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


Jahed Abedi, Hannah Dykaar, and Niayesh Afshordi

Sharif University of Technology
Institute for Research in Fundamental Sciences (IPM)
Perimeter Institute for Theoretical Physics

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

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

Jahed Abedi,[1,2,3,*] Hannah Dykaar,[4,5] and Niayesh Afshordi[3,5,†]

[1] *Department of Physics, Sharif University of Technology, P.O. Box 11155-9161, Tehran, Iran*
[2] *School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran*
[3] *Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, ON, N2L 2Y5, Canada*
[4] *Department of Physics, McGill University, 3600 rue University, Montreal, QC, H3A 2T8, Canada*
[5] *Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, N2L 3G1, Canada*

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 $2.9\sigma$ 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.

# Echoes from the Abyss: The Holiday Edition!

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

Jahed Abedi,[1,2,3,*] Hannah Dykaar,[4,5] and Niayesh Afshordi[3,5,†]

[1] *Department of Physics, Sharif University of Technology, P.O. Box 11155-9161, Tehran, Iran*
[2] *School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran*
[3] *Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, ON, N2L 2Y5, Canada*
[4] *Department of Physics, McGill University, 3600 rue University, Montreal, QC, H3A 2T8, Canada*
[5] *Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, N2L 3G1, Canada*

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).

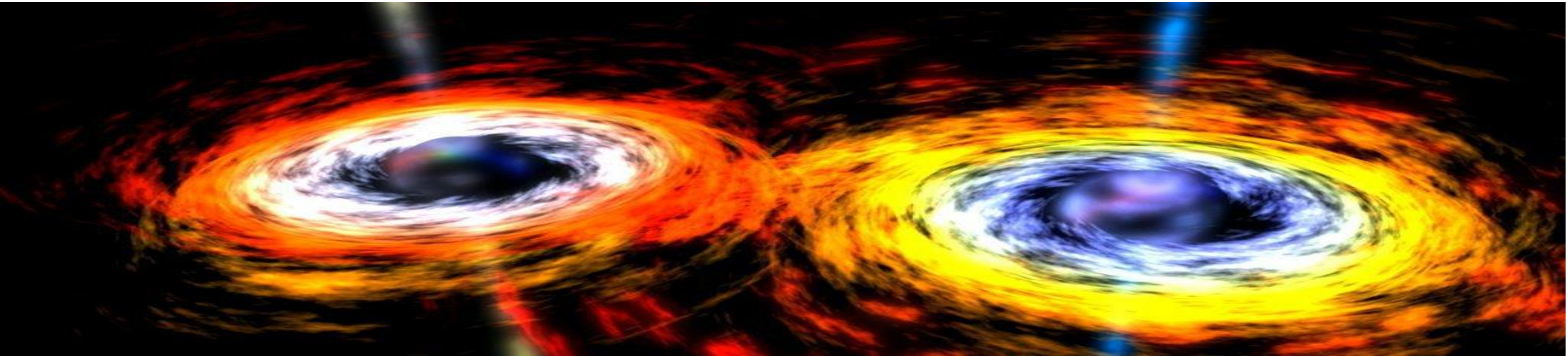
## Comments on: "Echoes from the abyss: Evidence for Planck-scale structure at black hole horizons"

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

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]

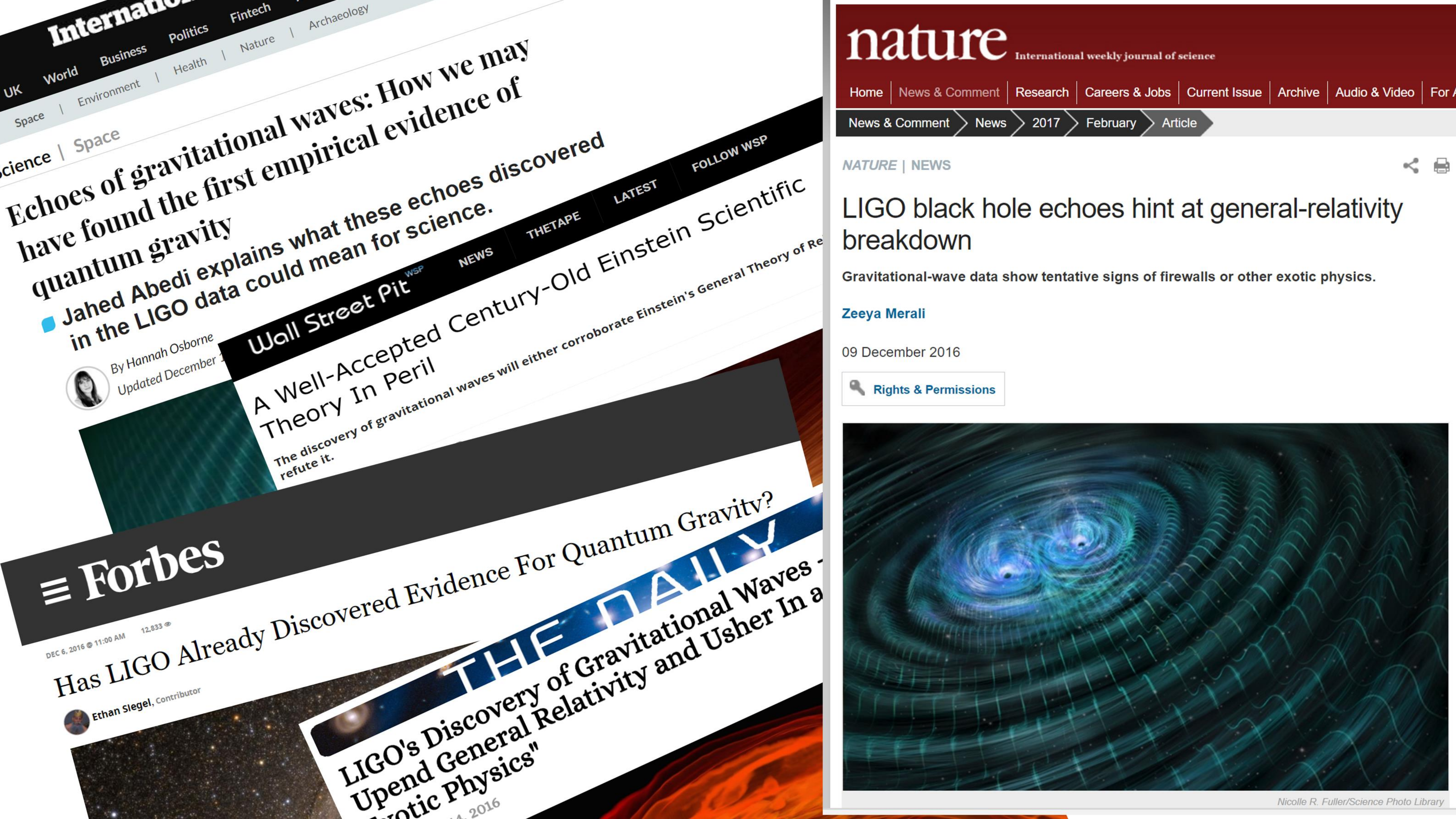
[1] *Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[2] *Leibniz Universität Hannover, D-30167 Hannover, Germany*
[3] *Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany*

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.

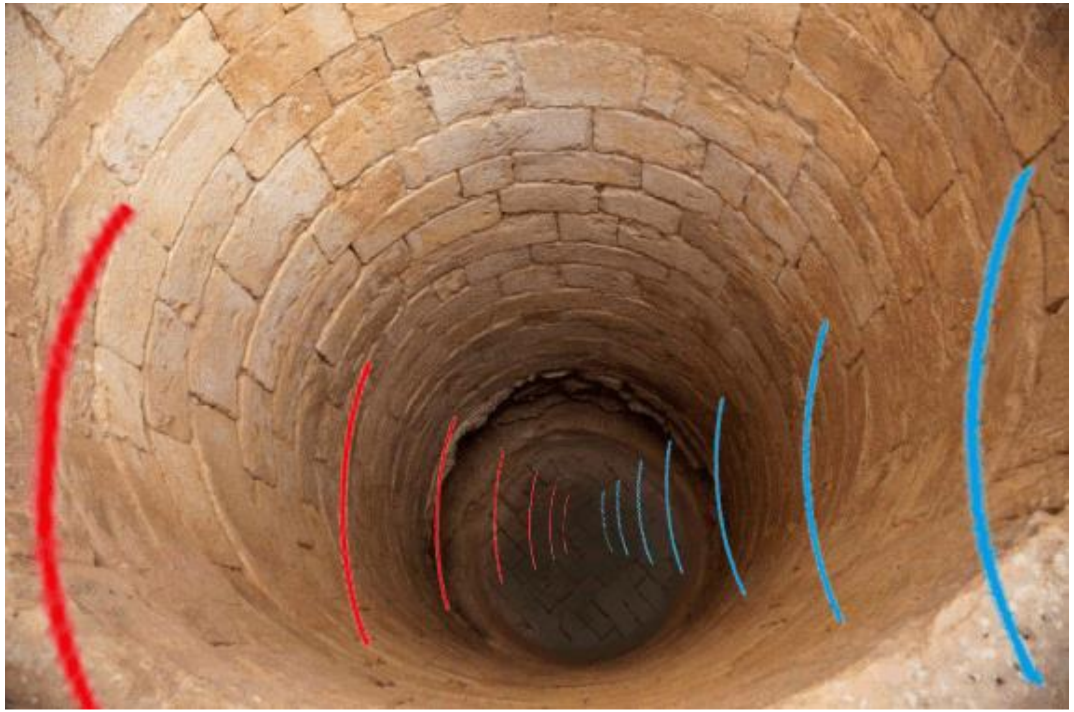


- **Echoes of a black hole, Ripples in space-time could herald the demise of general relativity and its replacement by a quantum theory of gravity**
  https://aeon.co/essays/do-ripples-in-space-time-herald-a-new-theory-of-gravity
- **Has LIGO Actually Proved Einstein Wrong – and Found Signs of Quantum Gravity?**
  https://thewire.in/86914/quantum-gravity-echoes-blackholes
- **Einstein's Theory of Relativity is 100 Years Old, But May Not Last**
  https://www.inverse.com/article/25051-how-long-will-einsteins-theory-of-relativity-hold-up
- **Rätselhaftes Echo aus Schwarzem Loch**
  http://science.orf.at/stories/2817345
- پژواکی از مغاک: شواهدی از ساختارهایی به اندازه پلانک در افق سیاهچاله
  http://www.psi.ir/farsi.asp?url=http://www.psi.ir/html/news/news/news2_f.asp?id=2155
- **Ecos a 3 sigmas en las ondas gravitacionales observadas por LIGO**
  http://francis.naukas.com/2016/12/08/posibles-ecos-en-la-onda-gravitacional-gw150914
- **В гравитационных волнах заметили нарушение общей теории относительности**
  https://nplus1.ru/news/2016/12/13/relativity
- **Onde gravitazionali, una strana eco fa traballare la Relatività**
  http://www.ansa.it/scienza/notizie/rubriche/spazioastro/2016/12/12/onde-gravitazionali-una-strana-eco-fa-traballare-la-teoria-della-relativita-_e8f35596-0a1f-4846-8eba-1f03f71a9d78.html
- **HOW THE ECHOES IN GRAVITATIONAL WAVES COULD DESTROY THE HUNDRED-YEAR LEGACY OF THE GENERAL THEORY OF RELATIVITY**
  http://stardrive.org/stardrive/index.php/news2/science/19849-how-the-echoes-in-gravitational-waves-could-destroy-the-hundred-year-legacy-of-the-general-theory-of-relativity
- **Эхо гравитационных волн указало на возможное нарушение Общей теории относительности**
  https://tjournal.ru/38539-eho-gravitacionnih-voln-ukazalo-na-vozmozhnoe-narushenie-obshei-teorii-otnositelnosti

- **Echoes in gravitational waves hint at a breakdown of Einstein's general relativity**
  http://www.sciencealert.com/echoes-in-gravitational-waves-hint-at-a-breakdown-of-einstein-s-general-relativity
- **ECHOES FROM THE ABYSS**
  https://briankoberlein.com/2016/12/03/echoes-from-the-abyss/
- **Gravitational waves proved Einstein right, now they may help prove him wrong too**
  https://room.eu.com/news/gravitational-waves-proved-einstein-right-now-they-may-help-prove-him-wrong-too
- **Dar vienas fizikos paradoksas: gravitacinėse bangose pastebėti bendrosios reliatyvumo teorijos pažeidimai**
  http://m.technologijos.lt/cat/121/article/S-58783
- **UN ORIZZONTE DEGLI EVENTI IN BILICO**
  https://www.astronomiamo.it/Articolo.aspx?Arg=Un_orizzonte_degli_eventi_in_bilico
- **Heeft LIGO naast zwaartekrachtsgolven soms ook effecten van kwantum zwaartekracht gedetecteerd?**
  http://www.astroblogs.nl/2016/12/13/heeft-ligo-naast-zwaartekrachtsgolven-soms-ook-effecten-van-kwantum-zwaartekracht-gedetecteerd/
- **Πώς τα βαρυτικά κύματα μπορούν να καταρρίψουν τον Αϊνστάιν και να μας οδηγήσουν στην κβαντική βαρύτητα**
  http://www.rizopoulospost.com/pws-ta-barytika-kymata-mporoun-na-kata/
- **Heeft een zwart gat een 'firewall'? Drie onderzoekers denken een manier te hebben gevonden om te bepalen wat zich afspeelt op het randje van een zwart gat.**
  https://www.kijkmagazine.nl/space/heeft-een-zwart-gat-een-firewall/
- **หลุมดำอาจมีกำแพงไฟ และทฤษฎีสัมพัทธภาพทั่วไปอาจจะผิด**
  http://www.narit.or.th/index.php/astronomy-news/2768-ligo-black-hole-firewalls
- **La strana eco delle onde gravitazionali fa traballare la Relatività?**
  https://oggiscienza.it/2016/12/23/eco-onde-gravitazionali-relativita/



International
UK World Business Politics Fintech
Space | Environment | Health | Nature | Archaeology
Science | Space
Echoes of gravitational waves: How we may have found the first empirical evidence of quantum gravity
Jahed Abedi explains what these echoes discovered in the LIGO data could mean for science.
By Hannah Osborne
Updated December
Wall Street Pit WSP
NEWS THETAPE LATEST FOLLOW WSP
A Well-Accepted Century-Old Einstein Scientific Theory In Peril
The discovery of gravitational waves will either corroborate Einstein's General Theory of Re
refute it.
Forbes
DEC 6, 2016 @ 11:00 AM 12,833
Has LIGO Already Discovered Evidence For Quantum Gravity?
Ethan Siegel, Contributor
THE DAILY
LIGO's Discovery of Gravitational Waves - Upend General Relativity and Usher In a Exotic Physics"
2016
nature International weekly journal of science
Home News & Comment Research Careers & Jobs Current Issue Archive Audio & Video
News & Comment News 2017 February Article
NATURE | NEWS
LIGO black hole echoes hint at general-relativity breakdown
Gravitational-wave data show tentative signs of firewalls or other exotic physics.
Zeeya Merali
09 December 2016
Rights & Permissions
Nicolle R. Fuller/Science Photo Library



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].


[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].

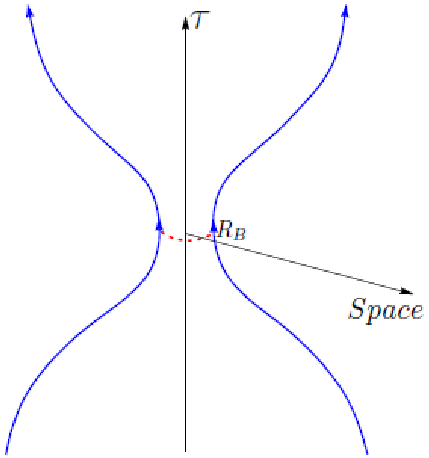
[3] O. Lunin and S. D. Mathur, Phys. Rev. Lett. **88**, 211303 (2002), arXiv:hep-th/0202072 [hep-th].

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

[5] J. Abedi and H. Arfaei, Class. Quant. Grav. **31**, 195005 (2014), arXiv:1308.1877 [hep-th].

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

[7] S. L. Braunstein, S. Pirandola, and K. Zyczkowski, Phys. Rev. Lett. **110**, 101301 (2013), arXiv:0907.1190 [quant-ph].

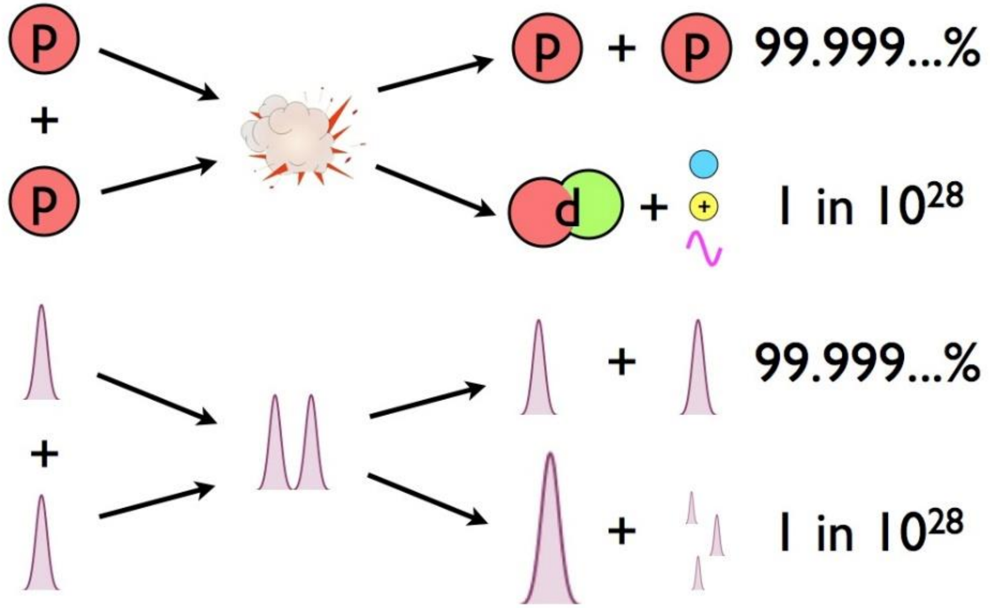



# Quantum Black Hole Tunneling

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

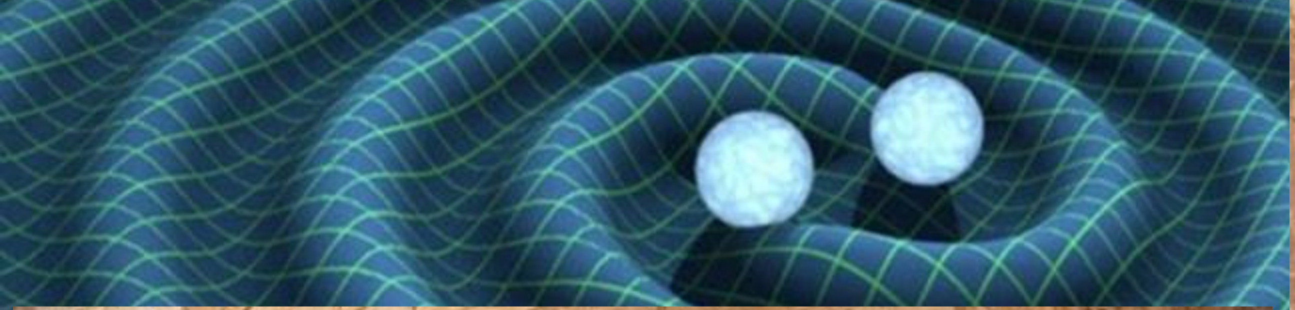
$$S_{BH\odot} = \frac{A_{BH\odot}}{4} = 4\pi M_\odot^2 = 2.66 \times 10^{78}$$ Kraus, and Mathur 2016

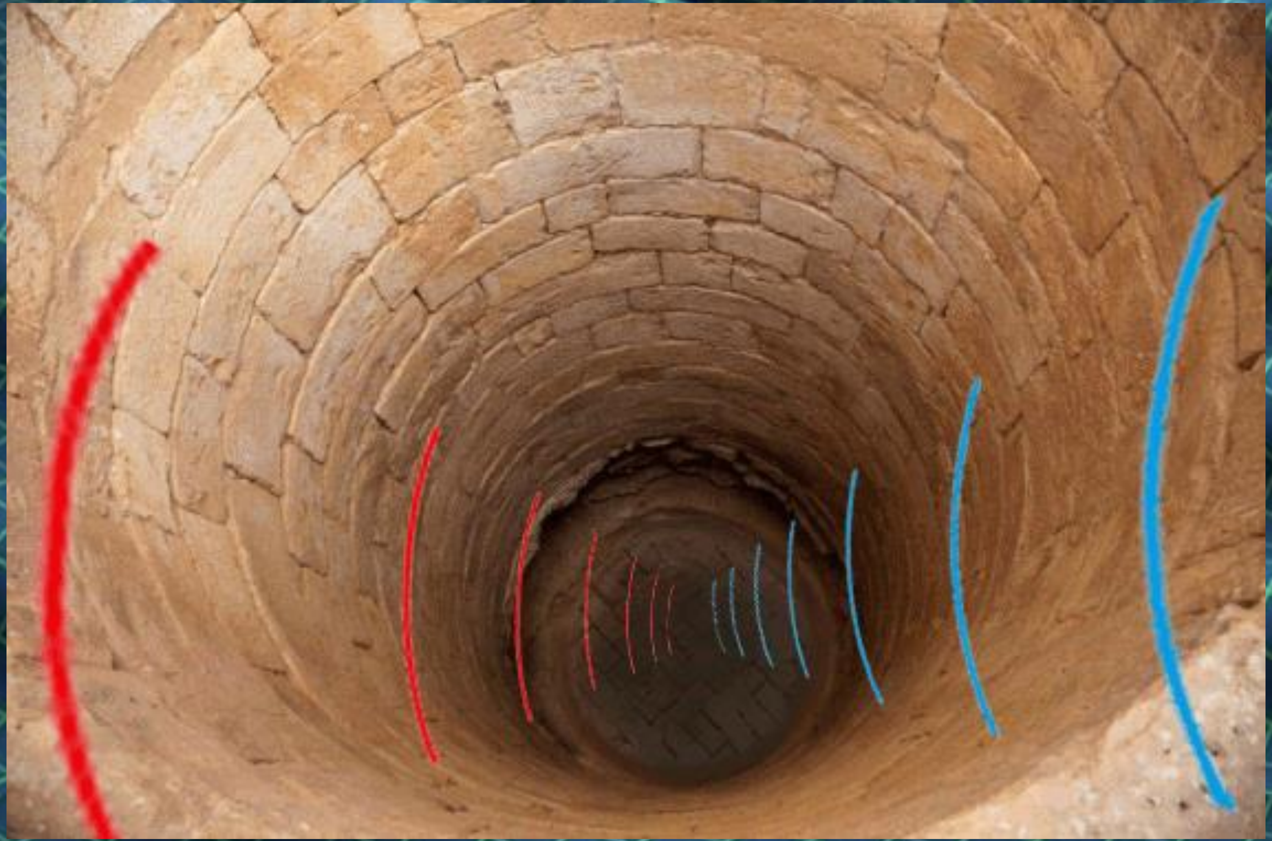
It's The Power Of Quantum Mechanics That Allows The Sun To Shine




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





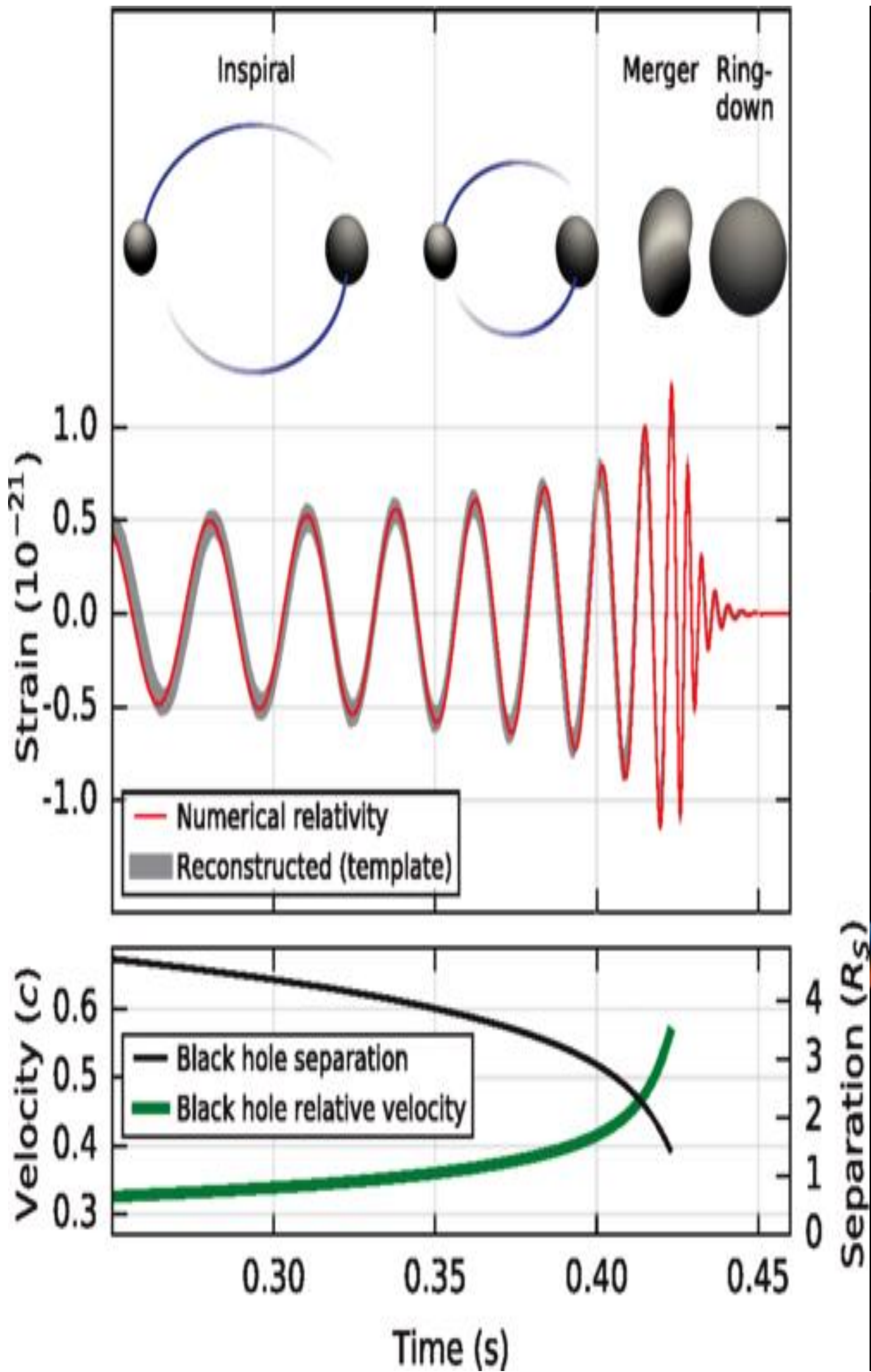

[1] A. Almheiri, D. Marolf, J. Polchinski, and J. Sully, JHEP **02**, 062 (2013), arXiv:1207.3123 [hep-th].

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

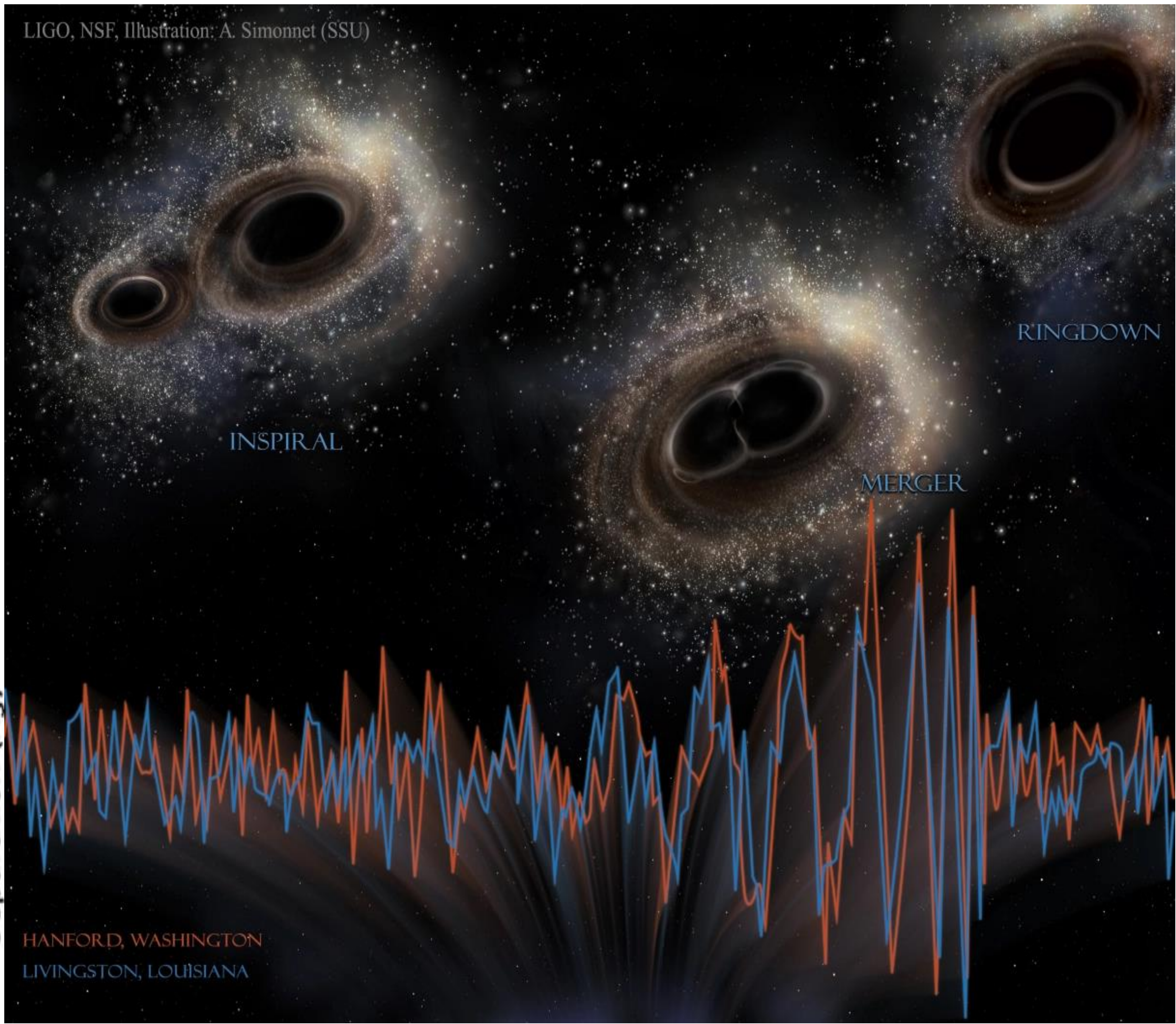
[3] O. Lunin and S. D. Mathur, Phys. Rev. Lett. **88**, 211303 (2002), arXiv:hep-th/0202072 [hep-th].

[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].



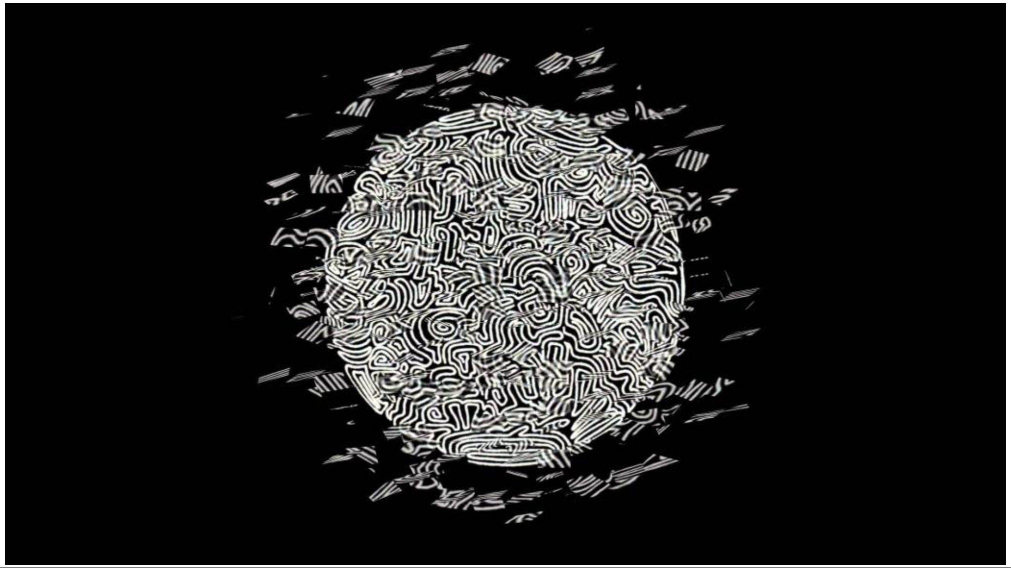
Inspiral
Merger
Ring-down
Strain ($10^{-21}$)
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity ($c$)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation ($R_S$)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

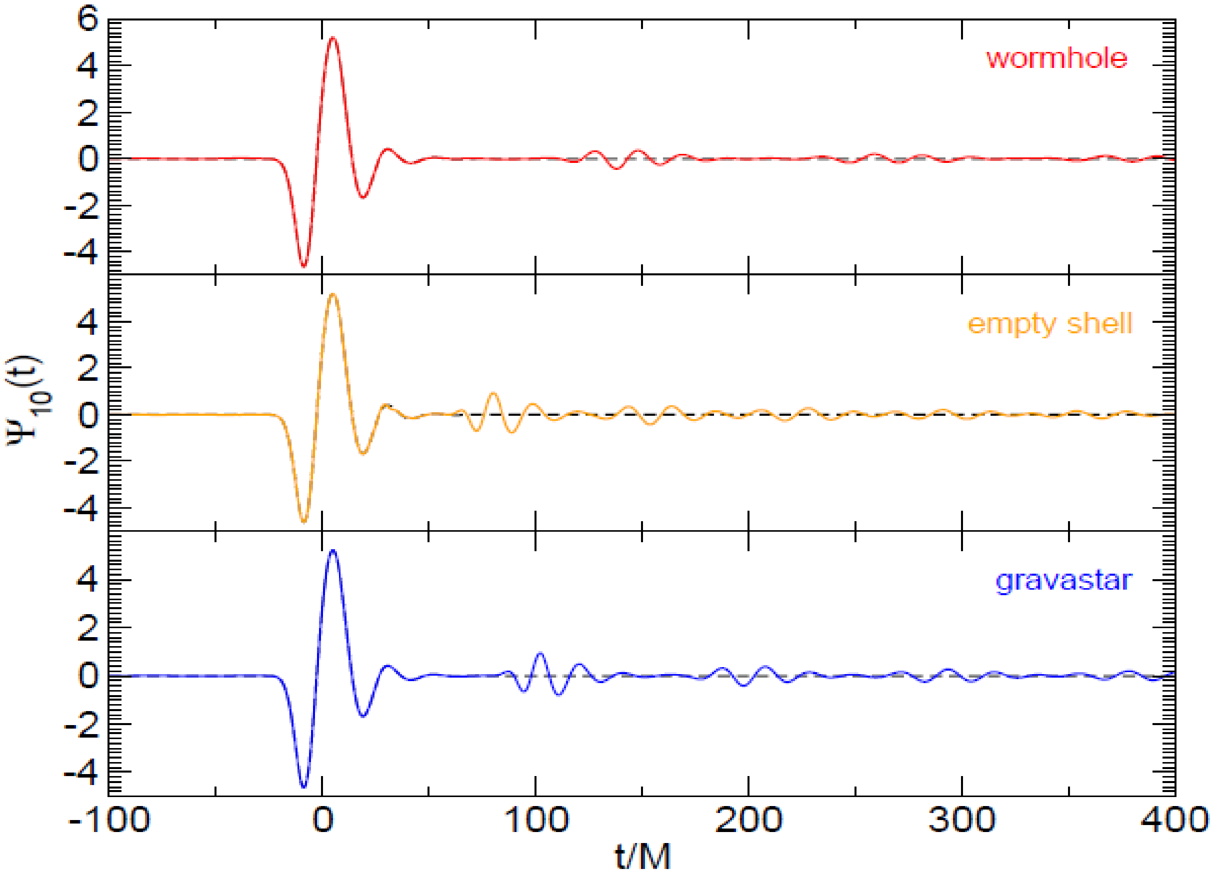
Introduction of structure near event horizon leads late, repeating, echoes of the ringdown phase of the black hole merger,

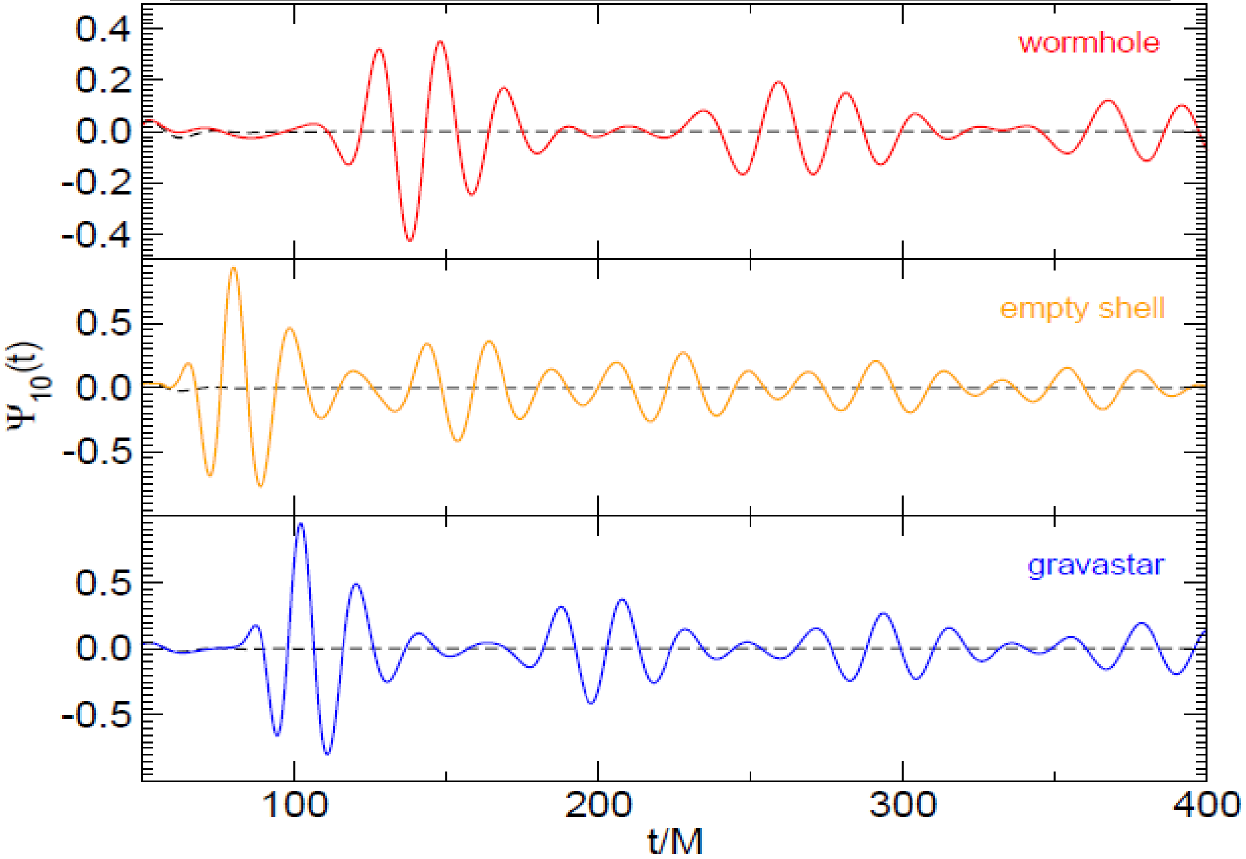
In classical General Relativity (GR), an observer falling into an astrophysical black hole is not expected to experience anything dramatic as she crosses the event horizon.




[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].

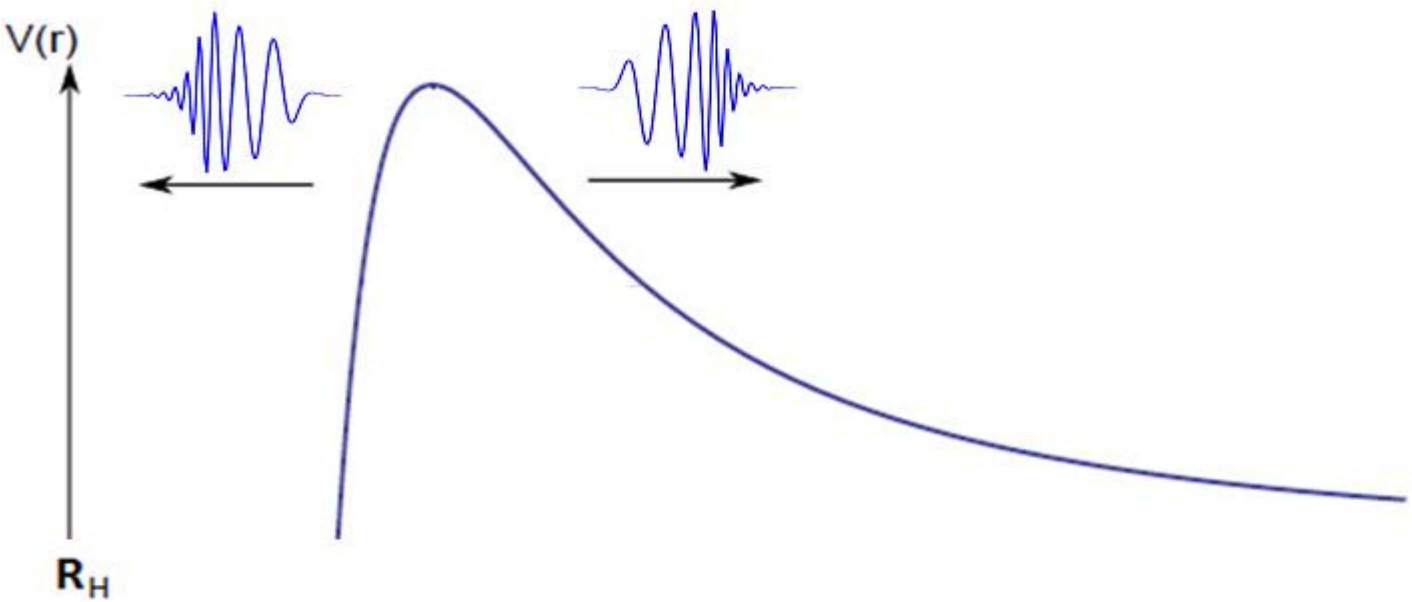
[14] V. Cardoso, S. Hopper, C. F. B. Macedo, C. Palenzuela, and P. Pani, (2016), arXiv:1608.08637 [gr-qc].

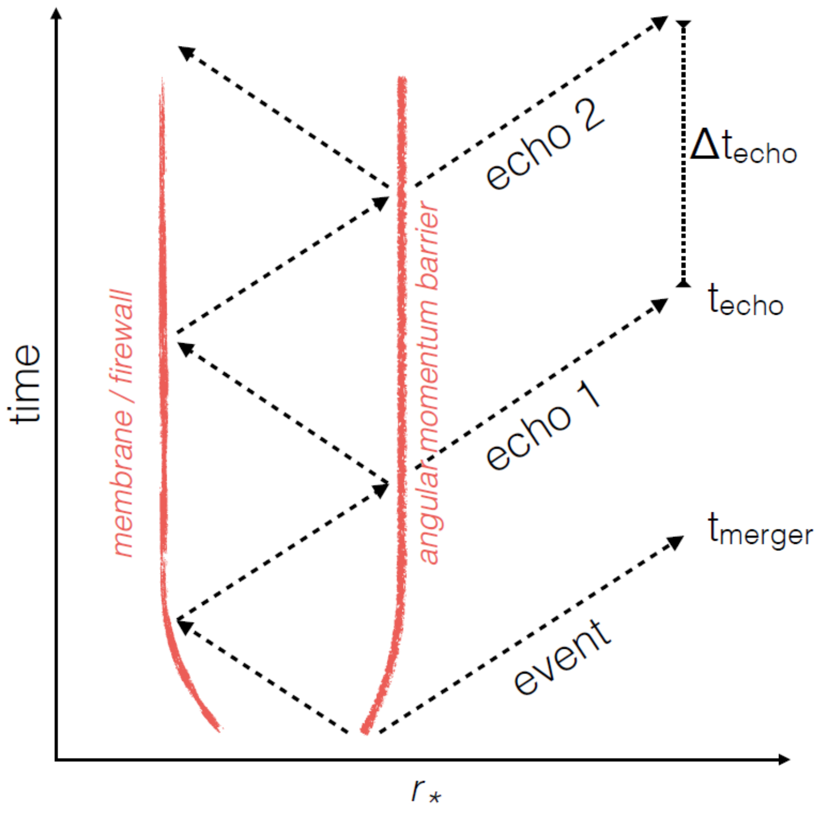



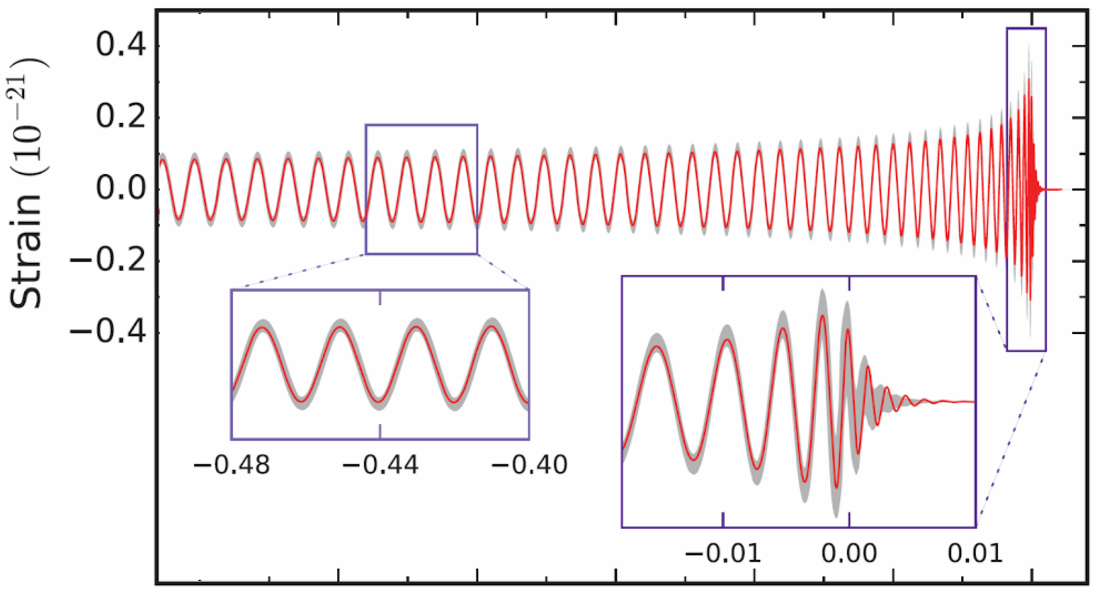



$$\Delta t_1 = \Delta t$$
$$= 2 \times r_*|_{r_+ + \Delta r}^{r_{max}} = 2 \times \int_{r_+ + \Delta r}^{r_{max}} \frac{r^2 + a^2}{r^2 - 2Mr + a^2} dr$$
$$= 2r_{max} - 2r_+ - 2\Delta r + 2\frac{r_+^2 + a^2}{r_+ - r_-} \ln(\frac{r_{max} - r_+}{\Delta r})$$
$$-2\frac{r_-^2 + a^2}{r_+ - r_-} \ln(\frac{r_{max} - r_-}{r_+ - r_- + \Delta r})$$

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




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

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

[19]

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 $\mu = 0.8$.

$\Delta r$ (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

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

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:

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

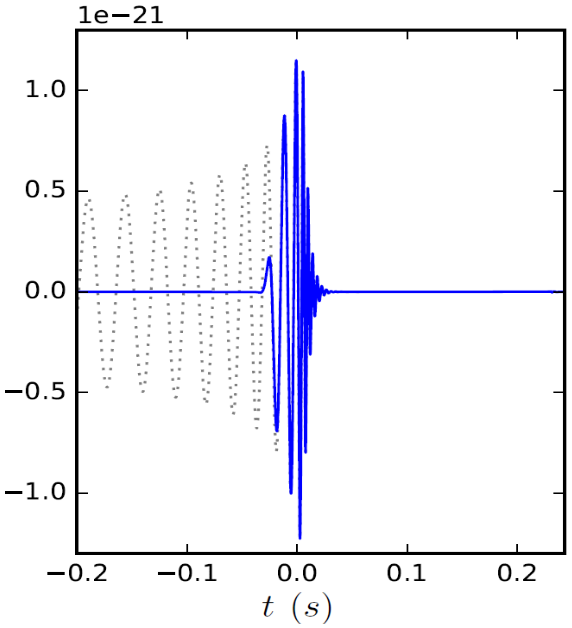
- then we get

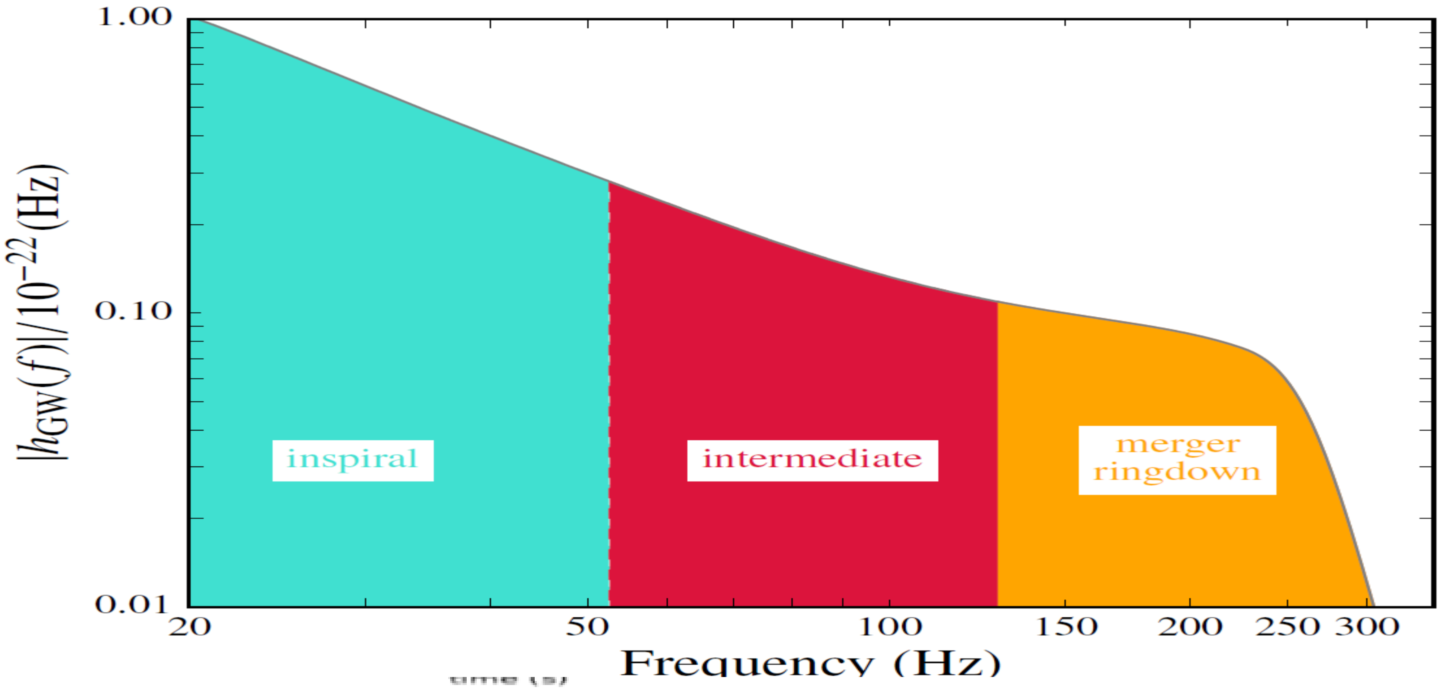
$$p_0 = -\frac{1}{256\pi^2 m^3} \simeq \left(\frac{m}{74\ M_\odot}\right)^{-3} p_{\rm DE,obs}!!$$

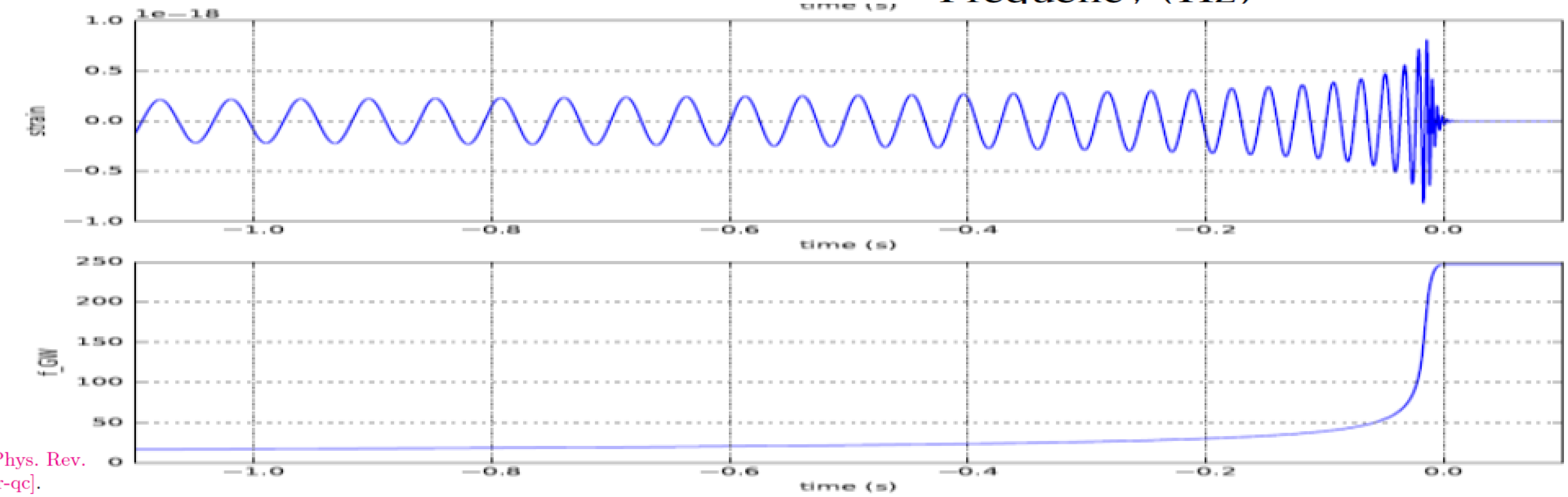
- *Pressure* has the same sign and magnitude as *Dark Energy* for stellar mass black holes!

# How to separate the ringdown?

GW150914

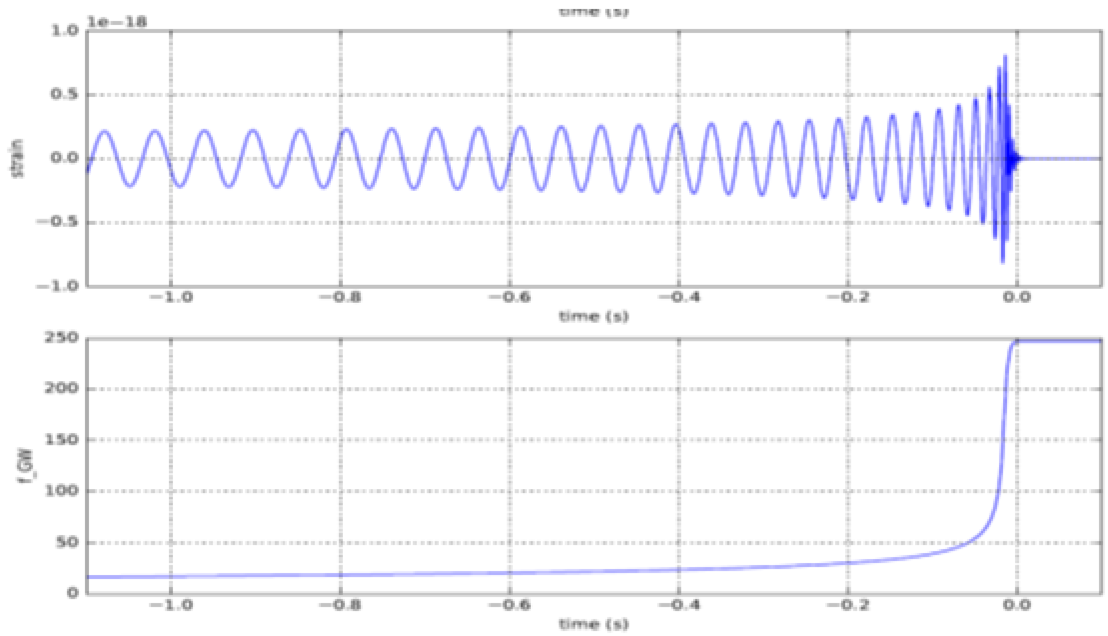



[25] B. P. Abbott *et al.* (Virgo, LIGO Scientific), Phys. Rev. Lett. **116**, 221101 (2016), arXiv:1602.03841 [gr-qc].

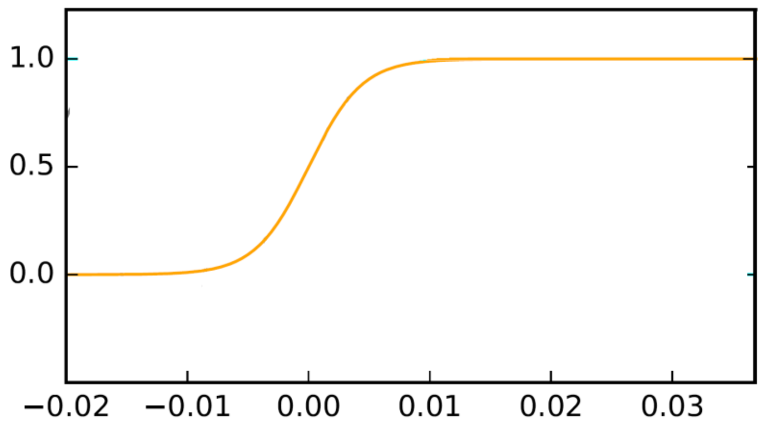
# How to separate the ringdown?




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

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

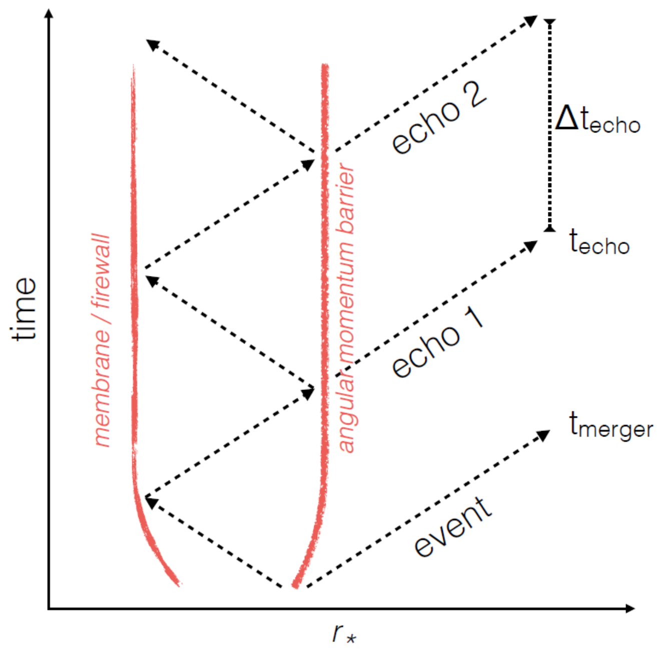
$$M_{TE,I}(t) \equiv$$
$$A\sum_{n=0}^{\infty}(-1)^{n+1}\gamma^n\mathcal{M}_{T,I}(t+t_{\rm merger}-t_{\rm echo}-n\Delta t_{\rm echo},t_0)$$



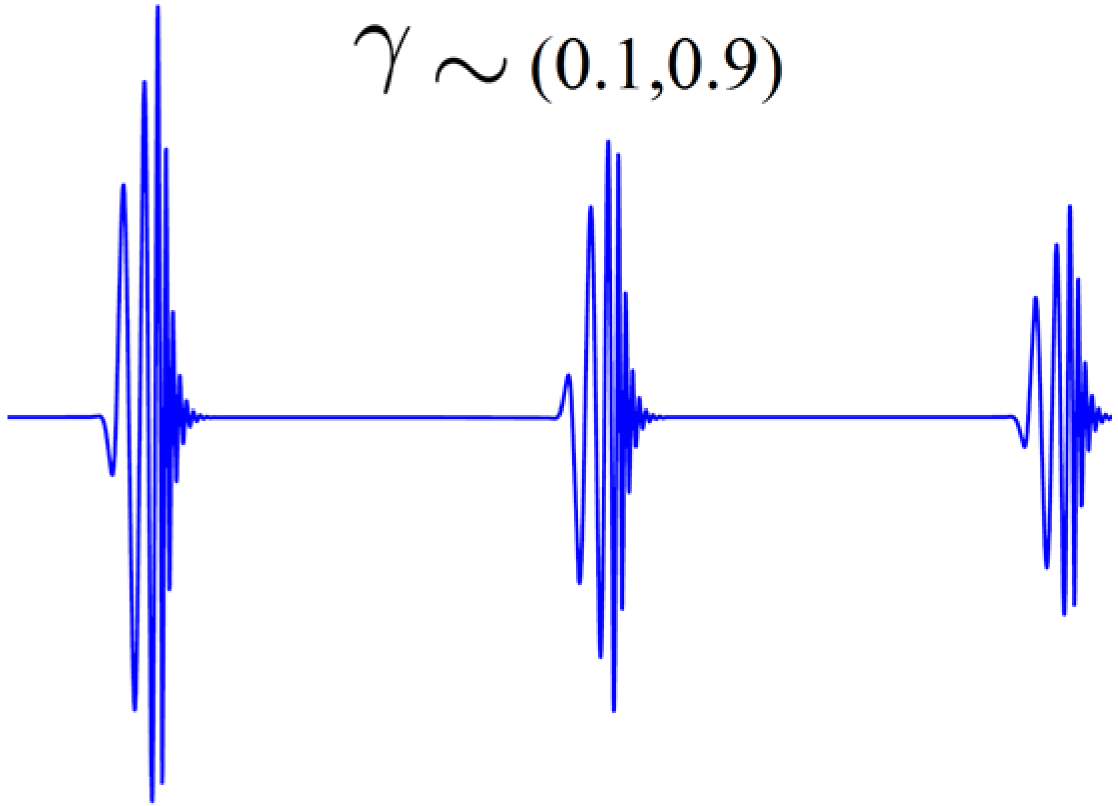
$$t_{0,GW150914} \sim (-0.03s, 0)$$

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

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




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



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

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

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

# Number of free parameters

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

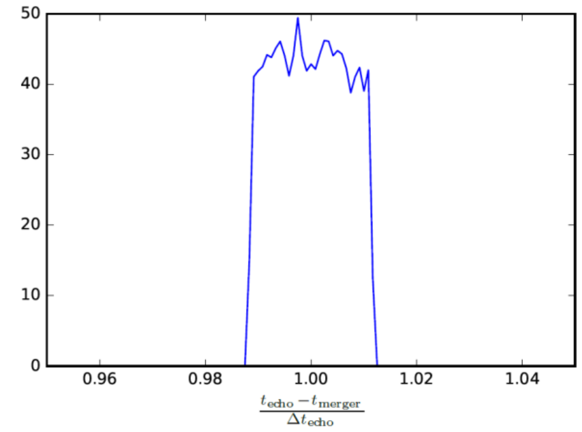
$$\Delta t_{\mathrm{echo},I}(\mathrm{sec}) = \begin{cases} 0.2925 \pm 0.00916 & I = \mathrm{GW150914} \\ 0.1013 \pm 0.01152 & I = \mathrm{GW151226} \\ 0.1778 \pm 0.02789 & I = \mathrm{LVT151012} \end{cases}$$

2 3 4

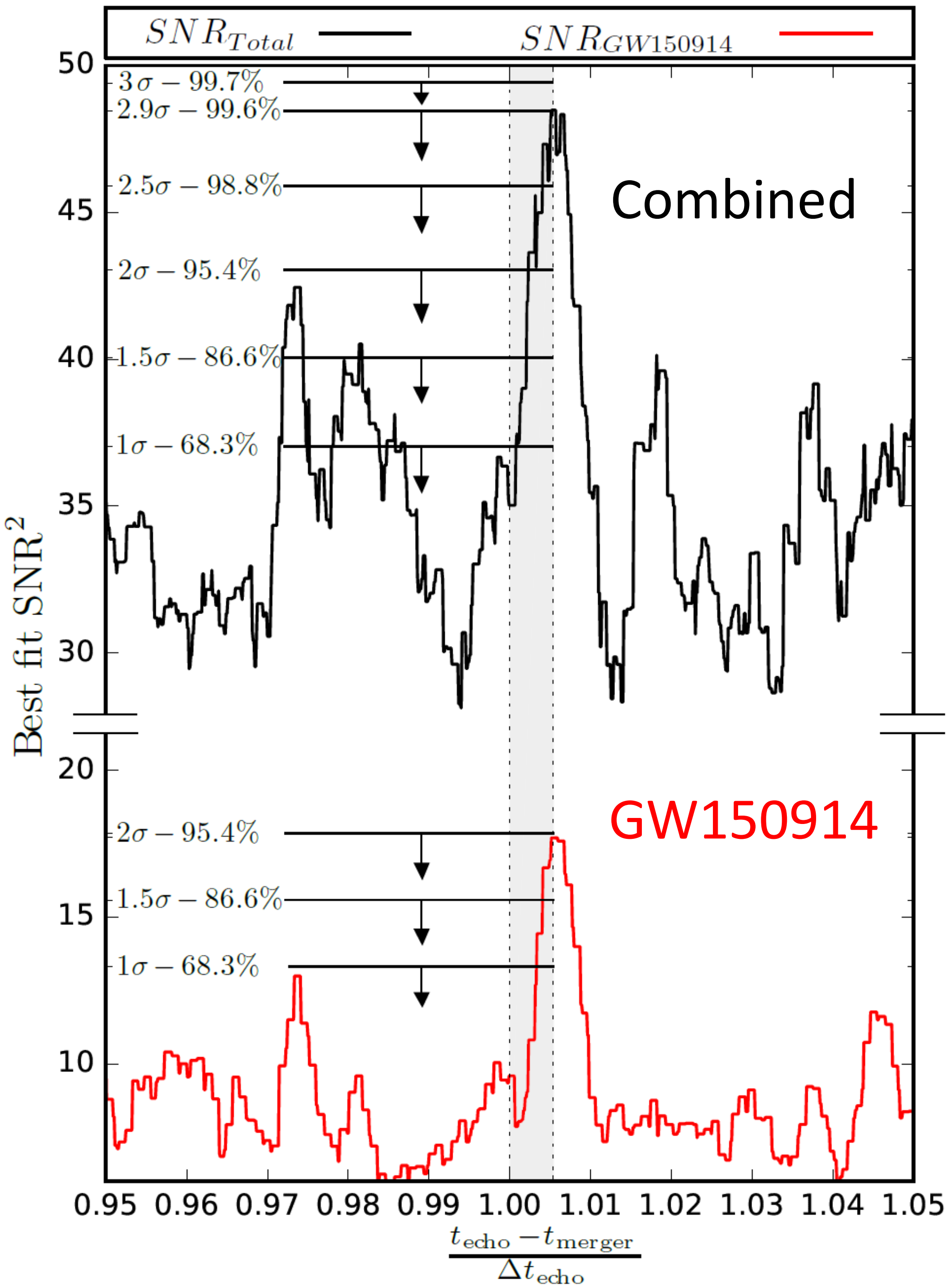
$t_{0,GW150914} \sim (-0.03s, 0)$

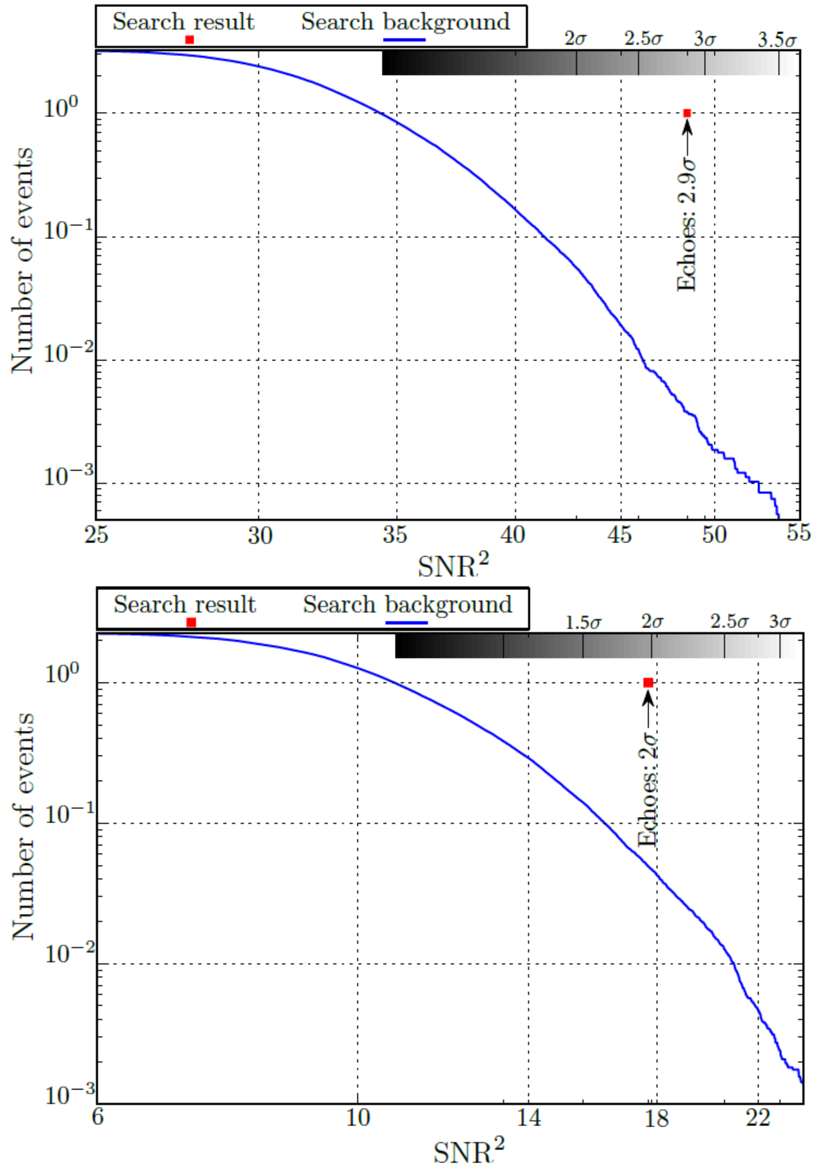
$t_{0,GW151226} \sim \frac{\Delta t_{pred,GW151226}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914}$

$t_{0,LVT151012} \sim \frac{\Delta t_{pred,LVT151012}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914}$ 5




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

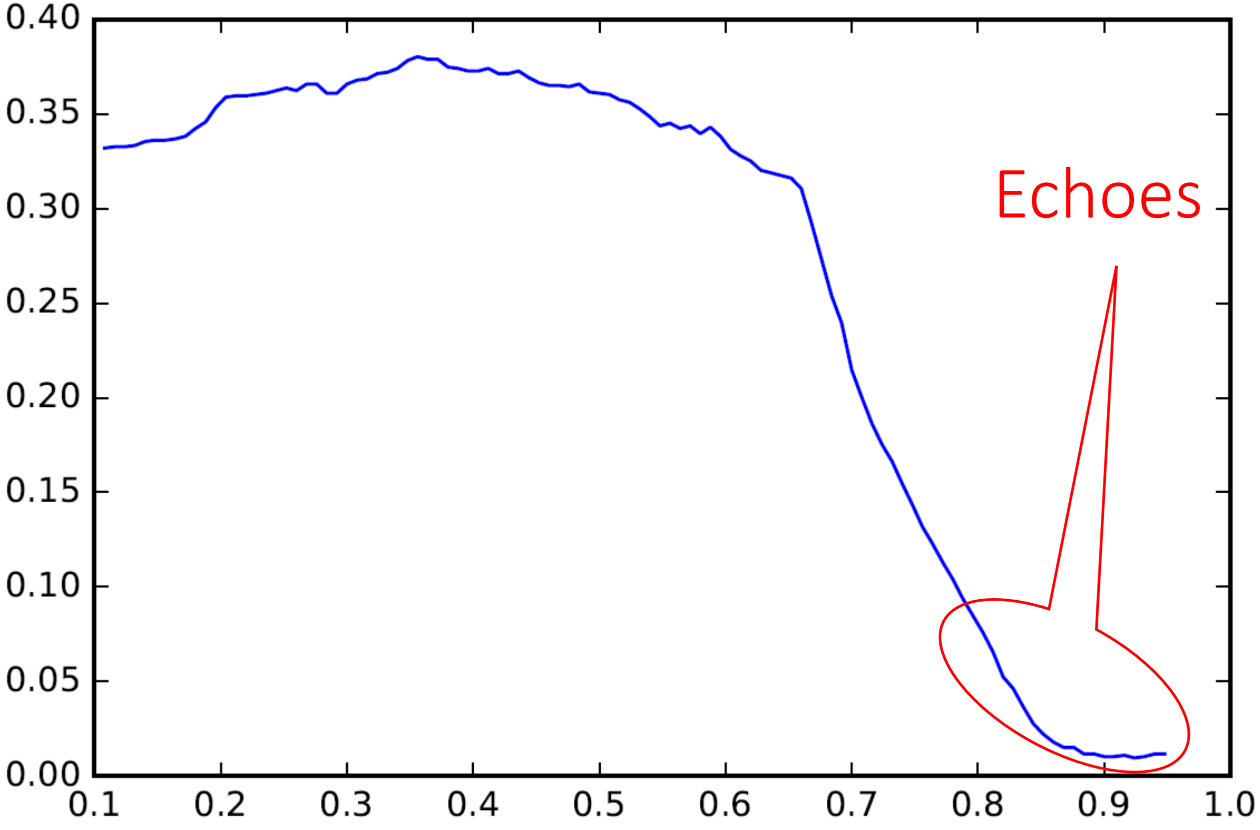


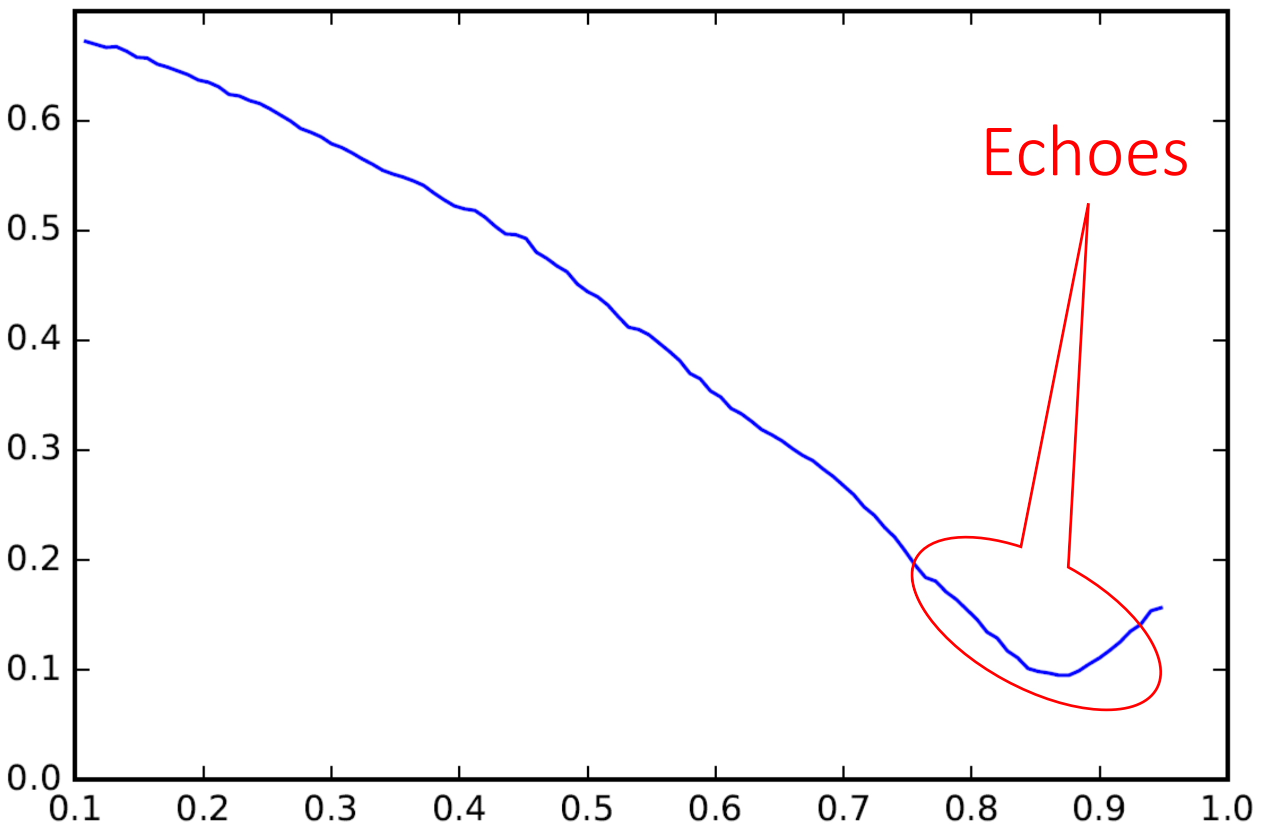

Average number of noise peaks higher than a particular SNR-value within a time-interval 0.54% techo for combined (top) and GW150914 (bottom) events. The red dots show the observed SNR peak at techo = 1.0054techo.

# Why echoes?

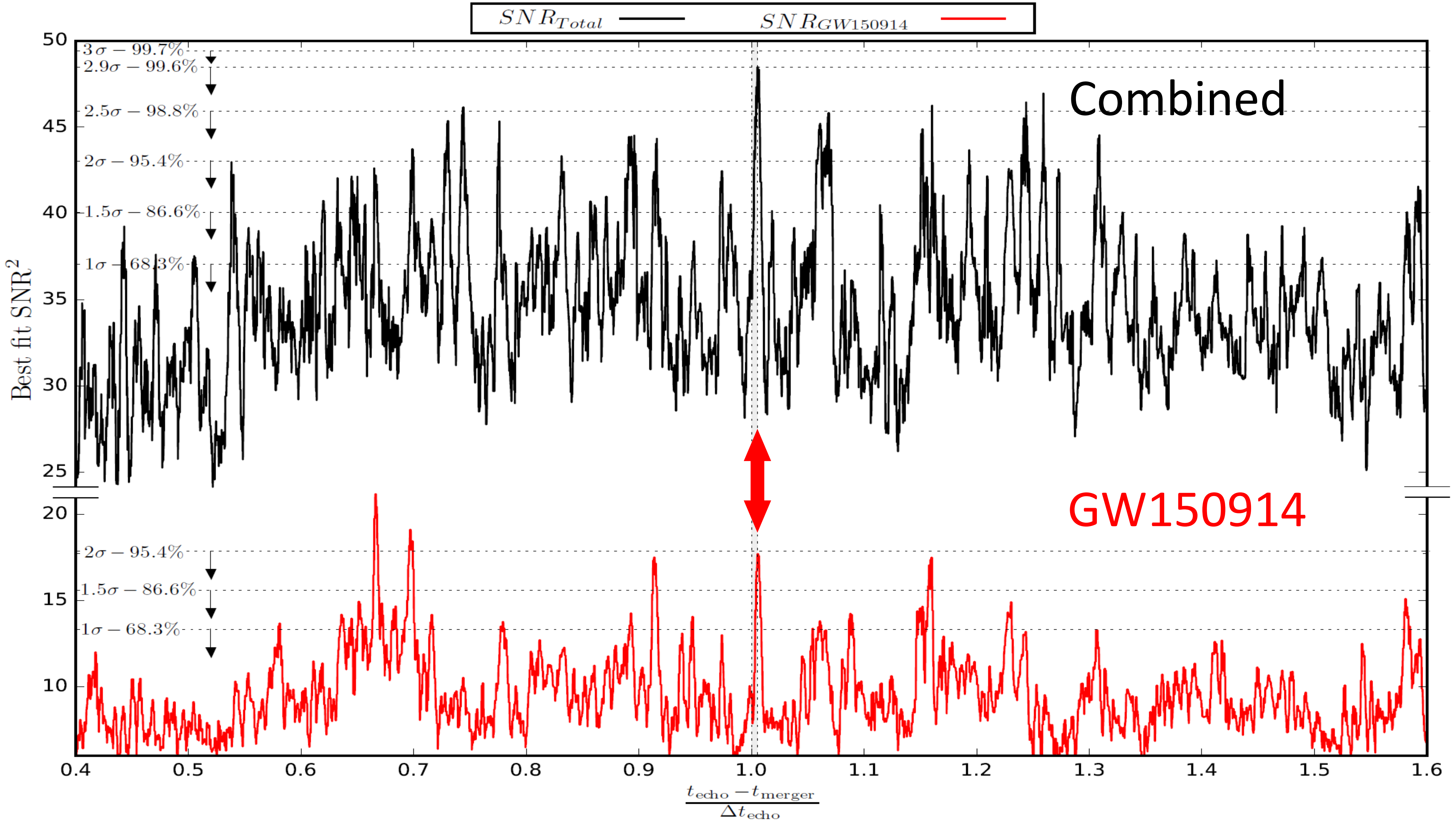
GW150914+GW151226+LVT151012



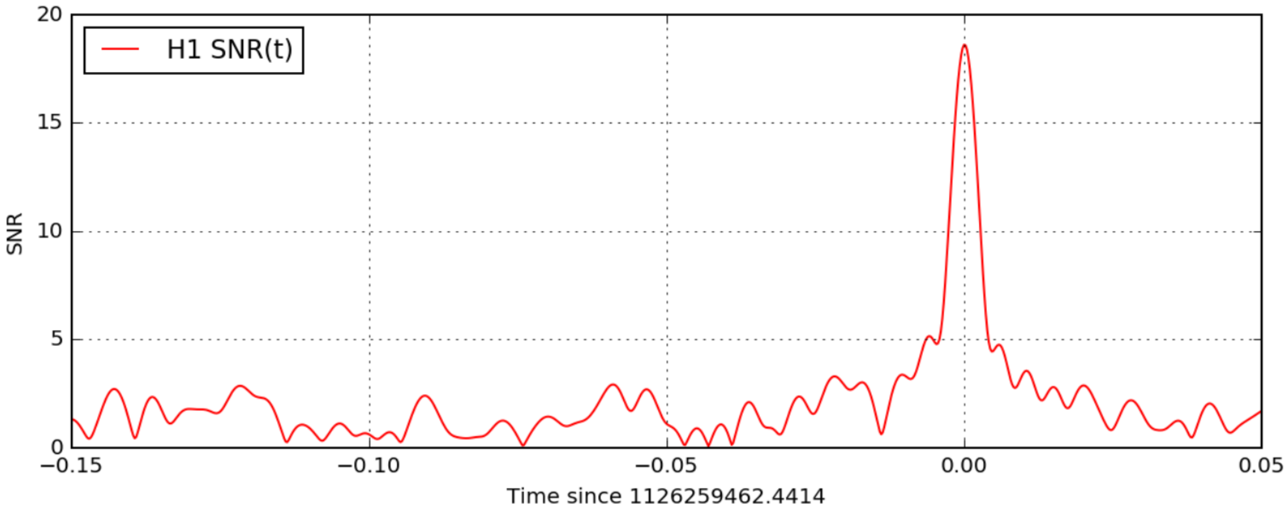

GW150914

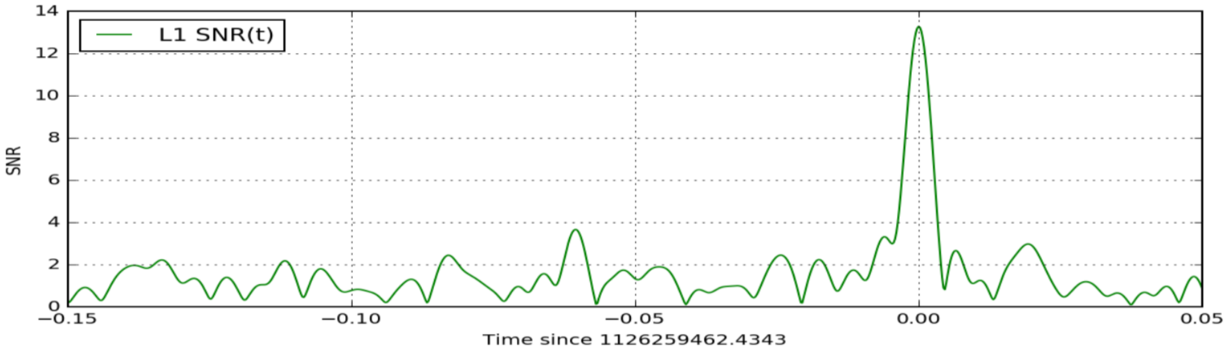


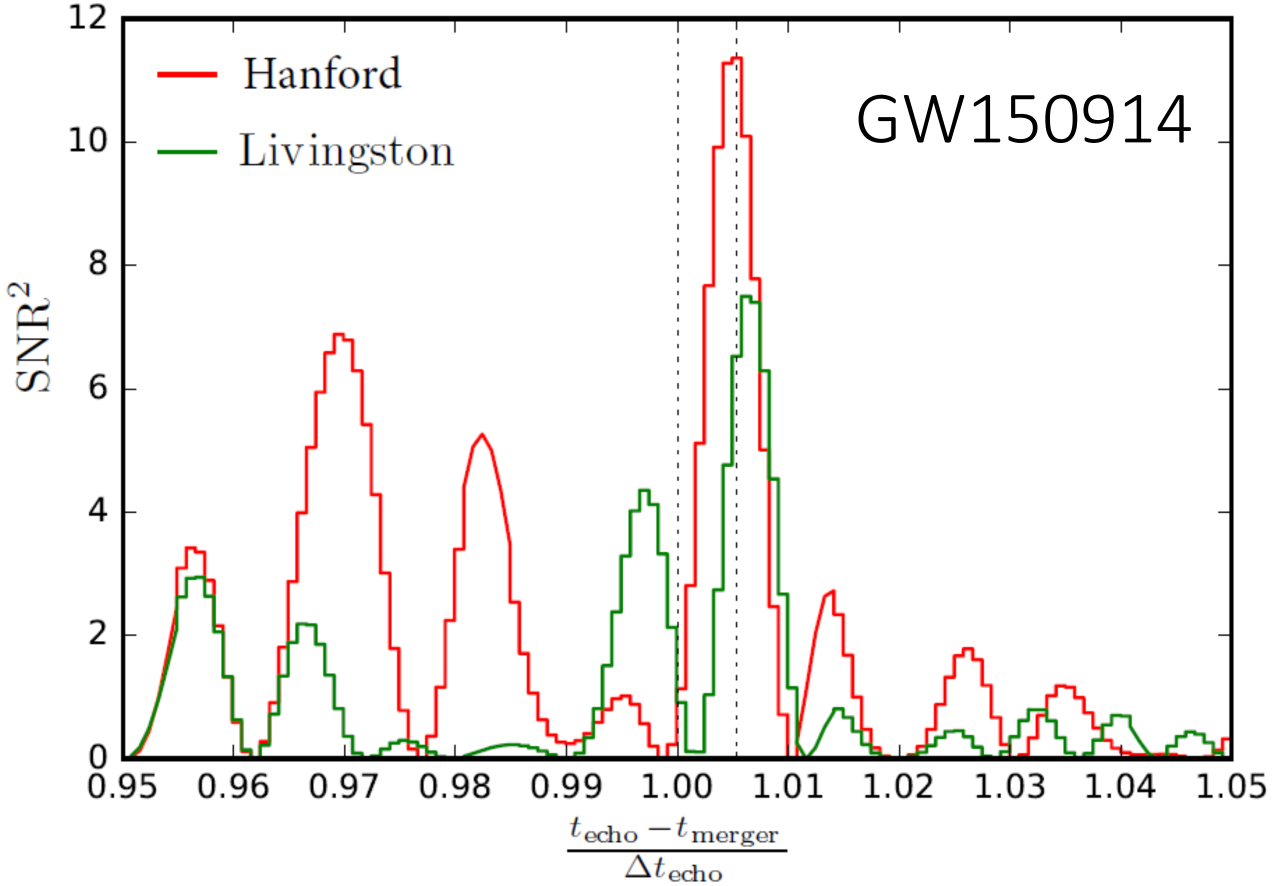

P-value as a function of gamma range starting from 0.1 to higher values for GW150914 and combined events.




Best fit (or maximum) SNR^2 for the combined (top) and GW150914 (bottom) events.

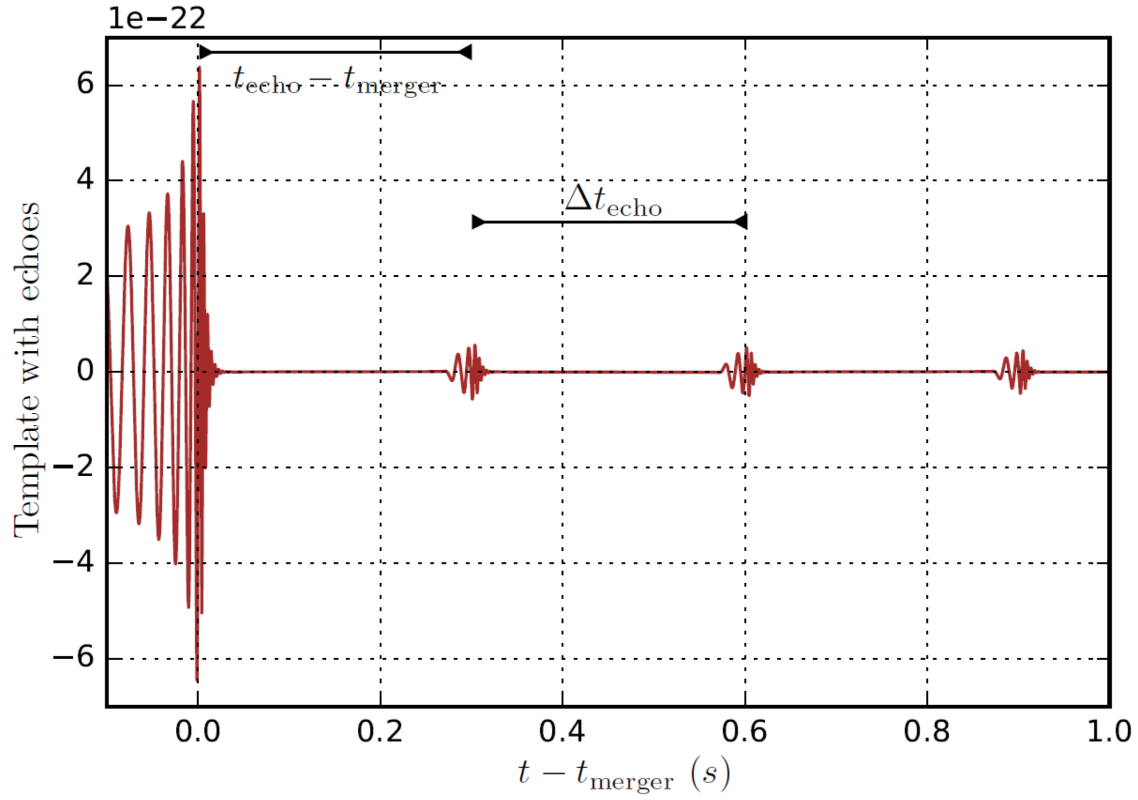



Interestingly, SNR ratio of GW150914 2.74/3.37 = 0.81 is comparable to the SNR ratio for the main event 13.3/18.6 = 0.72.

# Late echoes from Planck scale structure near horizon




| | Range | GW150914 | Combined |
|---|---|---|---|
| $(t_{echo} - t_{merger})/\Delta t_{echo}$ | (0.95,1.05) | 1.0054 | 1.0054 |
| $\gamma$ | (0.1,0.9) | 0.89 | 0.9 |
| $t_0/\overline{\Delta t}_{echo}$ | (-0.1,0) | -0.084 | -0.1 |
| Amplitude | | 0.0992 | 0.124 |
| $SNR_{max}$ | | 4.21 | 6.96 |
| p-value | | $4.6 \times 10^{-2}$ | $3.7 \times 10^{-3}$ |
| significance | | $2.0\sigma$ | $2.9\sigma$ |

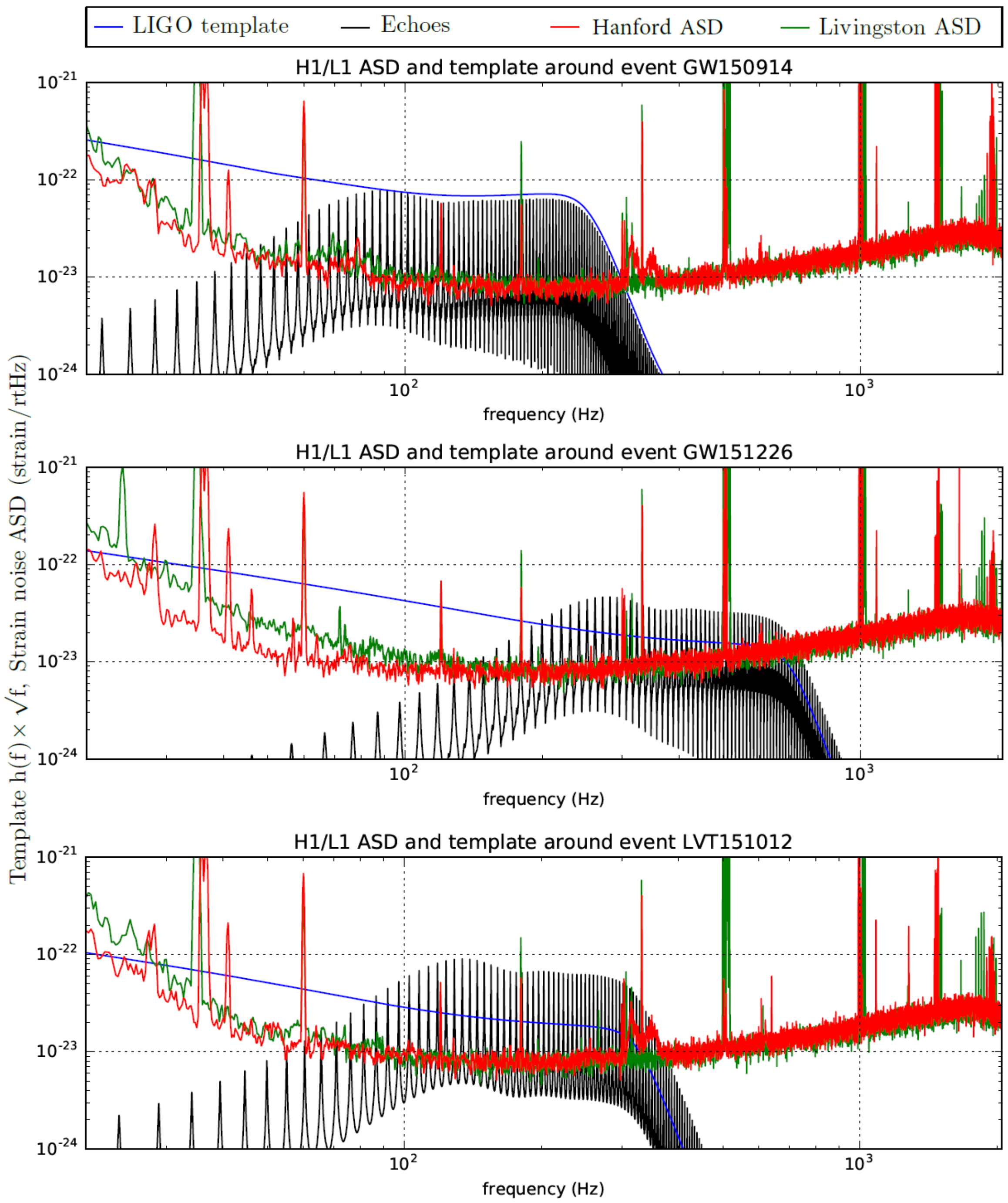
TABLE I: Best fit values for echo parameters of the highest SNR peak near the predicted $\Delta t_{echo}$, and their significance.

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

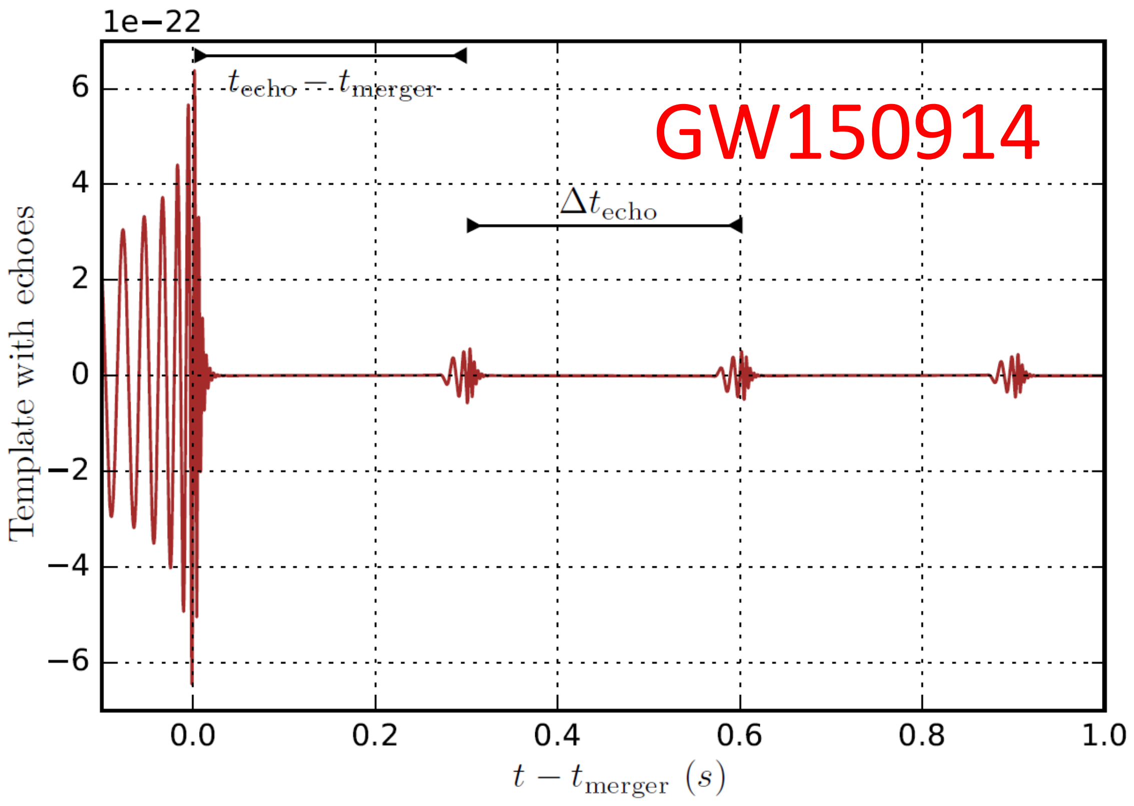
| | GW150914 | GW151226 | LVT151012 |
|---|---|---|---|
| $\Delta t_{echo,pred}$(sec) | 0.2925 $\pm$ 0.00916 | 0.1013 $\pm$ 0.01152 | 0.1778 $\pm$ 0.02789 |
| $\Delta t_{echo,best}$(sec) | 0.30068 | 0.09758 | 0.19043 |
| $SNR_{best,I}$ | 4.13 | 3.83 | 4.52 |

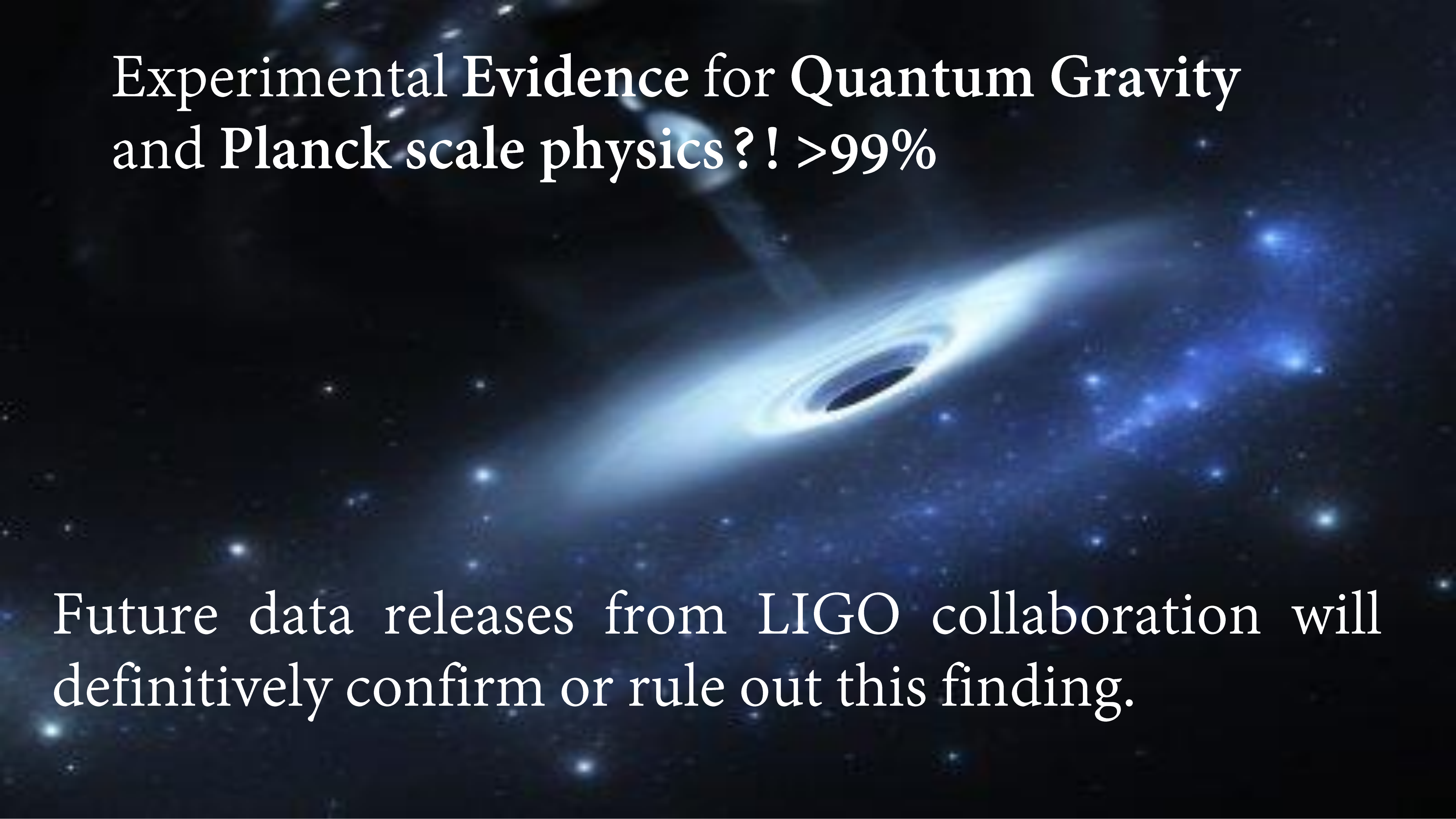
TABLE II: Theoretical expectations for $\Delta t_{echo}$'s of each merger event (Eq. 6), compared to their best combined fit within the $1\sigma$ credible region, and the contribution of each event to the joint SNR for the echoes (Eq. 10).

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




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.




Experimental Evidence for Quantum Gravity and Planck scale physics ?! >99%
Future data releases from LIGO collaboration will definitively confirm or rule out this finding.

# Thank you

# Probing the interior of exotic compact objects (ECOs)

## Discovering the interior of black holes

Ram Brustein[(1)], A.J.M. Medved[(2,3)]

(1) Department of Physics, Ben-Gurion University, Beer-Sheva 84105, Israel
(2) Department of Physics & Electronics, Rhodes University, Grahamstown 6140, South Africa
(3) National Institute for Theoretical Physics (NITheP), Western Cape 7602, South Africa

ramyb@bgu.ac.il, j.medved@ru.ac.za

**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

Andrea Maselli[1], Paolo Pani[2,3,4], Vitor Cardoso[4,5], Tiziano Abdelsalhin[2,3], Leonardo Gualtieri[2,3], Valeria Ferrari[2,3]

[1] *Theoretical Astrophysics, Eberhard Karls University of Tuebingen, Tuebingen 72076, Germany*
[2] *Dipartimento di Fisica, "Sapienza" Università di Roma, Piazzale Aldo Moro 5, 00185, Roma, Italy*
[3] *Sezione INFN Roma1, Piazzale Aldo Moro 5, 00185, Roma, Italy*
[4] *CENTRA, Departamento de Física, Instituto Superior Técnico – IST, Universidade de Lisboa – UL, Avenida Rovisco Pais 1, 1049 Lisboa, Portugal and*
[5] *Perimeter Institute for Theoretical Physics, 31 Caroline Street North Waterloo, Ontario N2L 2Y5, Canada*

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 $1-10$ 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

Ram Brustein[(1)], A.J.M. Medved[(2,3)], K. Yagi[(4)]

(1) Department of Physics, Ben-Gurion University, Beer-Sheva 84105, Israel
(2) Department of Physics & Electronics, Rhodes University, Grahamstown 6140, South Africa
(3) National Institute for Theoretical Physics (NITheP), Western Cape 7602, South Africa
(4) Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

ramyb@bgu.ac.il, j.medved@ru.ac.za, kyagi@princeton.edu

**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.

# Black hole echoes and howls

**Onset of superradiant instabilities in rotating spacetimes of exotic compact objects**


Shahar Hod

*The Ruppin Academic Center, Emeq Hefer 40250, Israel*

*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


$$\gamma \sim 1$$

**Black hole ringdown echoes and howls**


Hiroyuki Nakano[1,2], Norichika Sago[3], Hideyuki Tagoshi[4] and Takahiro Tanaka[2,5]

[1] *Faculty of Law, Ryukoku University, Kyoto 612-8577, Japan*

[2] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

[3] *Faculty of Arts and Science, Kyushu University, Fukuoka 819-0395, Japan*

[4] *Graduate School of Science, Osaka City University, Osaka 558-8585, Japan*

[5] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*



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


**Exotic Compact Objects and How to Quench their Ergoregion Instability**


Elisa Maggio,[1,2,*] Paolo Pani,[1,2,3,†] and Valeria Ferrari[1,2,‡]

[1] *Dipartimento di Fisica, "Sapienza" Università di Roma, Piazzale Aldo Moro 5, 00185, Roma, Italy.*

[2] *Sezione INFN Roma1, Piazzale Aldo Moro 5, 00185, Roma, Italy.*

[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.

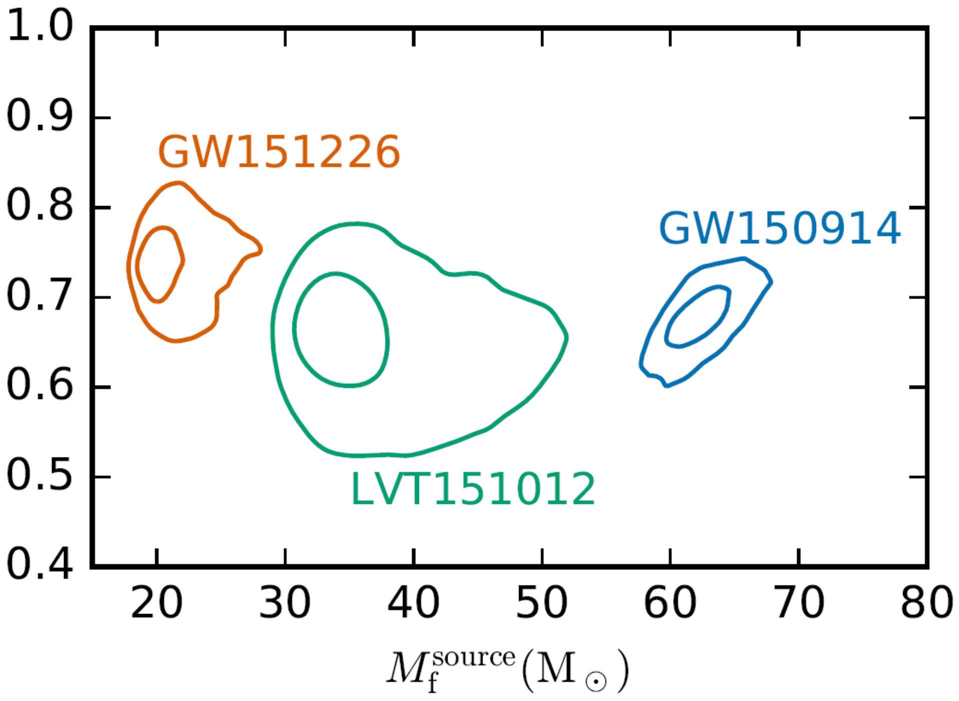
# The statistics of gaussian credible region

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

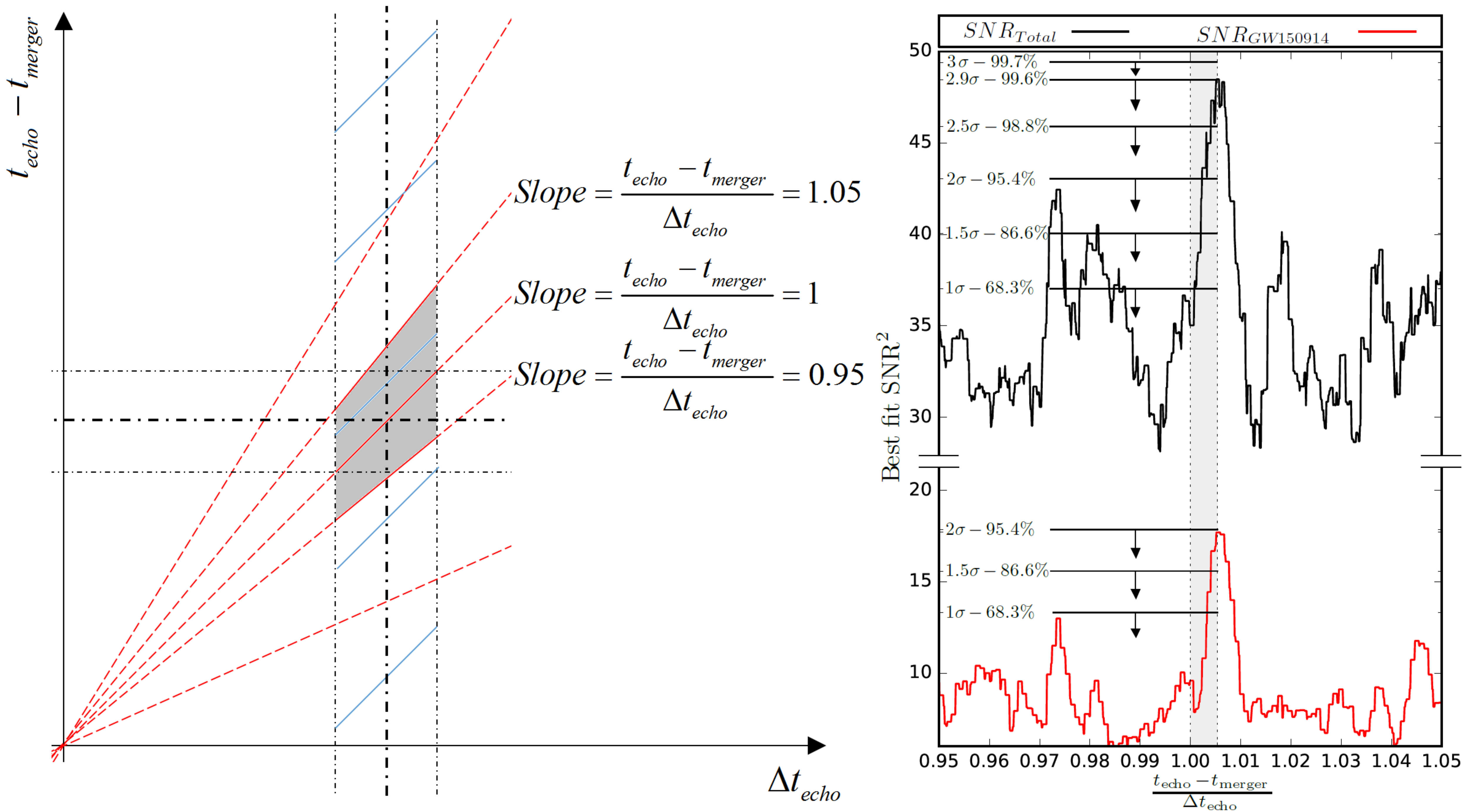
$$P(\Delta a, \Delta M) = \frac{\sqrt{\det M}}{2\pi} \exp\left(-\frac{1}{2}\alpha \Delta a^2 - \frac{1}{2}\beta \Delta M^2 - \gamma \Delta a \Delta M\right)$$

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

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




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



$t_{echo} - t_{merger}$
$\Delta t_{echo}$
$Slope = \frac{t_{echo} - t_{merger}}{\Delta t_{echo}} = 1.05$
$Slope = \frac{t_{echo} - t_{merger}}{\Delta t_{echo}} = 1$
$Slope = \frac{t_{echo} - t_{merger}}{\Delta t_{echo}} = 0.95$
$SNR_{Total}$
$SNR_{GW150914}$
$3\sigma - 99.7\%$
$2.9\sigma - 99.6\%$
$2.5\sigma - 98.8\%$
$2\sigma - 95.4\%$
$1.5\sigma - 86.6\%$
$1\sigma - 68.3\%$
$2\sigma - 95.4\%$
$1.5\sigma - 86.6\%$
$1\sigma - 68.3\%$
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
$\frac{t_{echo} - t_{merger}}{\Delta t_{echo}}$