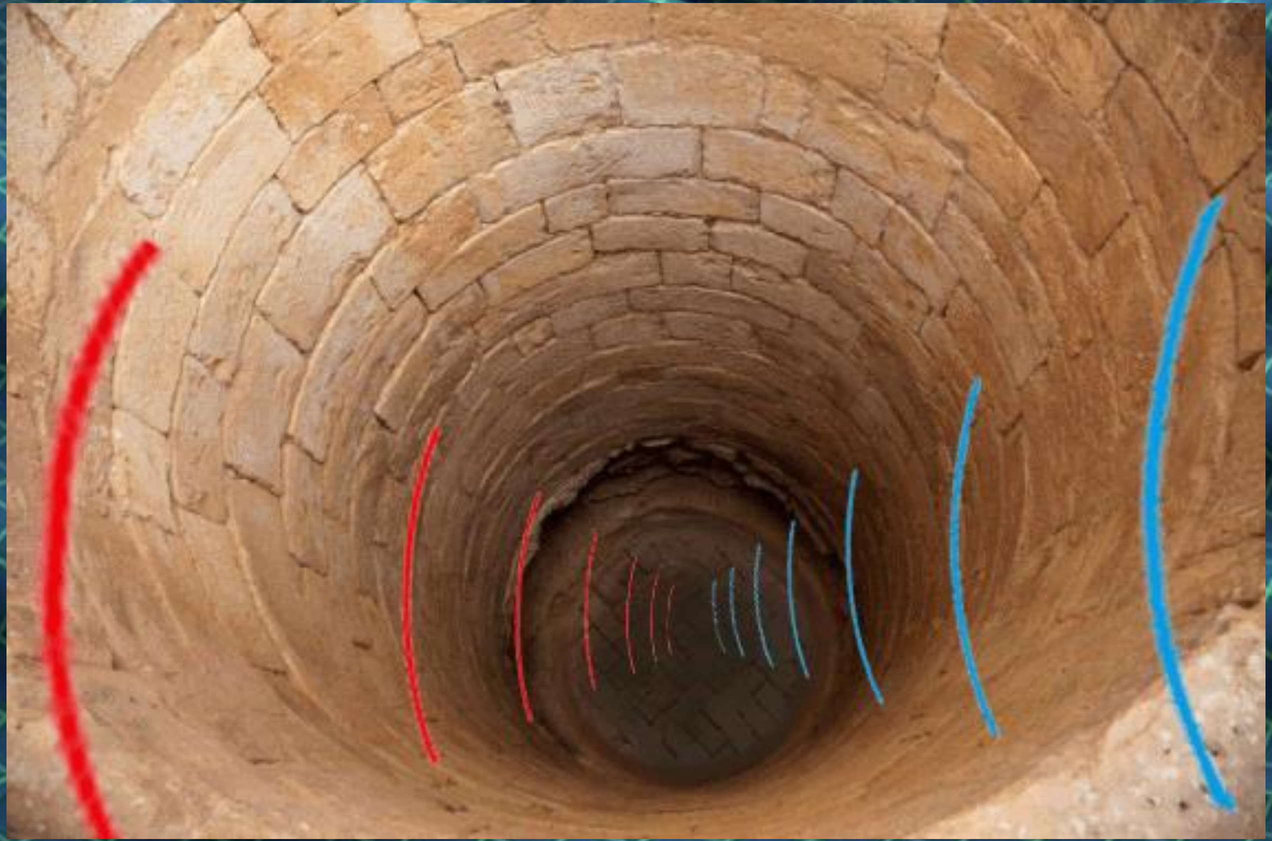
Quantum tunneling is what allows the Sun to shine!



http://www.forbes.com/sites/ethansiegel/2015/06/22/its-the-power-of-quantum-mechanics-that-allow-the-sun-to-shine/#78752a276127

QUANTUM BLACK HOLES





[1] A. Almheiri, D. Marolf, J. Polchinski, and J. Sully, JHEP **02**, 062 (2013), arXiv:1207.3123 [hep-th].

[2] O. Lunin and S. D. Mathur, Nucl. Phys. **B623**, 342 (2002), arXiv:hep-th/0109154 [hep-th].

[3] O. Lunin and S. D. Mathur, Phys. Rev. Lett. **88**, 211303 (2002), arXiv:hep-th/0202072 [hep-th].

[4] J. Maldacena and L. Susskind, Fortsch. Phys. **61**, 781 (2013), arXiv:1306.0533 [hep-th].

[6] J. Abedi and H. Arfaei, JHEP **03**, 135 (2016), arXiv:1506.05844 [gr-qc].

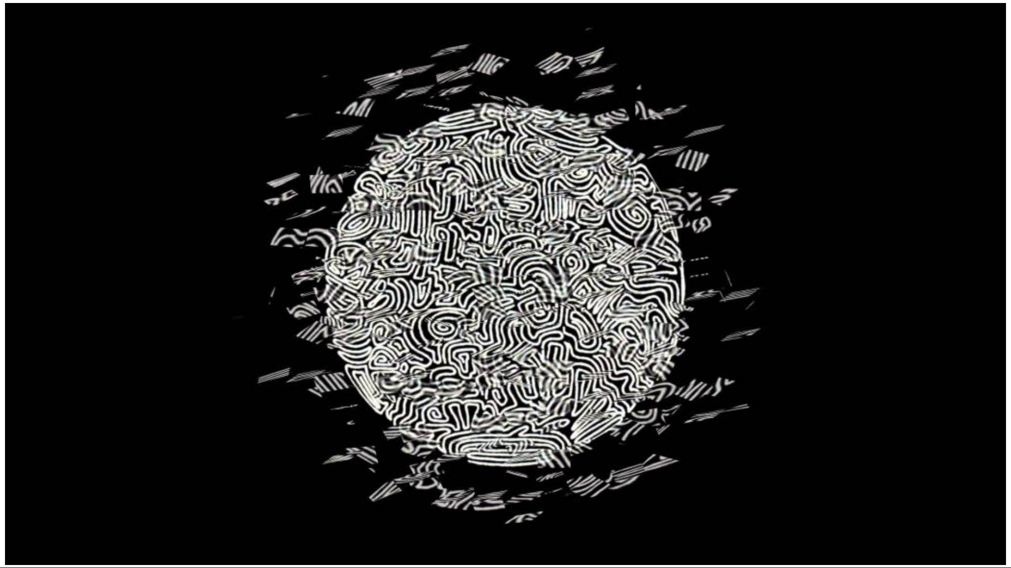
In classical General Relativity, an observer falling through the event horizon experiences "no drama".

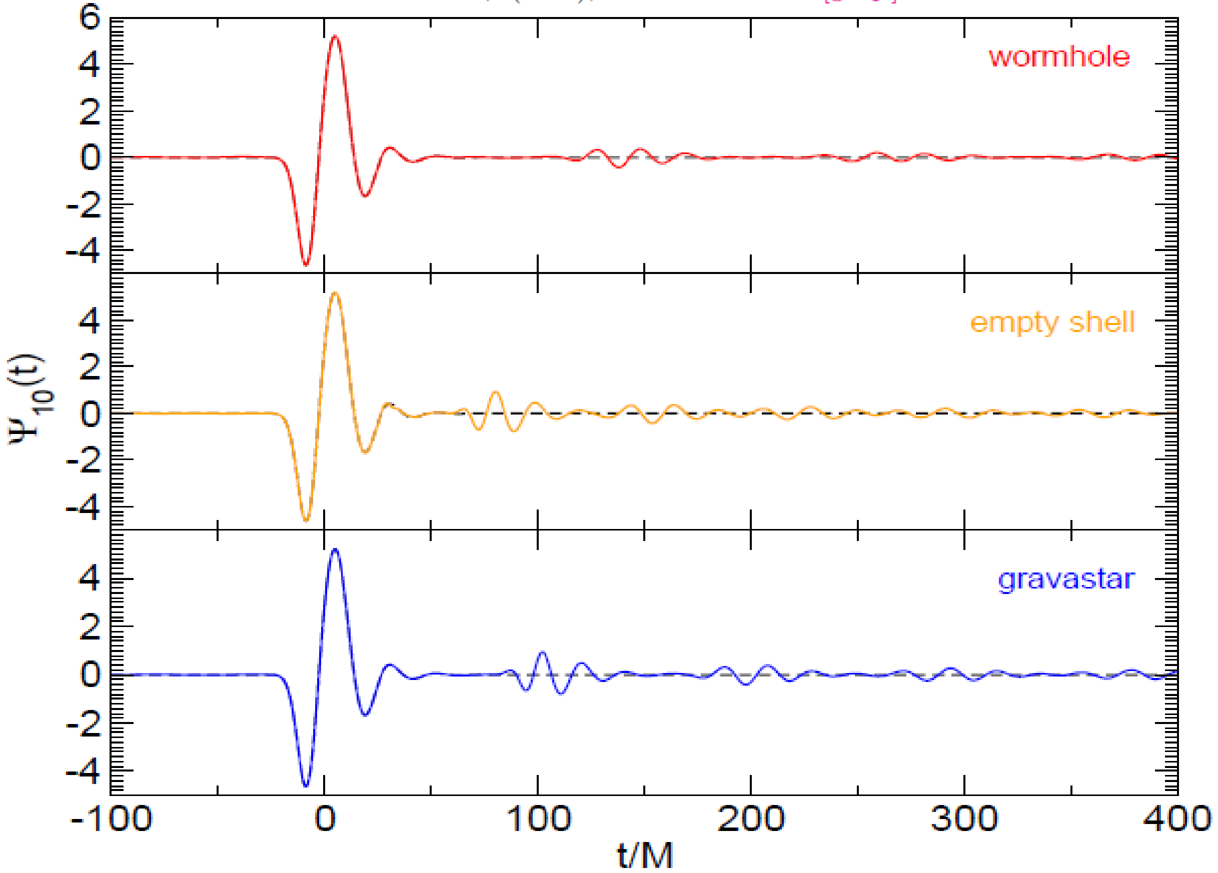
BUT

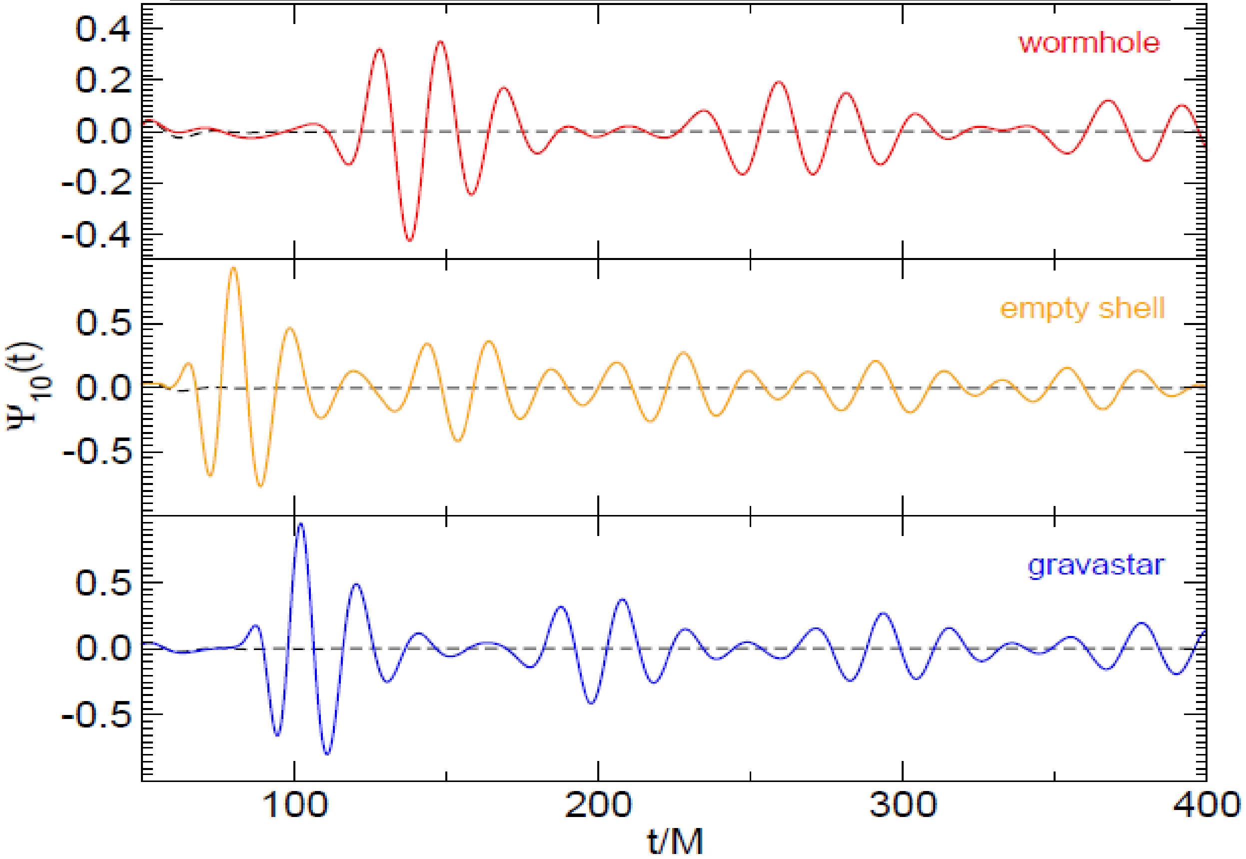
Structure near event horizon → late-time, repeating, echoes of the ringdown phase of the black hole merger

[13] V. Cardoso, E. Franzin, and P. Pani, Phys. Rev. Lett. **116**, 171101 (2016), [Erratum: Phys. Rev. Lett.117,no.8,089902(2016)], arXiv:1602.07309 [gr-qc].

[14] V. Cardoso, S. Hopper, C. F. B. Macedo, C. Palenzuela, and P. Pani, (2016), arXiv:1608.08637 [gr-qc].







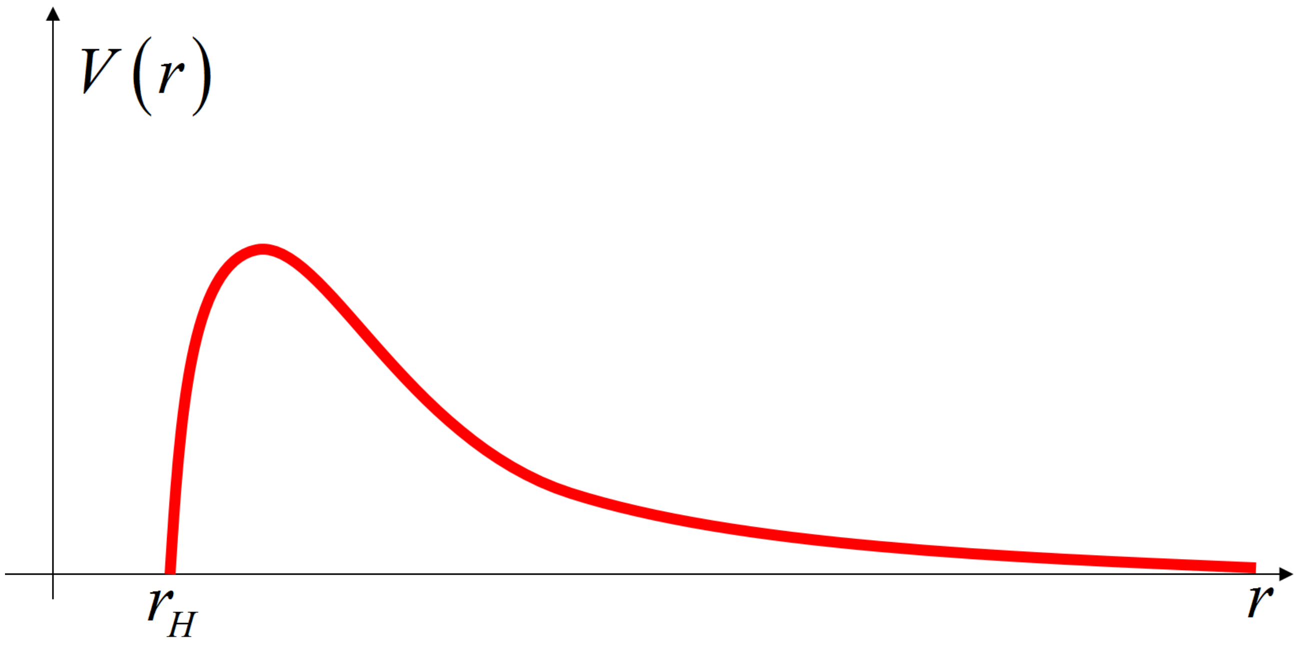
Angular momentum barrier

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2\, d\Omega_2^2,$$

$$\left(\frac{d^2}{dx^2} + \omega^2 - V(r)\right)\psi(r) = 0,$$

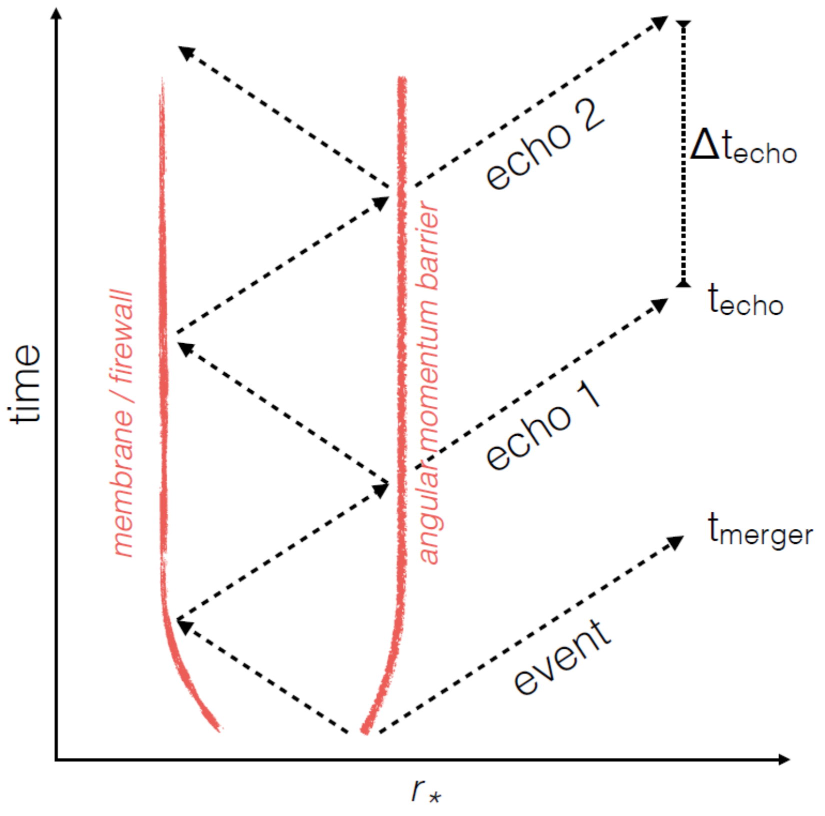
$$V(r) = f(r)\left[\frac{l(l+1)}{r^2} + \frac{f'(r)}{r}\right].$$

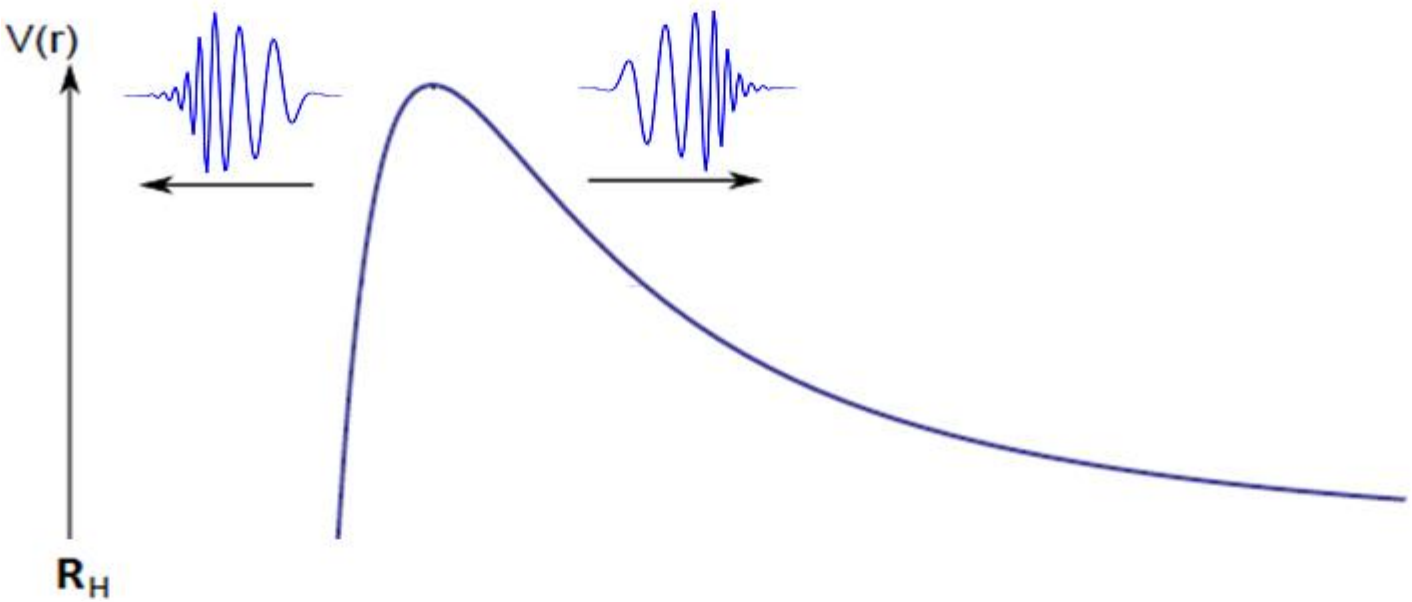
$$x \equiv \int \frac{dr}{f(r)},$$

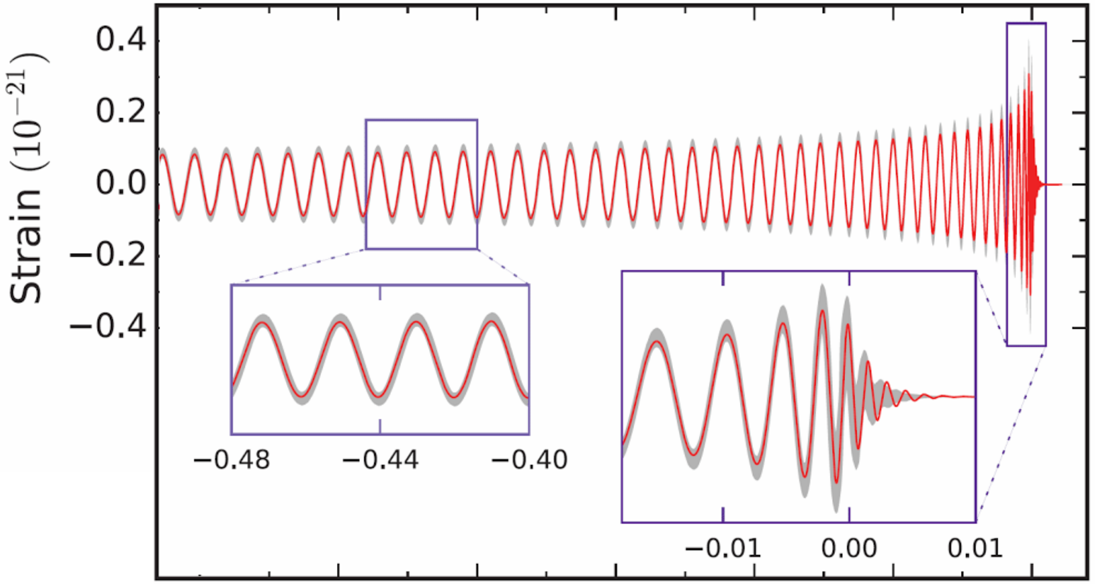


Planck-scale structure near horizon results in

$$\Delta t_{\rm echo} \simeq \frac{8GM}{c^3} \times \ln\left(\frac{M}{M_{\rm planck}}\right) + \text{spin corrections}$$



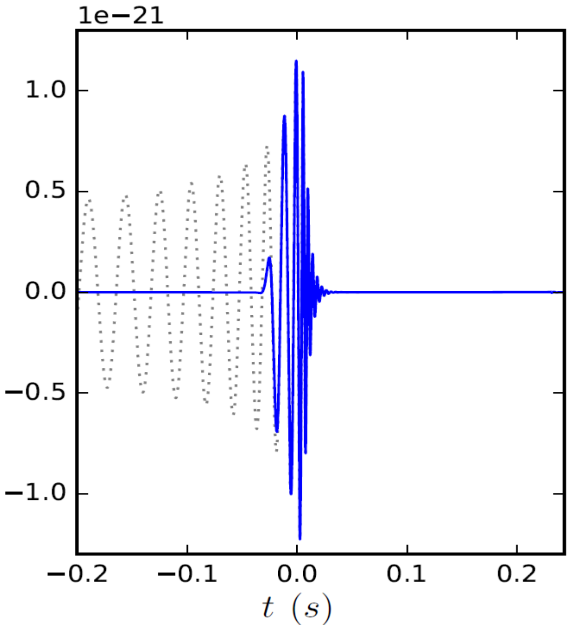


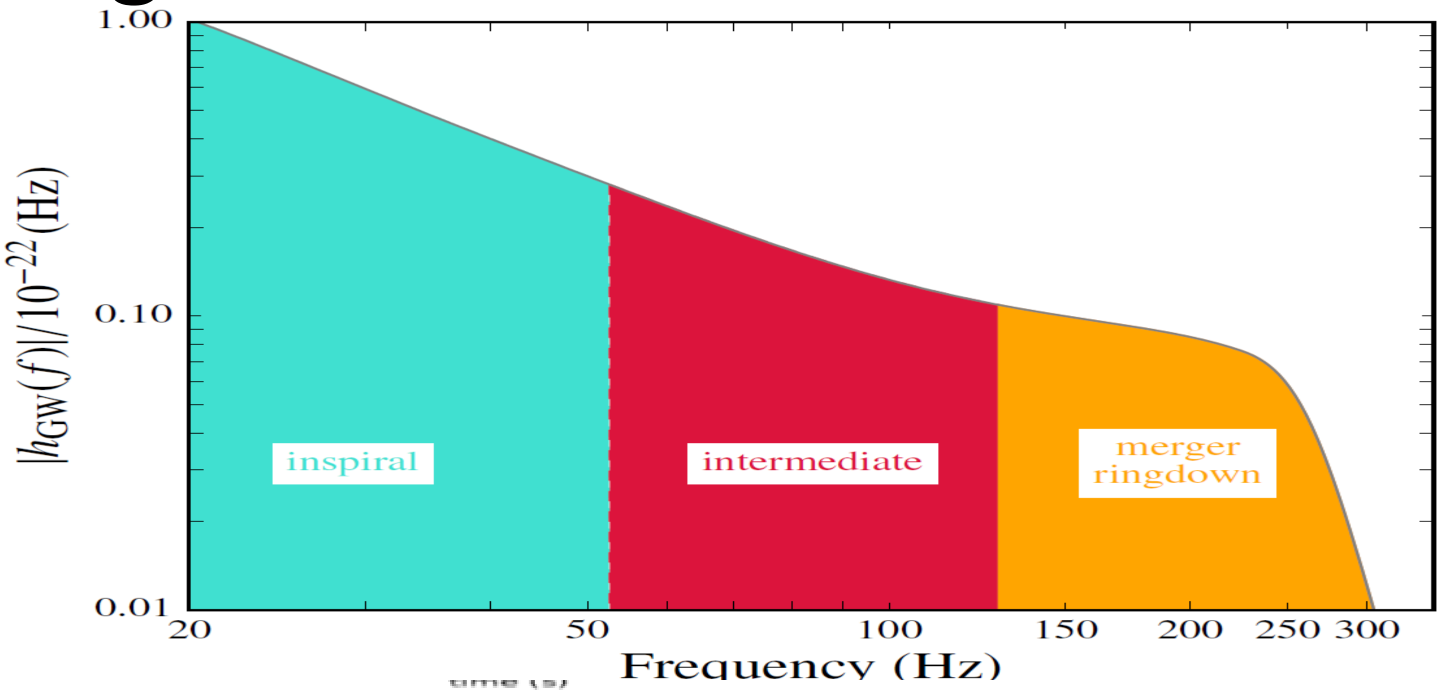


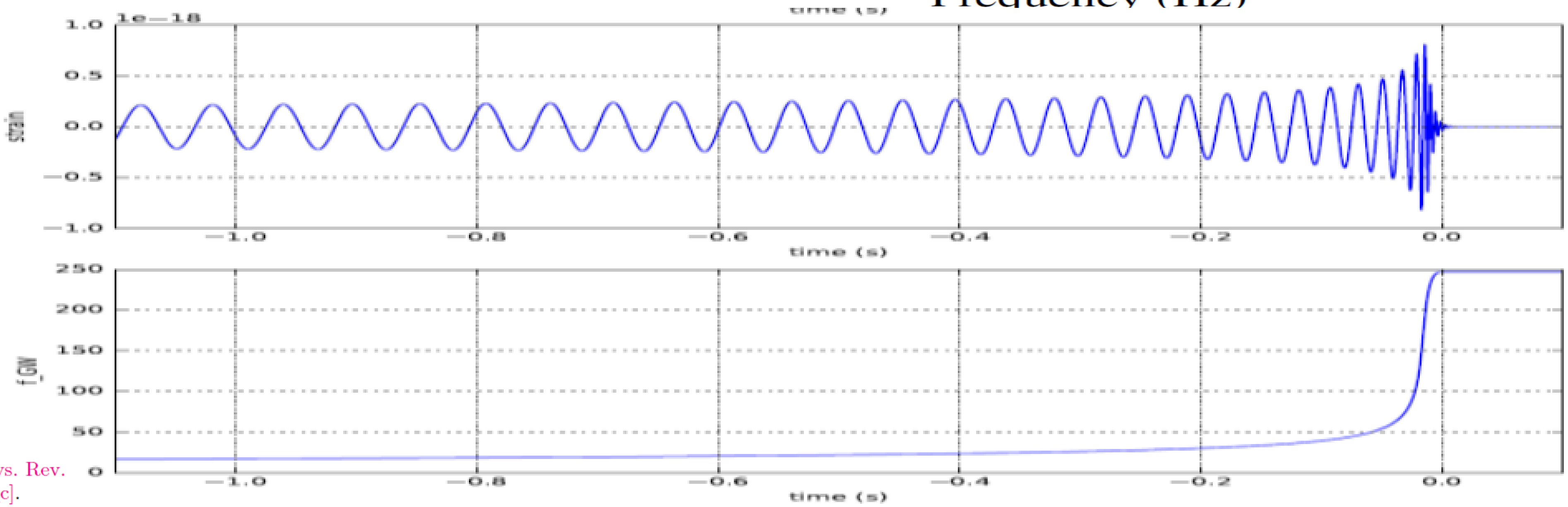
For the second echo we would have $\Delta t_2 = 2\Delta t_1$.

How to separate the ringdown?

GW150914



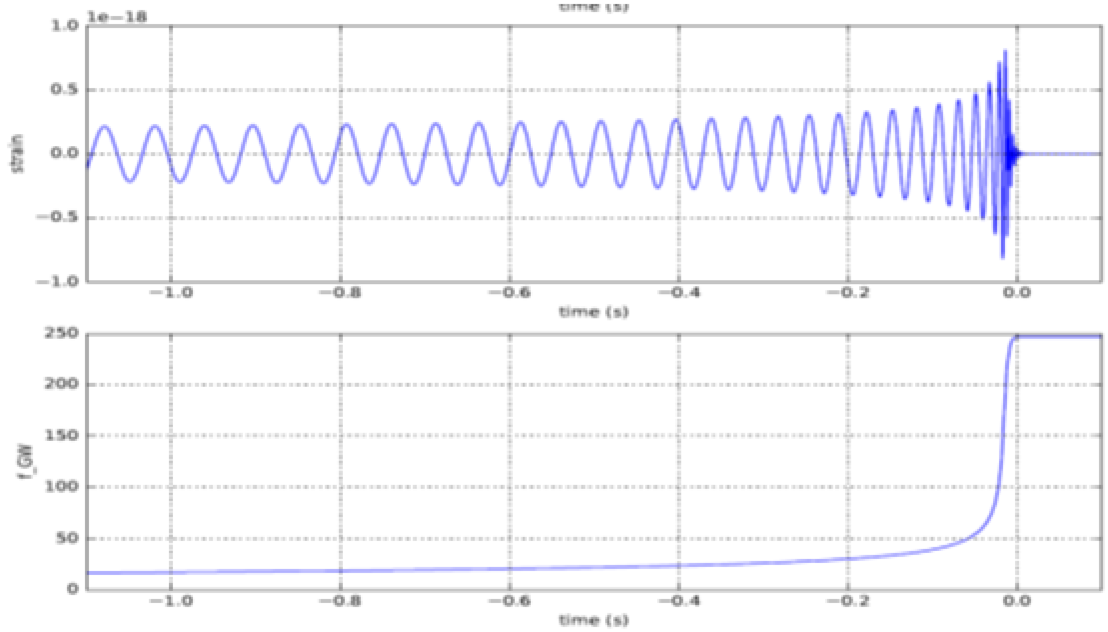




[25] B. P. Abbott *et al.* (Virgo, LIGO Scientific), Phys. Rev. Lett. **116**, 221101 (2016), arXiv:1602.03841 [gr-qc].

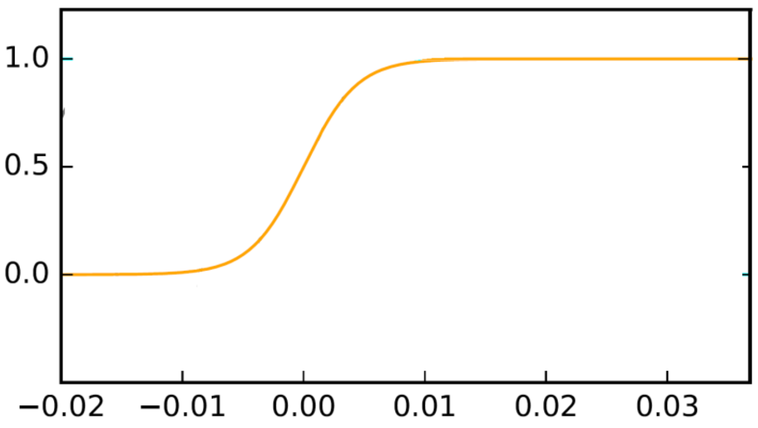
How to separate the ringdown?

$$\Theta_I(t,t_0) \equiv \frac{1}{2}\left\{1+\tanh\left[\frac{1}{2}\omega_I(t)(t-t_{\rm merger}-t_0)\right]\right\}$$



$$\mathcal{M}_{T,I}(t,t_0) \equiv \Theta_I(t,t_0)\mathcal{M}_I(t).$$

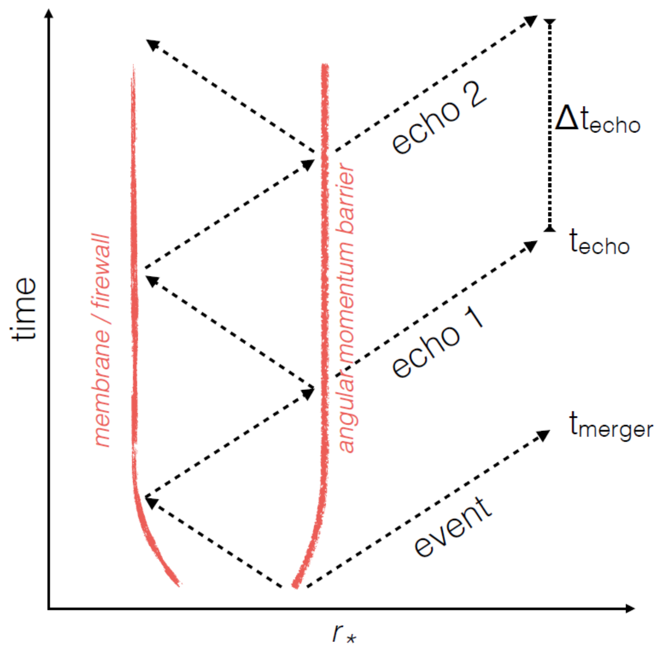
$$M_{TE,I}(t) \equiv$$
$$A\sum_{n=0}^{\infty}(-1)^{n+1}\gamma^n\mathcal{M}_{T,I}(t+t_{\rm merger}-t_{\rm echo}-n\Delta t_{\rm echo},t_0)$$



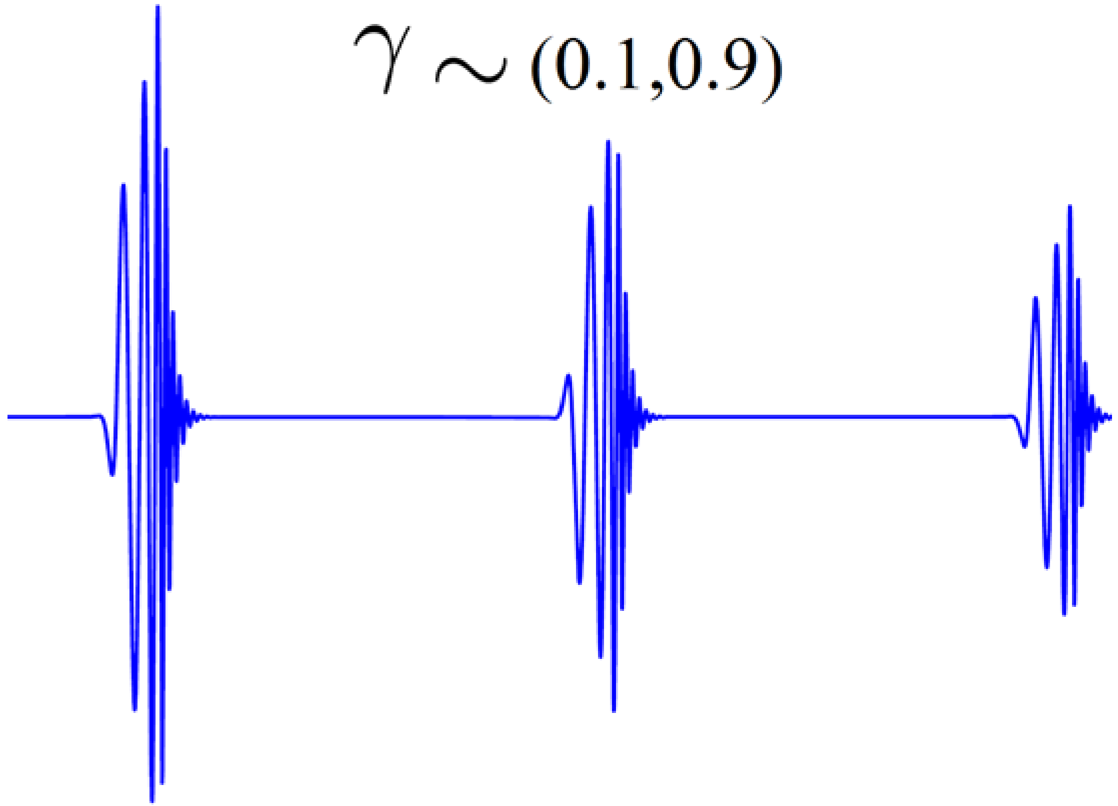
$$t_{0,GW150914} \sim (-0.03s, 0)$$

$$t_{0,GW151226} \sim \frac{\Delta t_{pred,GW151226}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914} = (-0.0104s, 0)$$

$$t_{0,LVT151012} \sim \frac{\Delta t_{pred,LVT151012}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914} = (-0.0182s, 0)$$



$$\gamma \sim (0.1, 0.9)$$



$$\mathcal{M}_{T,I}(t, t_0) \equiv \Theta_I(t, t_0)\mathcal{M}_I(t).$$

$$M_{TE,I}(t) \equiv$$

$$A \sum_{n=0}^{\infty} (-1)^{n+1} \gamma^n \mathcal{M}_{T,I}(t + t_{\text{merger}} - t_{\text{echo}} - n\Delta t_{\text{echo}}, t_0)$$

$$SNR_{Total} = \left(SNR_{GW150914}(t_{echoes}/\Delta t_{echoes,GW150914})^2 + SNR_{GW151226}(t_{echoes}/\Delta t_{echoes,GW151226})^2 + SNR_{LVT151012}(t_{echoes}/\Delta t_{echoes,LVT151012})^2\right)^{\frac{1}{2}}$$

Number of free parameters:

$\gamma \sim (0.1,0.9)$ 1

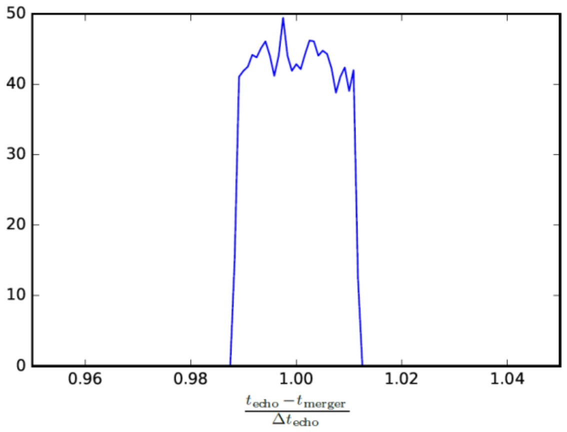
$$\Delta t_{\mathrm{echo},I}(\mathrm{sec}) = \begin{cases} 0.2925 \pm 0.00916 & I = \mathrm{GW150914} \\ 0.1013 \pm 0.01152 & I = \mathrm{GW151226} \\ 0.1778 \pm 0.02789 & I = \mathrm{LVT151012} \end{cases}$$

2, 3, 4

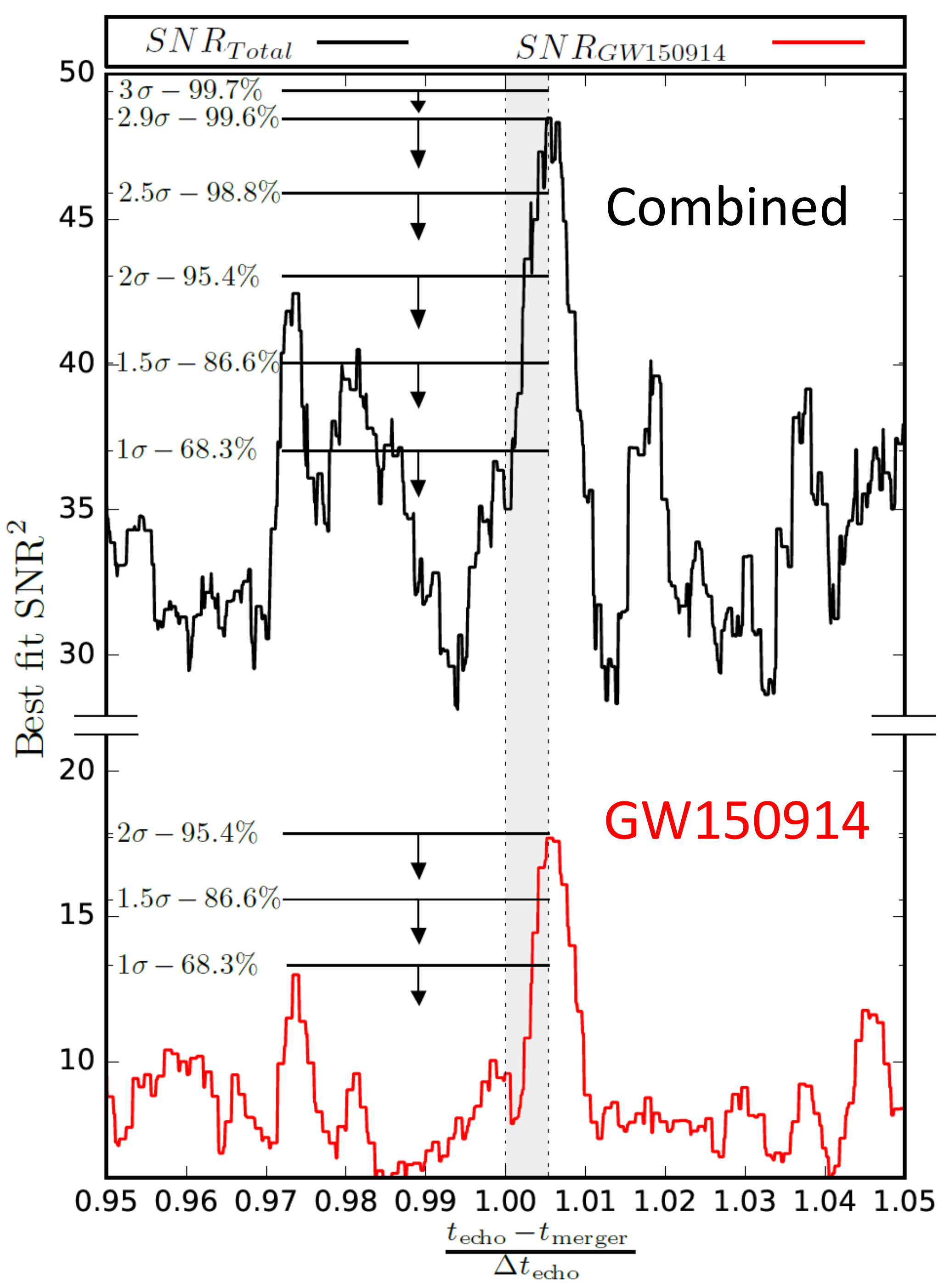
$$t_{0,GW150914} \sim (-0.03s, 0)$$
$$t_{0,GW151226} \sim \frac{\Delta t_{pred,GW151226}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914}$$
$$t_{0,LVT151012} \sim \frac{\Delta t_{pred,LVT151012}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914}$$

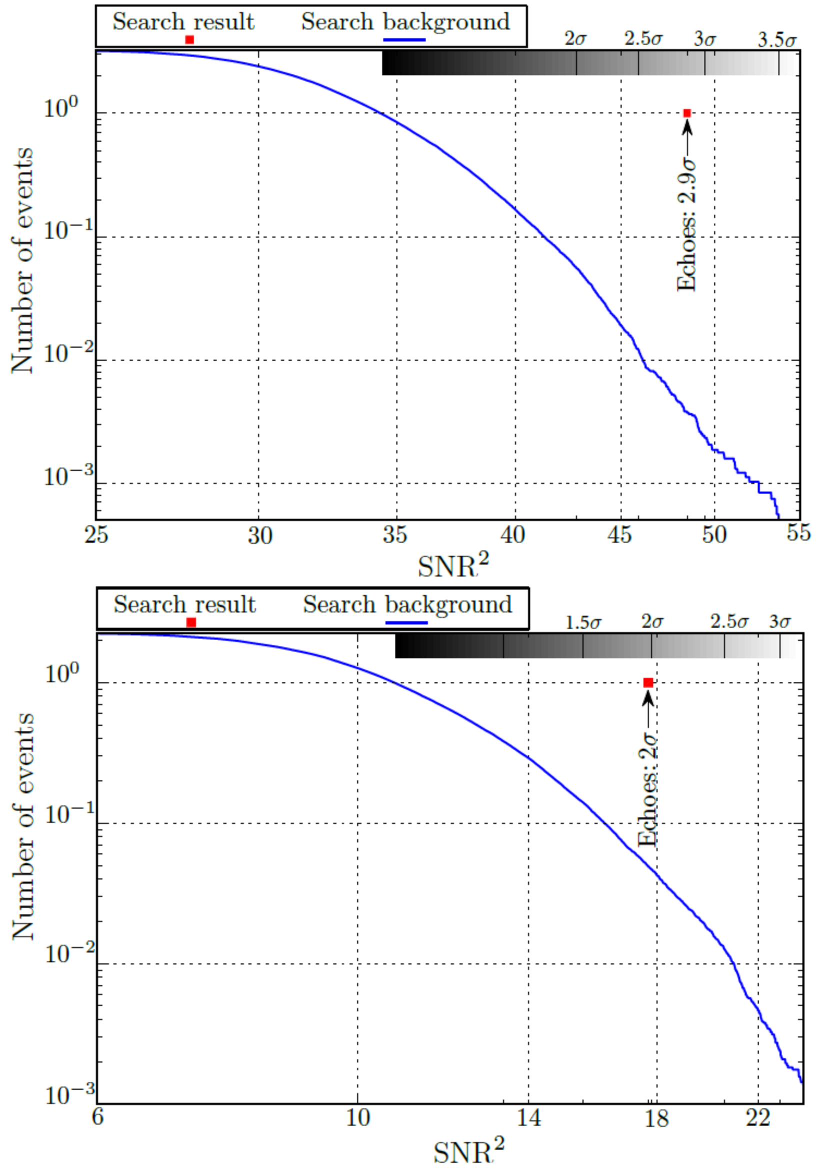
5

A is the over-all amplitude of the echo template (with respect to the main event) which we fit for, assuming a flat prior. 6

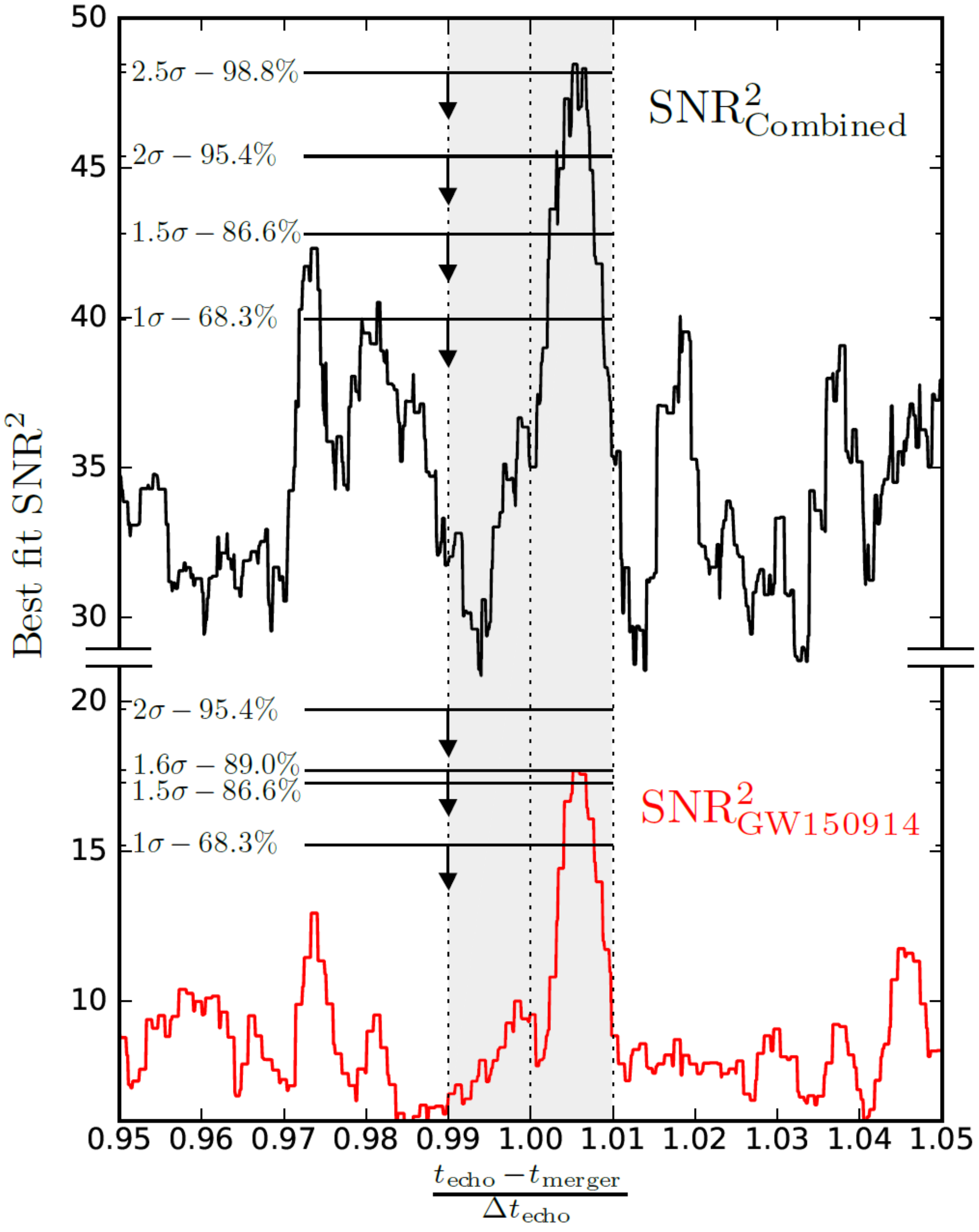


Resulting prior distribution assuming a random phase for the echo template.





Average number of noise peaks higher than a particular SNR-value within a time-interval 0.54% techo for combined (top) and GW150914 (bottom) events. The red dots show the observed SNR peak at techo = 1.0054techo.



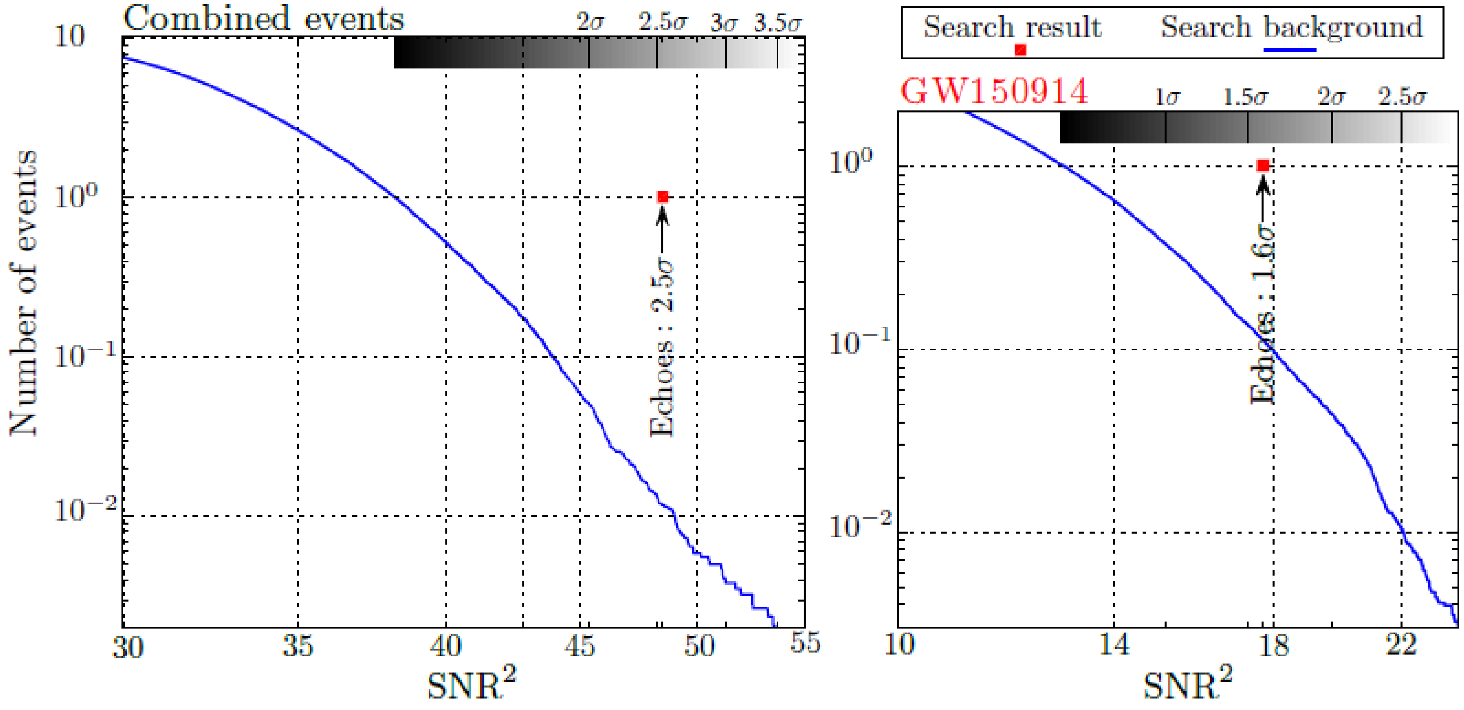
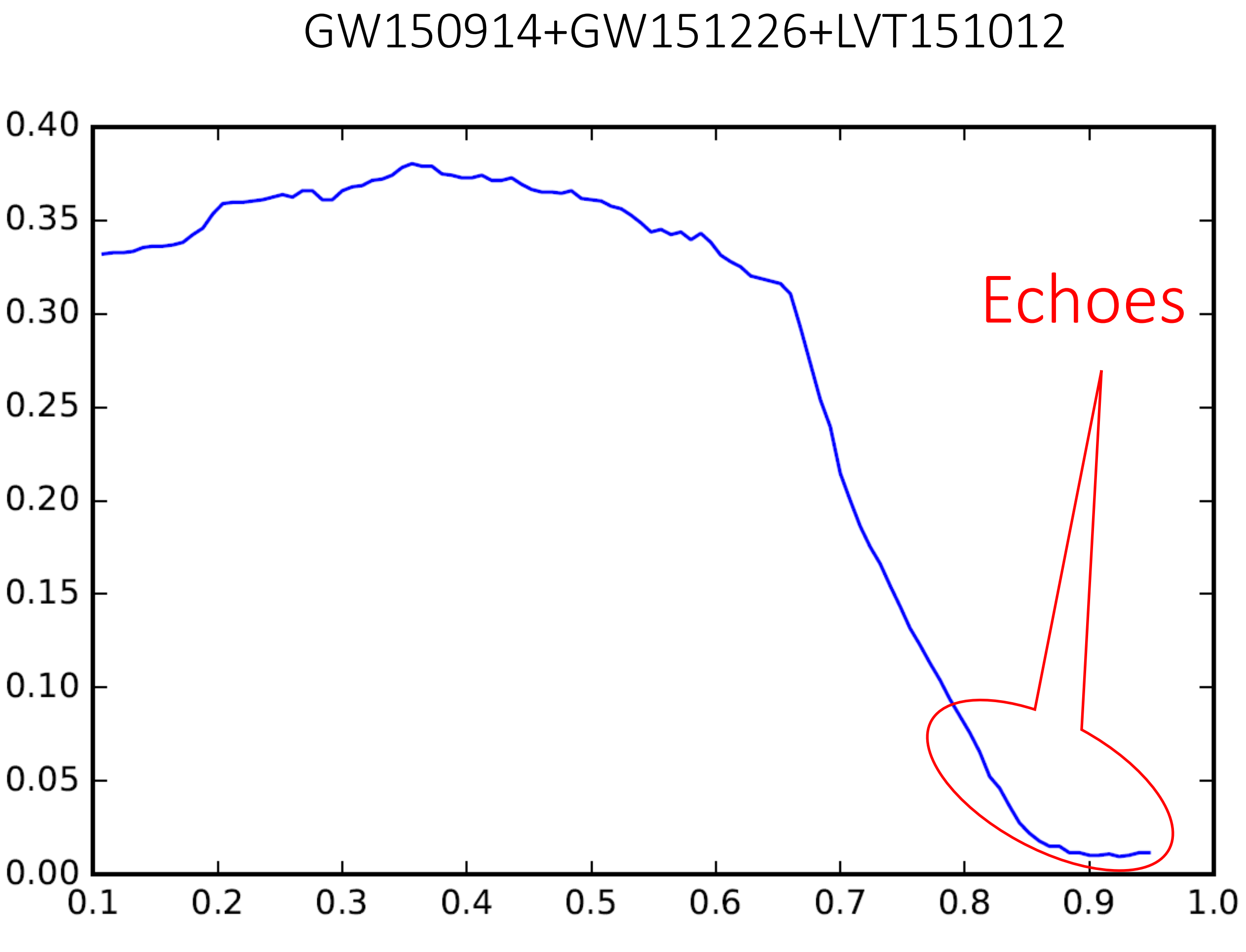
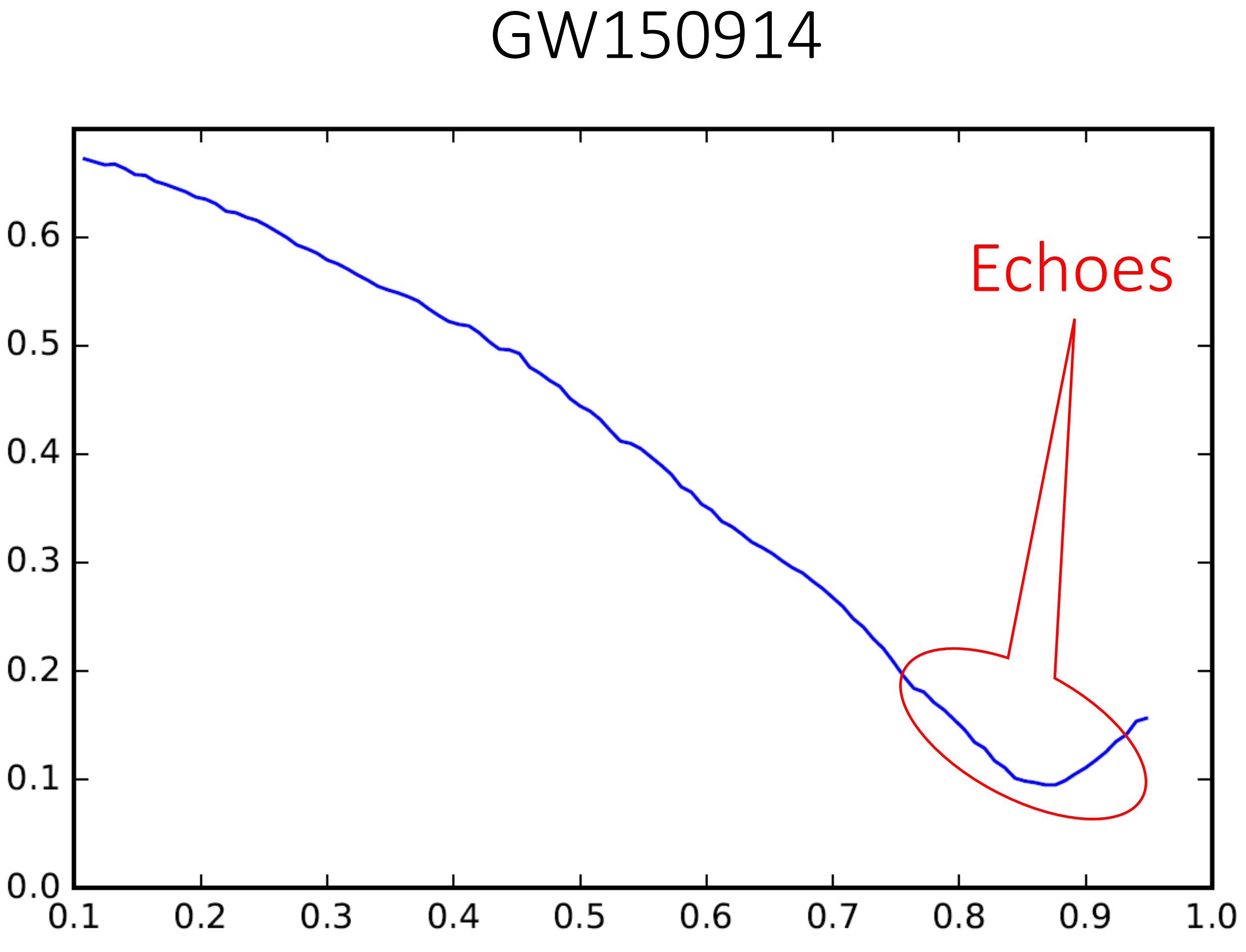


FIG. 5: Average number of noise peaks higher than a particular SNR-value within a time-interval $2\% \times \overline{\Delta t}_{\text{echo}}$ for combined (left) and GW150914 (right) events. The red dots show the observed SNR peak at $t_{\text{echo}} = 1.0054\Delta t_{\text{echo}}$ (Fig. 4). The horizontal bar shows the correspondence between SNR values and their significance.

How often would we see "echoes" in background?





False detection probability (p-value) as a function of \gamma

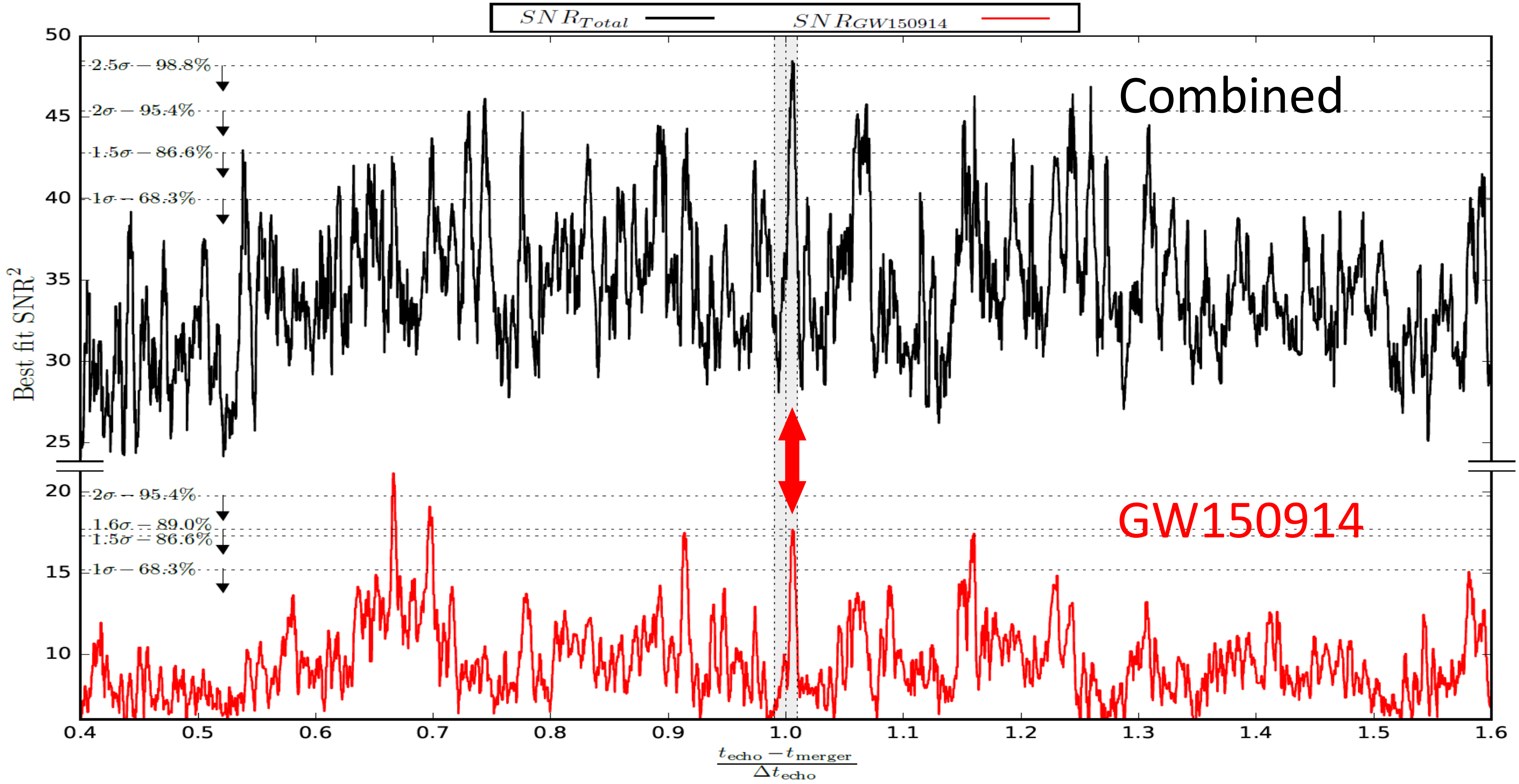
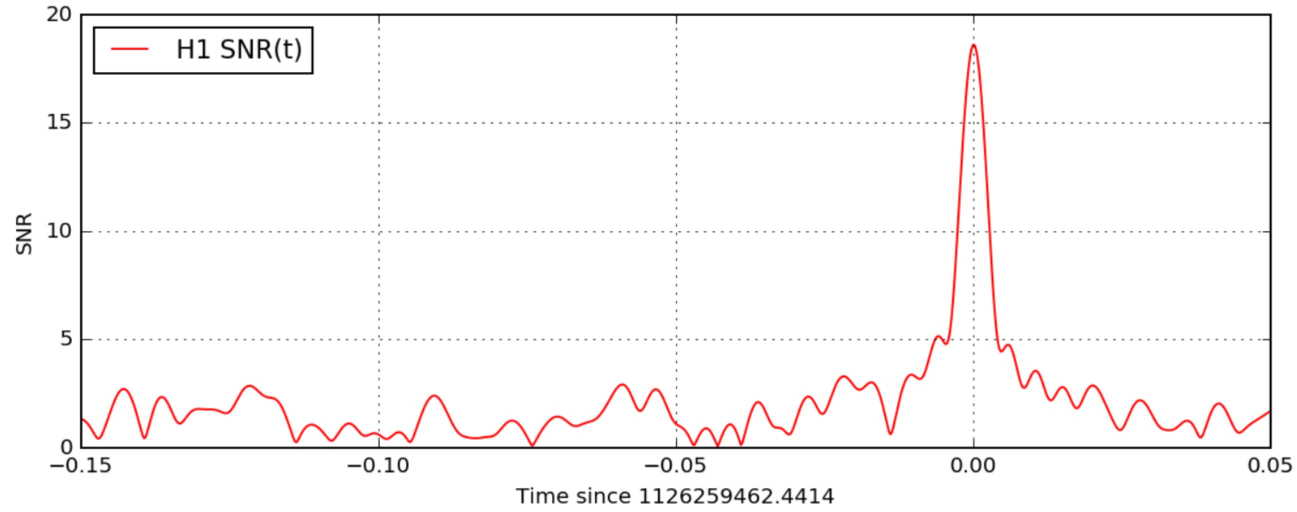
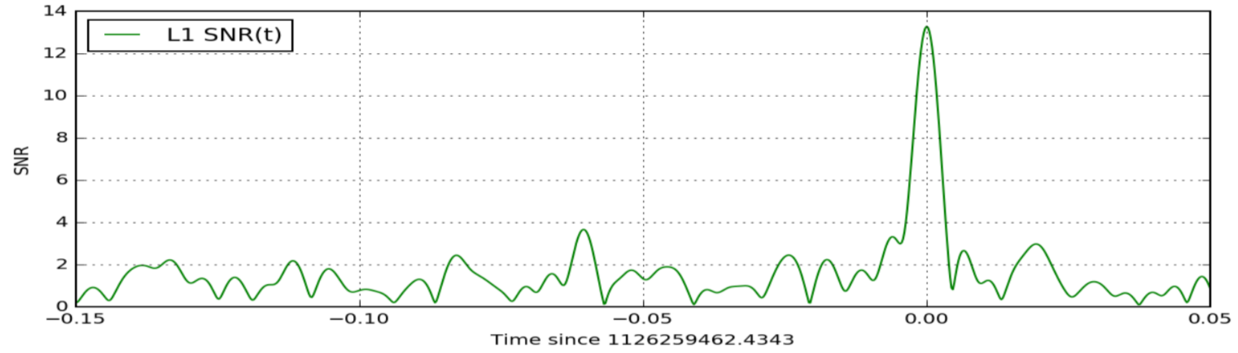
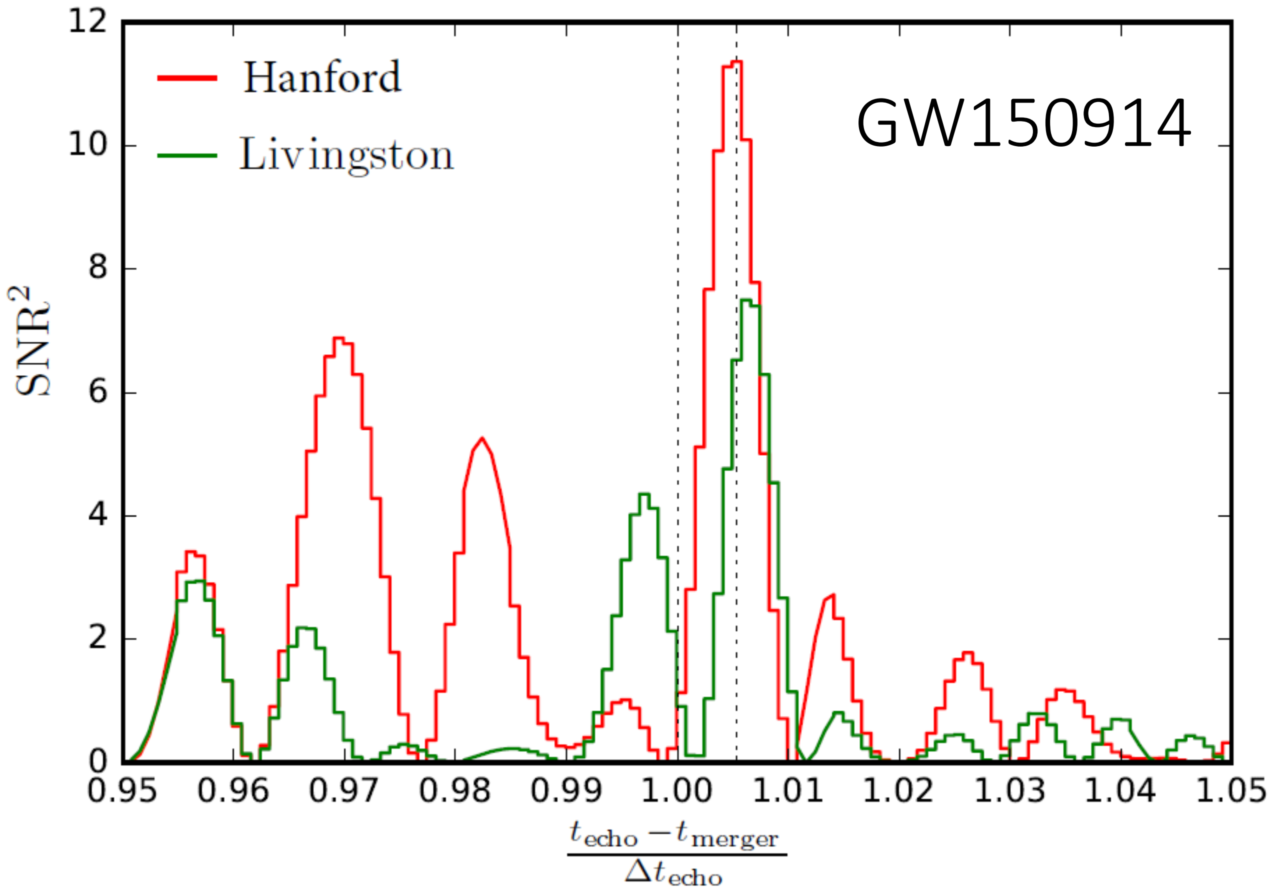


FIG. 3: Same as Fig. 4 in the main text, but over an extended range of $x = \frac{t_{\rm echo} - t_{\rm merger}}{\Delta t_{\rm echo}}$. The SNR peaks at the predicted value of $x = 1$ have 1.6σ and 2.5σ significance, for GW150914 and combined events respectively (See also [33]).

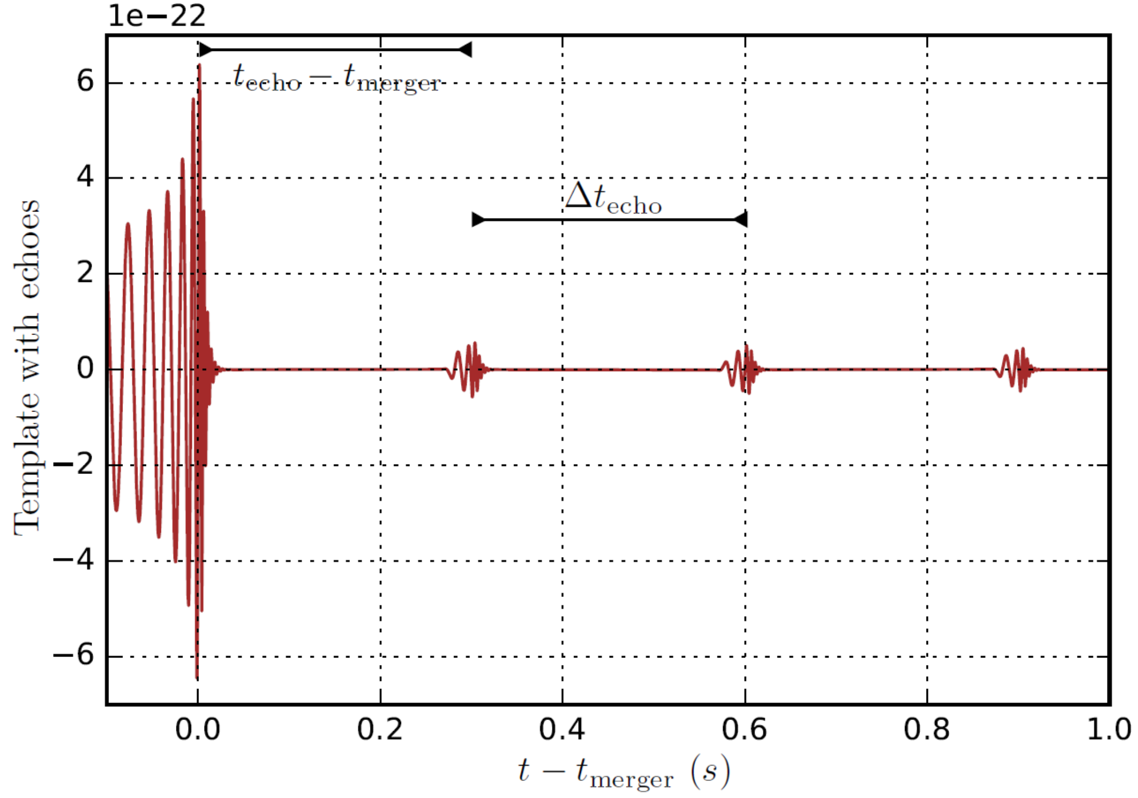






Interestingly, SNR ratio of GW150914 2.74/3.37 = 0.81 is comparable to the SNR ratio for the main event 13.3/18.6 = 0.72.

Late echoes from Planck scale structure near horizon



$$\Delta t_{\mathrm{echo},I}(\mathrm{sec}) = \begin{cases} 0.2925 \pm 0.00916 & I = \mathrm{GW150914} \\ 0.1013 \pm 0.01152 & I = \mathrm{GW151226} \\ 0.1778 \pm 0.02789 & I = \mathrm{LVT151012} \end{cases}$$

	GW150914	GW151226	LVT151012
Final mass $M_{\rm f}/{\rm M}_\odot$	$67.8^{+3.7\pm0.6}_{-3.3\pm0.7}$	$22.6^{+6.7\pm2.2}_{-1.5\pm0.1}$	$42^{+16\pm5}_{-3\pm0}$
Final spin $a_{\rm f}$	$0.68^{+0.05\pm0.01}_{-0.06\pm0.02}$	$0.74^{+0.06\pm0.03}_{-0.06\pm0.03}$	$0.66^{+0.09\pm0.00}_{-0.10\pm0.02}$
Source redshift z	$0.090^{+0.029\pm0.003}_{-0.036\pm0.008}$	$0.094^{+0.035\pm0.004}_{-0.039\pm0.001}$	$0.201^{+0.086\pm0.003}_{-0.091\pm0.008}$

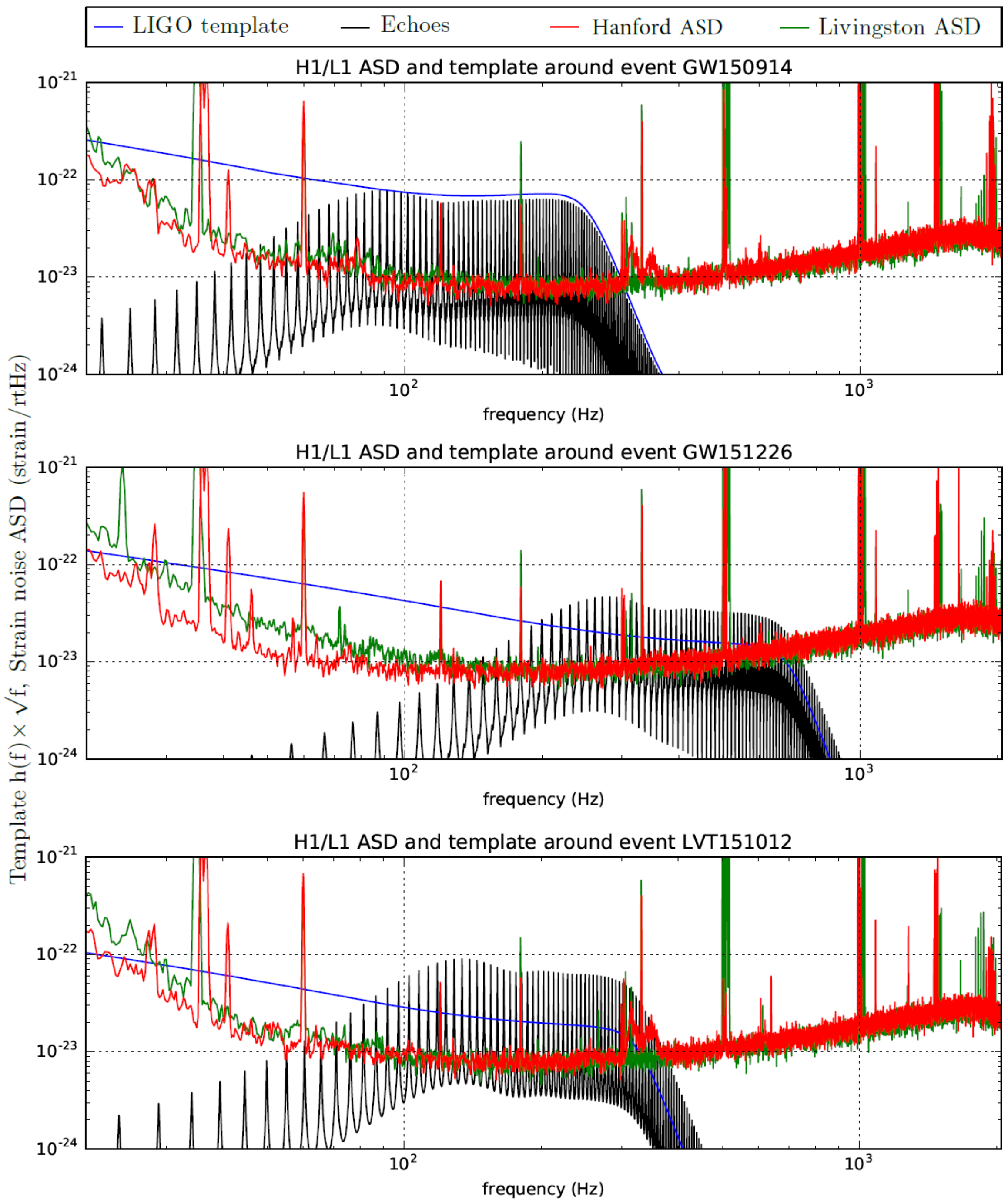
	Range	GW150914	Combined
$(t_{\rm echo} - t_{\rm merger})/\Delta t_{\rm echo}$	(0.99,1.01)	1.0054	1.0054
γ	(0.1,0.9)	0.89	0.9
$t_0/\overline{\Delta t}_{\rm echo}$	(-0.1,0)	-0.084	-0.1
Amplitude[a]		0.0992	0.124
$\mathrm{SNR}_{\rm max}$		4.21	6.96
p-value		0.11	0.011
significance		$\boxed{1.6\sigma}$	$\boxed{2.5\sigma}$

[a] The combined amplitude is given by: $A_{\rm average} = \dfrac{\sum_I \frac{SNR_I^2}{|A_I|}}{\sum_I \frac{SNR_I^2}{A_I^2}}$

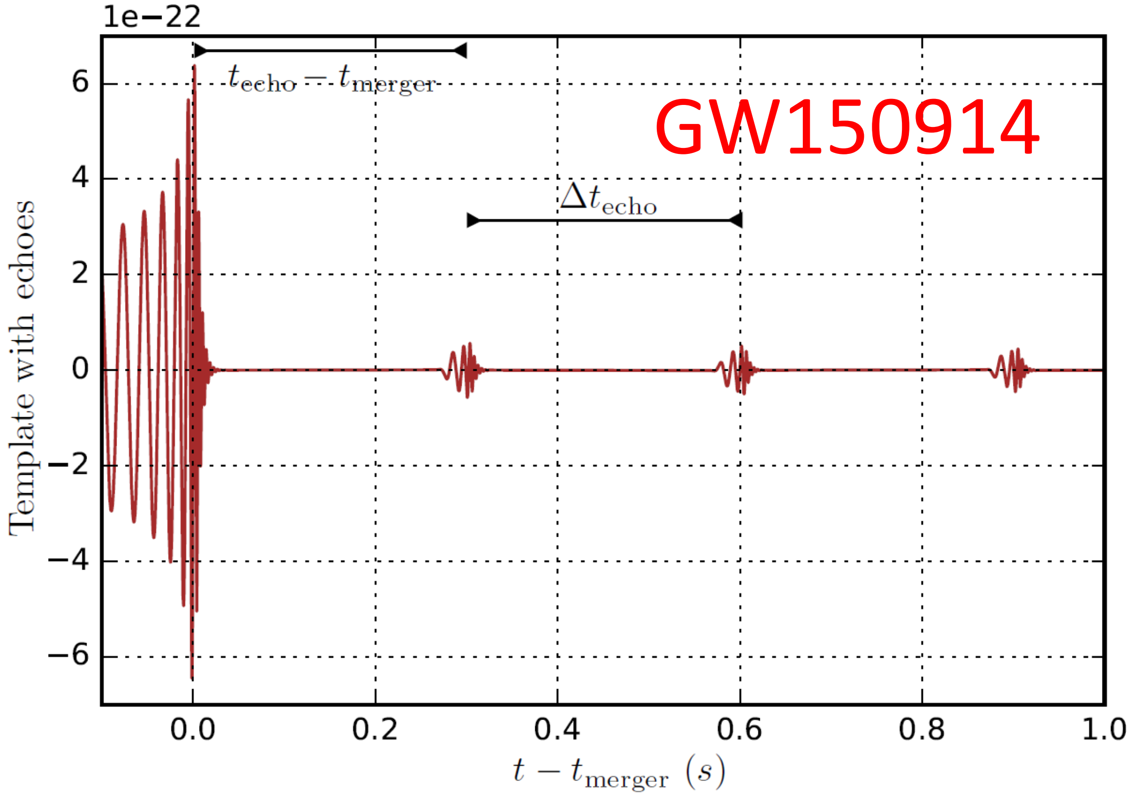
TABLE I: Best fit values for echo parameters of the highest SNR peak near the predicted $\Delta t_{\rm echo}$, and their significance.

	GW150914	GW151226	LVT151012
$\Delta t_{\rm echo,pred}(\rm sec)$	0.2925 ± 0.00916	0.1013 ± 0.01152	0.1778 ± 0.02789
$\Delta t_{\rm echo,best}(\rm sec)$	0.30068	0.09758	0.19043
$\lvert A_{\rm best,I}\rvert$	0.091	0.33	0.34
$\mathrm{SNR}_{\rm best,I}$	4.13	3.83	4.52

TABLE II: Theoretical expectations for $\Delta t_{\rm echo}$'s of each merger event (Eq. 6), compared to their best combined fit within the 1σ credible region, and the contribution of each event to the joint SNR for the echoes (Eq. 10).



Best fit templates for LIGO main events and echoes (using the joint best fit), in Fourier space. The amplitude spectral distribution (ASD) for each detector is shown for comparison.



Extraordinary claims require extraordinary evidence

Experimental **Evidence** for
Quantum Gravity and
Planck scale physics
at 99% confidence?!!$>$**2.5**σ

Future data releases from LIGO collaboration or more accurate models may confirm or rule out this finding.


Thank you

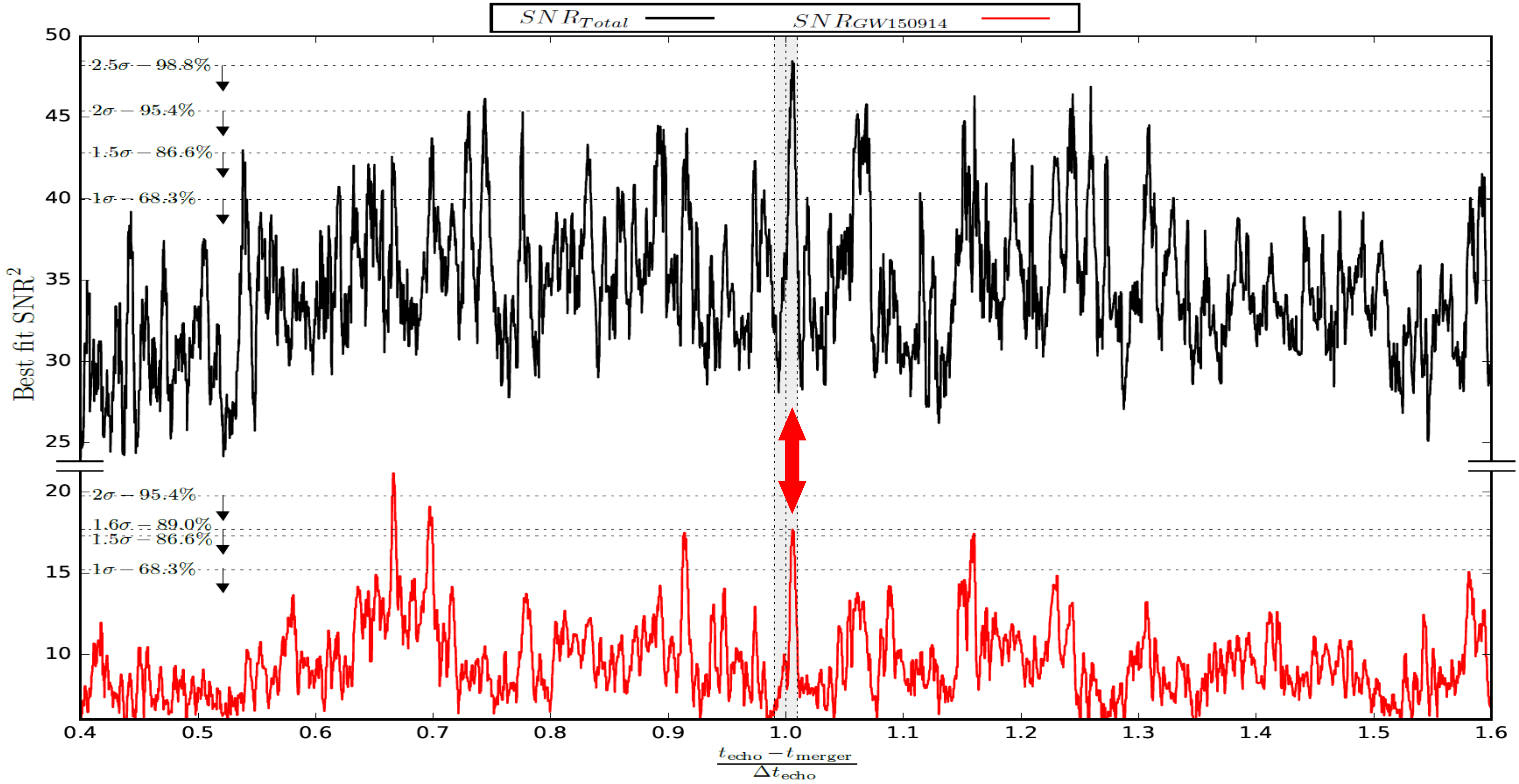
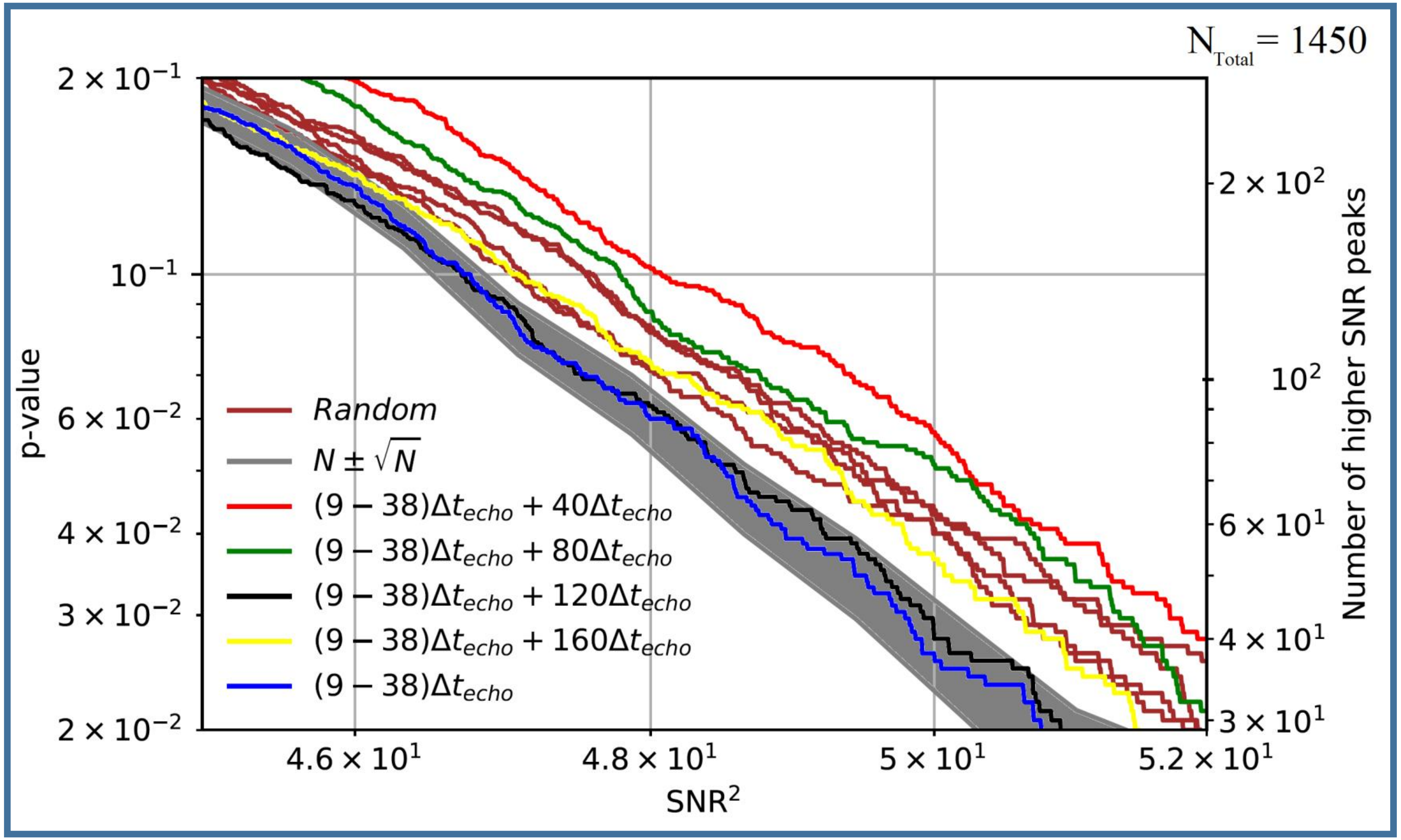


FIG. 3: Same as Fig. 4 in the main text, but over an extended range of $x = \frac{t_{\rm echo} - t_{\rm merger}}{\Delta t_{\rm echo}}$. The SNR peaks at the predicted value of $x = 1$ have 1.6σ and 2.5σ significance, for GW150914 and combined events respectively (See also [33]).



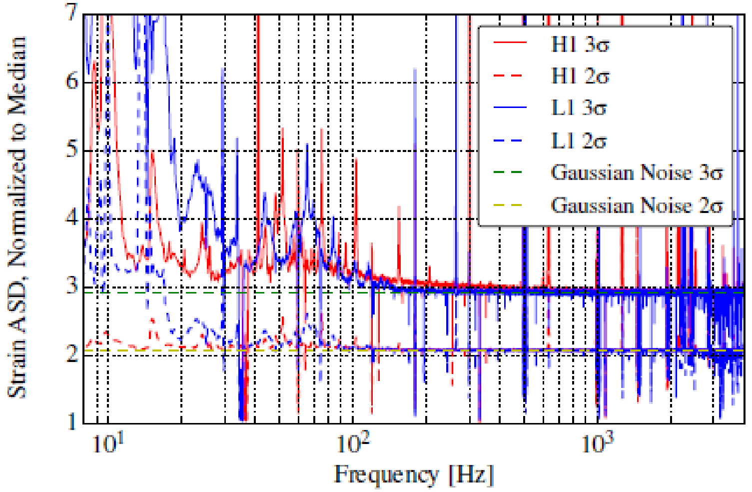


FIG. 15. 95th (2σ) and 99.7th (3σ) percentiles of the noise in each frequency bin during five days of operations (Oct 15-20). The expectations for stationary Gaussian noise at each percentile are given by the colored dashed lines. Both detectors exhibit some non-stationary behavior at low frequencies, due to varying noise couplings with the environment.

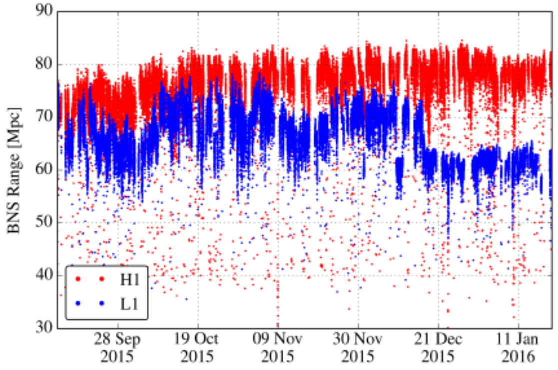
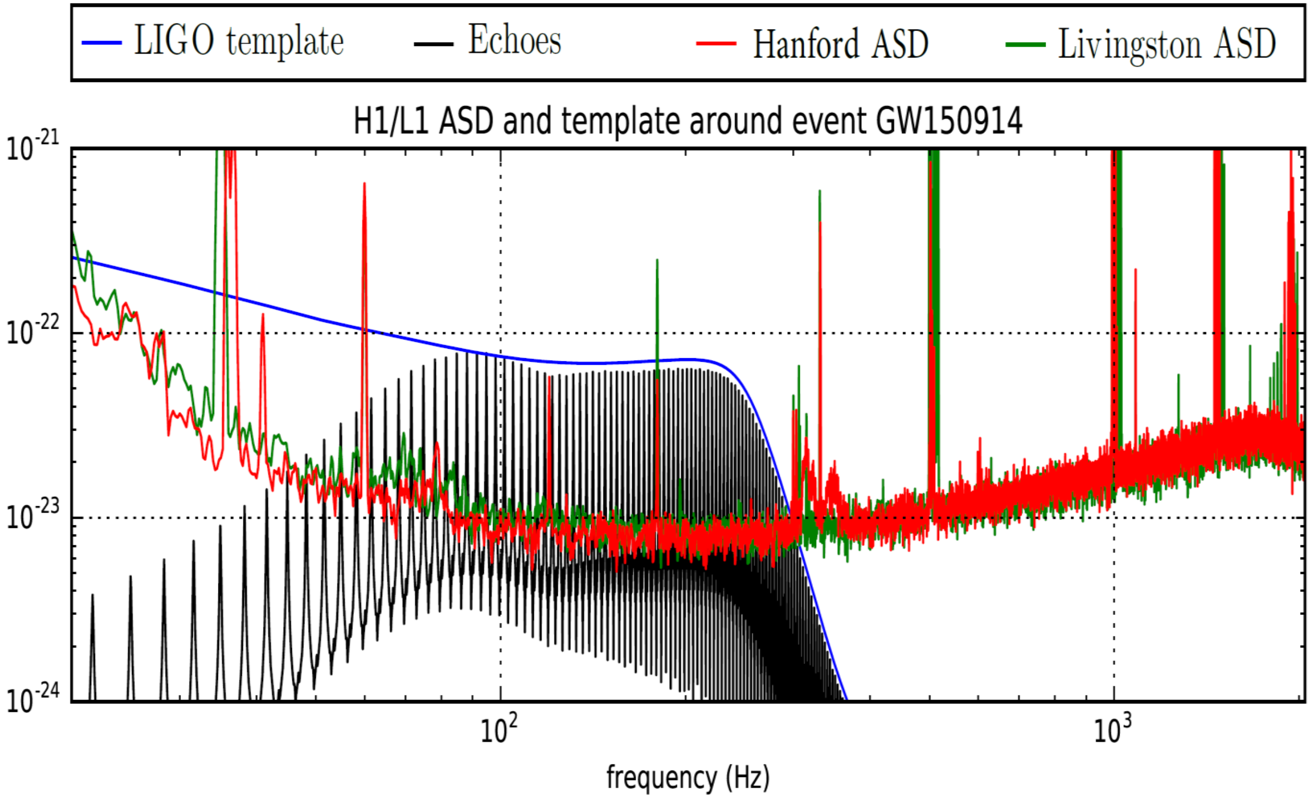


FIG. 14. Sensitivity of the two Advanced LIGO detectors to binary neutron star inspirals, averaged over sky position and orientation and 1 minute of data. The sensitivity drop in the L1 interferometer at the end of the run was caused by electronics noise at one of the end stations. This noise was identified and eliminated shortly after the observing run.

[4] D. V. Martynov *et al.* (LIGO Scientific), Phys. Rev. D93, 112004 (2016), arXiv:1604.00439 [astro-ph.IM].



15.3 Analysis challenges

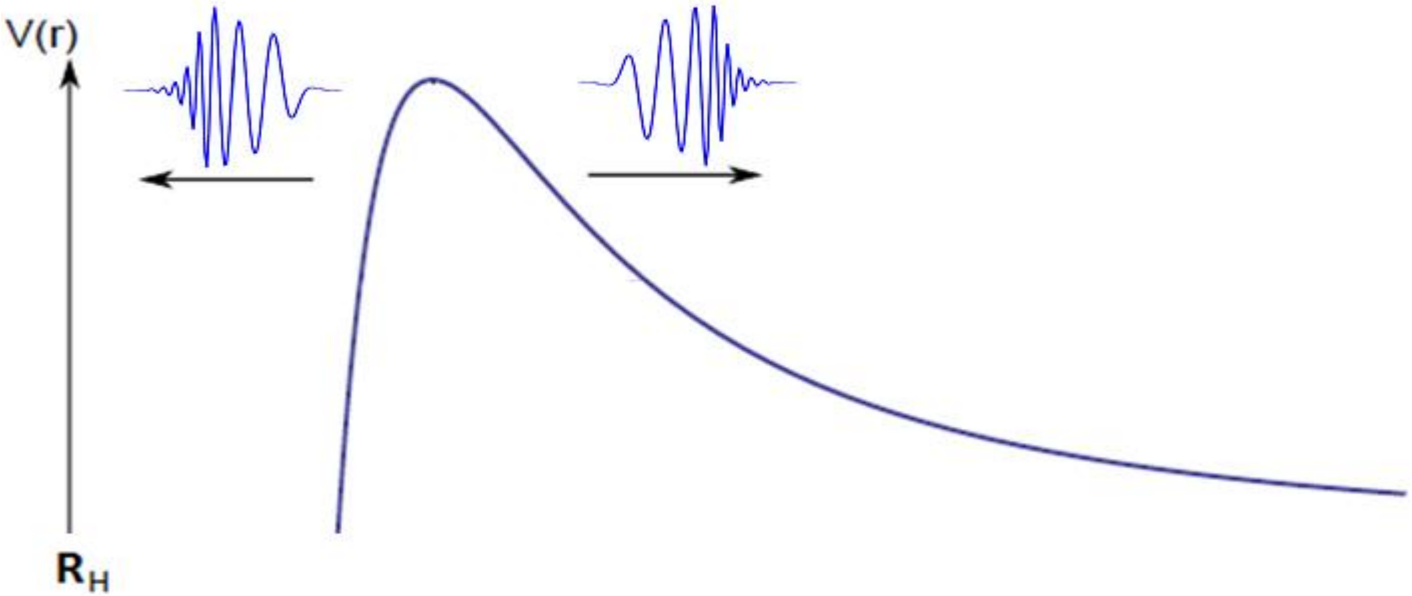
Once the reconstructed physics objects are available for analysis, *selection criteria* must be designed and applied to them. Most often, these selection criteria are designed on the basis of a *Monte Carlo simulation* of relevant underlying physics processes as well as a simulation of the response of the detector to final-state physics objects. The choice of selection criteria is often a balance between many complementary challenges.

The first challenge is the optimisation and enhancement of the statistical significance of a signal process which involves achieving a high efficiency for signal as well as a high rejection power for background. Frequently, these selection criteria consist of *cuts* on a variety of kinematic features derived from the four-momenta of the final-state physics objects. Additional criteria may be placed upon other characteristics such as particle-identification information. The higher the signal efficiency and background rejection, the fewer data are required to achieve a physics result. In the era of expensive or limited data-taking opportunities, this endeavour has recruited advanced multivariate techniques to exploit fully the information within the data.

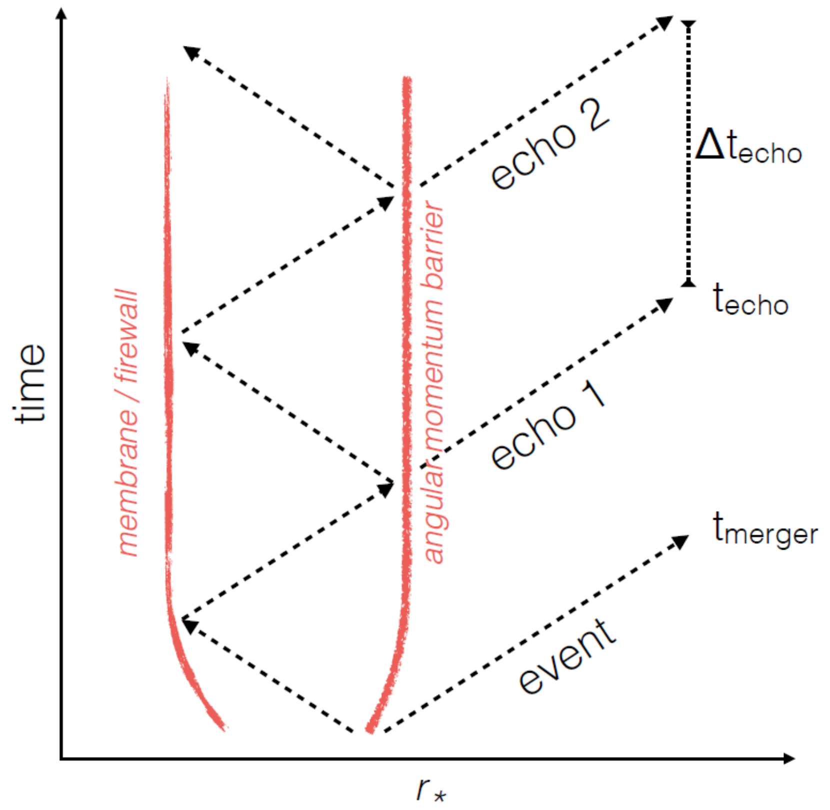
Particle Detectors, Grupen C., Shwartz B.

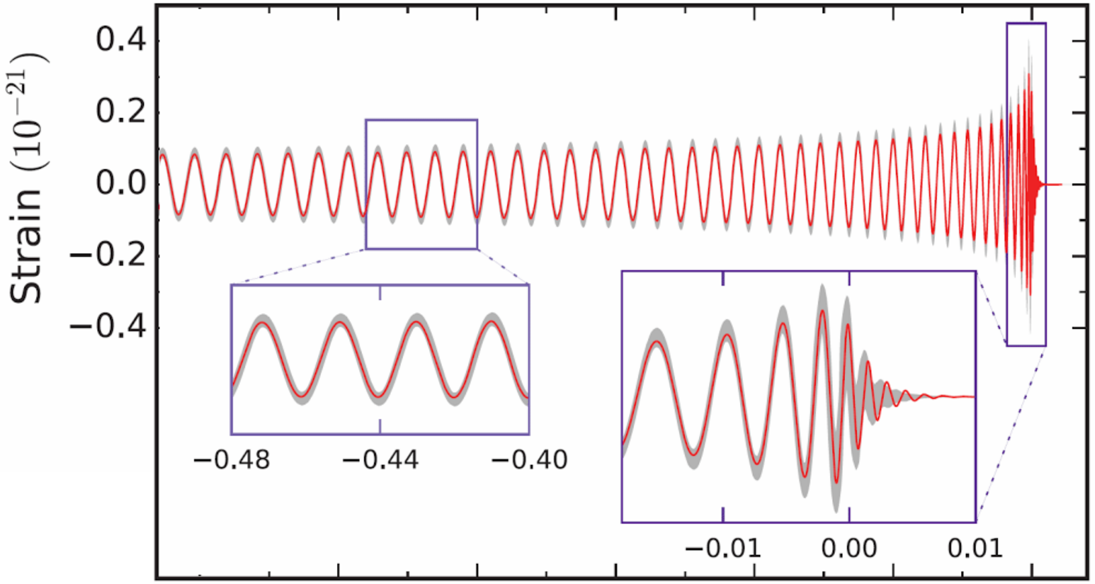
$$
\begin{aligned}
\Delta t_1 &= \Delta t \\
&= 2 \times r_*|_{r_+ + \Delta r}^{r_{max}} = 2 \times \int_{r_+ + \Delta r}^{r_{max}} \frac{r^2 + a^2}{r^2 - 2Mr + a^2} dr \\
&= 2r_{max} - 2r_+ - 2\Delta r + 2\frac{r_+^2 + a^2}{r_+ - r_-} \ln\left(\frac{r_{max} - r_+}{\Delta r}\right) \\
&\quad - 2\frac{r_-^2 + a^2}{r_+ - r_-} \ln\left(\frac{r_{max} - r_-}{r_+ - r_- + \Delta r}\right)
\end{aligned}
$$

$$r_+ = M(1 + \sqrt{1 - a^2}), \; r_- = M(1 - \sqrt{1 - a^2})$$



For the second echo we would have $\Delta t_2 = 2\Delta t_1$.





$$
\begin{aligned}
&2r_{max}^4(r_{max}-3)^2 \\
&+4r_{max}^2[(1-\mu^2)r_{max}^2-2r_{max}-3(1-\mu^2)]a^2 \\
&+(1-\mu^2)[(2-\mu^2)r_{max}^2+2(2+\mu^2)r_{max} \\
&\qquad +(2-\mu^2)]a^4=0
\end{aligned}
$$

where $\mu = m/(l+\frac{1}{2})$ and $\hat{r}_{\max} = r_{\max}/M$. For the dominant QNM, $r_{\max} < 3M$ and $(l,m) = (2,2)$ resulting in $\mu = 0.8$.

Δr (location of the firewall) must be given in terms of the proper length,

$$
l_p \simeq \int_{r_+}^{r_+ + \Delta r} \sqrt{g_{rr} dr}|_{\theta=0}
$$

Then we obtain,

$$
\Delta r|_{\theta=0} = \frac{\sqrt{1-a^2} l_p^2}{4M(1+\sqrt{1-a^2})}
$$

[19] H. Yang, A. Zimmerman, A. Zenginolu, F. Zhang, E. Berti, and Y. Chen, Phys. Rev. D88, 044047 (2013), [Phys. Rev.D88,044047(2013)], arXiv:1307.8086 [gr-qc].

Gravitational Aether proposal

In this model, the right hand side of the Einstein field equation is modified as:

$$(8\pi G')^{-1} G_{\mu\nu} = T_{\mu\nu} - \frac{1}{4} T^{\alpha}_{\alpha} g_{\mu\nu} + p'(u'_{\mu} u'_{\nu} + g_{\mu\nu}), \quad (1)$$

This has decoupling symmetry similar to Unimodular gravity

$$T_{\mu\nu} \to T'_{\mu\nu} = T_{\mu\nu} + C g_{\mu\nu}$$

This means that contributions to the energy-momentum tensor proportional to the metric do not couple to gravity

Stellar Black Holes and the Origin of Cosmic Acceleration

Chanda Prescod-Weinstein,[1,2,*] Niayesh Afshordi,[1,†] and Michael L. Balogh[2,‡]

- We can solve for the black hole spacetime in this theory

$$ds^2 = \left(1 - \frac{2m}{r}\right)[1 + 4\pi p_0 f(r)]^2\, dt^2 - \left(1 - \frac{2m}{r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

- p_0 is the aether pressure at infinity

$$f(r) = \frac{1}{2}\left(1 - \frac{2m}{r}\right)^{-1/2}(-30m^2 + 5mr + r^2) + \frac{15}{2}m^2 \ln\left[\frac{r}{m} - 1 + \frac{r}{m}\left(1 - \frac{2m}{r}\right)^{1/2}\right],$$

- If we assume the temperature near the horizon is Planckian:

$$\boxed{1 + z_{\max} \sim \frac{\text{Planck temperature}}{\text{Hawking temperature}}}$$

- then we get

$$\boxed{p_0 = -\frac{1}{256\pi^2 m^3} \simeq \left(\frac{m}{74\, M_\odot}\right)^{-3} p_{\mathrm{DE,obs}}!!}$$

- *Pressure* has the same sign and magnitude as *Dark Energy* for stellar mass black holes!

And you guessed it! Planck-scale structure replaces black hole horizon

Onset of superradiant instabilities in rotating spacetimes of exotic compact objects

Shahar Hod
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and
The Hadassah Institute, Jerusalem 91010, Israel
(Dated: April 21, 2017)

Exotic compact objects, horizonless spacetimes with reflective properties, have intriguingly been suggested by some quantum-gravity models as alternatives to classical black-hole spacetimes. A remarkable feature of spinning horizonless compact objects with reflective boundary conditions is the existence of a *discrete* set of critical surface radii, $\{r_c(\bar{a};n)\}_{n=1}^{n=\infty}$, which can support spatially regular static (*marginally-stable*) scalar field configurations (here $\bar{a} \equiv J/M^2$ is the dimensionless angular momentum of the exotic compact object). Interestingly, the outermost critical radius $r_c^{\max} \equiv \max_n\{r_c(\bar{a};n)\}$ marks the boundary between stable and unstable exotic compact objects: spinning objects whose reflecting surfaces are situated in the region $r_c > r_c^{\max}(\bar{a})$ are stable, whereas spinning objects whose reflecting surfaces are situated in the region $r_c < r_c^{\max}(\bar{a})$ are superradiantly unstable to scalar perturbation modes. In the present paper we use analytical techniques in order to explore the physical properties of the critical (marginally-stable) spinning exotic compact objects. In particular, we derive a remarkably compact *analytical* formula for the discrete spectrum $\{r_c^{\max}(\bar{a})\}$ of critical radii which characterize the marginally-stable exotic compact objects. We explicitly demonstrate that the analytically derived resonance spectrum agrees remarkably well with numerical results that recently appeared in the physics literature.

Exotic Compact Objects and How to Quench their Ergoregion Instability

Elisa Maggio,[1,2,*] Paolo Pani,[1,2,3,†] and Valeria Ferrari[1,2,‡]
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[3] *CENTRA, Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049 Lisboa, Portugal.*

Gravitational-wave astronomy can give us access to the structure of black holes, potentially probing microscopic or even Planckian corrections at the horizon scale, as those predicted by some quantum-gravity models of exotic compact objects. A generic feature of these models is the replacement of the horizon by a reflective surface. Objects with these properties are prone to the so-called ergoregion instability when they spin sufficiently fast. We investigate in detail a simple model consisting of scalar perturbations of a Kerr geometry with a reflective surface near the horizon. The instability depends on the spin, on the compactness, and on the reflectivity at the surface. The instability time scale increases logarithmically in the black-hole limit but, for a perfectly reflecting object, this is not enough to prevent the instability from occurring on dynamical time scales. However, we find that an absorption rate at the surface as small as 0.4% (reflectivity coefficient as large as $|\mathcal{R}|^2 = 0.996$) is sufficient to quench the instability completely. Our results suggest that exotic compact objects are not necessarily ruled out by the ergoregion instability.

Black hole ringdown echoes and howls

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[3] *Faculty of Arts and Science, Kyushu University, Fukuoka 819-0395, Japan*
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Recently the possibility of detecting echoes of ringdown gravitational waves from binary black hole mergers was shown. The presence of echoes is expected if the black hole is surrounded by a mirror that reflects gravitational waves near the horizon. Here, we present a little more sophisticated templates motivated by a waveform which is obtained by solving the linear perturbation equation around a Kerr black hole with a complete reflecting boundary condition. We also point out that the completely reflecting boundary leads to a super-radiant instability, and hence it is not consistent with the presence of rotating black holes.

Subject Index E31, E02, E01, E38

Discovering the interior of black holes

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Abstract

The detection of gravitational waves from black hole (BH) mergers provides an inroad toward probing the interior of astrophysical BHs. The general-relativistic description of a BH's interior is that of empty spacetime with a (possibly) super-dense core. Recently, however, the hypothesis that the BH interior does not exist has been gaining traction, as it provides a means for resolving the BH information-loss problem. Here, we propose a simple method for answering the question: Does the BH interior exist and, if so, does it contain some distribution of matter or is it mostly empty? Our proposal is premised on the idea that, similar to the case of relativistic, ultra-compact stars, any BH-like object whose interior has some matter distribution should support fluid modes in addition to the conventional and universally present spacetime modes. In particular, the Coriolis-induced Rossby (r-) modes, whose spectrum is mostly insensitive to the composition of the interior matter, should be a universal feature of a BH-like object. In fact, the characteristic properties of these modes are determined by only the object's mass and speed of rotation. The r-modes oscillate at a lower frequency, decay at a slower rate and produce weaker gravitational waves than do those of the spacetime class. Hence, they imprint a model-independent signature of a non-empty interior in the gravitational-wave spectrum resulting from a BH merger.

Probing Planckian corrections at the horizon scale with LISA binaries

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Several quantum-gravity models of compact objects predict microscopic or even Planckian corrections at the horizon scale. We discuss two model-independent, smoking-gun effects of these corrections in the gravitational waveform of a compact binary, namely the absence of tidal heating and the presence of tidal deformability. For events detectable by the future space-based interferometer LISA, we show that the effect of tidal heating dominates and allows one to constrain putative corrections down to the Planck scale, up to redshift $z \sim 9$. Furthermore, the measurement of the tidal Love numbers with LISA can constrain the compactness of an exotic compact object down to microscopic scales in conservative scenarios, and down to the Planck scale in the case of a highly spinning binary at $1-10\,\mathrm{Gpc}$. Our analysis suggests that spinning, supermassive binaries provide unparalleled tests of quantum-gravity effects at the horizon scale.

When black holes collide: Probing the interior composition by the spectrum of ringdown modes and emitted gravitational waves

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Abstract

The merger of colliding black holes (BHs) should lead to the production of ringdown or quasinormal modes (QNMs), which may very well be sensitive to the state of the interior. We put this idea to the test with a recent proposal that the interior of a BH consists of a bound state of highly excited, long, closed, interacting strings; figuratively, a collapsed polymer. We show that such BHs do indeed have a distinct signature in their QNM spectrum: A new class of modes whose frequencies are parametrically lower than the lowest-frequency mode of a classical BH and whose damping times are parametrically longer. The reason for the appearance of the new modes is that our model contains another scale, the string length, which is parametrically larger than the Planck length. This distinction between the collapsed-polymer model and general-relativistic BHs could be made with gravitational-wave observations and offers a means for potentially measuring the strength of the coupling in string theory. For example, GW150914 already allows us to probe the strength of the string coupling near the regime which is predicted by the unification of the gravitational and gauge-theory couplings. We also derive bounds on the amplitude of the collapsed-polymer QNMs that can be placed by current and future gravitational-wave observations.

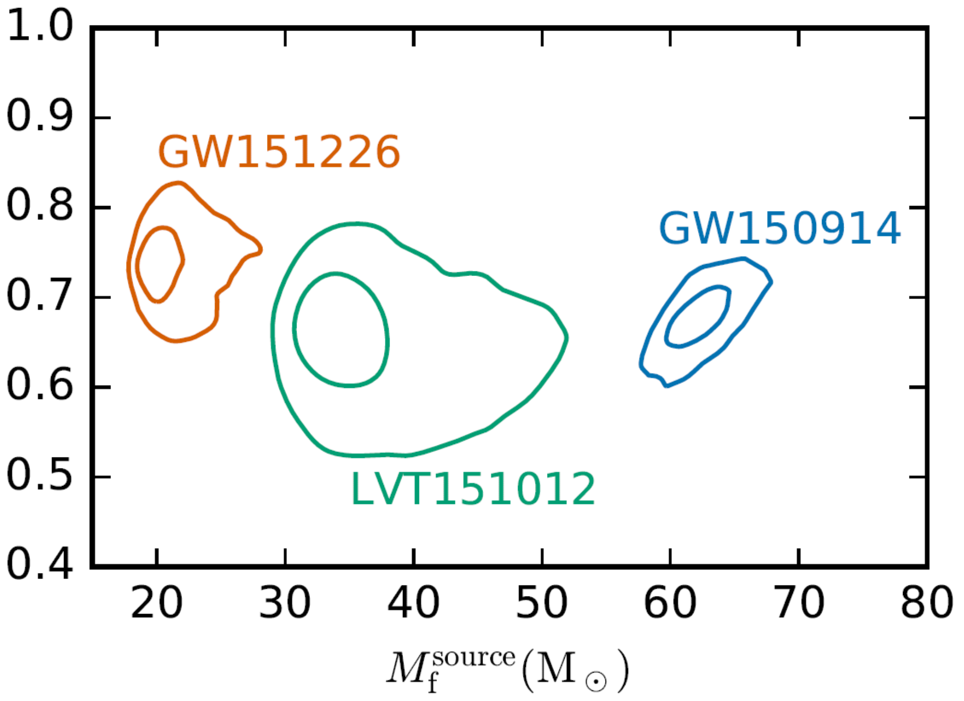
The statistics of gaussian credible region

A two dimensional random mass M and angular a variables of black hole has following gaussian probability distribution.

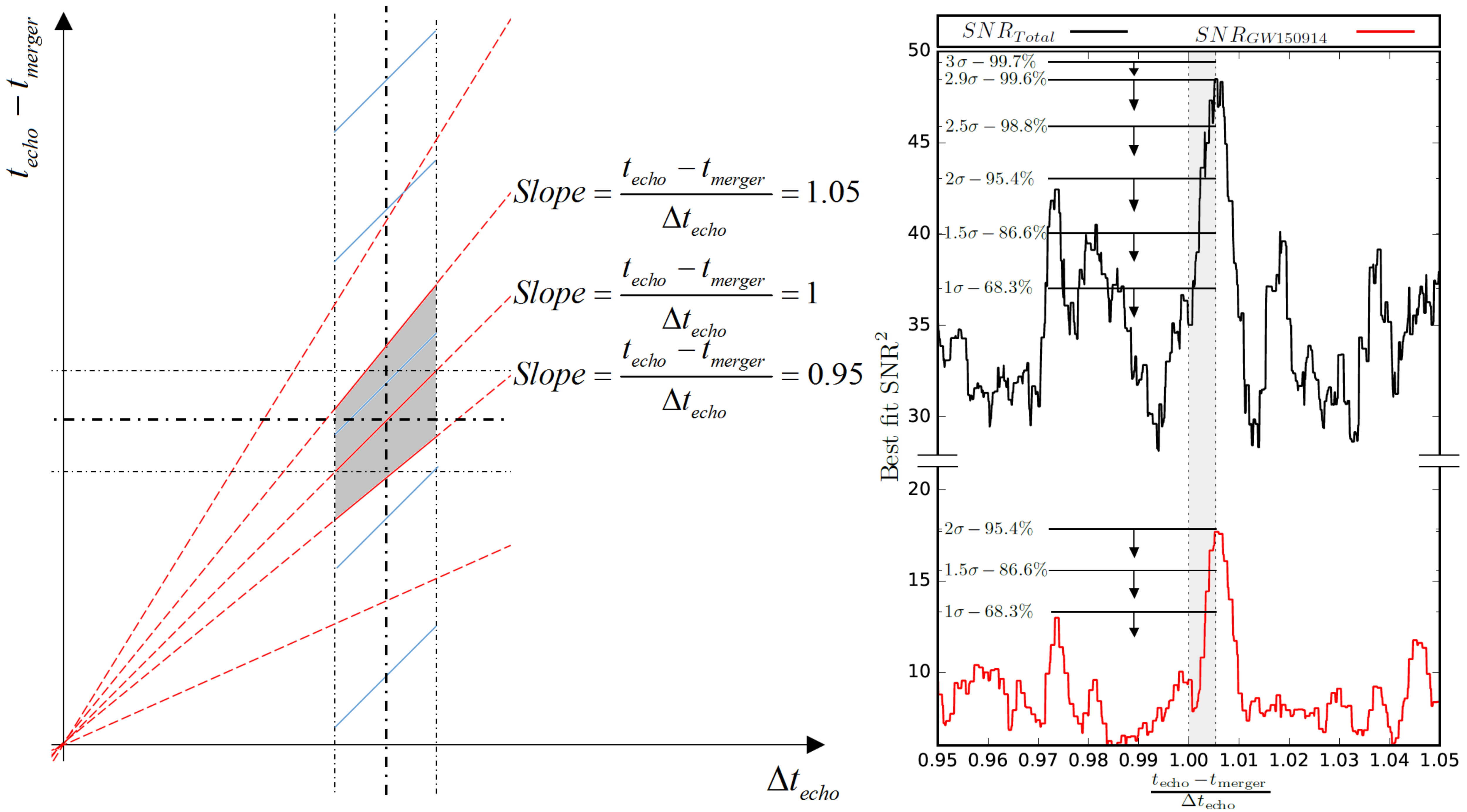
$$P(\Delta a, \Delta M) = \frac{\sqrt{\det M}}{2\pi} \exp(-\frac{1}{2}\alpha \Delta a^2 - \frac{1}{2}\beta \Delta M^2 - \gamma \Delta a \Delta M)$$

$$P(\Delta t) = \int \delta_D(\Delta t'(a, M) - \Delta t) P(a - \bar{a}, M - \bar{M}) da dM = \int \frac{dM}{|\frac{\partial \Delta t'}{\partial a}|} P(a - \bar{a}, M - \bar{M})$$

$$\Delta a = a - \langle a \rangle \quad , \quad \Delta M = M - \langle M \rangle$$



$$\Delta t = 2r_{max} - 2r_+ - 2\Delta r + 2\frac{r_+^2 + a^2}{r_+ - r_-} \ln(\frac{r_{max} - r_+}{\Delta r}) - 2\frac{r_-^2 + a^2}{r_+ - r_-} \ln(\frac{r_{max} - r_-}{r_+ - r_- + \Delta r})$$



$t_{echo} - t_{merger}$
Δt_{echo}
$Slope = \frac{t_{echo} - t_{merger}}{\Delta t_{echo}} = 1.05$
$Slope = \frac{t_{echo} - t_{merger}}{\Delta t_{echo}} = 1$
$Slope = \frac{t_{echo} - t_{merger}}{\Delta t_{echo}} = 0.95$
SNR_{Total}
$SNR_{GW150914}$
$3\sigma - 99.7\%$
$2.9\sigma - 99.6\%$
$2.5\sigma - 98.8\%$
$2\sigma - 95.4\%$
$1.5\sigma - 86.6\%$
$1\sigma - 68.3\%$
$2\sigma - 95.4\%$
$1.5\sigma - 86.6\%$
$1\sigma - 68.3\%$
Best fit SNR^2
50
45
40
35
30
20
15
10
0.95 0.96 0.97 0.98 0.99 1.00 1.01 1.02 1.03 1.04 1.05
$\frac{t_{\mathrm{echo}} - t_{\mathrm{merger}}}{\Delta t_{\mathrm{echo}}}$