

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

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Abstract: 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 false detection probability of 1% (corresponding to  $2.5\sigma$  significance level). We also report the results of same search for echoes in the new black hole merger event GW170104. Future observations from interferometric detectors at higher sensitivity, along with more physical echo templates, will be able to confirm (or rule out) this finding, providing possible empirical evidence for alternatives to classical black holes, such as in firewall or fuzzball paradigms.

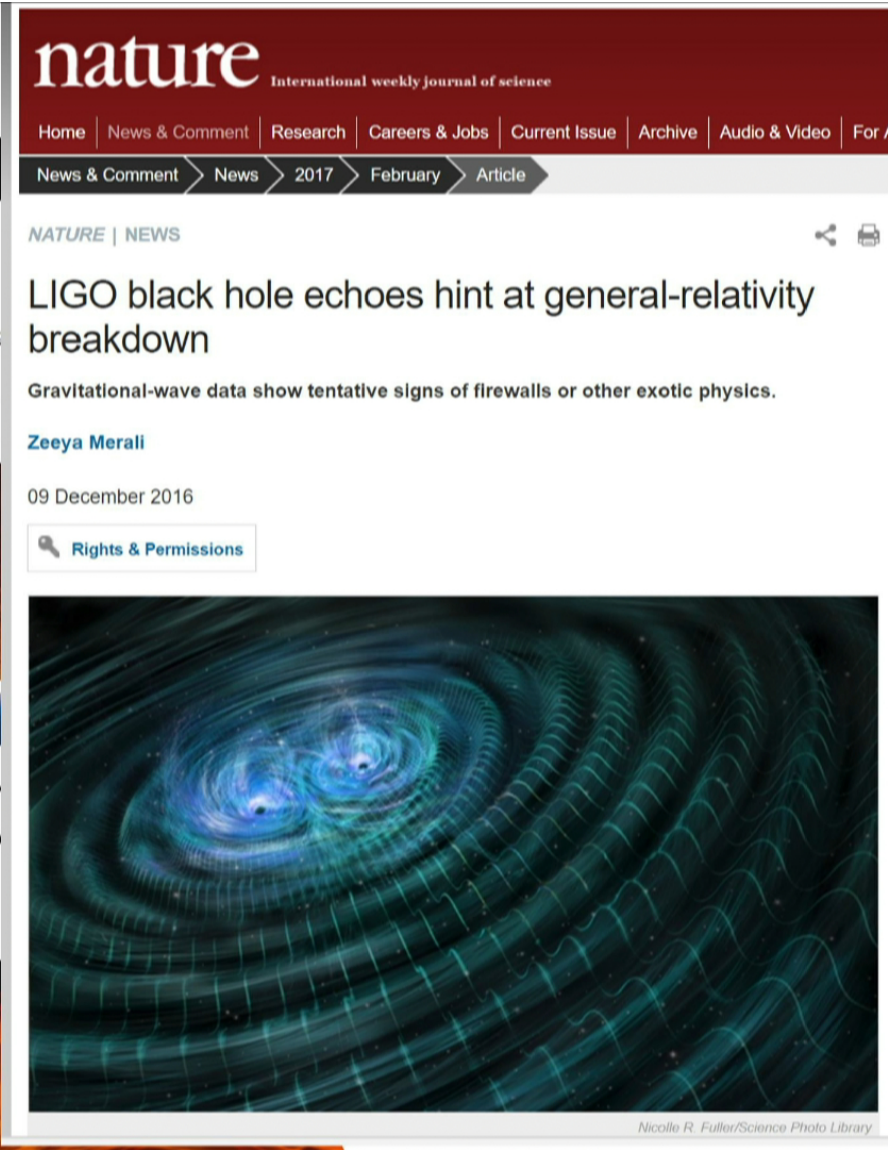
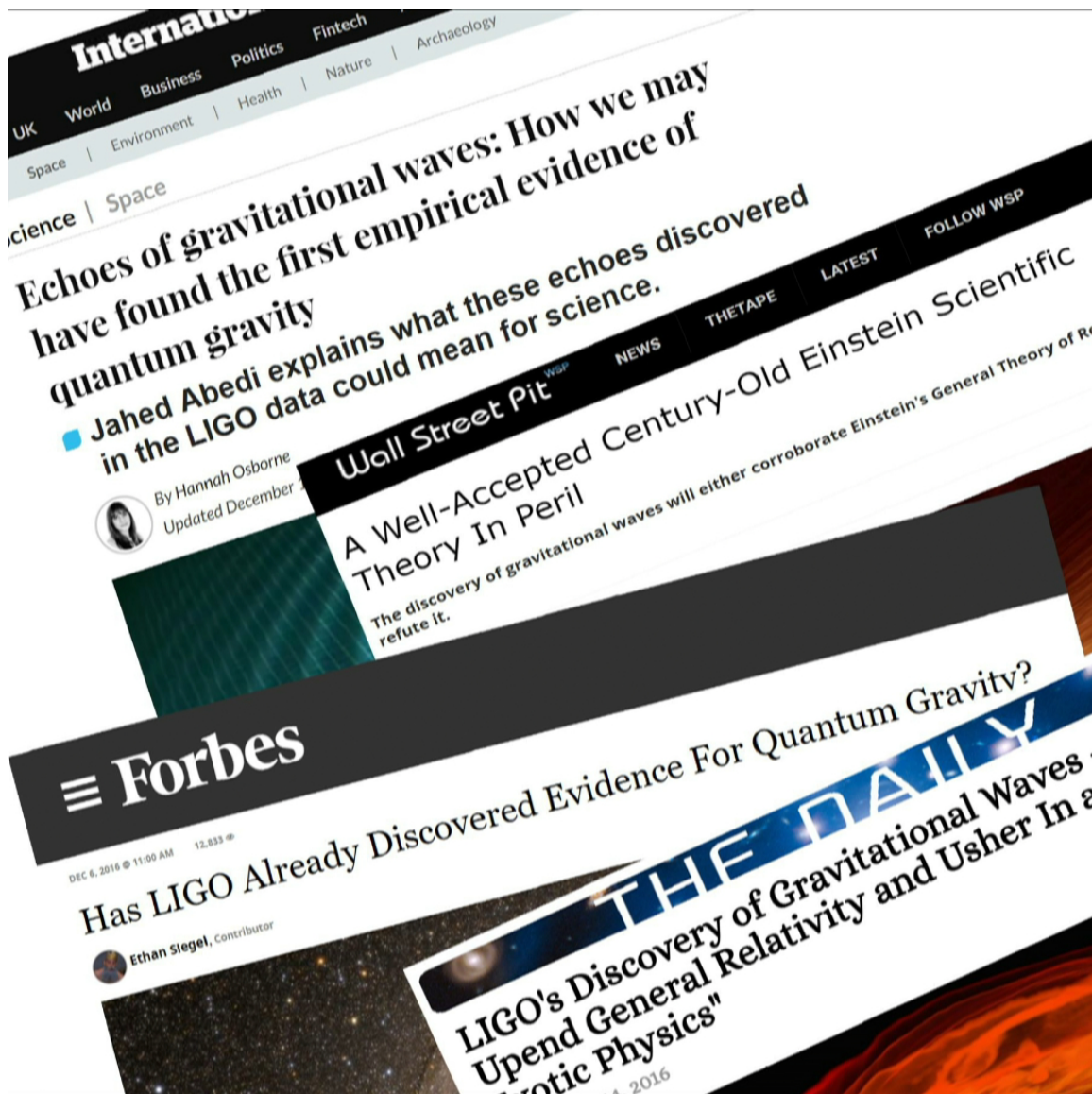
# Echoes from the Abyss: Tentative Evidence for Planck-scale structure at black hole horizons

Jahed Abedi, Hannah Dykaar, and Niayesh Afshordi

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



<https://lukach.deviantart.com/art/black-hole-in-the-blue-sky-330482026>





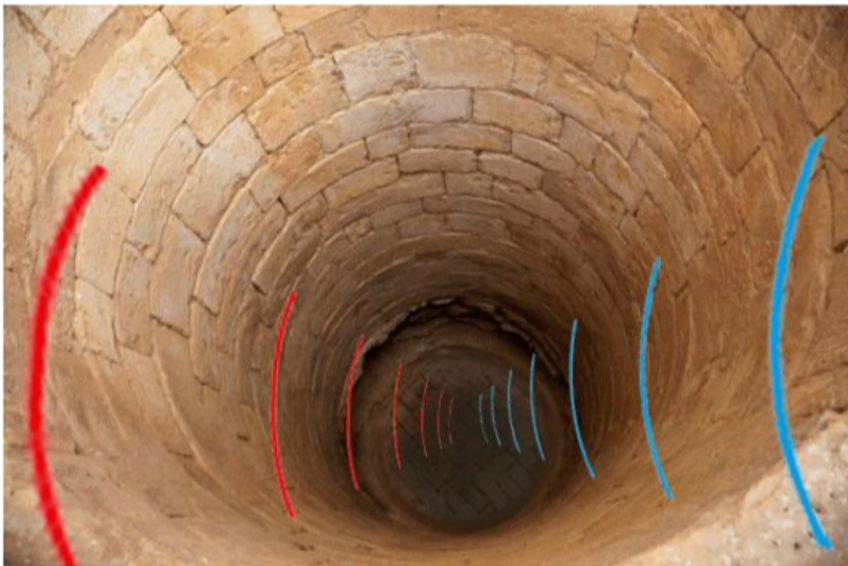
There is mounting, albeit controversial, [theoretical evidence](#) that quantum black holes might be significantly different from their classical counterparts.

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 and firewall paradigms.

## Theory puts Planckian physics at horizon

- Observable gravitational wave echoes from quantum fluctuations of black hole horizon
  - *Abedi* --- *Coming Soon*
- (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*
  - ...

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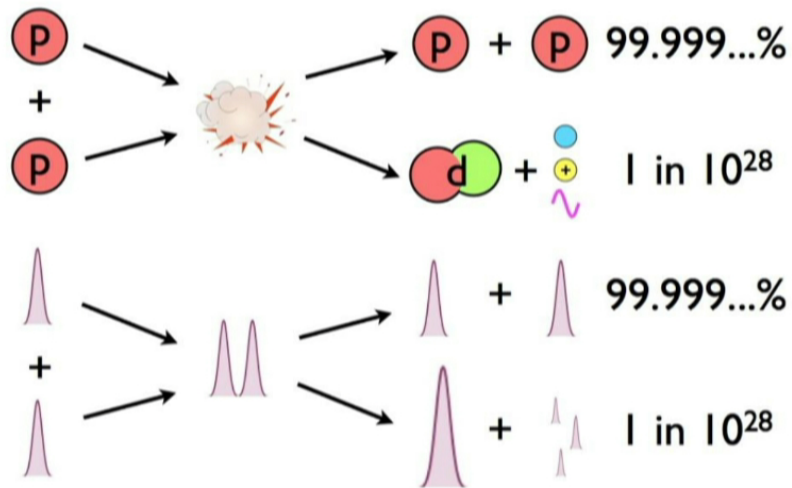


# Quantum Black Hole Tunneling (into Fuzzball)

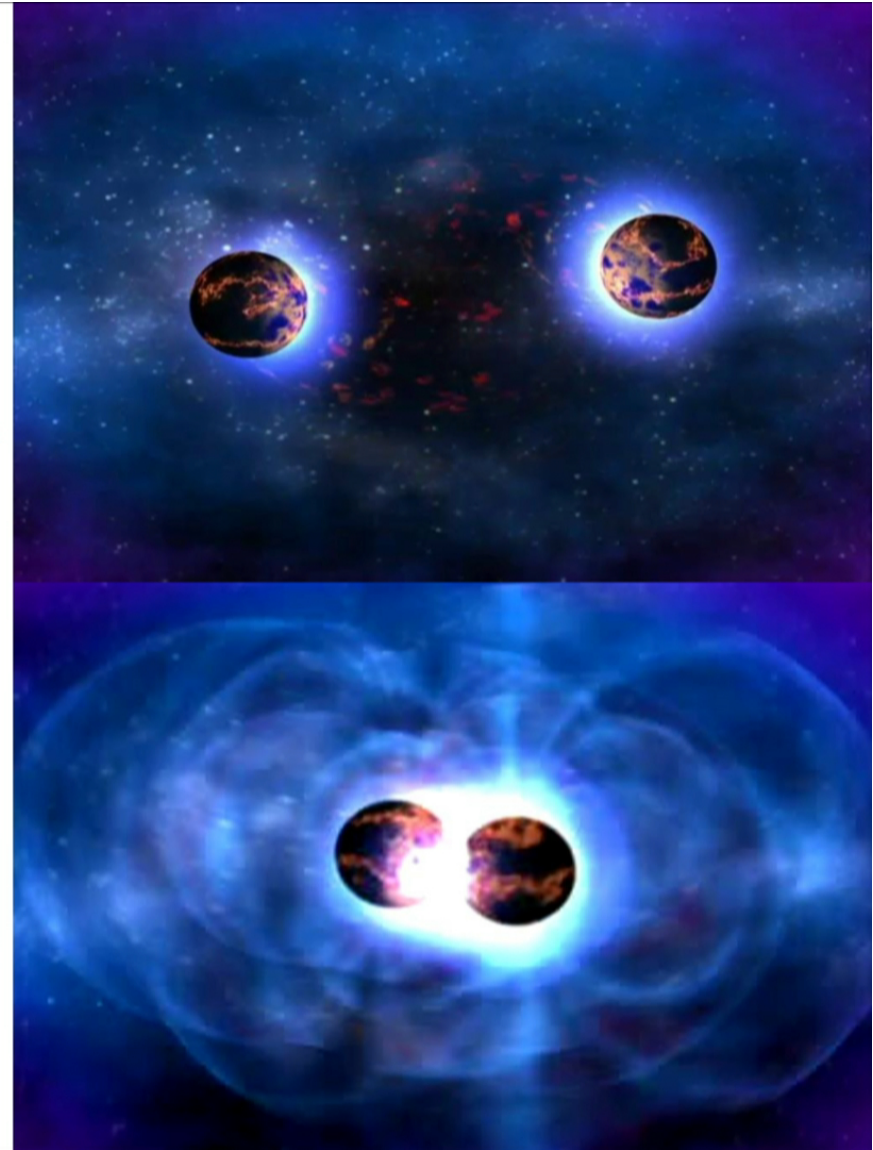
$$e^{(\text{entropy})} \times e^{-\alpha M^2} \sim 1$$

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

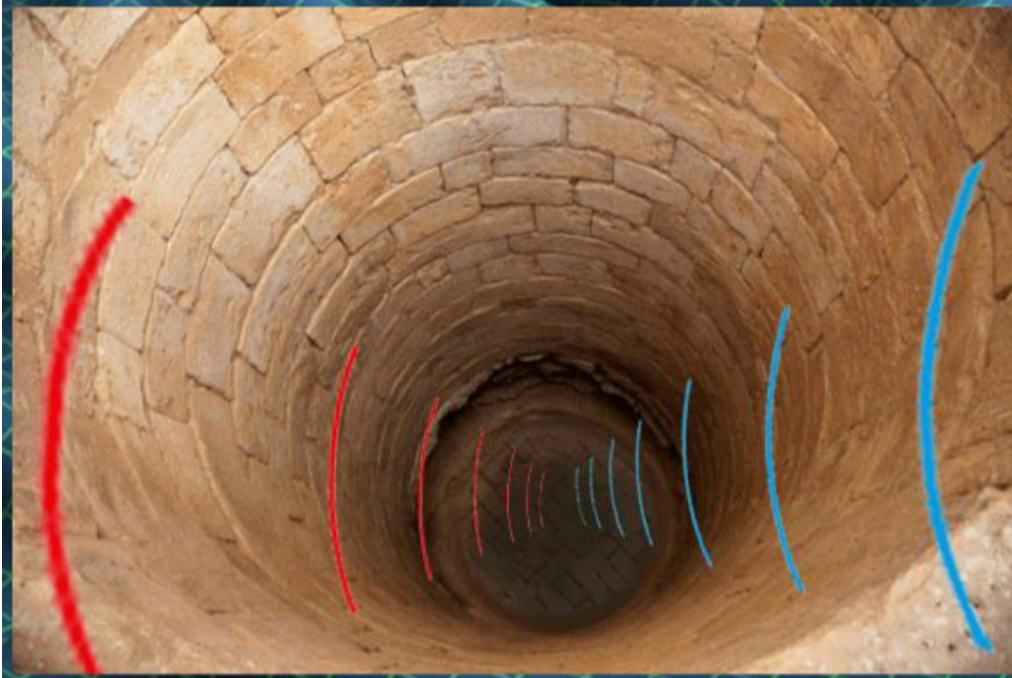
Quantum tunneling is what allows the Sun to shine!



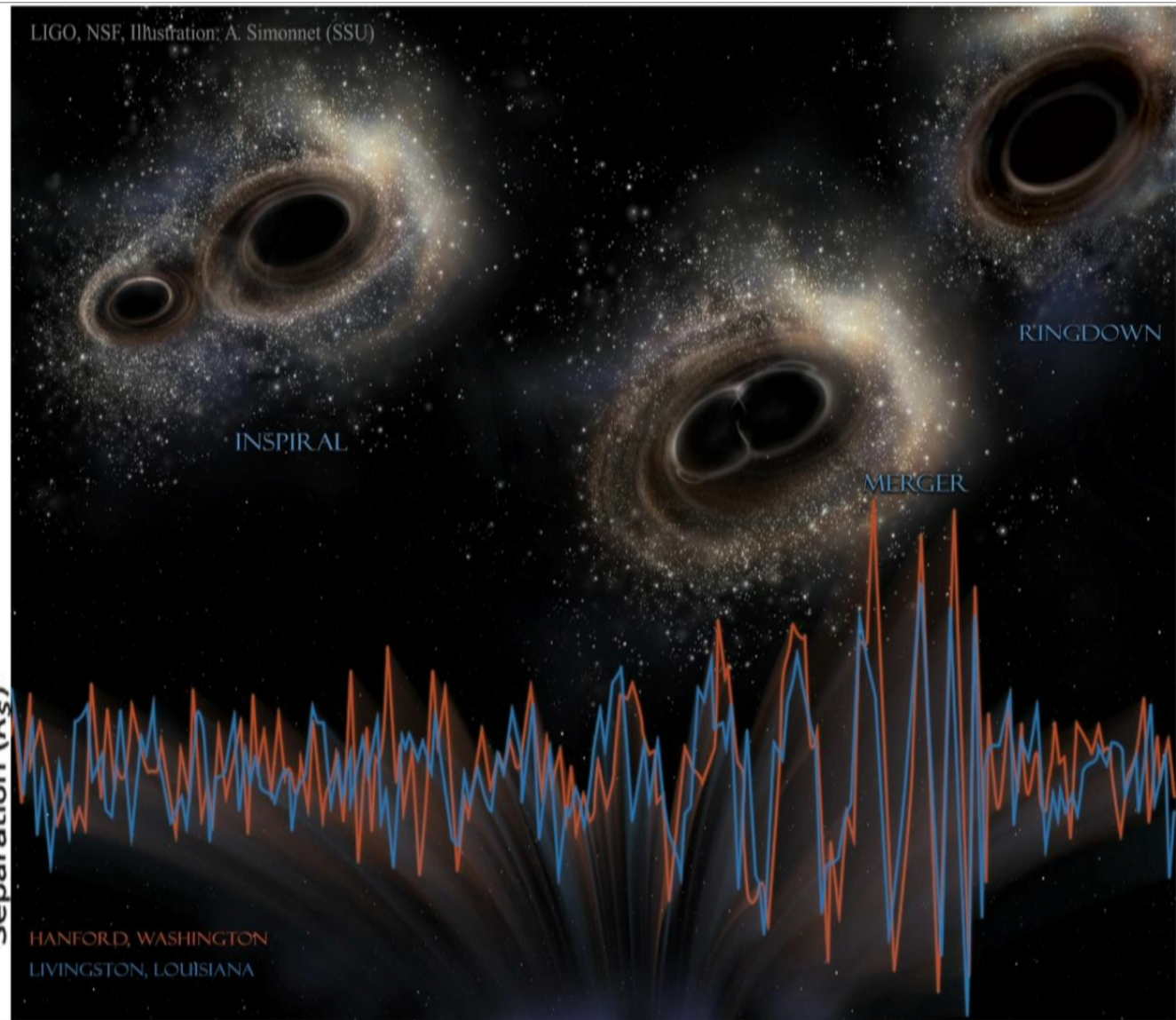
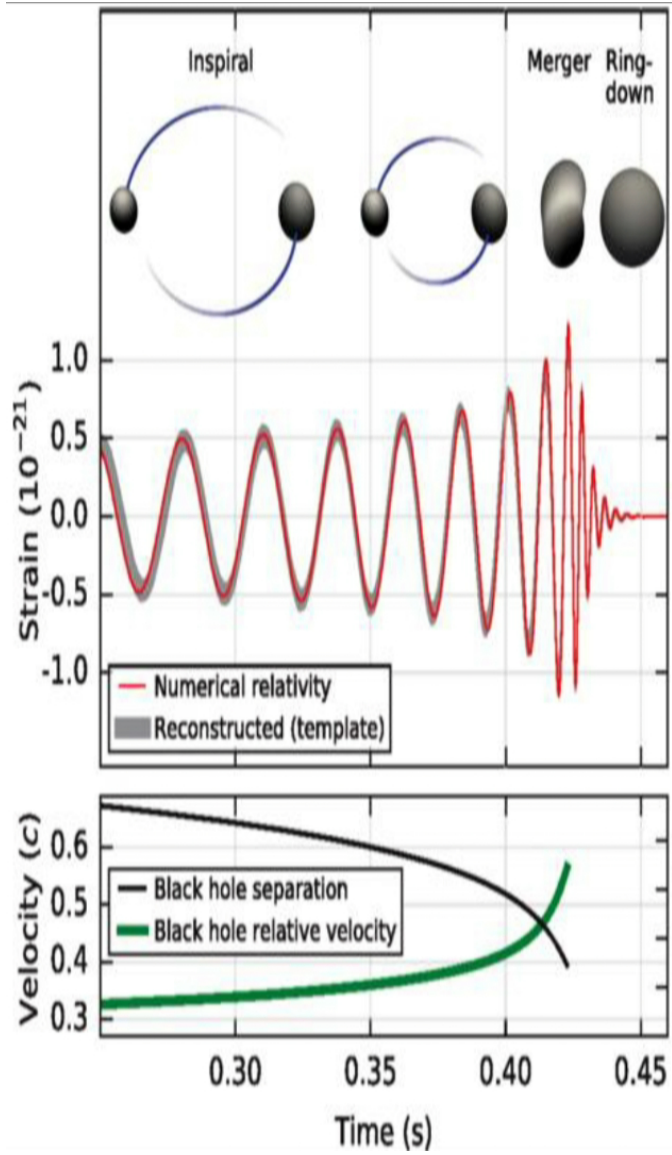
<http://www.forbes.com/sites/ethansiegel/2015/06/22/its-the-power-of-quantum-mechanics-that-allow-the-sun-to-shine/#78752a276127>

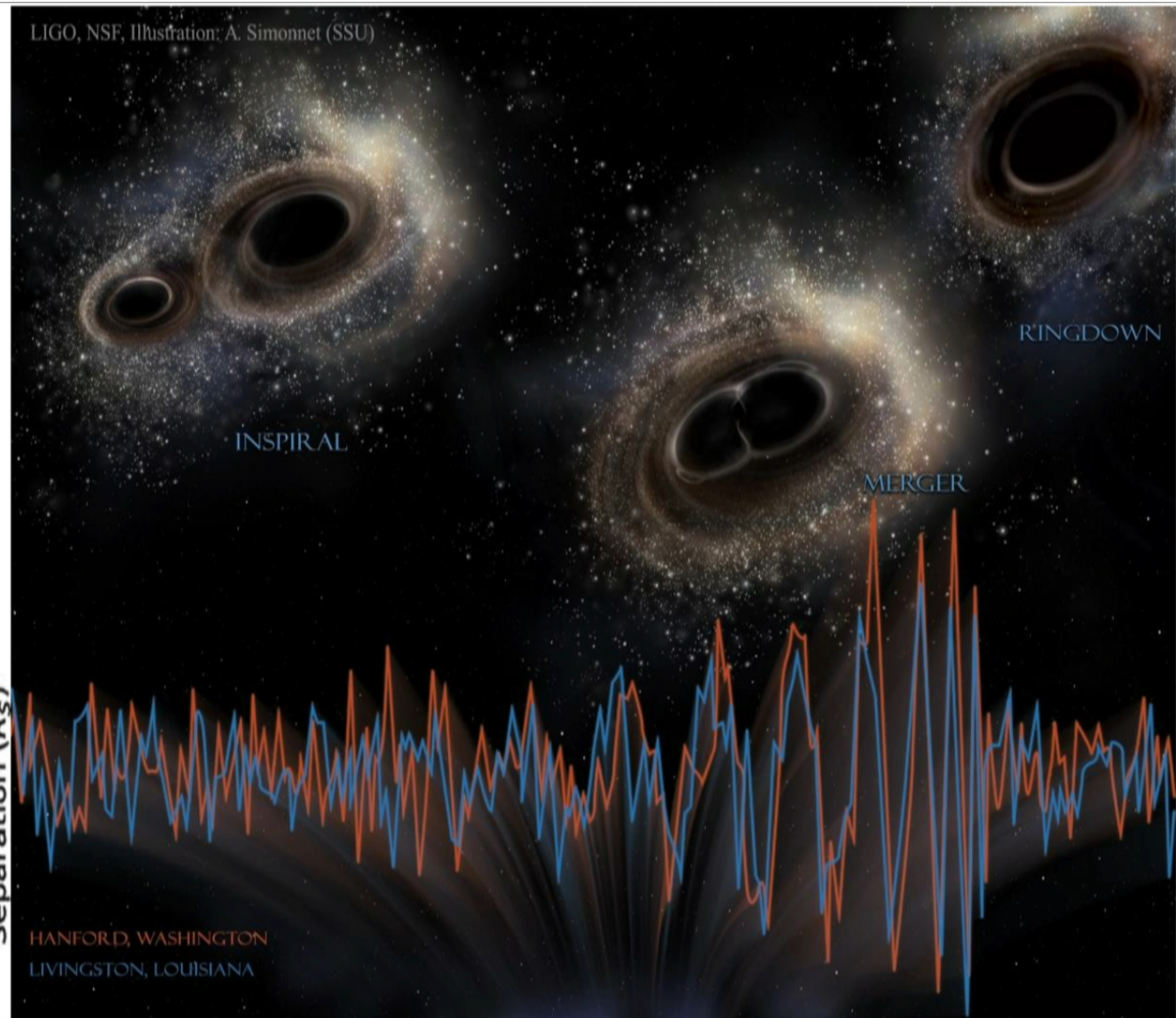
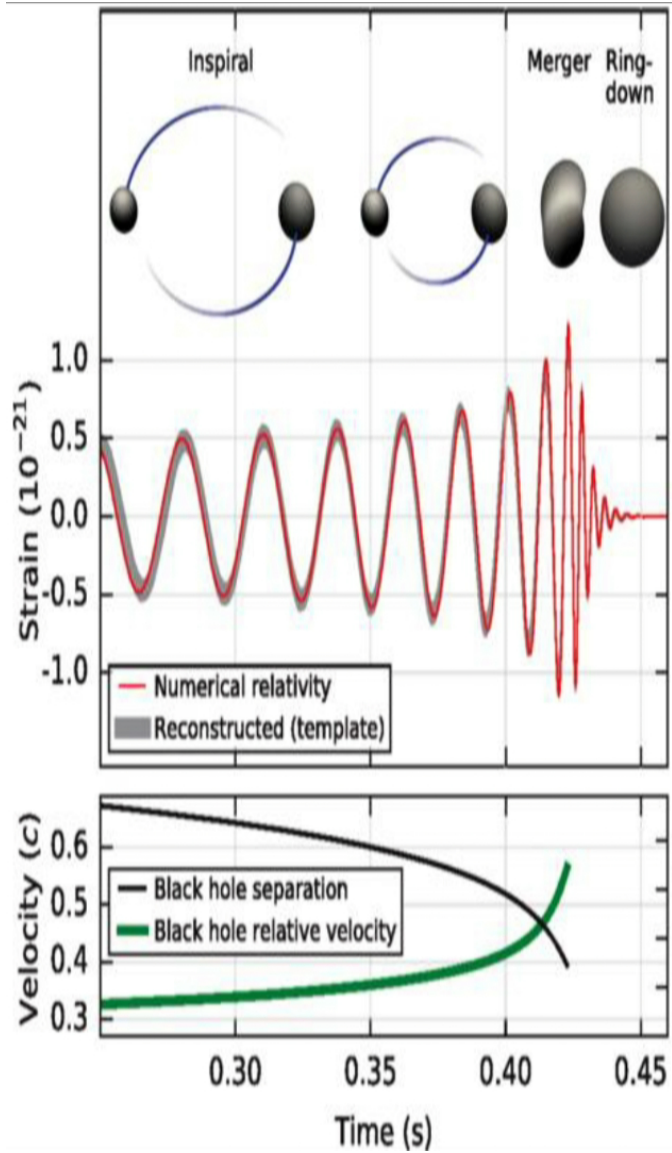


# QUANTUM BLACK HOLES



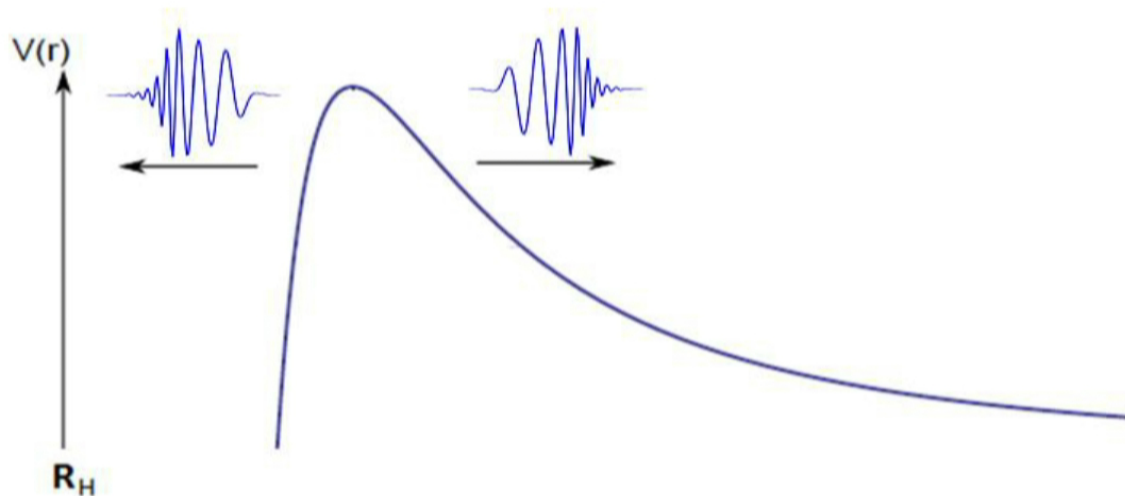
- [1] A. Almheiri, D. Marolf, J. Polchinski, and J. Sully, *JHEP* **02**, 062 (2013), [arXiv:1207.3123 \[hep-th\]](#).
- [2] O. Lunin and S. D. Mathur, *Nucl. Phys.* **B623**, 342 (2002), [arXiv:hep-th/0109154 \[hep-th\]](#).
- [3] O. Lunin and S. D. Mathur, *Phys. Rev. Lett.* **88**, 211303 (2002), [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 \[gr-qc\]](#).



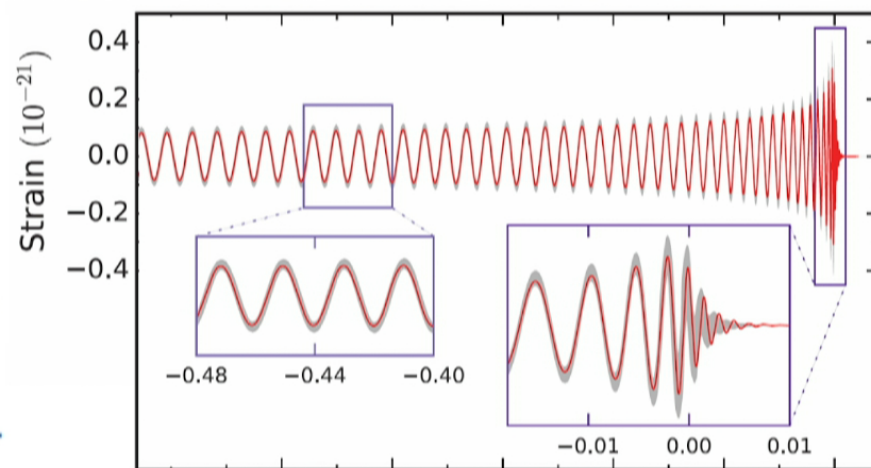
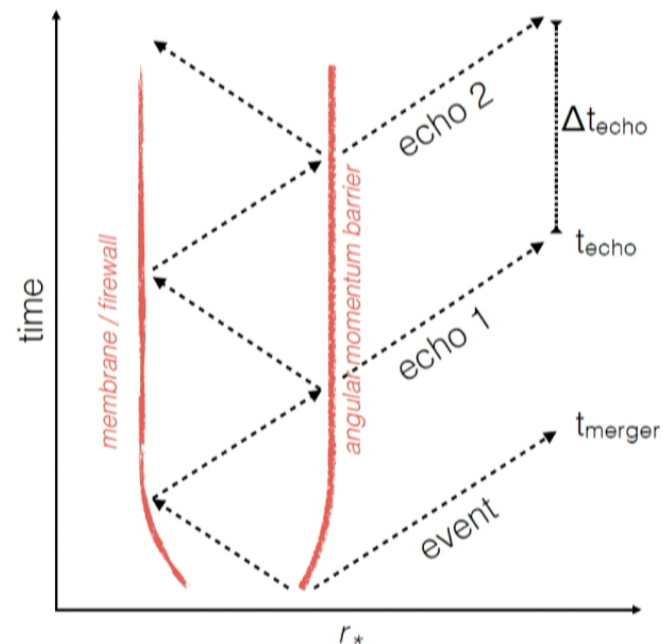


**Planck-scale structure near horizon results in**

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

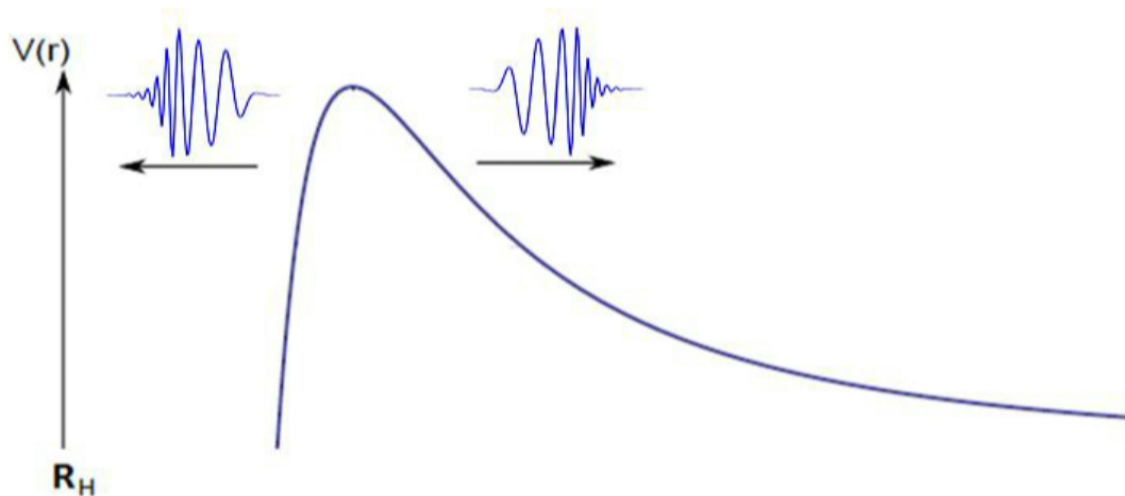


For the second echo we would have  $\Delta t_2 = 2\Delta t_1$ .

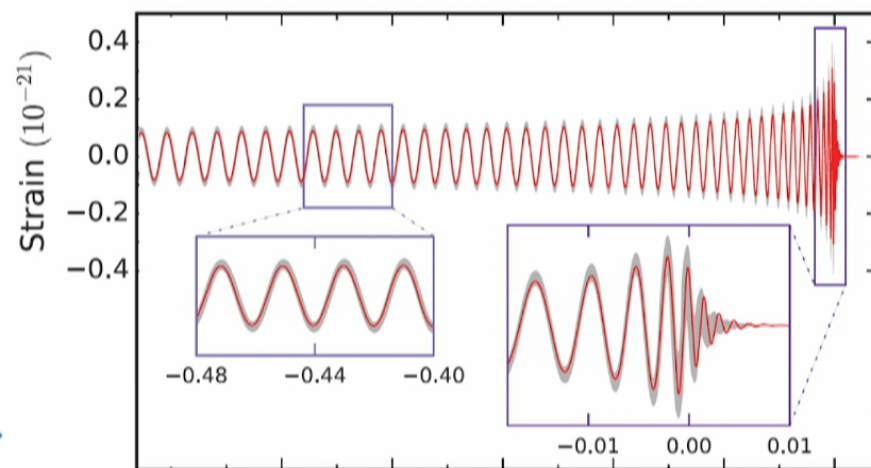
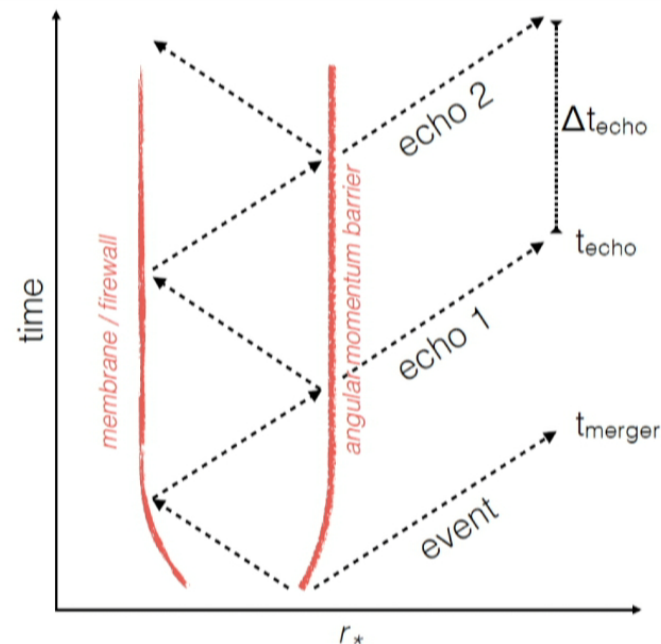


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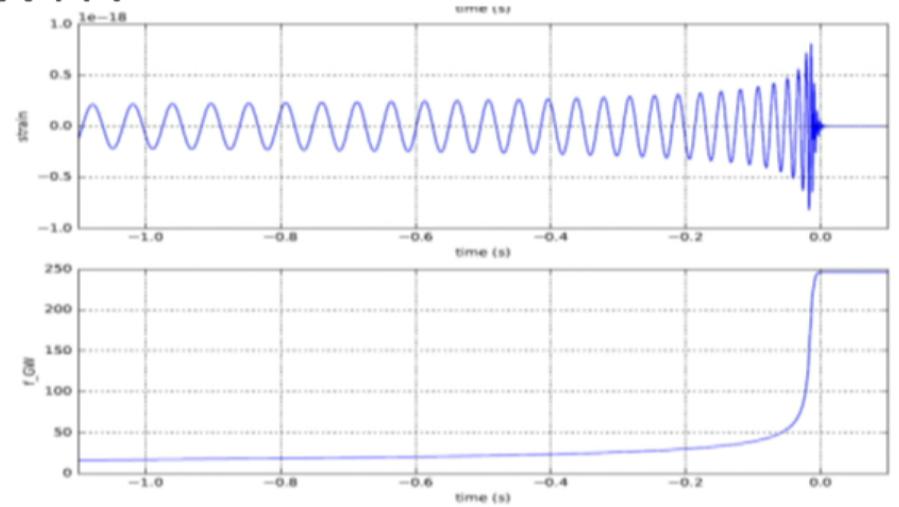


For the second echo we would have  $\Delta t_2 = 2\Delta t_1$ .



# How to separate the ringdown?

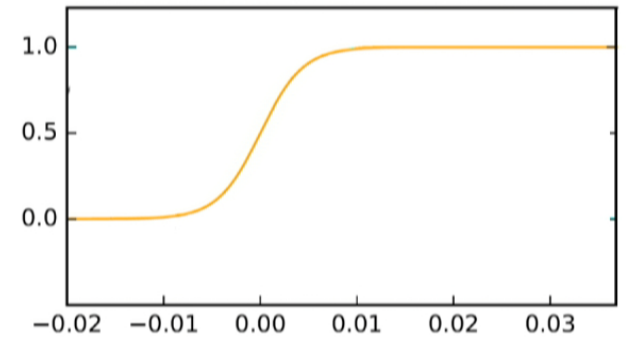
$$\Theta_I(t, t_0) \equiv \frac{1}{2} \left\{ 1 + \tanh \left[ \frac{1}{2} \omega_I(t) (t - t_{\text{merger}} - t_0) \right] \right\}$$



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

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

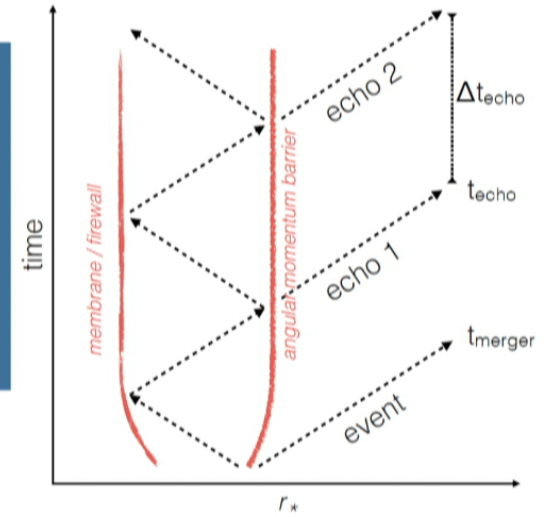
$$A \sum_{n=0}^{\infty} (-1)^{n+1} \gamma^n \mathcal{M}_{T,I}(t + t_{\text{merger}} - t_{\text{echo}} - n \Delta t_{\text{echo}}, t_0)$$



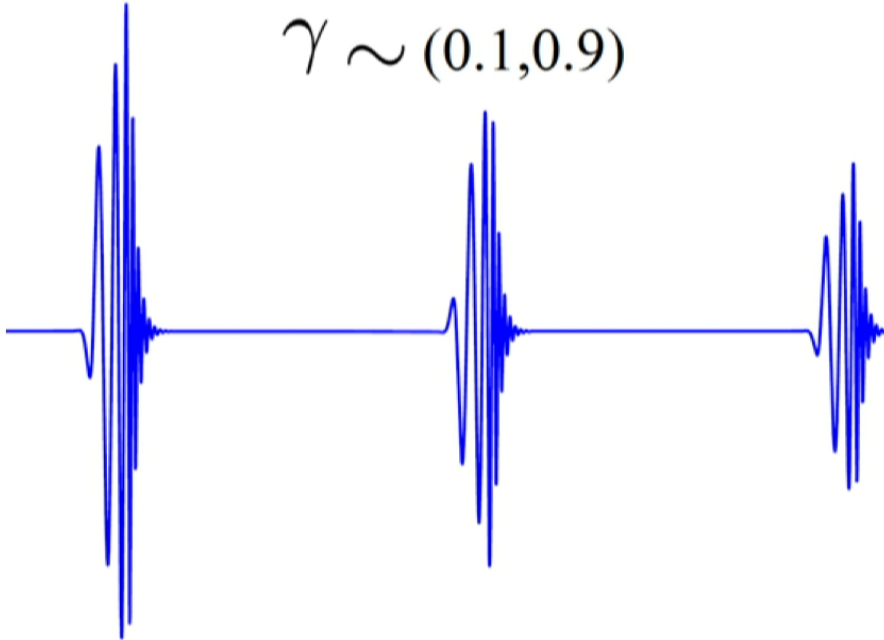
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$$t_{0,I} \sim (-0.1, 0) \Delta t_{pred,I}$$

$I = GW150914, LVT151012, GW151226$



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



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

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

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

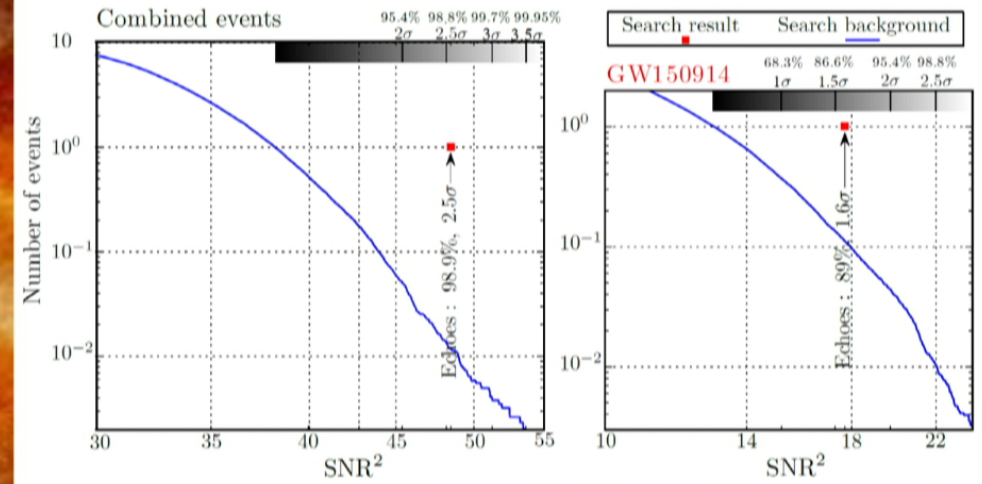
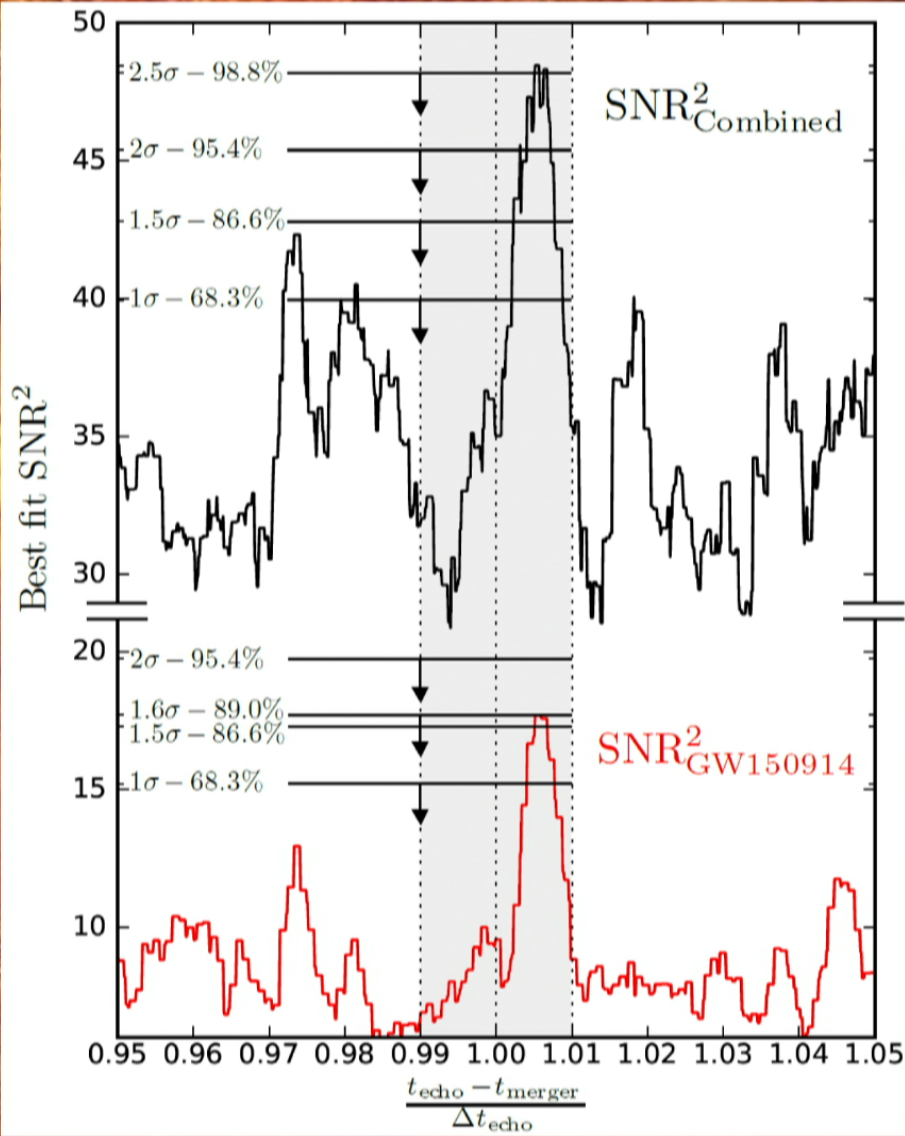
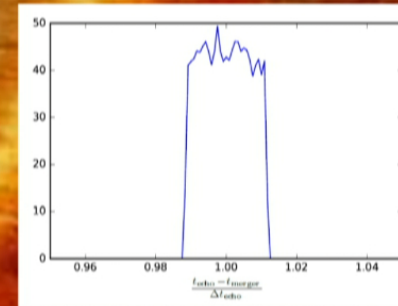


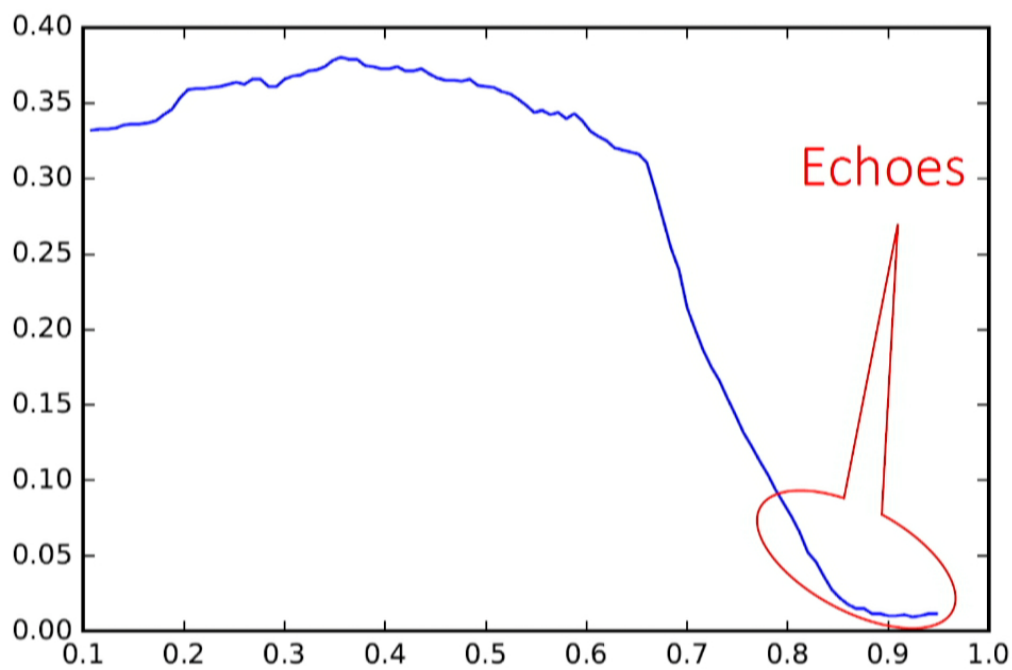
FIG. 5: Average number of noise peaks higher than a particular SNR-value within a time-interval  $2\% \times \Delta t_{\text{echo}}$  for combined (left) and GW150914 (right) events. The red dots show the observed SNR peak at  $t_{\text{echo}} = 1.0054 \Delta t_{\text{echo}}$  (Fig. 4). The horizontal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



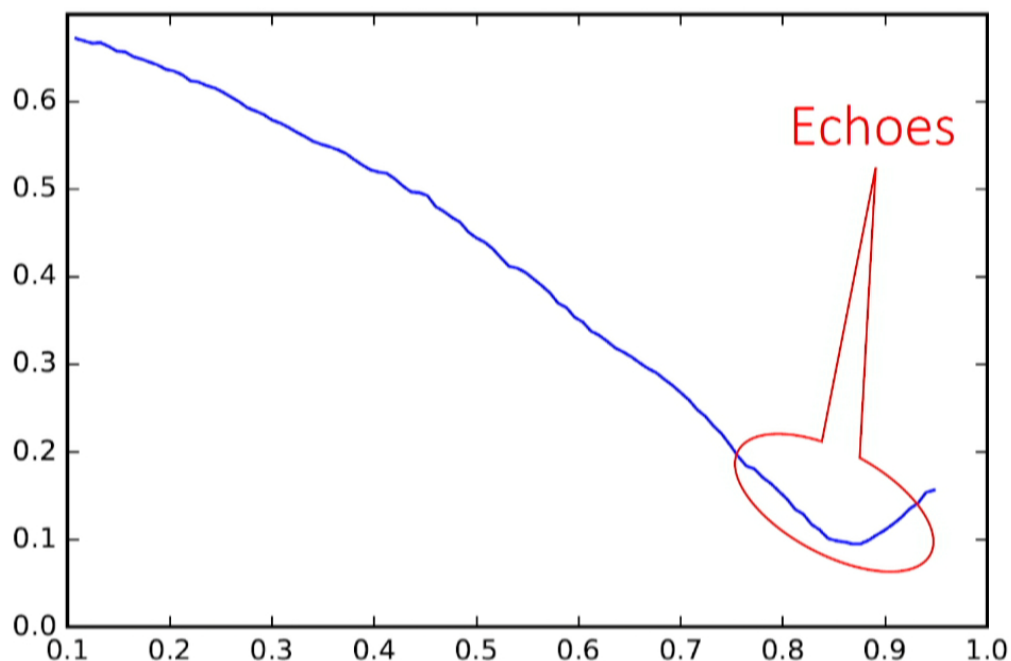
Resulting prior distribution assuming a random phase for the echo template.

# How often would we see “echoes” in background?

GW150914+GW151226+LVT151012



GW150914



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

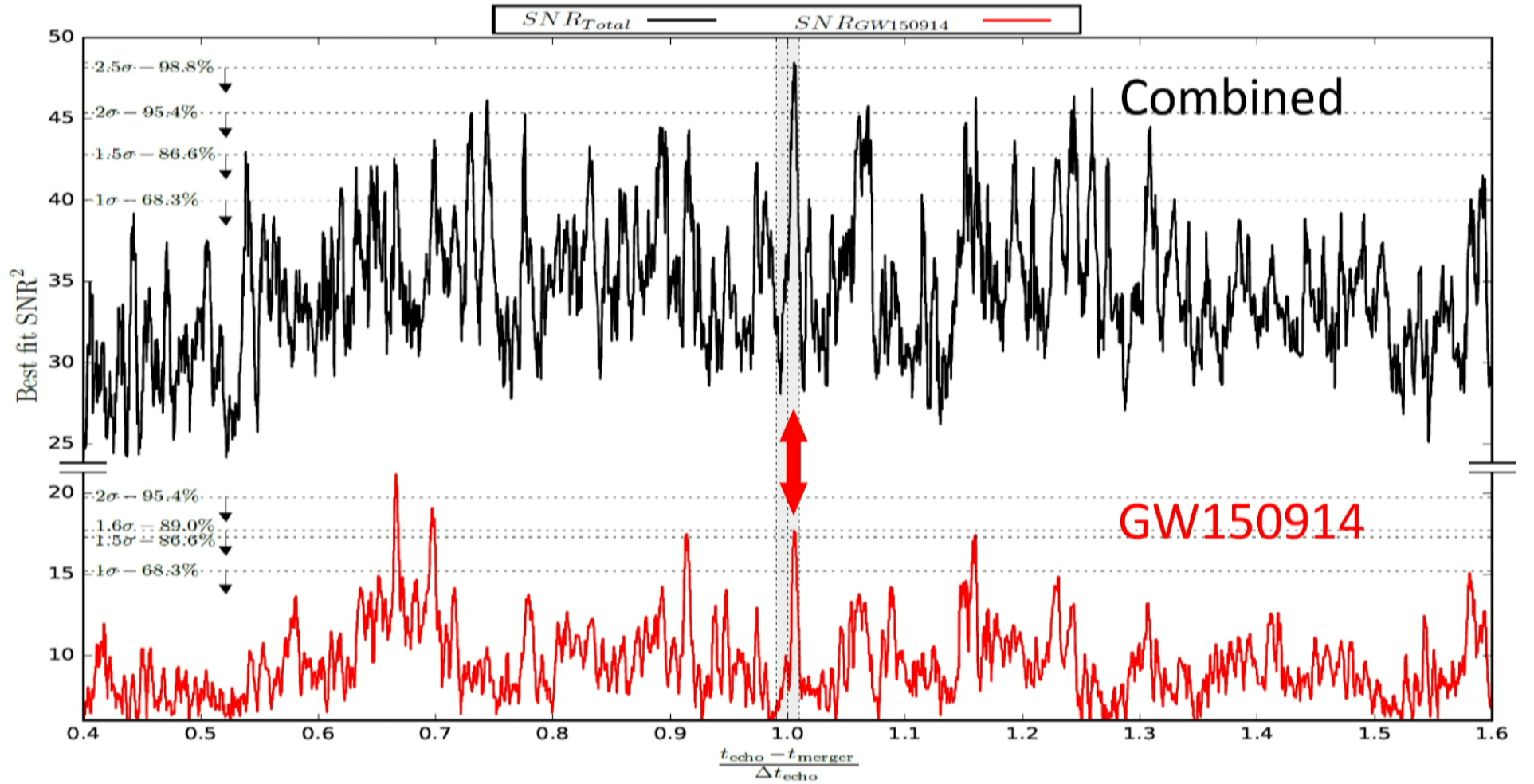
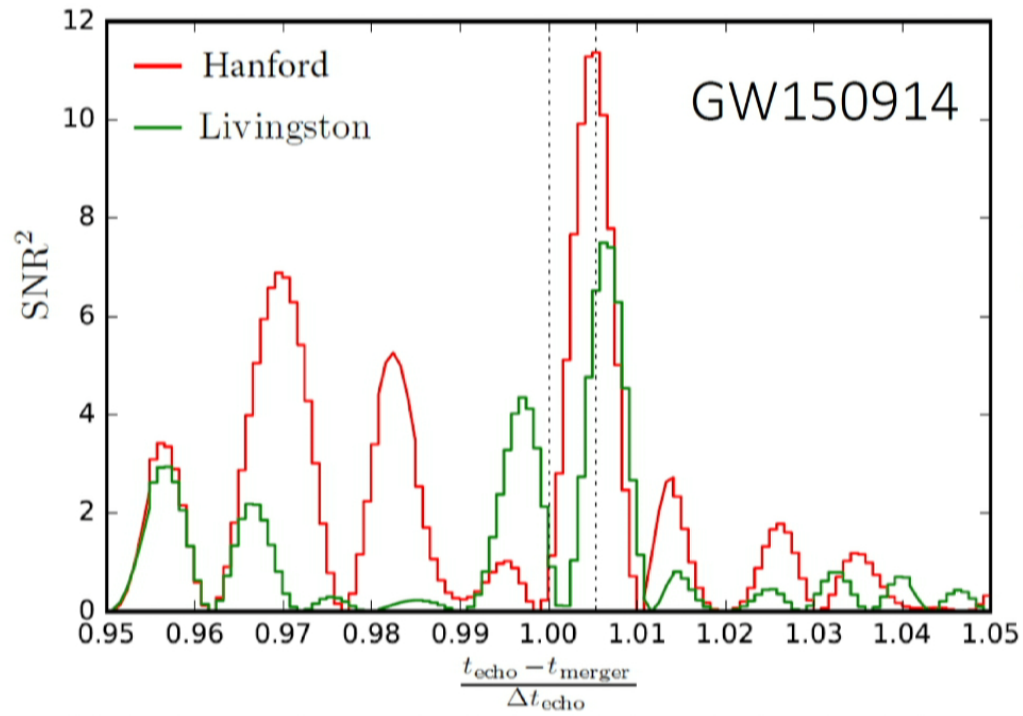
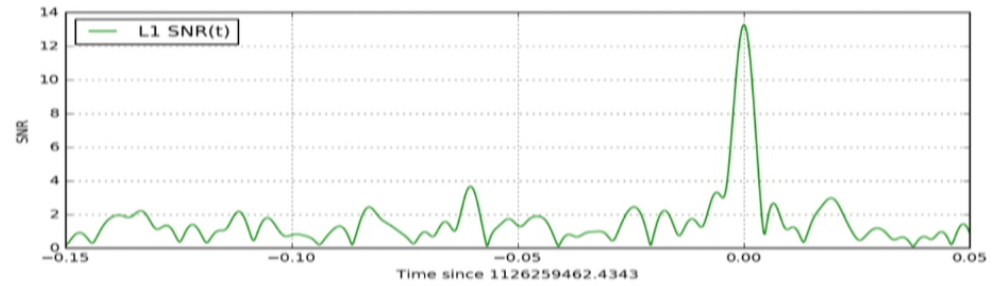
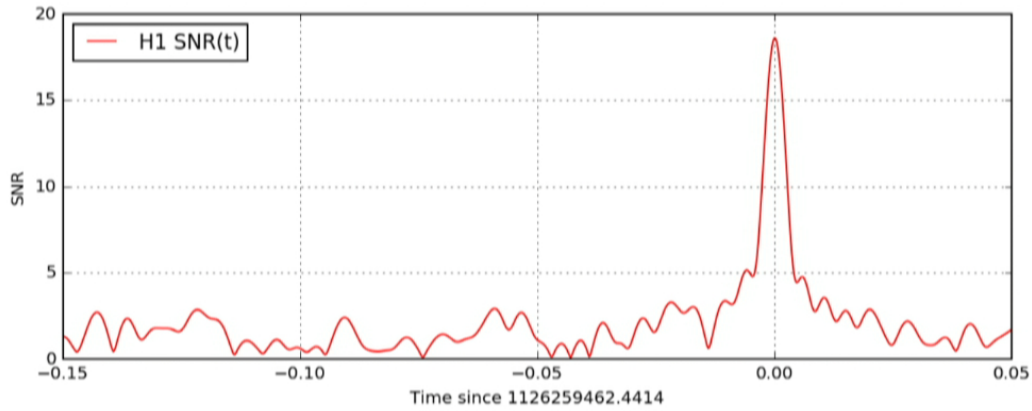
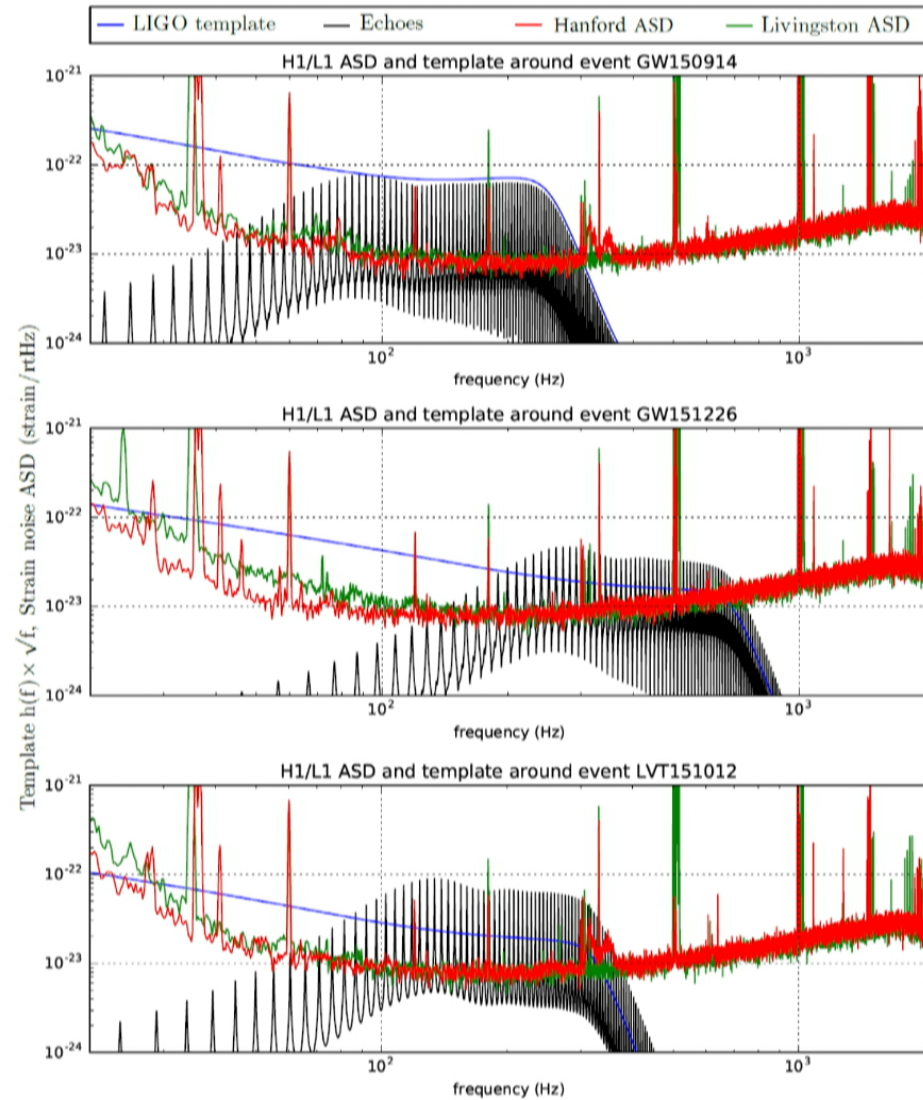


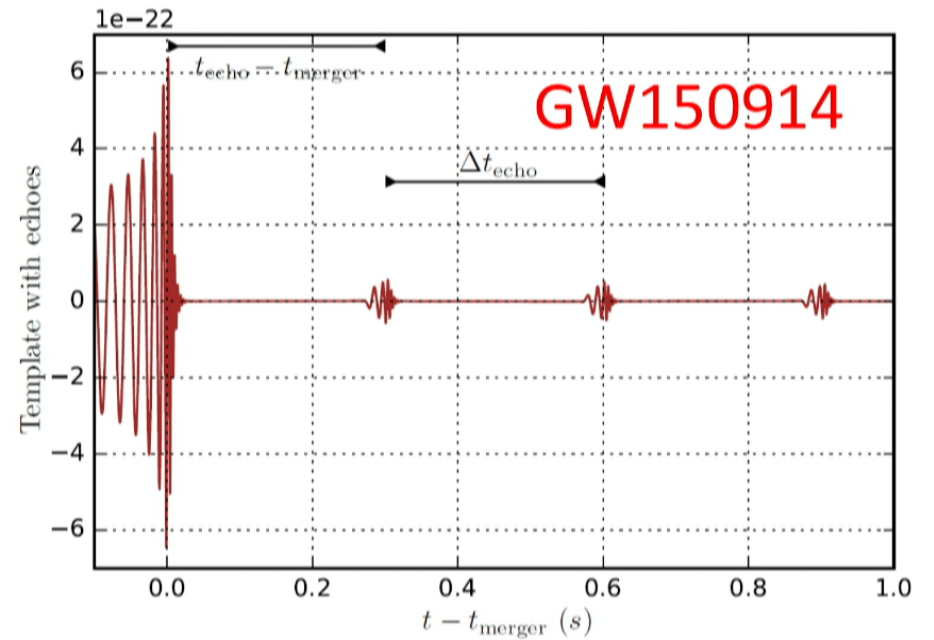
FIG. 3: Same as Fig. 4 in the main text, but over an extended range of  $x = \frac{t_{\text{echo}} - t_{\text{merger}}}{\Delta t_{\text{echo}}}$ . The SNR peaks at the predicted value of  $x = 1$  have  $1.6\sigma$  and  $2.5\sigma$  significance, for GW150914 and combined events respectively (See also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



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



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 $\sigma$**

Future observations from interferometric detectors at higher sensitivity or more accurate models may confirm or rule out this finding.

A visualization of a gravitational well, showing a blue grid surface with concentric ripples. Two white spheres are positioned near the center of the well, representing celestial bodies. The text "Thank you" is overlaid in the center of the image.

Thank you