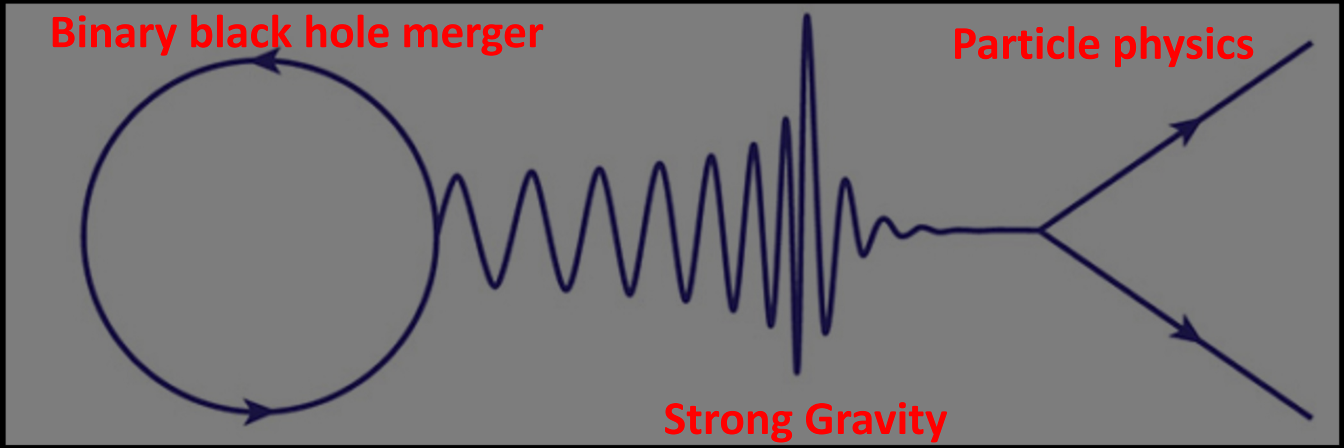
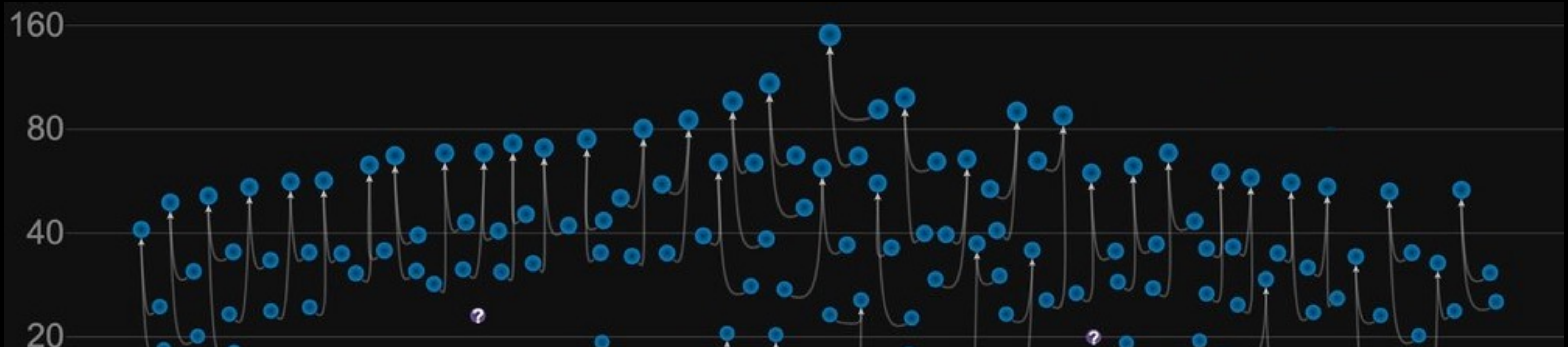
On the edge of quantum black holes

University of Stavanger

Jahed Abedi



Workshop on LISA Data Analysis
November 21-25, Toulouse



Do we have event horizon?

- Test GR: Event horizon is one of predictions of GR.
- What about quantum nature of black hole horizon?
- What it has to do with LISA?

Stimulated Hawking Radiation: Black holes as a lab for new physics

Hawking radiation flux is small as it originates from Planckian vacuum fluctuations

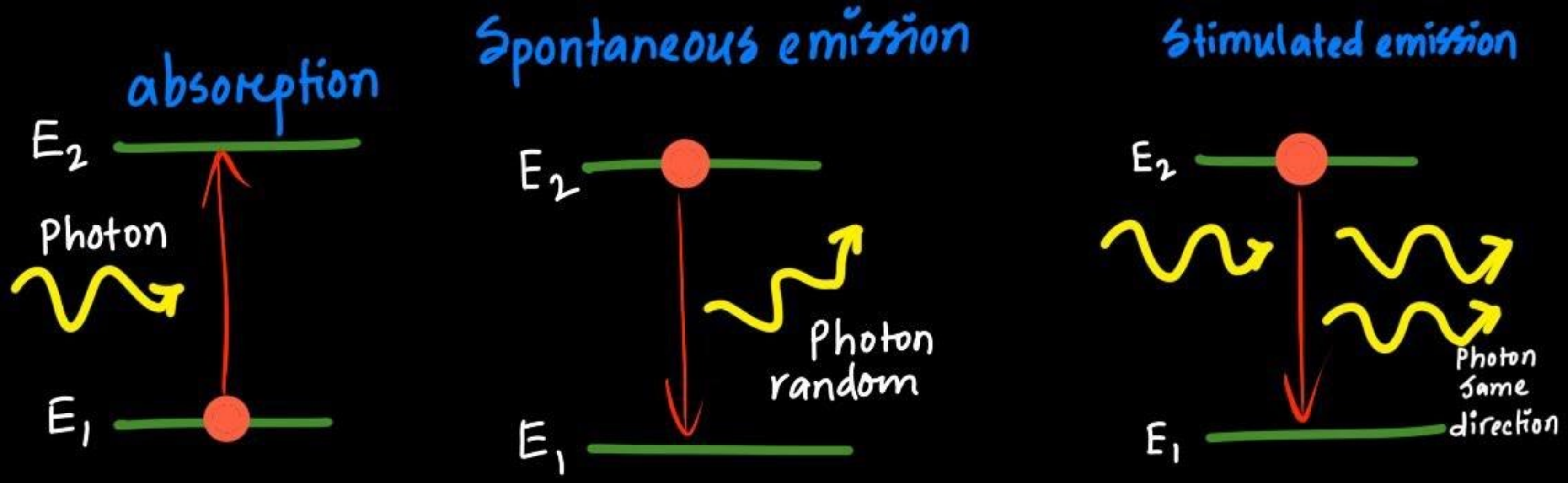
$$G_{\mu\nu} = \langle T_{\mu\nu} \rangle$$

Frequency of Gravitational waves$\sim \frac{1}{M} \sim T_H$

$$Required\ frequency\ to\ excite\ quantum\ mechanical\ states\ of\ black\ hole \sim \frac{Black\ hole\ mass}{Number\ of\ black\ hole\ states} \sim \frac{M}{M^2} = \frac{1}{M} \sim T_H$$

One may consider echoes as stimulated emission of Hawking radiation, caused by the GWs that excite the quantum BH microstructure

Stimulated Hawking Radiation:



Spontaneous emission for black hole occurs at times $\sim M^3$

Stimulated Hawking radiation is **faster than spontaneous emission** by the number of photons/gravitons. If frequency is 1/M and energy is M, number of particles is $\sim M^2$. So time scale emission is $M^3/M^2 = M$

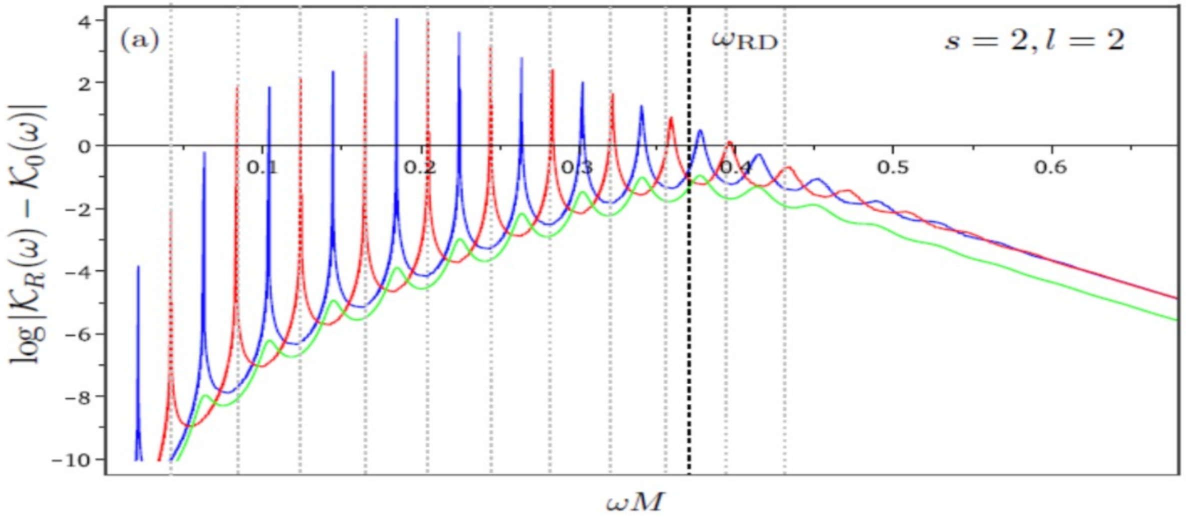
Quantum mechanics imply that we have minimum Planck length, which is **about 10^{-35} meters**.

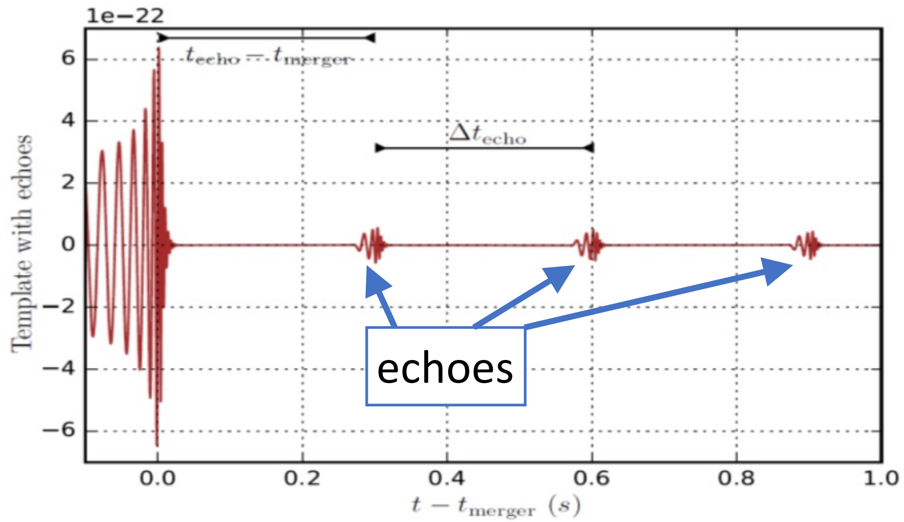
So the time for the waves reaching the minimum distance of return (**Planckian** horizon) is not infinite.

Therefore a time to reach the stationary state drops to ~ 1 sec after the merger for $\sim 300 M_{\odot}$ (redshifted mass) black hole

$$\Delta t_{\rm echo} \simeq \frac{4GM_{\rm BH}}{c^3}\left(1+\frac{1}{\sqrt{1-a^2}}\right)\times\ln\left(\frac{M_{\rm BH}}{M_{\rm planck}}\right)$$
$$\simeq 1.128 \text{ sec}\left(\frac{M_{\rm BH}}{300\ M_{\odot}}\right)\times\frac{1}{2}\left(1+\frac{1}{\sqrt{1-a^2}}\right),$$

We might have stimulated Hawking radiation after ~ 1 sec from merger time for GW190521
Or we have stimulated Hawking radiation after ~ 1 hour from merger time of $\sim 10^6 M_{\odot}$



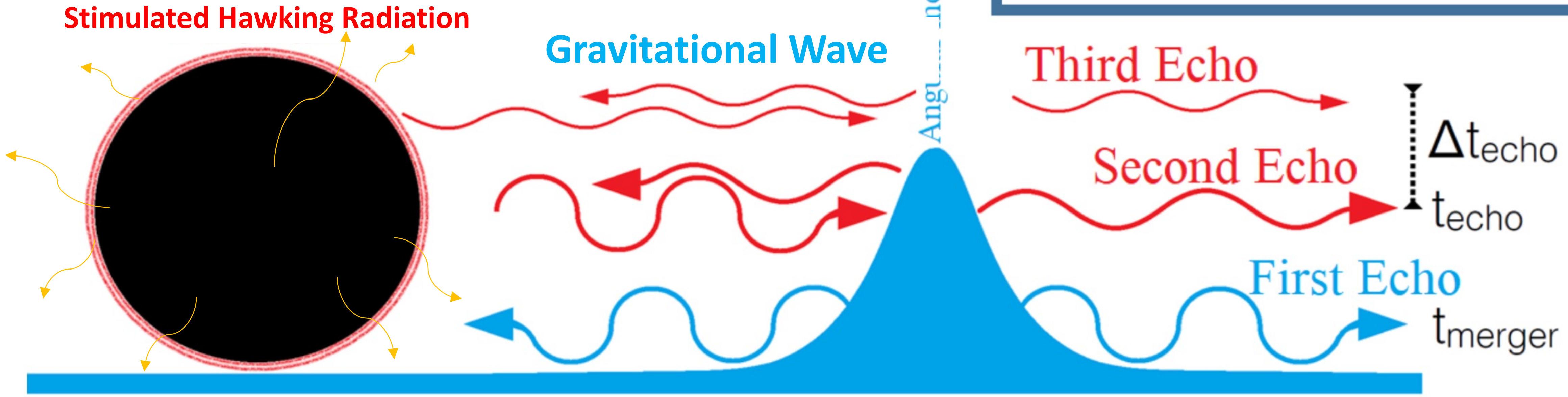


Gravitational wave echoes through new windows Randy S. Conklin, Bob Holdom, Jing Ren

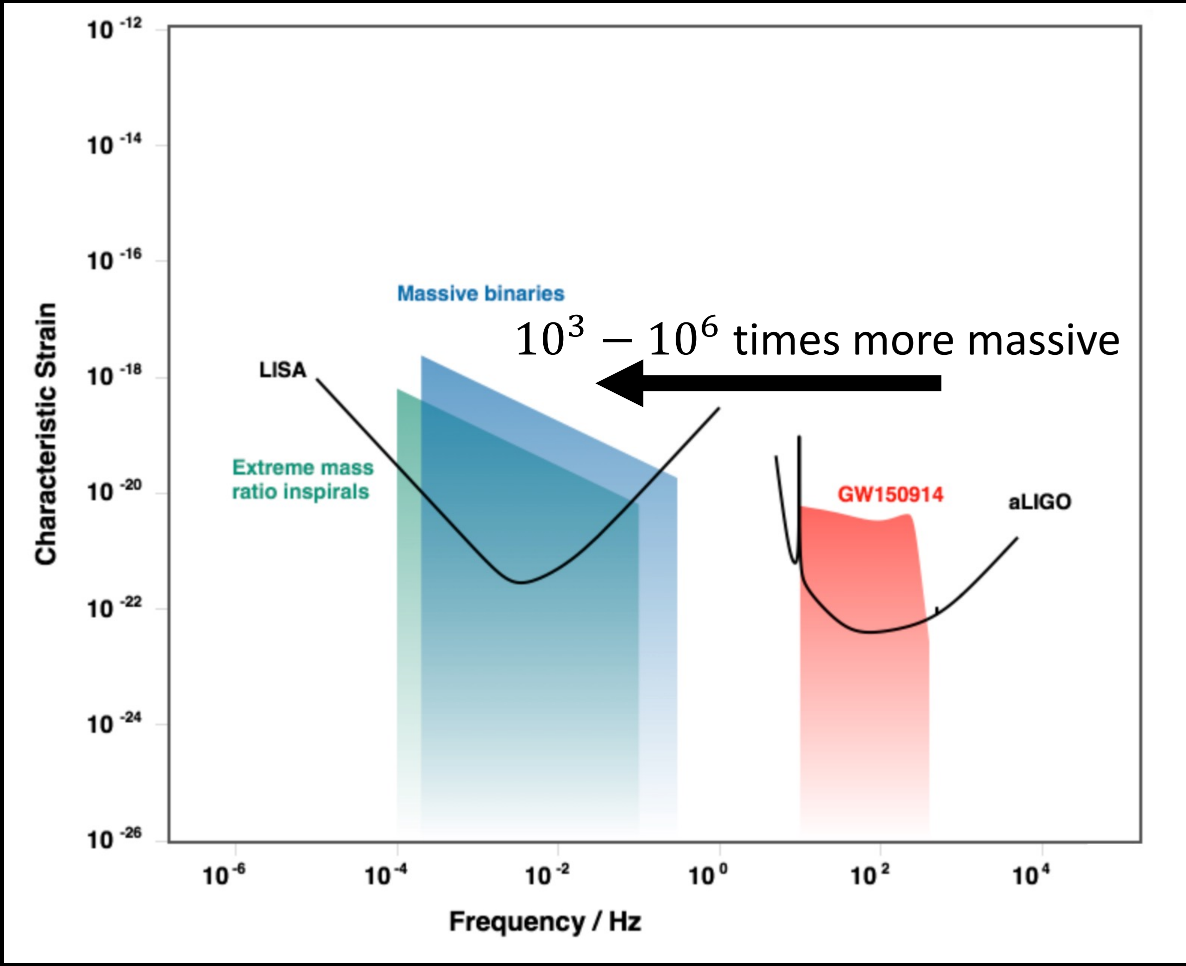
$$h(t) \propto \sum_n \delta_D(t - n\Delta t_{echo} - t_0), \quad \text{or} \quad h_f \propto \sum_n \delta_D(f - nf_{echo})$$

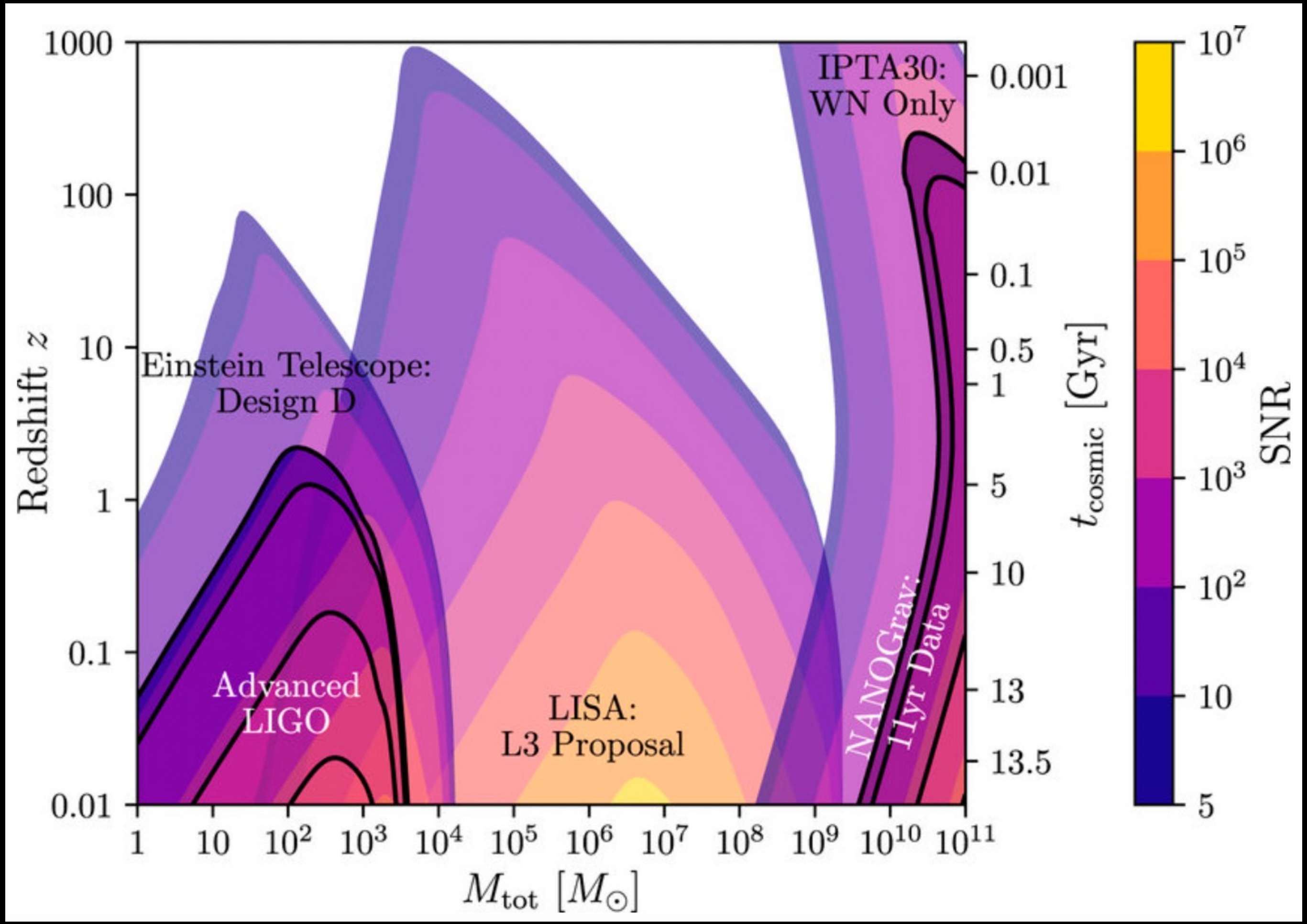
Planck-scale structure near horizon results in

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



What it has to do with LISA?



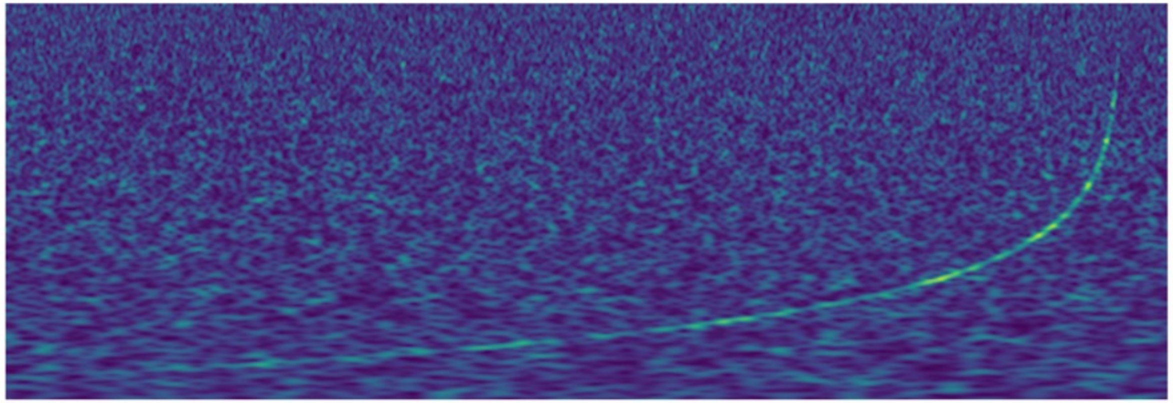


http://gwplotter.com Moore et. al.

Kaiser et. al. **DOI** 10.1088/1361-6382/abd4f6

PyCBC

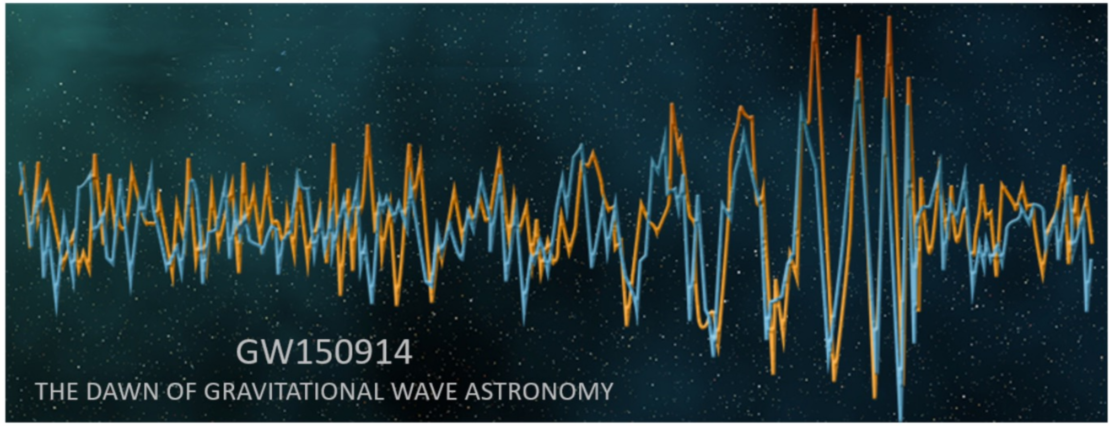
Free and open software to study gravitational waves.



PyCBC is a software package used to explore astrophysical sources of gravitational waves. It contains algorithms that can detect coalescing compact binaries and measure the astrophysical parameters of detected sources. PyCBC was used in the first direct detection of gravitational waves by LIGO and is used in the ongoing analysis of LIGO and Virgo data. PyCBC was featured in Physics World as a good example of a large collaboration publishing its research products, including its software.

coherent WaveBurst

An open source software for gravitational-wave data analysis



Coherent WaveBurst is an open source software package devised to search for a broad range of gravitational-wave (GW) transients without prior knowledge of the signal waveform. As a search pipeline, it identifies coherent events in data from multiple GW detectors and reconstructs a GW signal associated with these events by using the maximum likelihood analysis.

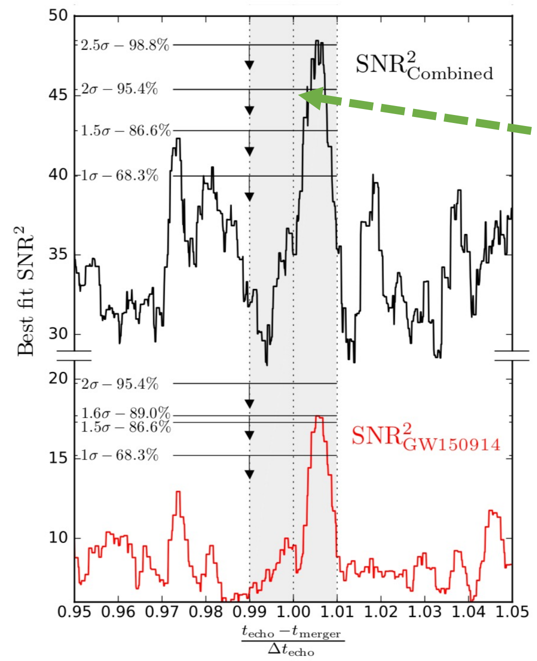
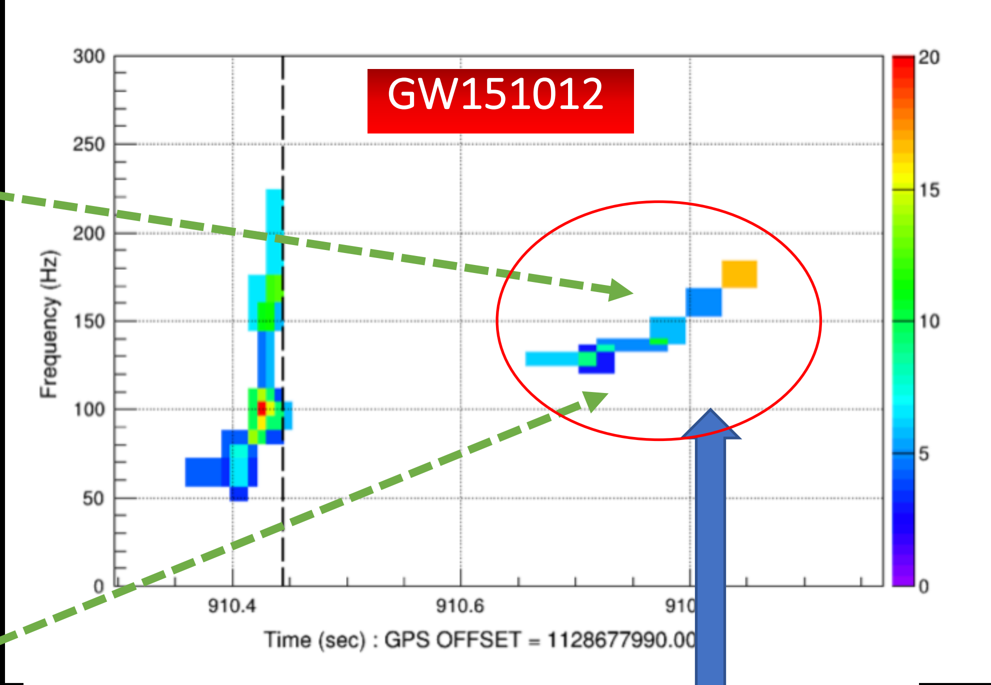


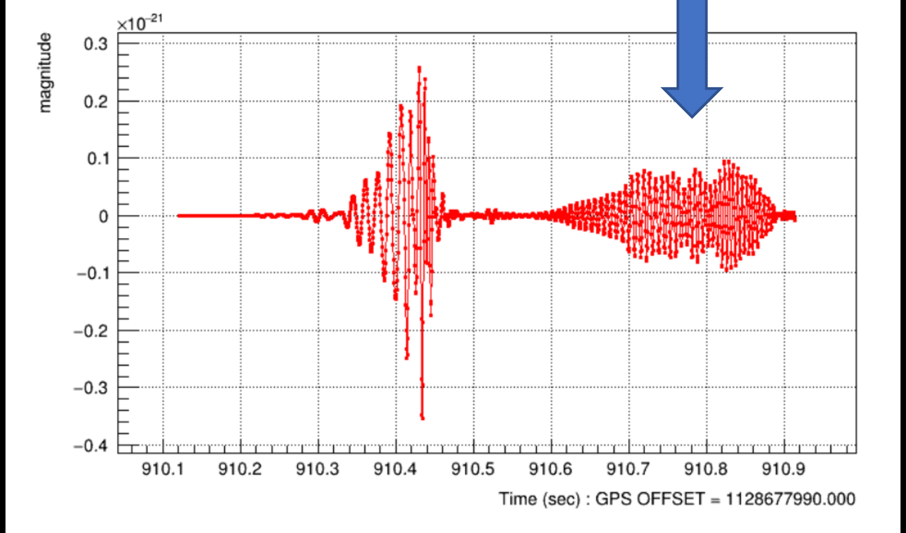
FIG. 4: Best fit (or maximum) SNR^2 near the expected time of merger echoes (Eq's. 1 and 6), for the combined (top) and GW150914 (bottom) events. The significance of the peaks is quantified by the p-value of their SNR$_{\text{max}}$ within the gray rectangle (see Appendix E for detail of calculation).

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

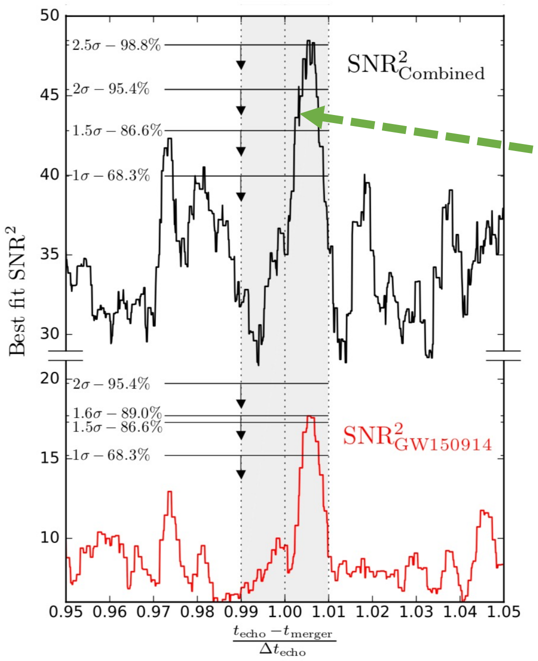
TABLE II: Theoretical expectations for Δt_{echo}'s of each merger event (Eq. 6), compared to their best combined fit within the 1σ credible region, and the contribution of each event to the joint SNR for the echoes (Eq. 10).

Abedi et al (Oct 2017)





Credit: Salemi et al, 2019



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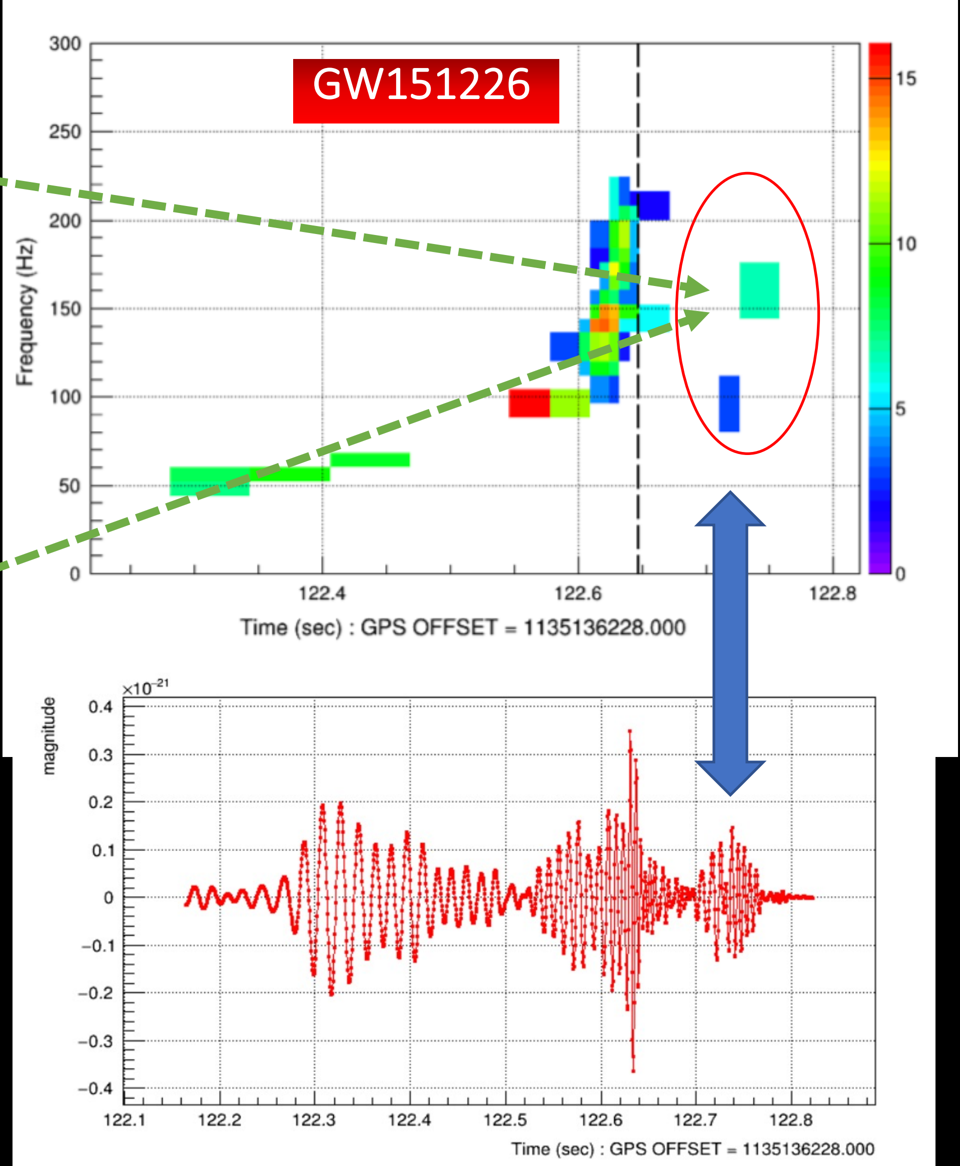


Credit: Salemi et al, 2019

Echoes from GW170817:

2019 Buchalter Cosmology First Prize,

$$p - value = 1.6\times10^{-5}$$

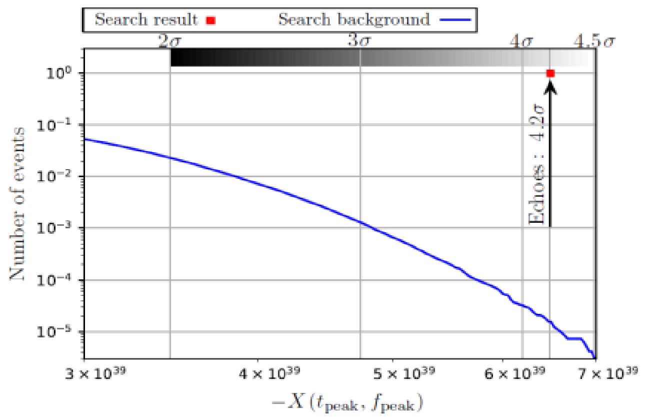


FIG. 5: Average number of noise peaks higher than a particular -X(t,f) within a frequency-intervals of 63-92 Hz and time-intervals of 1 sec for LIGO noise near GW170817 event. The red square shows the observed $-X(t_{\rm peak}, f_{\rm peak})$ peak at 1.0 sec after the merger. The horizontal bar shows the correspondence between $X(t, f)$ values and their significance. This histogram obtained from producing ~2 weeks data out of off-source 2048 sec available data [34].

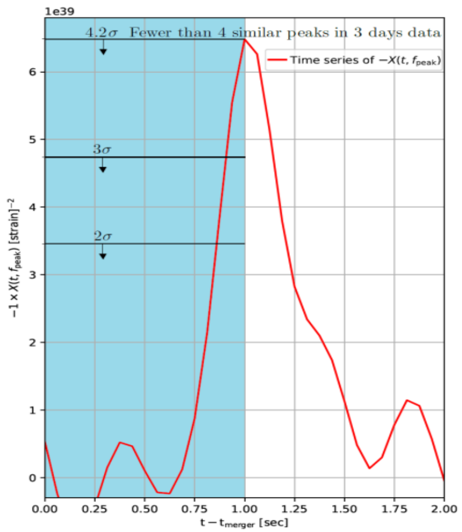
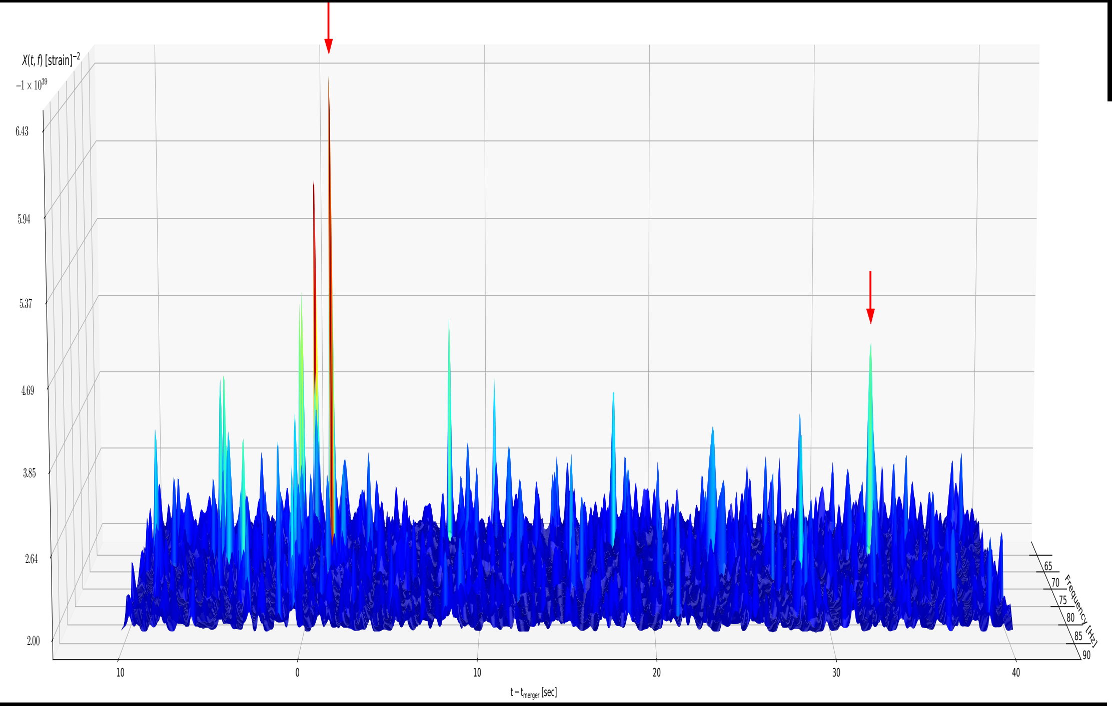
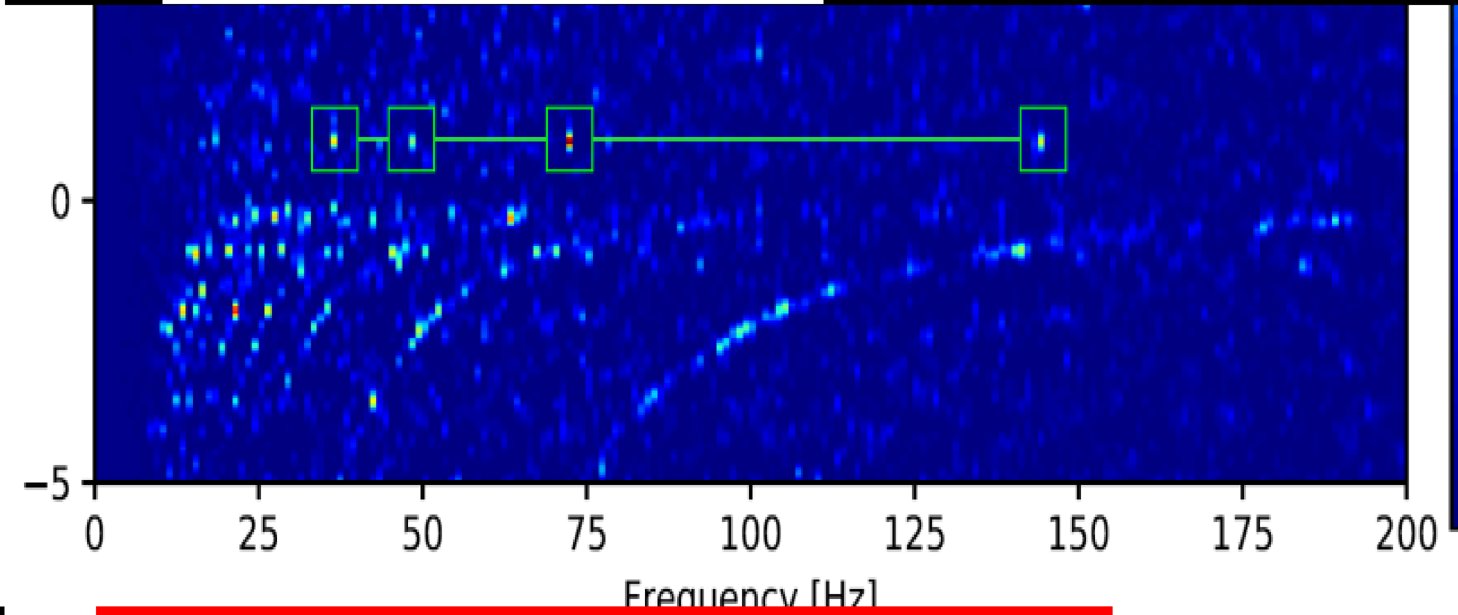


FIG. 6: Amplitude-time representations of first (and most significant) echo peak at 1.0 sec after the merger and frequency of 72 Hz. The shaded region is 0-1 sec prior range after the merger, first adopted in [21], which we use to estimate p-value . The maximum of the peak is 6.48×10^{39}.





Abedi & Afshordi 2018 **arXiv:1803.10454**

Confirmation

WHEN DID THE REMNANT OF GW170817 COLLAPSE TO A BLACK HOLE?

RAMANDEEP GILL,[1,2] ANTONIOS NATHANAIL,[1] AND LUCIANO REZZOLLA[1]

[1]*Institut für Theoretische Physik, Max-von-Laue-Strasse 1, D-60438 Frankfurt, Germany*
[2]*Department of Natural Sciences, The Open University of Israel, 1 University Road, POB 808, Raanana, 4353701, Israel*

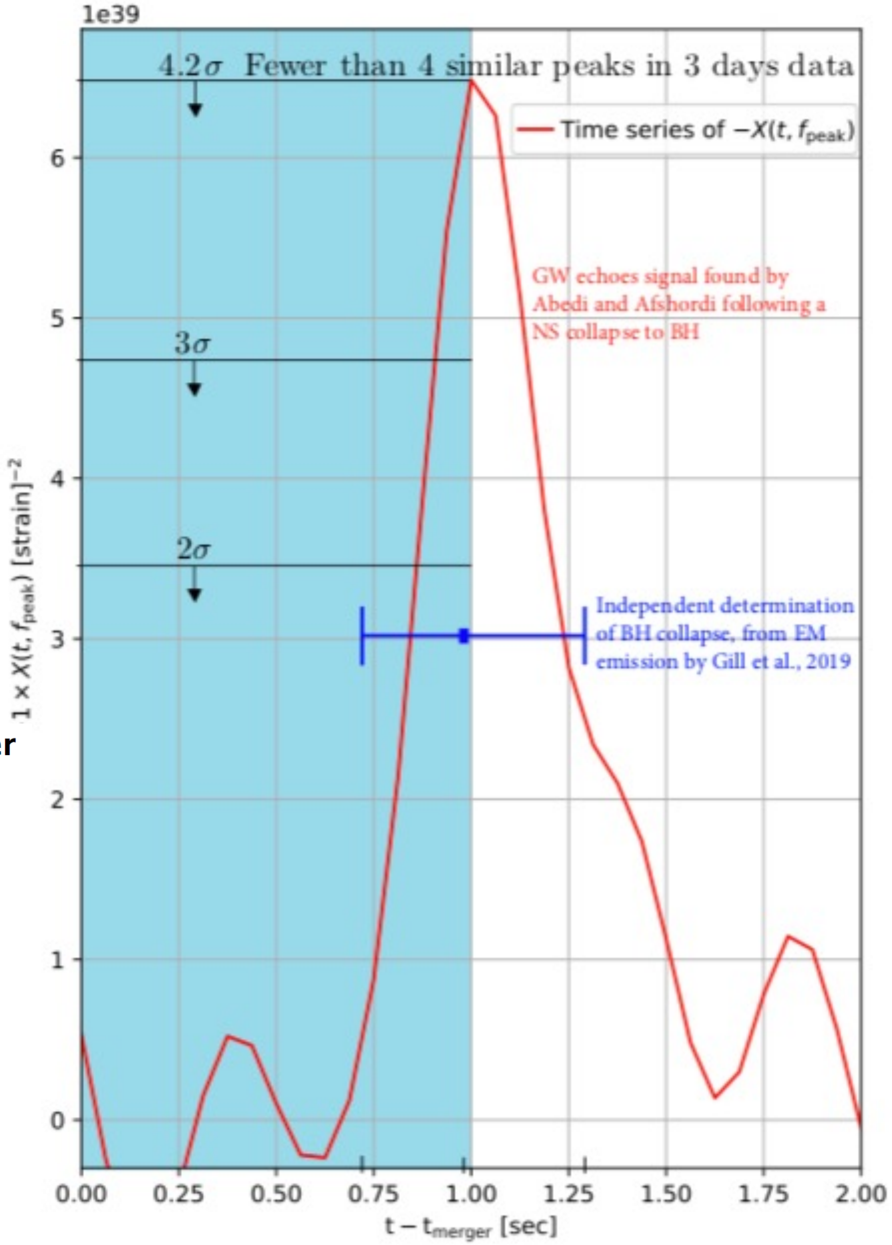
ABSTRACT

The main hard pulse of prompt gamma-ray emission in GRB 170817A had a duration of ~ 0.5 s and its onset was delayed with respect to the gravitational-wave chirp signal by $t_{\rm del} \approx 1.74$ s. Detailed follow-up of the subsequent broadband kilonova emission revealed a two-component ejecta – a lanthanide-poor ejecta with mass $M_{\rm ej,blue} \approx 0.025\,M_\odot$ that powered the early but rapidly fading blue emission and a lanthanide-rich ejecta with mass $M_{\rm ej,red} \approx 0.04\,M_\odot$ that powered the longer lasting redder emission. Both the prompt gamma-ray onset delay and the existence of the blue ejecta with modest electron fraction, $0.2 \lesssim Y_e \lesssim 0.3$, can be explained if the collapse to a black hole was delayed by the formation of a hypermassive neutron star (HMNS). Here, we determine the survival time of the merger remnant by combining two different constraints, namely, the time needed to produce the requisite blue-ejecta mass and that necessary for the relativistic jet to bore its way out of the expanding ejecta. In this way, we determine that the remnant of GW170817 must have collapsed to a black hole after $t_{\rm coll} = 0.98^{+0.31}_{-0.26}$ s. We also discuss how future detections and the delays between the gravitational and electromagnetic emissions can be used to constrain the properties of the merged object.

Echoes from the Abyss: A highly spinning black hole remnant for the binary neutron star merger GW170817

Jahed Abedi (AEI, Hanover), Niayesh Afshordi (Waterloo/PI)

The first direct observation of a binary neutron star (BNS) merger was a watershed moment in multi-messenger astronomy. However, gravitational waves from GW170817 have only been observed prior to the BNS merger, but electromagnetic observations all follow the merger event. While post-merger gravitational wave signal in general relativity is too faint (given current detector sensitivities), here we present the first tentative detection of post-merger gravitational wave "echoes" from a highly spinning "black hole" remnant. The echoes may be expected in different models of quantum black holes that replace event horizons by exotic Planck-scale structure and tentative evidence for them has been found in binary black hole merger events. The fact that the echo frequency is suppressed by $\log M$ (in Planck units) puts it squarely in the LIGO sensitivity window, allowing us to build an optimal model-agnostic search strategy via cross-correlating the two detectors in frequency/time. We find a tentative detection of echoes at $f_{\rm echo} \simeq 72$ Hz, around 1.0 sec after the BNS merger, consistent with a 2.6-2.7 $M_\odot$ "black hole" remnant with dimensionless spin $0.84 - 0.87$. Accounting for all the "look-elsewhere" effects, we find a significance of 4.2σ, or a false alarm probability of 1.6×10^{-5}, i.e. a similar cross-correlation within the expected frequency/time window after the merger cannot be found more than 4 times in 3 days. If confirmed, this finding will have significant consequences for both physics of quantum black holes and astrophysics of binary neutron star mergers [Note added: This result is independently confirmed by arXiv:1901.04138, who use the electromagnetic observations to infer $t_{\rm coll} = 0.98^{+0.31}_{-0.26}$ sec for black hole formation].



An executive summary of these observations is shown in Tables 20 and 21 as positive evidence (p-value$\leq$ 0.05) and failed results, respectively.

	Authors	Method	Data	p-value
1	Abedi, Dykaar, Afshordi (ADA) 2017 [1]	ADA template	O1	1.1%
2	Conklin, Holdom, Ren 2018 [4]	spectral comb	O1+O2	0.2% - 0.8%
3	Westerweck, et al. 2018 [6]	ADA template	O1	2.0%
4	Nielsen, et al. 2019 [7]	ADA+Bayes	GW151012, GW151226	2%
5	Uchikata, et al. 2019 [2]	ADA template	O1	5.5%
6	Uchikata, et al. 2019 [2]	ADA template	O2	3.9%
7	Salemi, et al. 2019 [8]	coherent WaveBurst	GW151012, GW151226	0.4%,3%
8	Abedi, Afshordi 2019 [3]	spectral comb	BNS	0.0016%
9	Gill, Nathanail, Rezolla 2019 [145]	Astro Modelling	BNS EM	$t_{\rm coll} = t_{\rm echo}$

Table 20. Table of positive results (p-value$\leq$ 0.05) by different groups (The p-value for Nielsen et al. above [7] is a rough estimate, based on the log-Bayes = 1.66).

	Authors	Method	Data	possible caveat
1	Westerweck, et al. 2018 [6]	ADA template	O1	"Infinite" prior
2	Nielsen, et al. 2019 [7]	ADA+Bayes	GW150914	mass-ratio dependence
3	Uchikata, et al. 2019 [2]	ADA, hi-pass	O1,O2	no low-frequencies
4	Salemi, et al. 2019 [8]	coherent WaveBurst	O1,O2	mass-ratio dependence, only 1st echo
5	Lo, et al. 2019 [9]	ADA+Bayes	O1	"Infinite" prior
6	Tsang, et al. 2019 [140]	BayesWave	O1+O2	needs very loud echoes ([redacted]9 free parameters!)

Table 21. Table of failed searches and their possible caveat.

Abedi et al. 2020

LIGO/Virgo and KAGRA:

Tests of General Relativity with Binary Black Holes from the second LIGO–Virgo Gravitational-Wave Transient Catalog

The LIGO Scientific Collaboration and the Virgo Collaboration
(compiled 29 October 2020)

TABLE X. Results of search for GW echoes. A positive value of the log Bayes factor $\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$ indicates a preference for the IMRE model over the IMR model, while a negative value of the log Bayes factor suggests instead a preference for the IMR model over the IMRE model.

Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$	Event	$\log_{10} \mathcal{B}^{\rm IMRE}_{\rm IMR}$
GW150914	−0.57	GW170809	−0.22
GW151226	−0.08	GW170814	−0.49
GW170104	−0.53	GW170818	−0.62
GW170608	−0.44	GW170823	−0.34
GW190408_181802	−0.93	GW190706_222641	−0.10
GW190412	−1.30	GW190707_093326	0.08
GW190421_213856	−0.11	GW190708_232457	−0.87
GW190503_185404	−0.36	GW190720_000836	−0.45
GW190512_180714	−0.56	GW190727_060333	0.01
GW190513_205428	−0.03	GW190728_064510	0.01
GW190517_055101	0.16	GW190828_063405	0.10
GW190519_153544	−0.10	GW190828_065509	−0.01
GW190521	−1.82	GW190910_112807	−0.22
GW190521_074359	−0.72	GW190915_235702	0.17
GW190602_175927	0.13	GW190924_021846	−0.03
GW190630_185205	0.08		

$t_{echo} < 0.5$ sec

arXiv.org > gr-qc > arXiv:2112.06861

General Relativity and Quantum Cosmology

[Submitted on 13 Dec 2021]

Tests of General Relativity with GWTC-3

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration:

TABLE XIV. Results of the echoes analysis (Sec. VIII B). List of p-values for signal to noise Bayes Factor $\mathcal{B}^{\rm S}_{\rm N}$ for the events that are analysed. In the absence of any echoes signal these should be uniformly distributed between [0, 1]. Fig. 15 shows the corresponding PP plot with 90% credible intervals superimposed on it. There is no evidence for the presence of echoes.

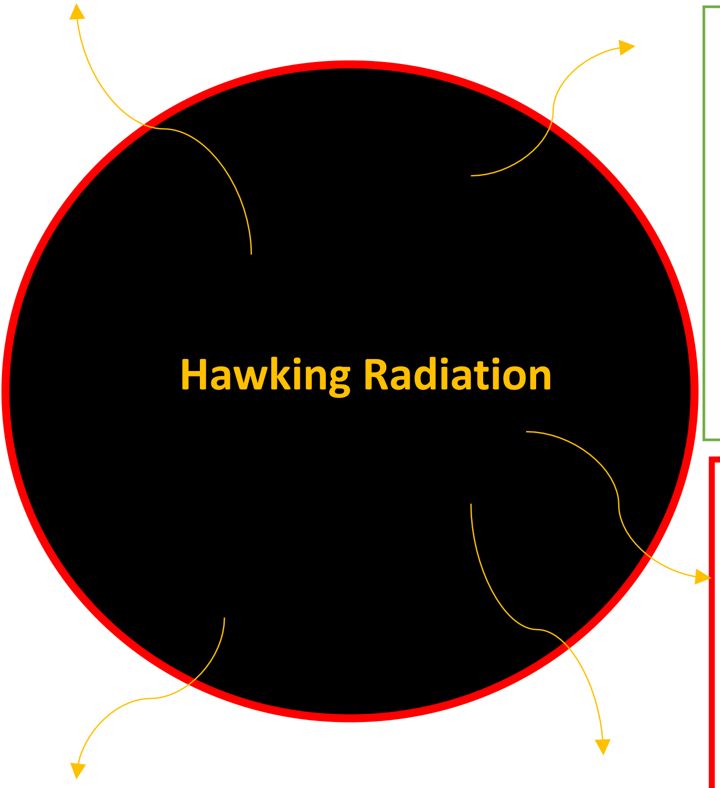
Event	p-value
GW191109_010717	0.35
GW191129_134029	0.35
GW191204_171526	0.37
GW191215_223052	0.23
GW191216_213338	0.88
GW191222_033537	0.89
GW200115_042309	0.44
GW200129_065458	0.33
GW200202_154313	0.43
GW200208_130117	0.24
GW200219_094415	0.18
GW200224_222234	0.59
GW200225_060421	0.69
GW200311_115853	0.42
GW200316_215756	0.27

missing GW190521

Boltzmann reflectivity

$\widetilde{\omega} = \omega - m\Omega_H$ Near horizon frequency

ω Frequency at infinity



Near the horizon it is natural to expect having quantum mechanical reflection given by Boltzmann factor

$$\boldsymbol{h_{GR}(\omega)exp\left(-\frac{|\omega - m\Omega_H|}{2T_H}\right)}$$

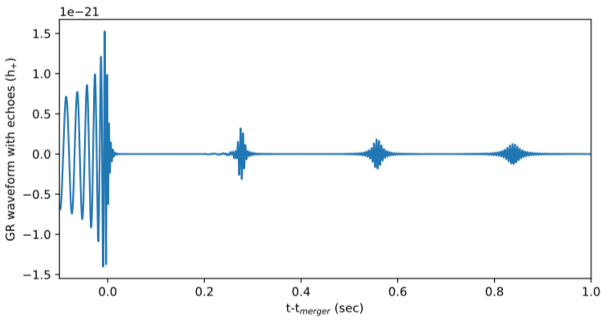
m=2 for quadrupolar gravitational radiation).
T_H is Hawking temperature.
$\boldsymbol{M(\omega)}$ is ringdown mode.

Successive echoes imply that the waveform changes to:

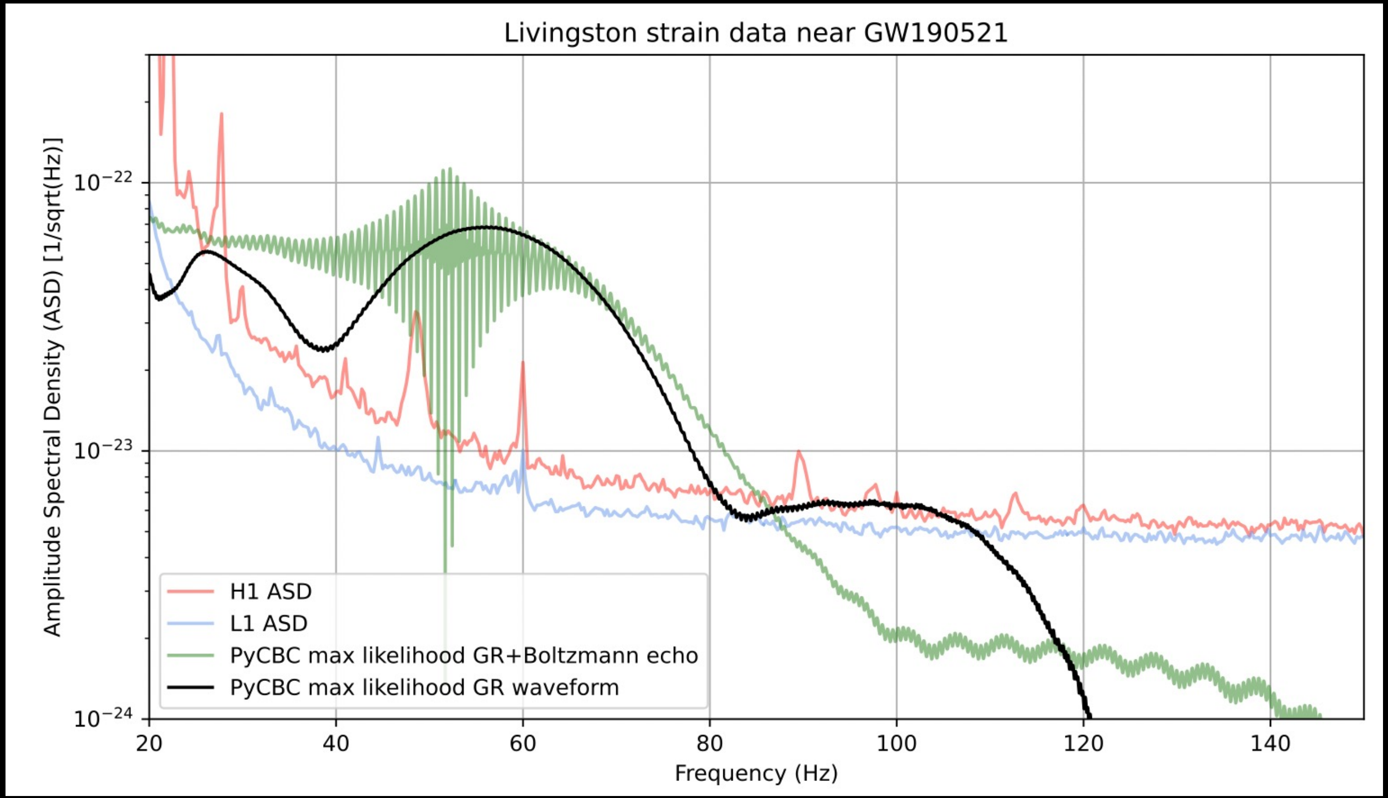
$$h_{\rm GR+echoes}(\omega) = h_{\rm GR}(\omega)\left[1 + Ae^{i\phi}\sum_{n=1}^{\infty}\mathcal{R}^n\right],$$

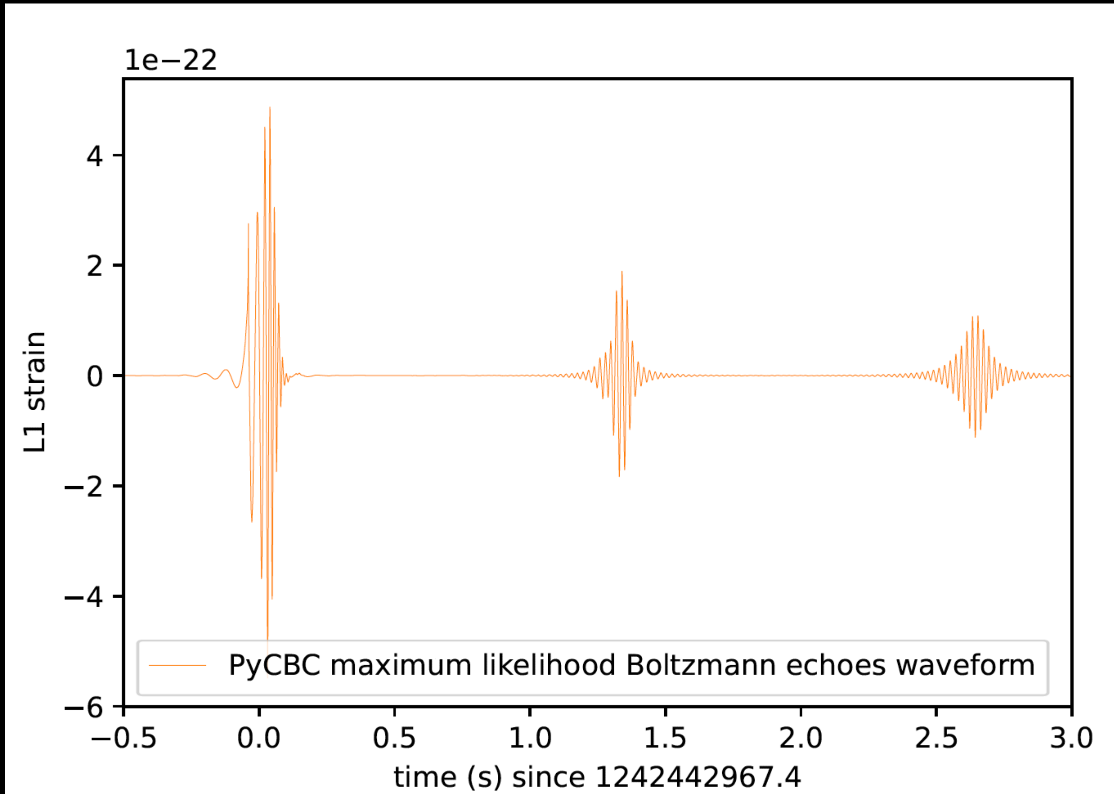
$$\mathcal{R} \equiv \mp \exp\left[-\frac{\hbar|\omega - 2\Omega_H|}{2kT_H} + i\omega\Delta t_{\rm echo}\right]$$

Boltzmann Echoes (Oshita, et al., 2020)



Boltzmann echoes



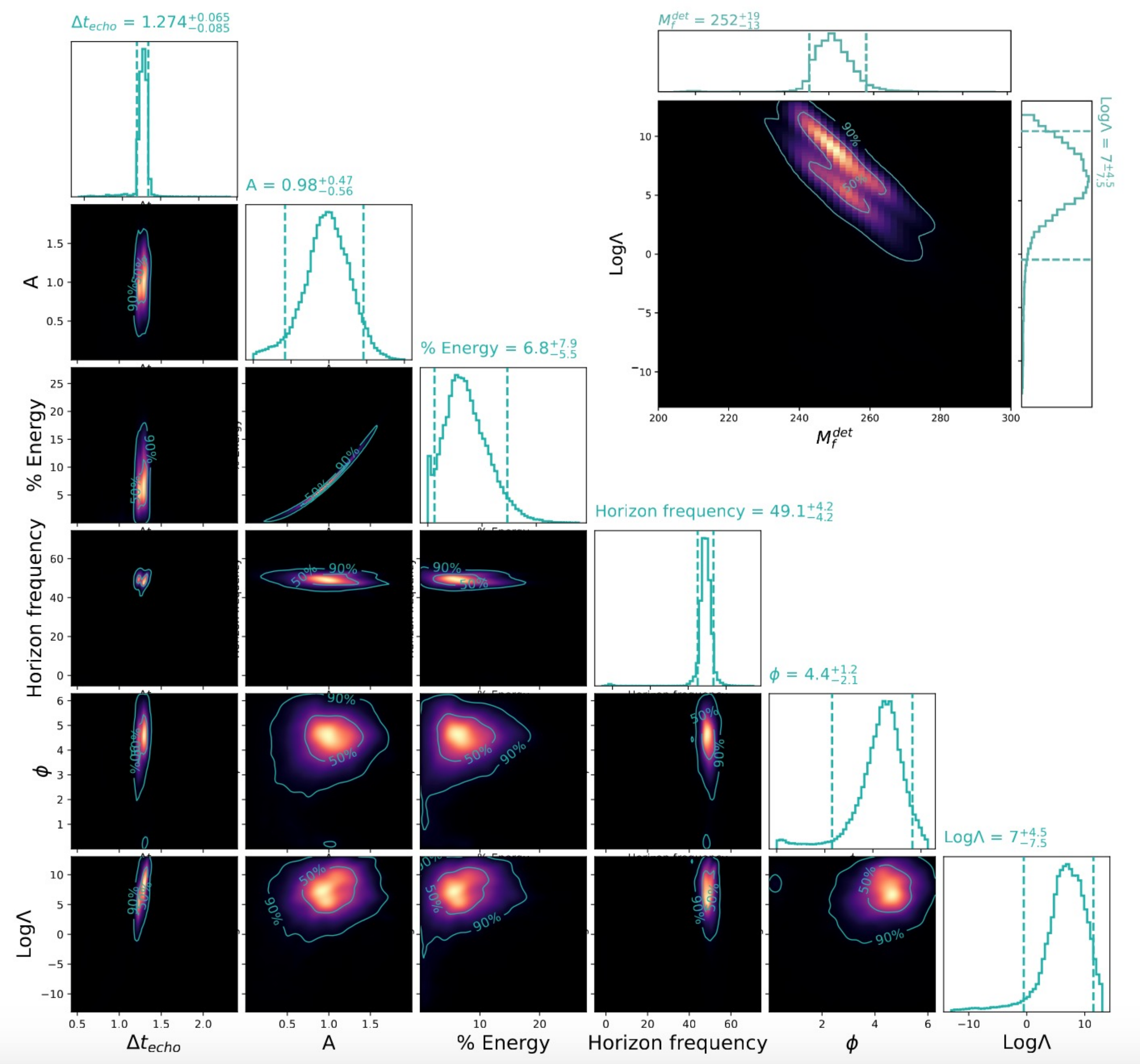


GW190521

arXiv:2201.00047

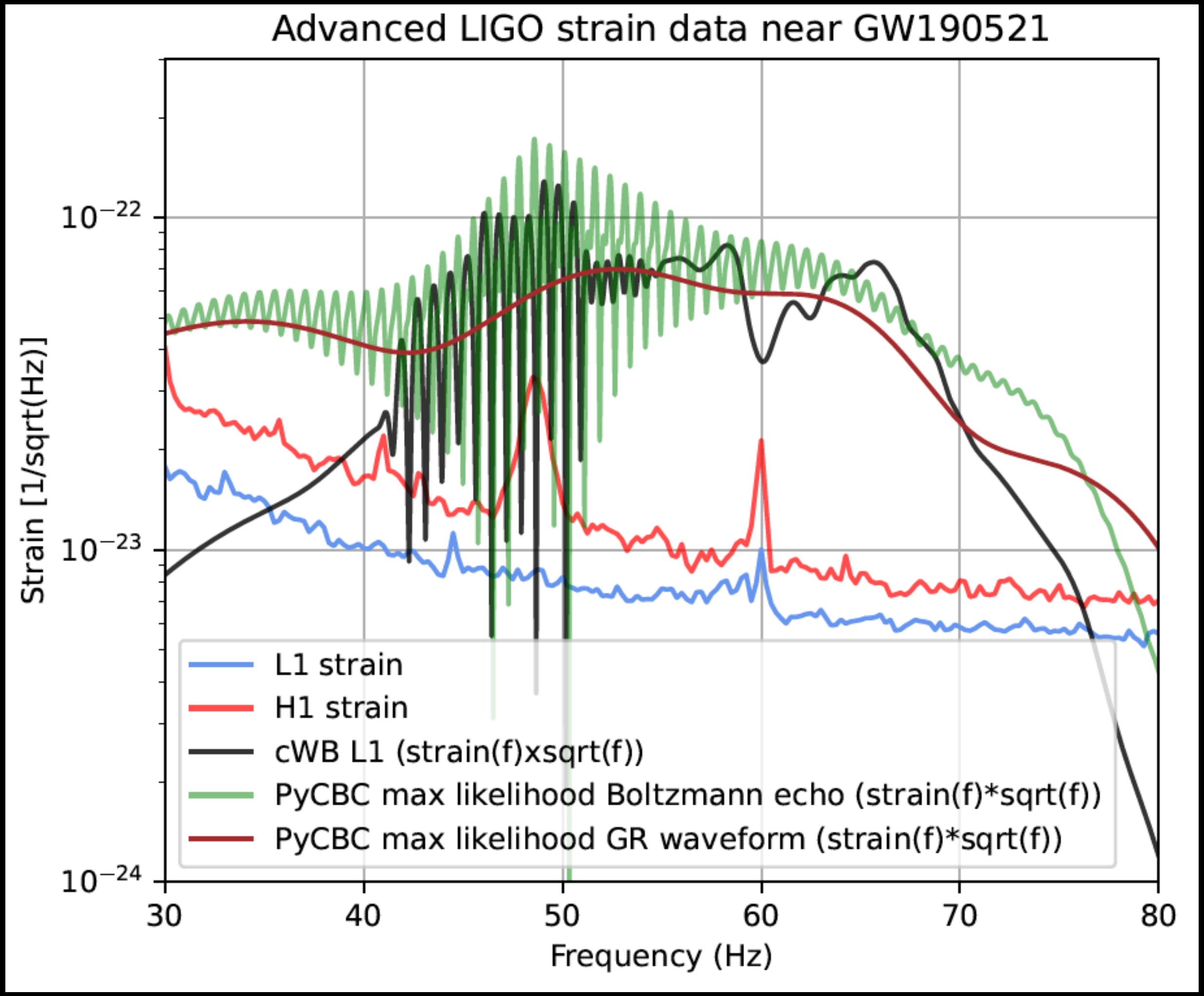
Bayes factor = 7

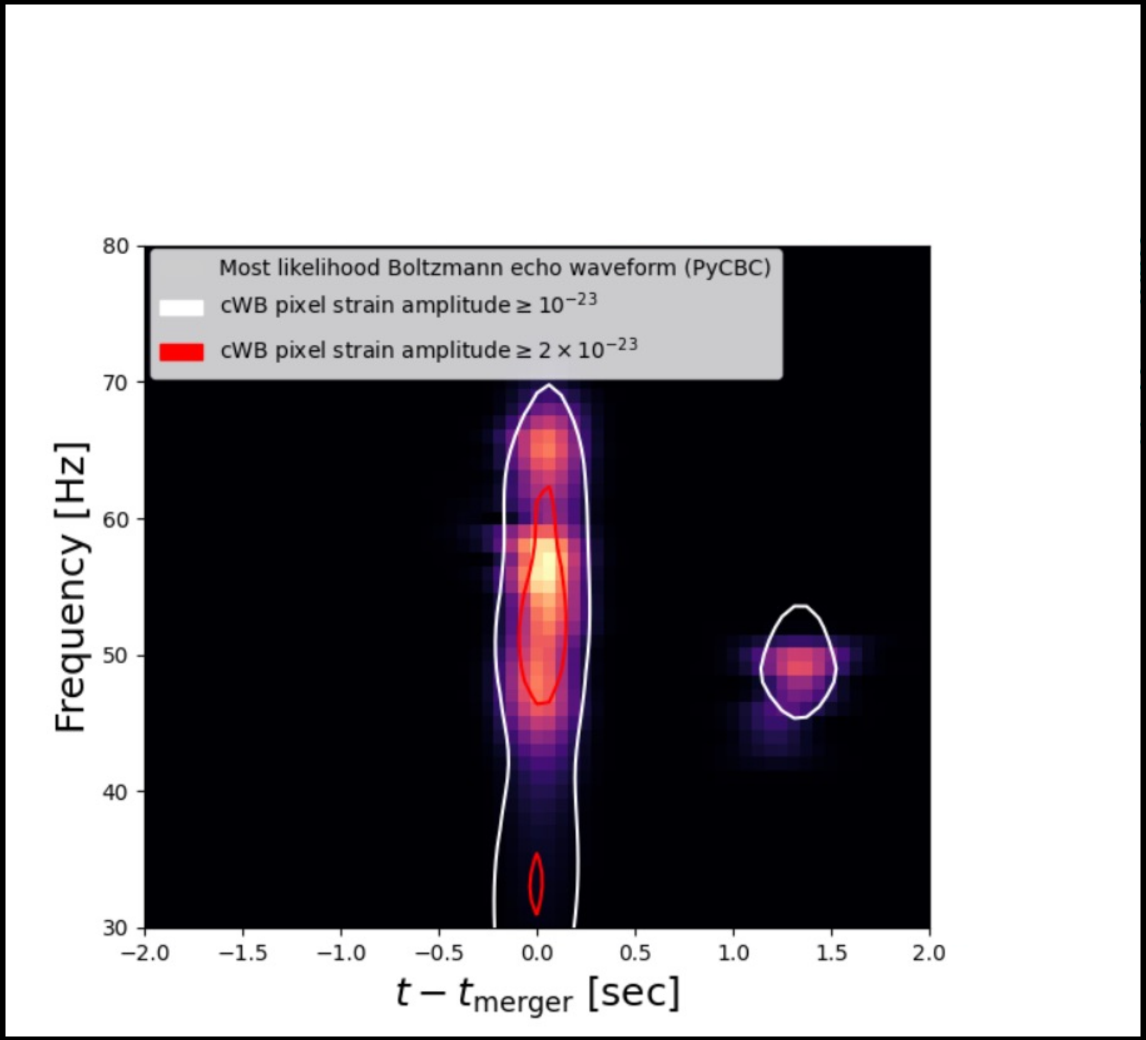
Preference for echoes



GW190521

PyCBC vs cWB





Combining 65 LVK events

We assume echo model is the same for all the events

In particular we assume all the events have same echo amplitude A compared to their main event signal

GW191222_033537	GW170729	GW190929_012149
GW200220_061928	GW190412	GW190828_063405
GW151012	GW190424_180648	GW190630_185205
GW190915_235702	GW200202_154313	GW200224_222234
GW191109_010717	GW200225_060421	GW200219_094415
GW190602_175927	GW200209_085452	GW170818
GW190527_092055	GW190408_181802	GW190910_112807
GW170809	GW190706_222641	GW150914
GW190503_185404	GW190727_060333	GW200208_130117
GW191230_180458	GW170608	GW191216_213338
GW190620_030421	GW190708_232457	GW190521
GW190514_065416	GW190720_000836	GW190925_232845
GW190728_064510	GW190731_140936	GW200112_155838
GW190814	GW200311_115853	GW200216_220804
GW200128_022011	GW190421_213856	GW191215_223052
GW170814	GW190413_134308	GW190512_180714
GW170104	GW190517_055101	GW151226
GW200302_015811	GW170823	GW190521_074359
GW190828_065509	GW200316_215756	GW190924_021846
GW191129_134029	GW190719_215514	GW191204_171526
GW190707_093326	GW190513_205428	GW190413_052954
GW200129_065458	GW190519_153544	

Combining 65 LVK events

We fix the amplitude A for all events and combine the bayes factors

$$Overall\ Bayes\ factor = \prod_{i=events} B_i(A)$$

Successive echoes imply that the waveform changes to:

$$h_{\mathrm{GR+echoes}}(\omega) = h_{\mathrm{GR}}(\omega)\left[1 + Ae^{i\phi}\sum_{n=1}^{\infty}\mathcal{R}^n\right]$$

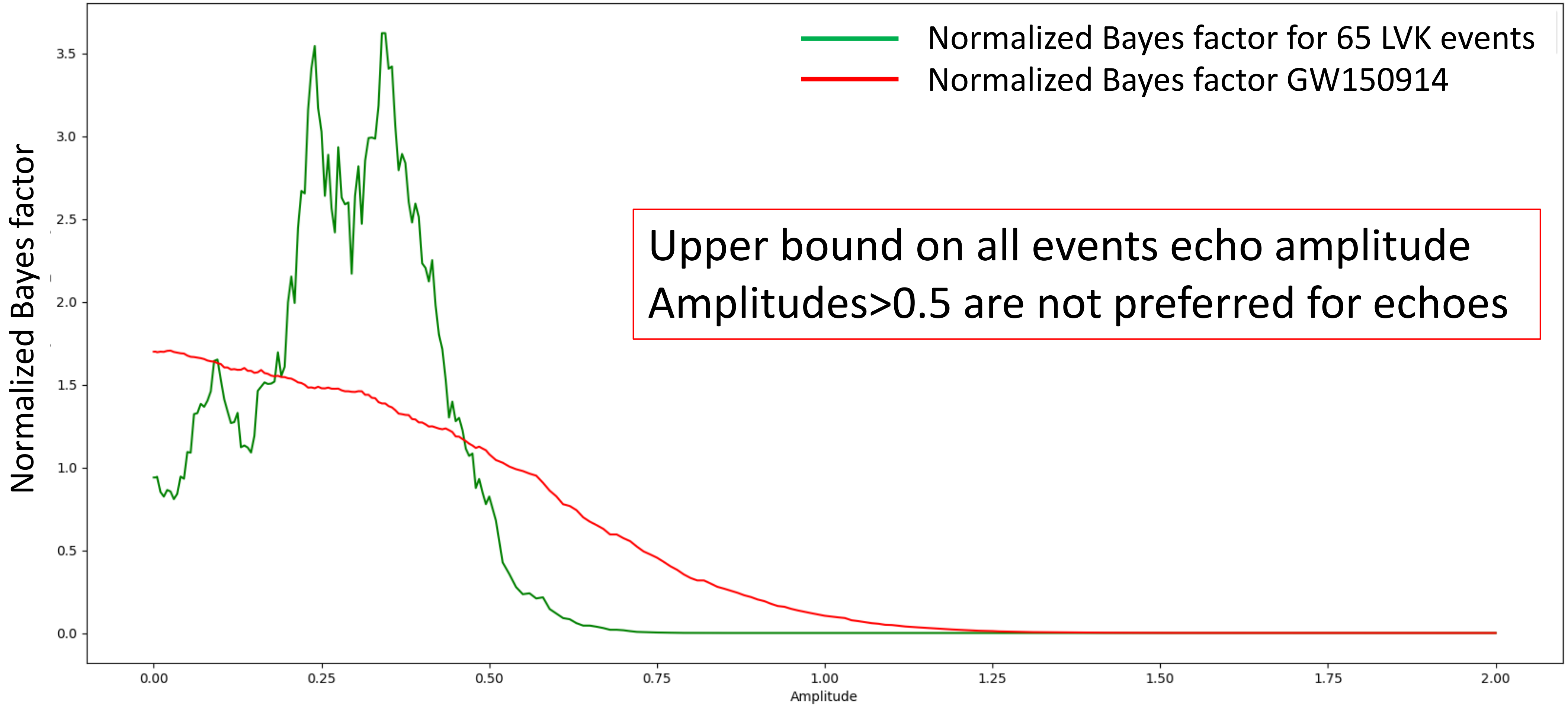
$$\mathcal{R} \equiv \mp \exp\left[-\frac{\hbar|\omega - 2\Omega_H|}{2kT_H} + i\omega\Delta t_{\mathrm{echo}}\right]$$

Boltzmann Echoes (Oshita, et al., 2020)

We vary the amplitude A within 0-2 and plot overall Bayes factor in terms of A

Combining 65 LVK events

Will be published soon



Combining 65 LVK events

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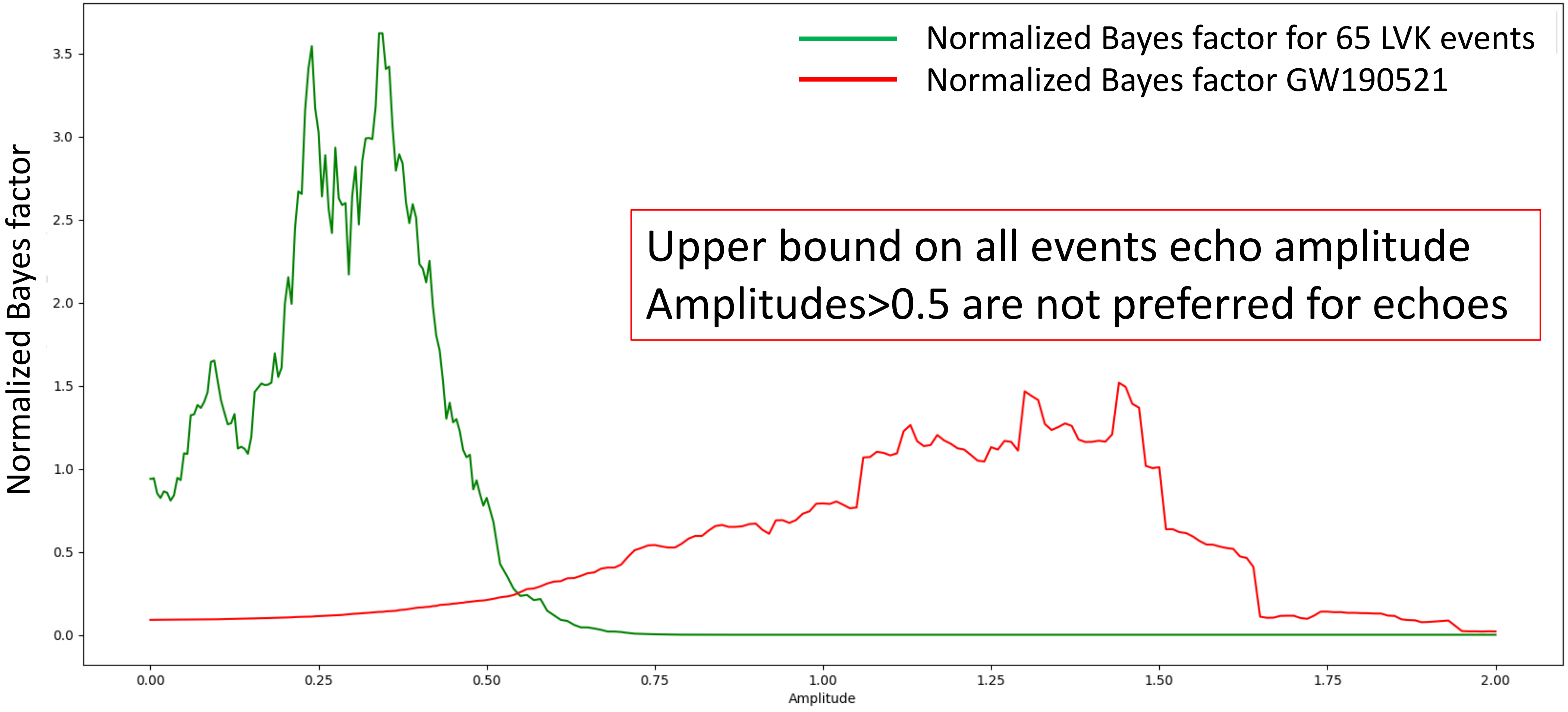
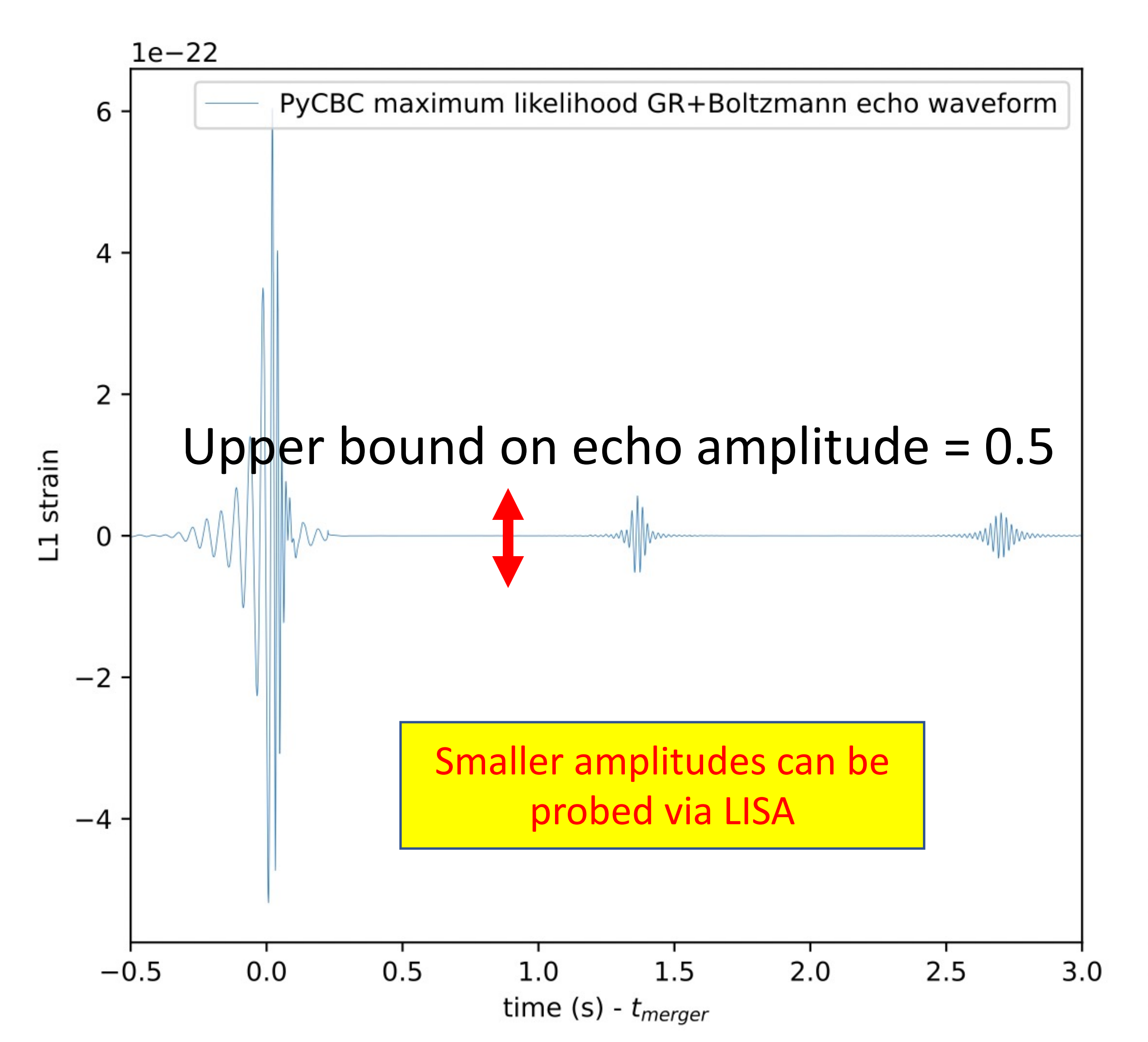


Combining 65 LVK events



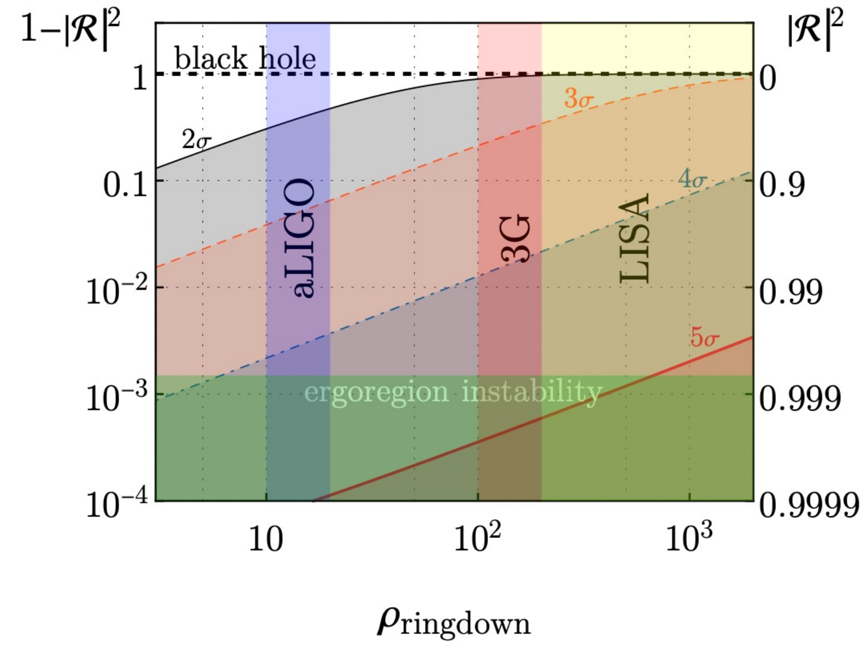


FIG. 6. Projected exclusion plot for the ECO reflectivity $\mathcal{R}$ as a function of the SNR in the ringdown phase. The shaded areas represent regions that can be excluded at a given confidence level (2σ, 3σ, 4σ, 5σ). Vertical bands are typical SNR achievable by aLIGO/Virgo, 3G, and LISA in the ringdown phase, whereas the horizontal band is the region excluded by the ergoregion instability [40, 41]. We assumed $\chi = 0.7$ for the spin of the merger remnant, the result depends only mildly on the spin.

Maggio et. al. 2019 arXiv:1907.03091

- **Conclusion**
- We found upper bound for amplitude of echoes with combining 65 events.
- Next generation detectors such as LISA using this search can give a better constraint on amplitude of echoes from massive binary black holes and extreme mass ratio inspirals.

Thank you