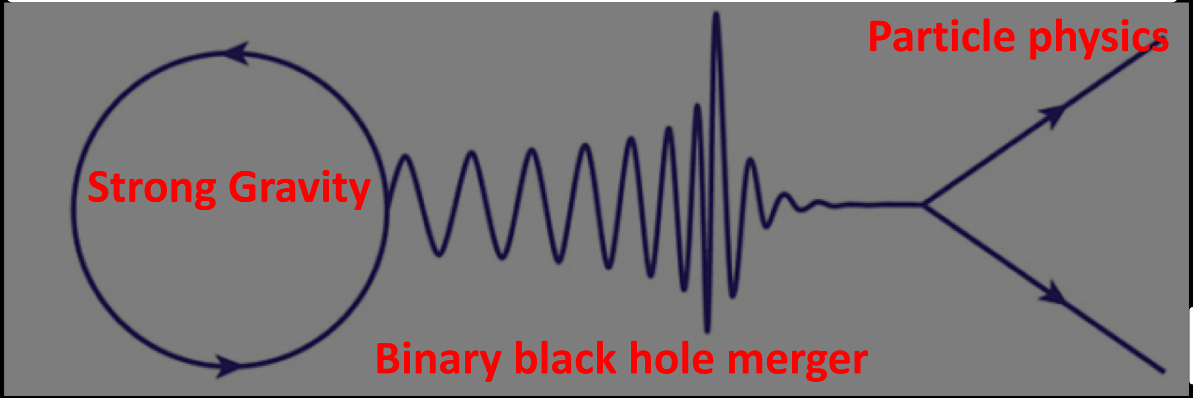
GW190521: Search for Echoes due to Stimulated Hawking Radiation from Black Holes

University of Stavanger

Jahed Abedi



GRASS Padova 2022
GRAvitational-wave Science&technology Symposium

In collaboration with Luis F. Longo & Niayesh Afshordi arXiv:2201.00047

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

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

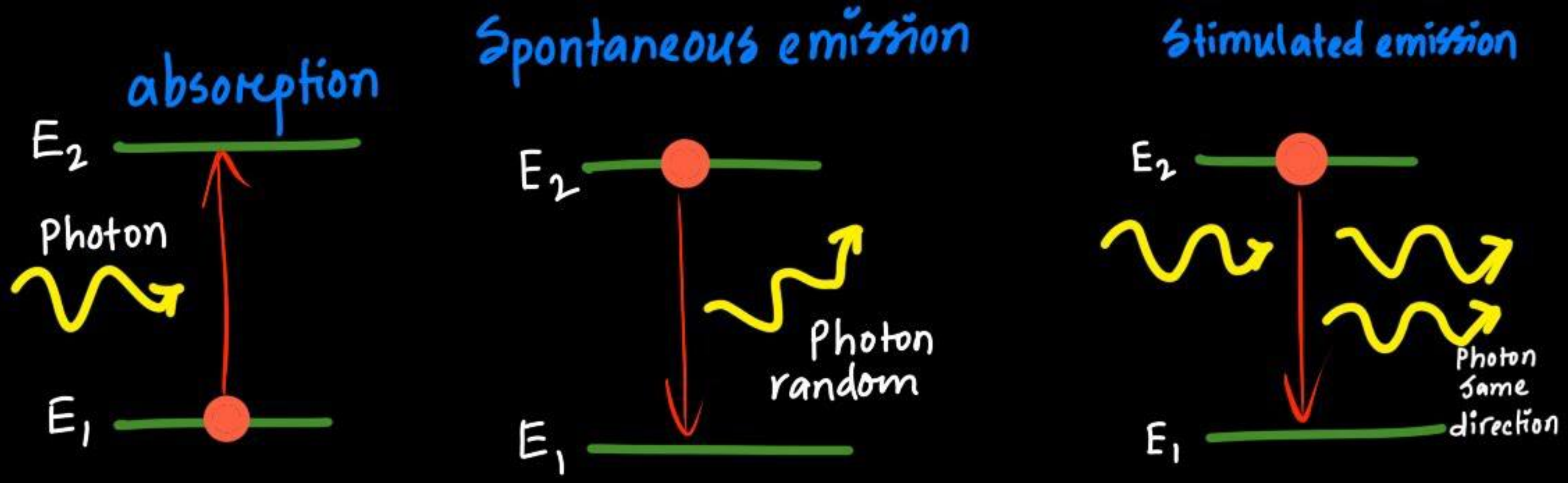
$$G_{\mu\nu} = \langle T_{\mu\nu} \rangle$$

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 $M^3/M^2 = M$

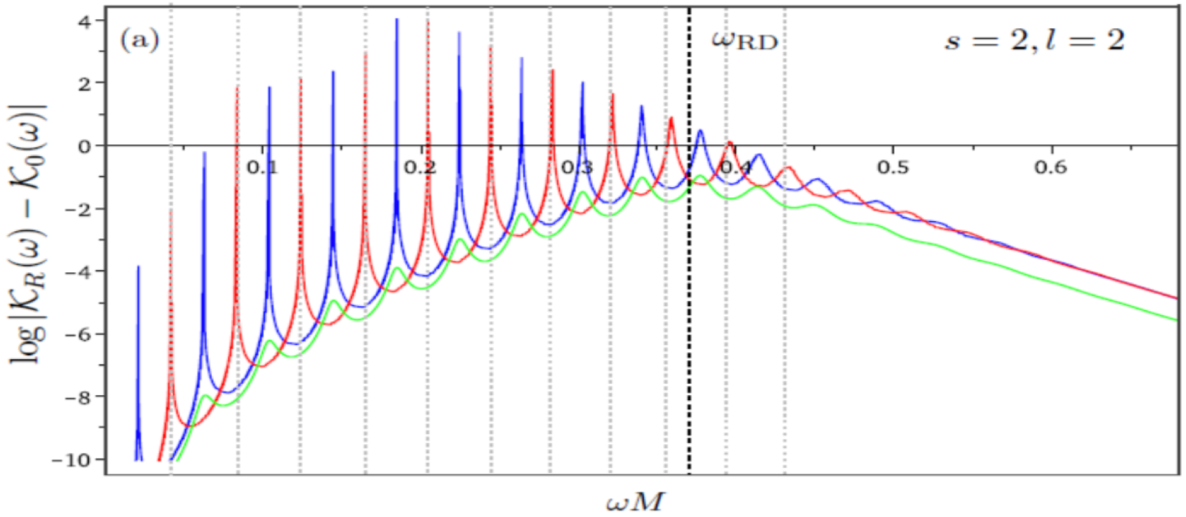
Quantum mechanics imply that we have minimum Planck length, which is **about 10^{-35} meters**.

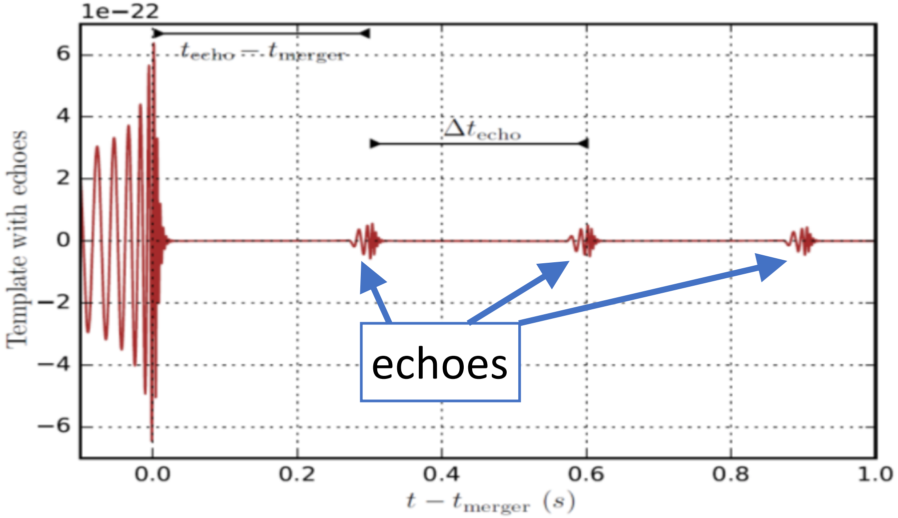
So the time for the waves reaching the minimum distance of return (**Planckian** horizon) is not infinite.

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



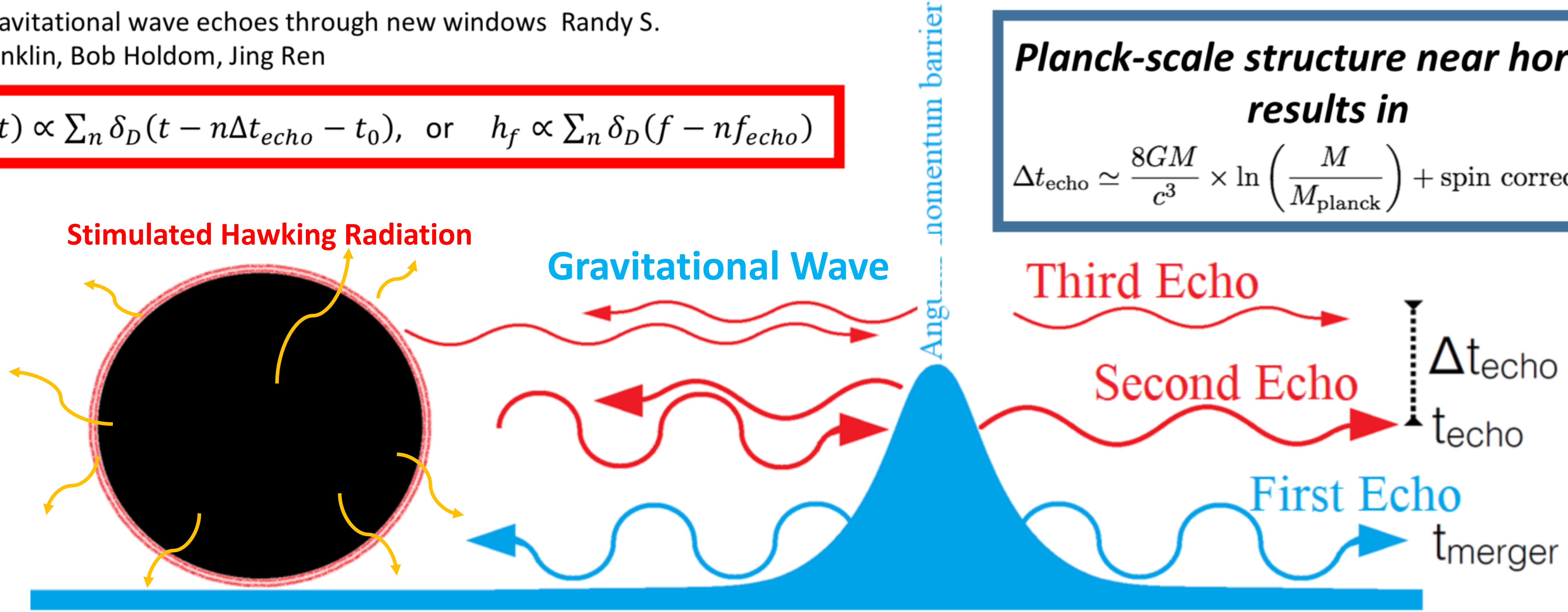


Gravitational wave echoes through new windows Randy S. Conklin, Bob Holdom, Jing Ren

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

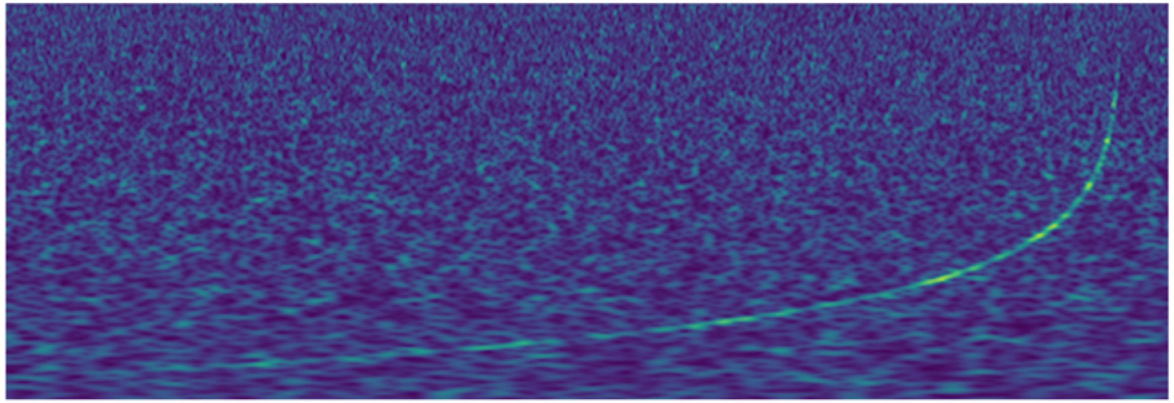
Planck-scale structure near horizon results in

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



PyCBC

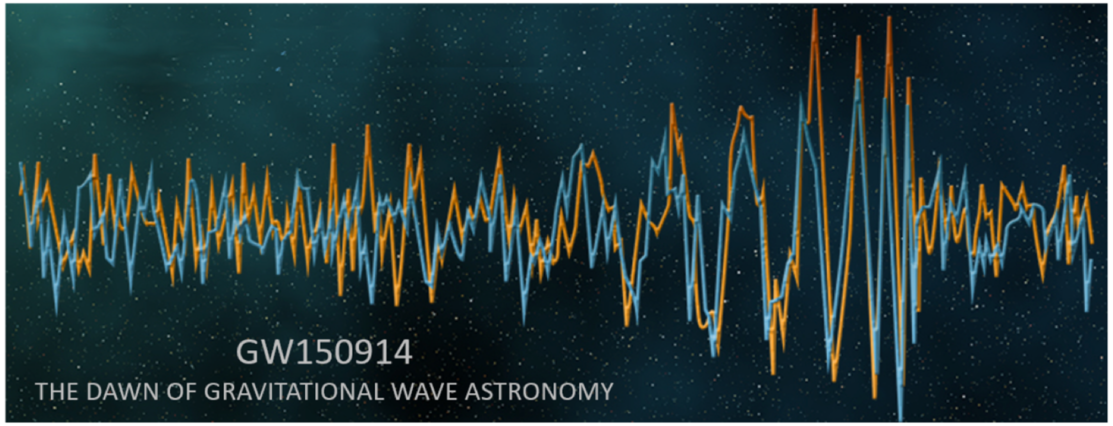
Free and open software to study gravitational waves.



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.

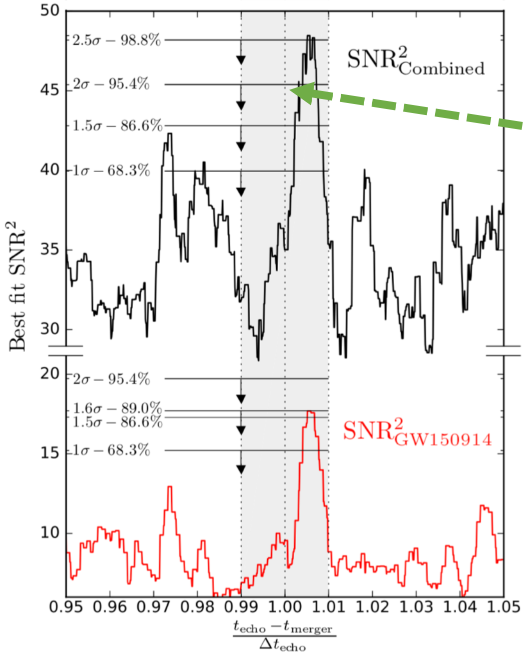
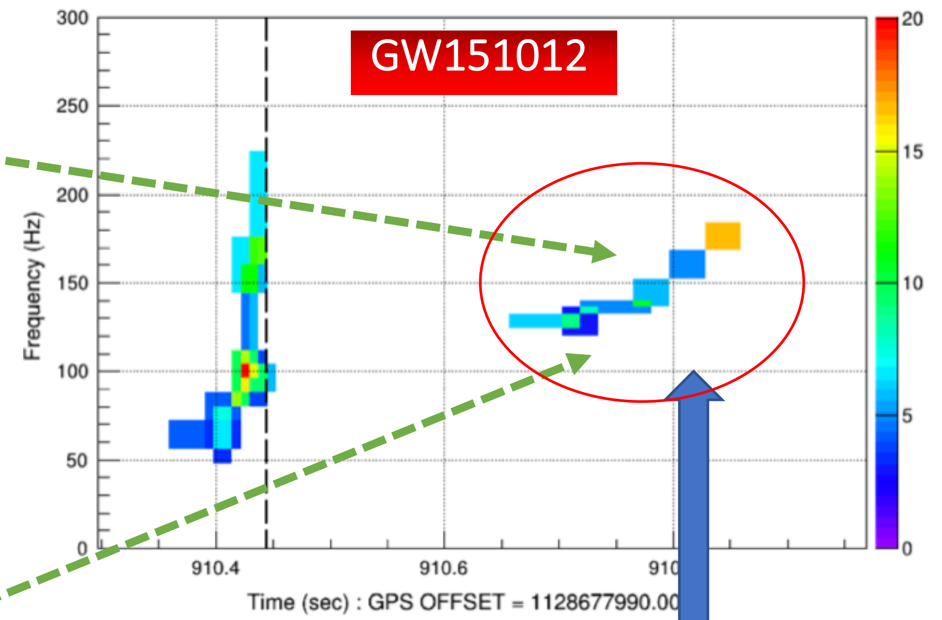


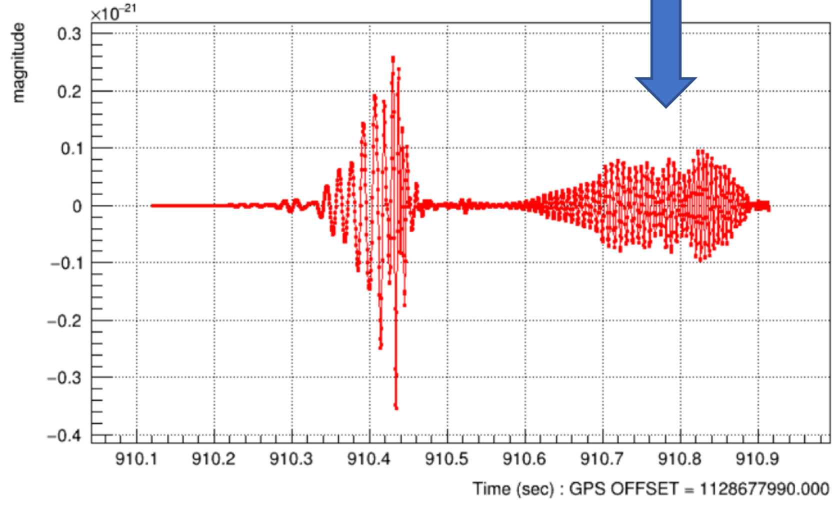
FIG. 4: Best fit (or maximum) SNR^2 near the expected time of merger echoes (Eq's. 1 and 6), for the combined (top) and GW150914 (bottom) events. The significance of the peaks is quantified by the p-value of their SNR_{max} within the gray rectangle (see Appendix E for detail of calculation).

	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
$\|A_{best,I}\|$	0.091	0.33	0.34
$SNR_{best,I}$	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

Co-localization of GW151012

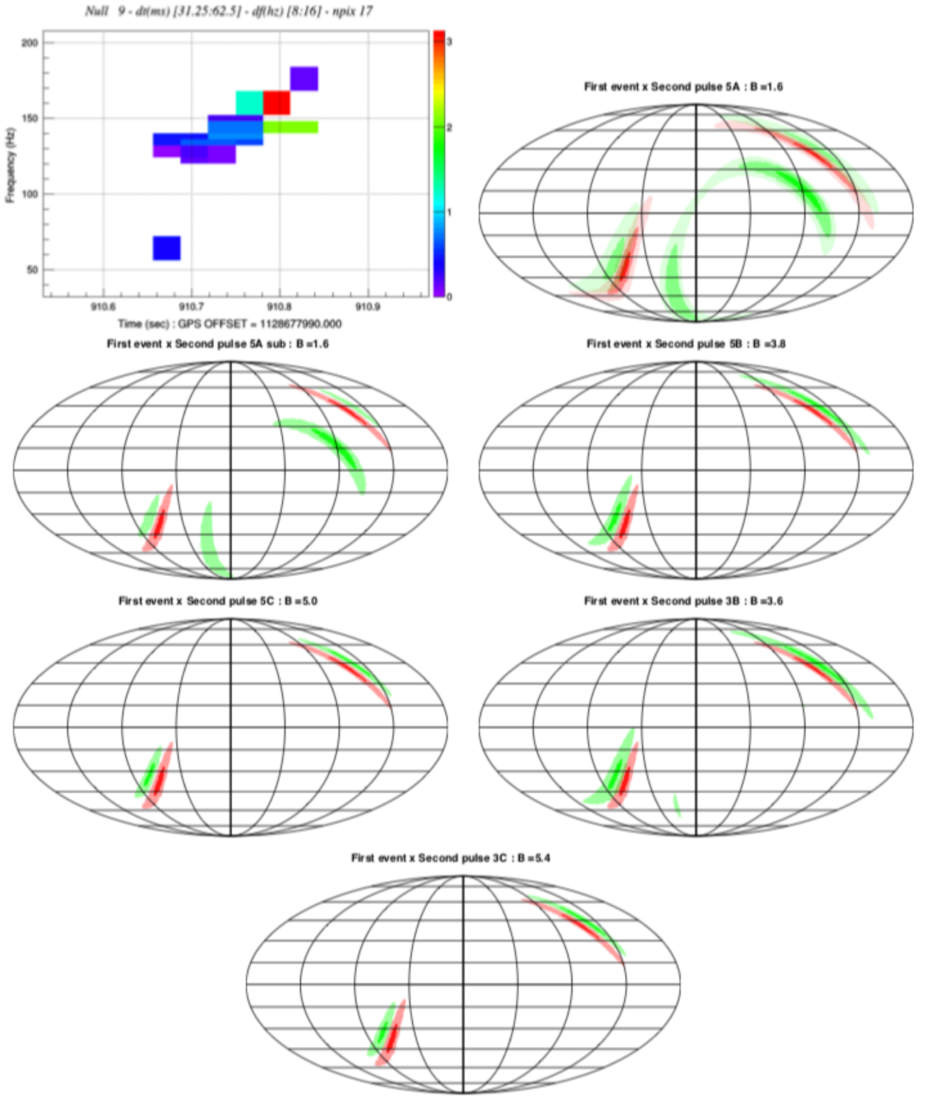
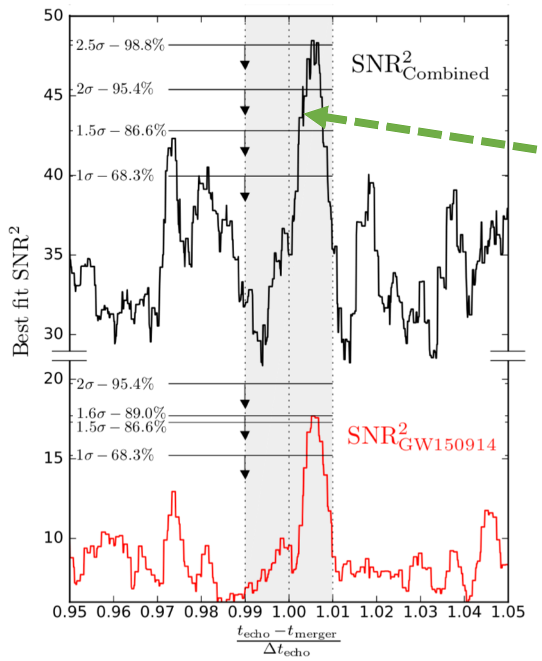


FIG. 7: Co-localization analysis for GW151012. We performed several reconstructions with different search thresholds. The panels are named according to their thresholds: A-B-C index relates with different search parameters configurations and the numbers (5 or 3) relates pixel pattern configuration [54]. All searches prefer the hypothesis of sky co-localization of echoes and main event, at Bayes factors of 1.6-5.4.

All searches for GW151012 prefer the hypothesis of sky co-localization of echoes and main event, at Bayes factors of 1.6-5.4.

Luis F. Longo

Abedi et al (Dec 2021)



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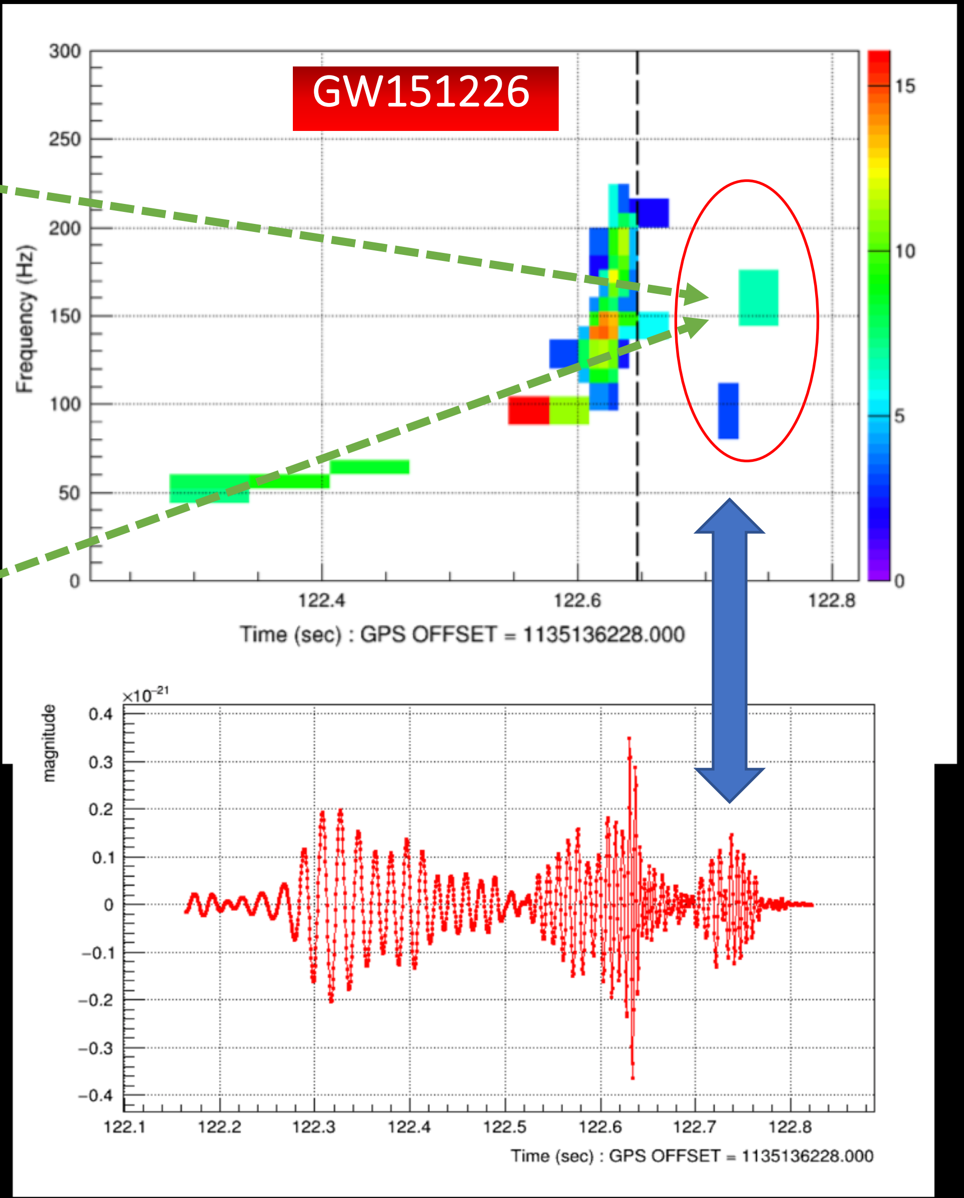


Credit: Salemi et al, 2019

Echoes from GW170817:

2019 Buchalter Cosmology First Prize,

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

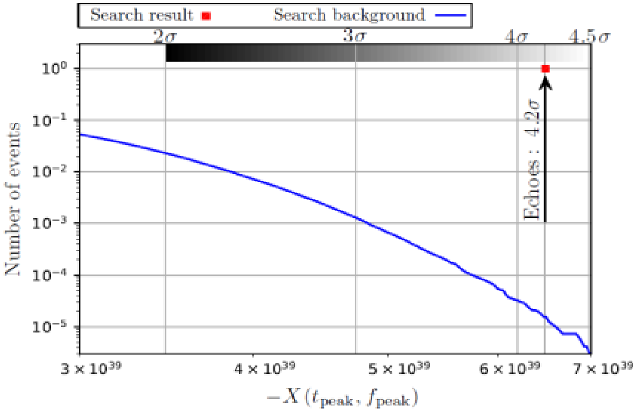


FIG. 5: Average number of noise peaks higher than a particular -X(t,f) within a frequency-intervals of 63-92 Hz and time-intervals of 1 sec for LIGO noise near GW170817 event. The red square shows the observed $-X(t_{\rm peak}, f_{\rm peak})$ peak at 1.0 sec after the merger. The horizontal bar shows 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].

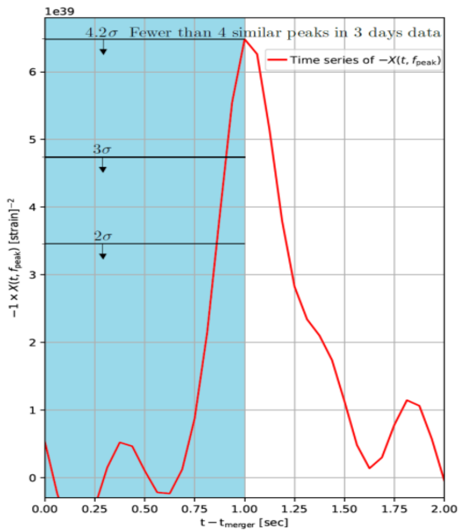
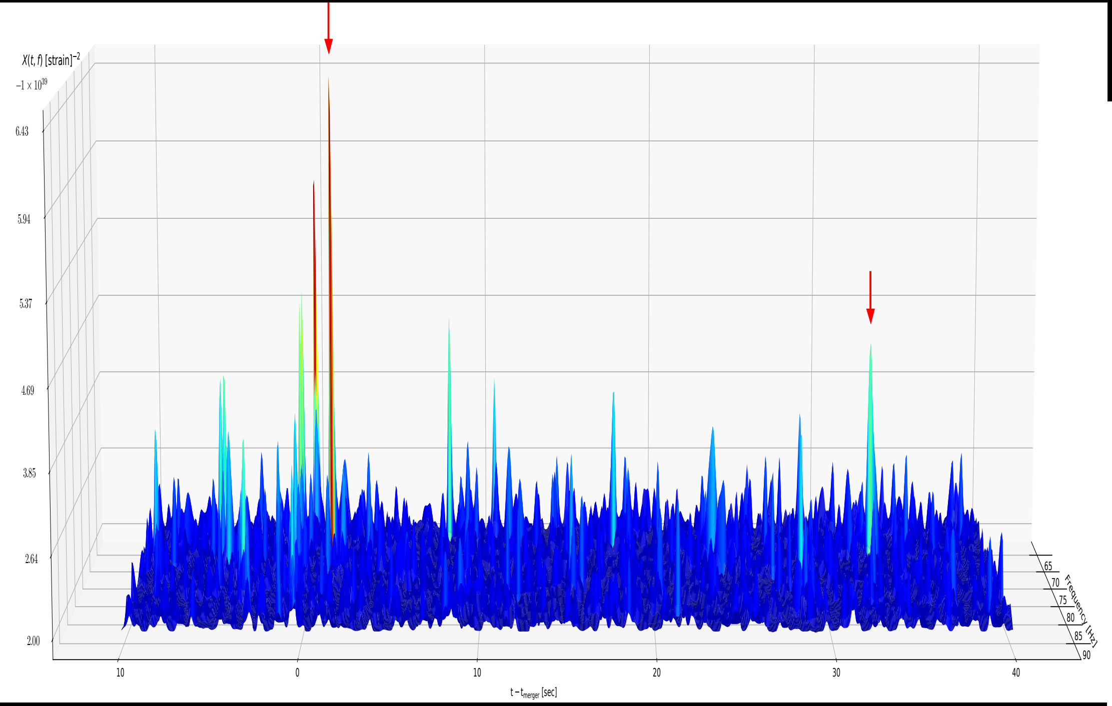
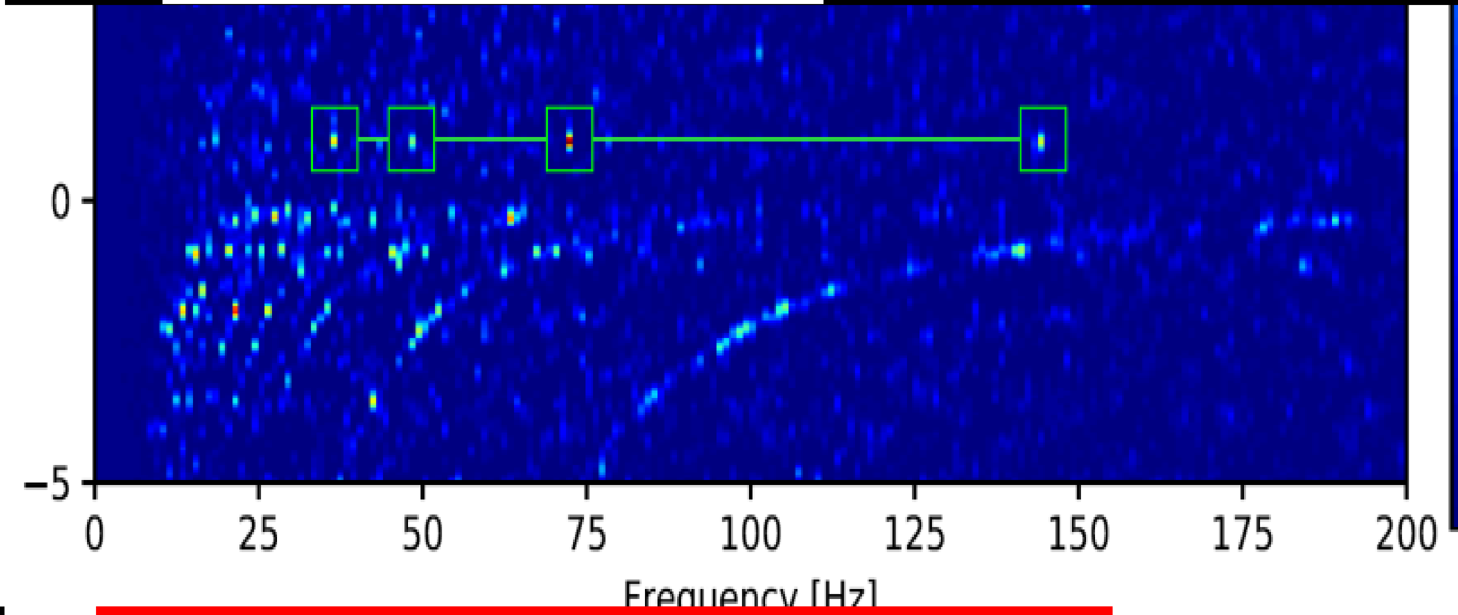


FIG. 6: Amplitude-time representations of first (and most significant) echo peak at 1.0 sec after the merger and frequency of 72 Hz. The shaded region is 0-1 sec prior range after the merger, first adopted in [21], which we use to estimate p-value . The maximum of the peak is 6.48×10^{39}.





Abedi & Afshordi 2018 **arXiv:1803.10454**

Confirmation

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

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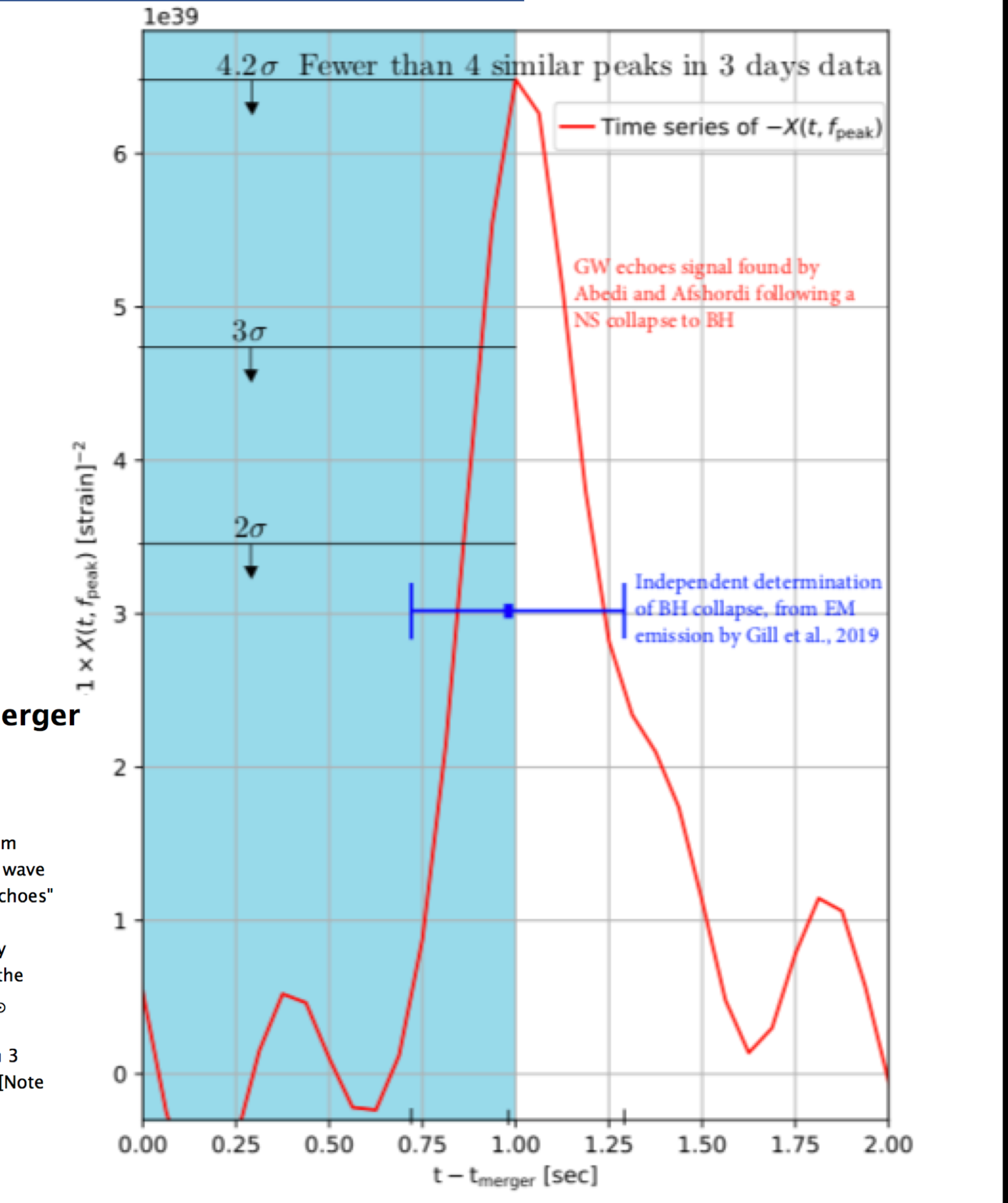
ABSTRACT

The main hard pulse of prompt gamma-ray emission in GRB 170817A had a duration of $\sim 0.5\,\mathrm{s}$ and its onset was delayed with respect to the gravitational-wave chirp signal by $t_{\rm del} \approx 1.74\,\mathrm{s}$. 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 $t_{\rm coll} = 0.98^{+0.31}_{-0.26}\,\mathrm{s}$. 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

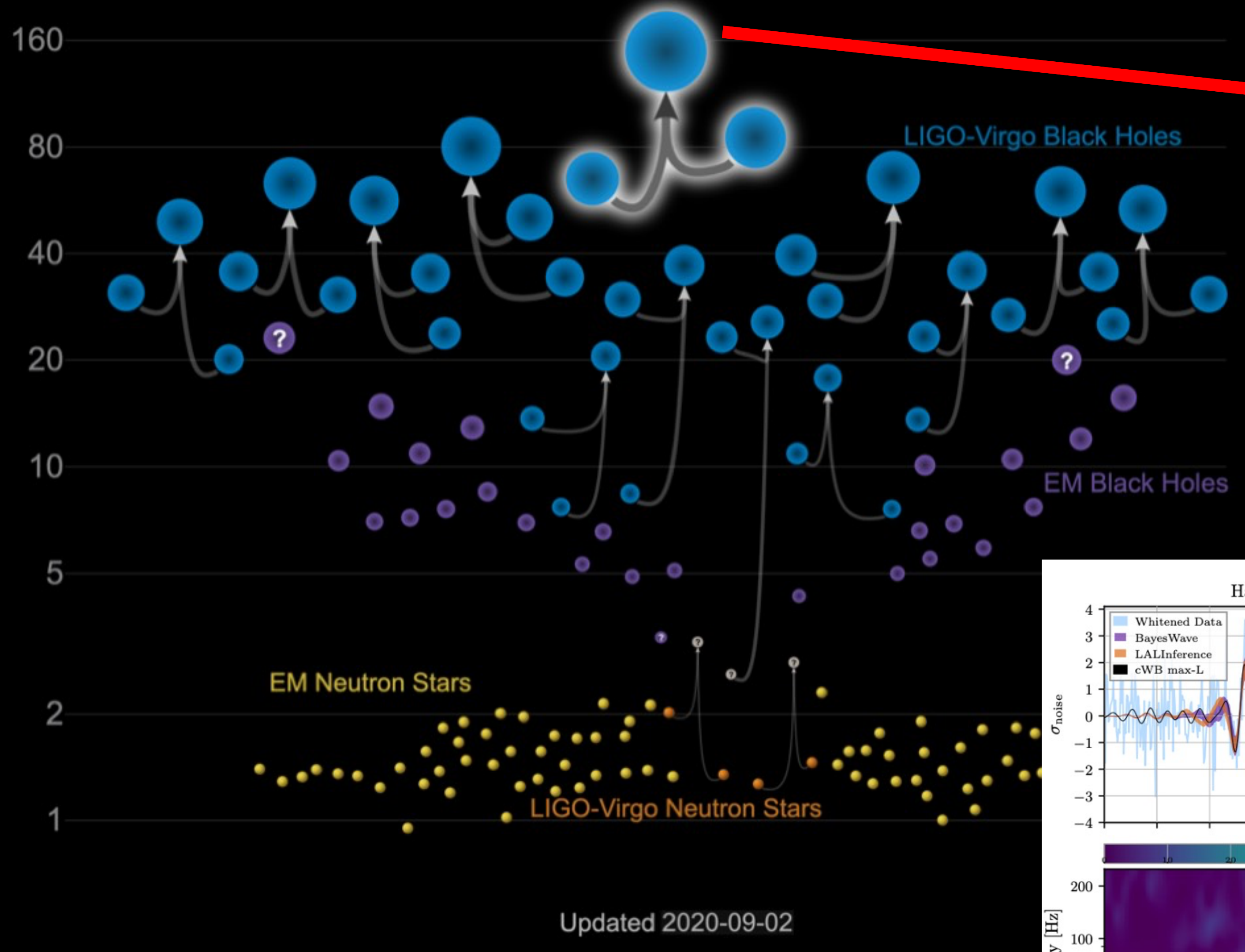
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration:

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

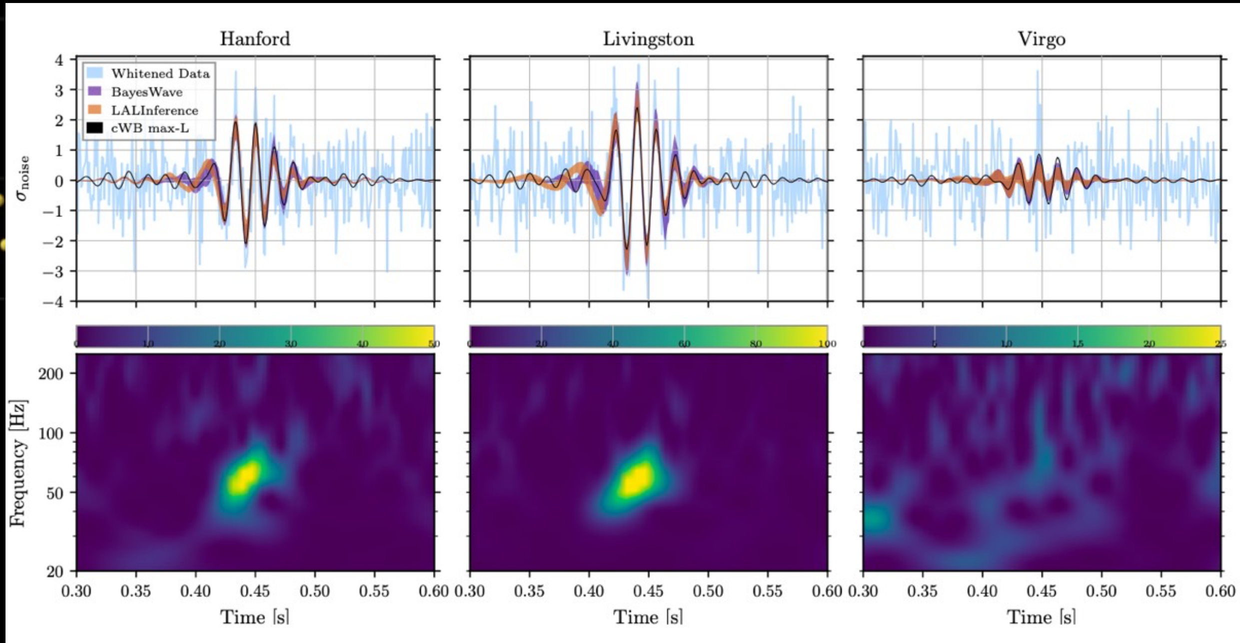
GW190521 the most massive and energetic black-hole merger yet.



GW190521

9 solar masses were radiated as energy in the form of gravitational waves

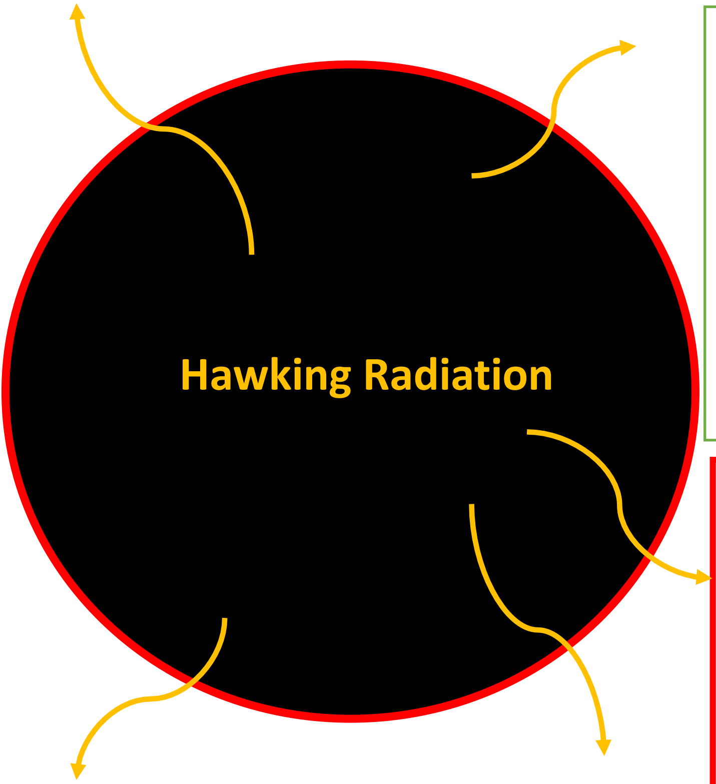
Mass equivalent to 142 times that of the Sun, making this the first clear detection of an intermediate-mass black hole.



Boltzmann reflectivity

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

ω Frequency at infinity



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

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

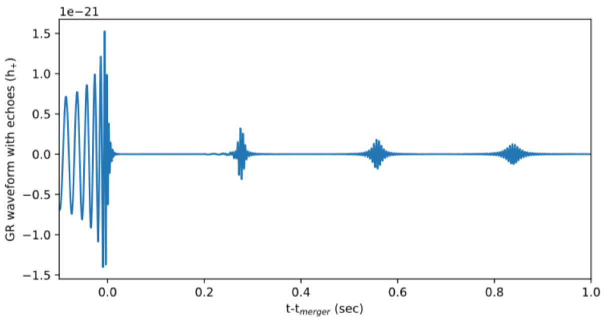
m=2 for quadrupolar gravitational radiation).
T_H is Hawking temperature.
$\boldsymbol{M(\omega)}$ is ringdown mode.

Successive echoes imply that the waveform changes to:

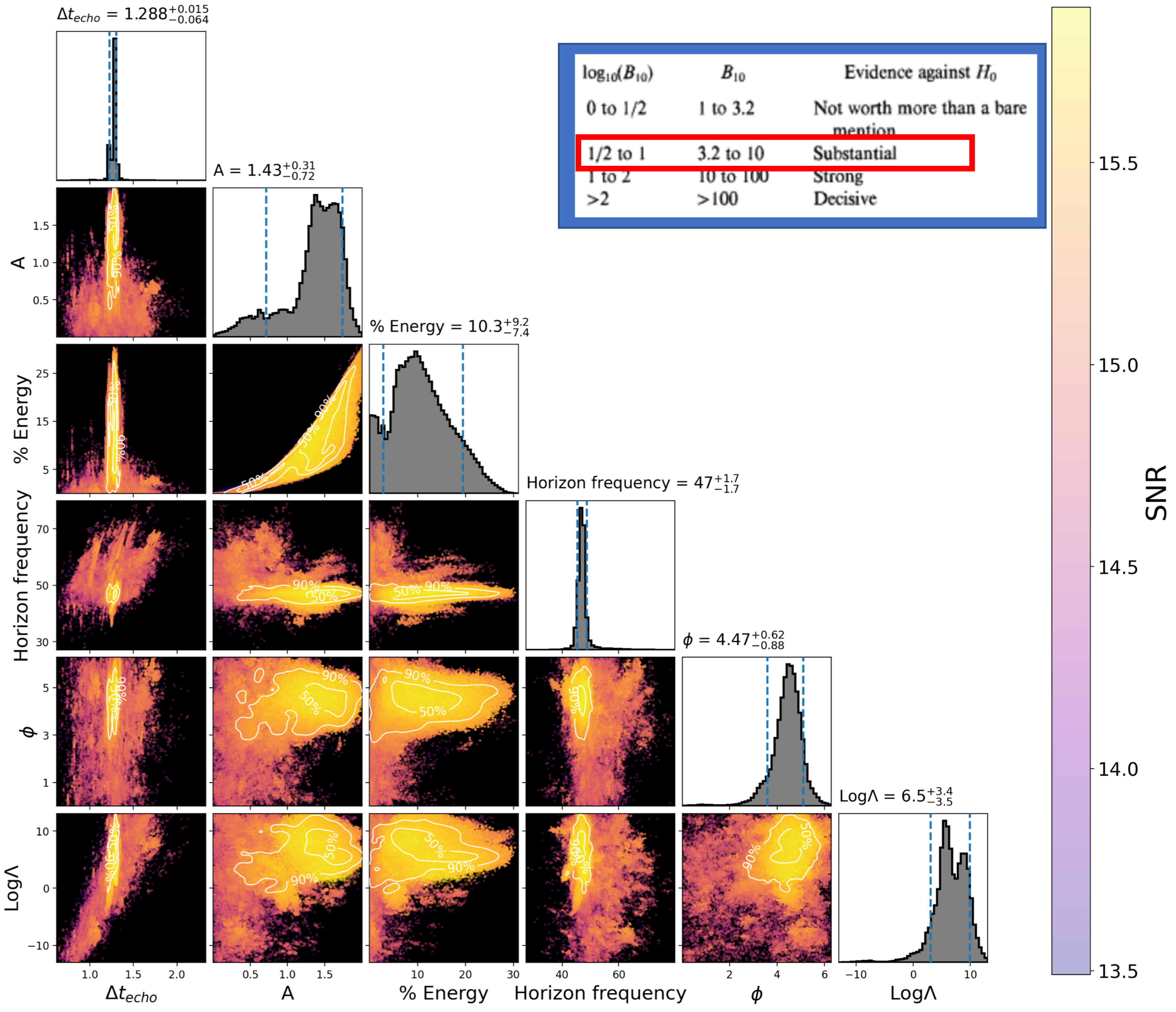
$$h_{\rm GR+echoes}(\omega) = h_{\rm GR}(\omega)\left[1 + Ae^{i\phi}\sum_{n=1}^{\infty}\mathcal{R}^n\right],$$

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

Boltzmann Echoes (Oshita, et al., 2020)



$\log_{10}(B_{10})$	B_{10}	Evidence against H_0
0 to 1/2	1 to 3.2	Not worth more than a bare mention
1/2 to 1	3.2 to 10	Substantial
1 to 2	10 to 100	Strong
>2	>100	Decisive

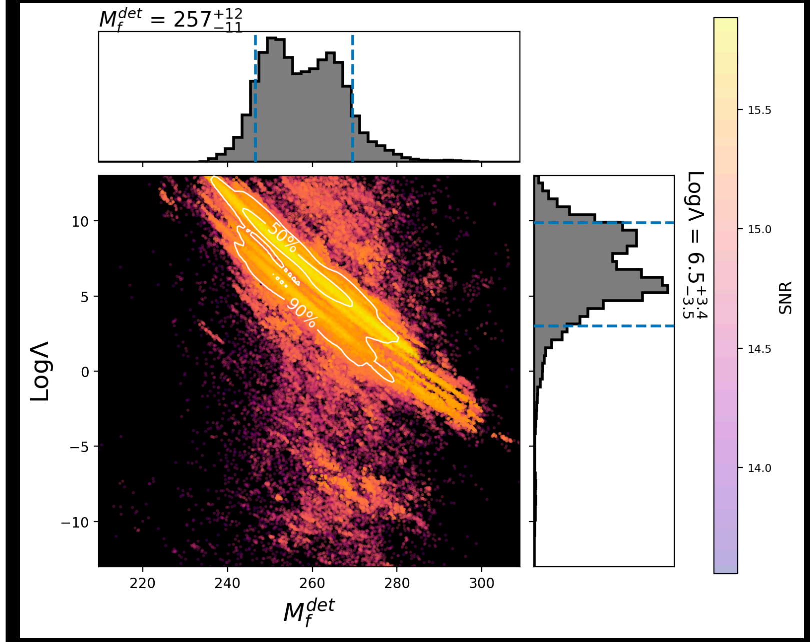


Bayes factor = 7

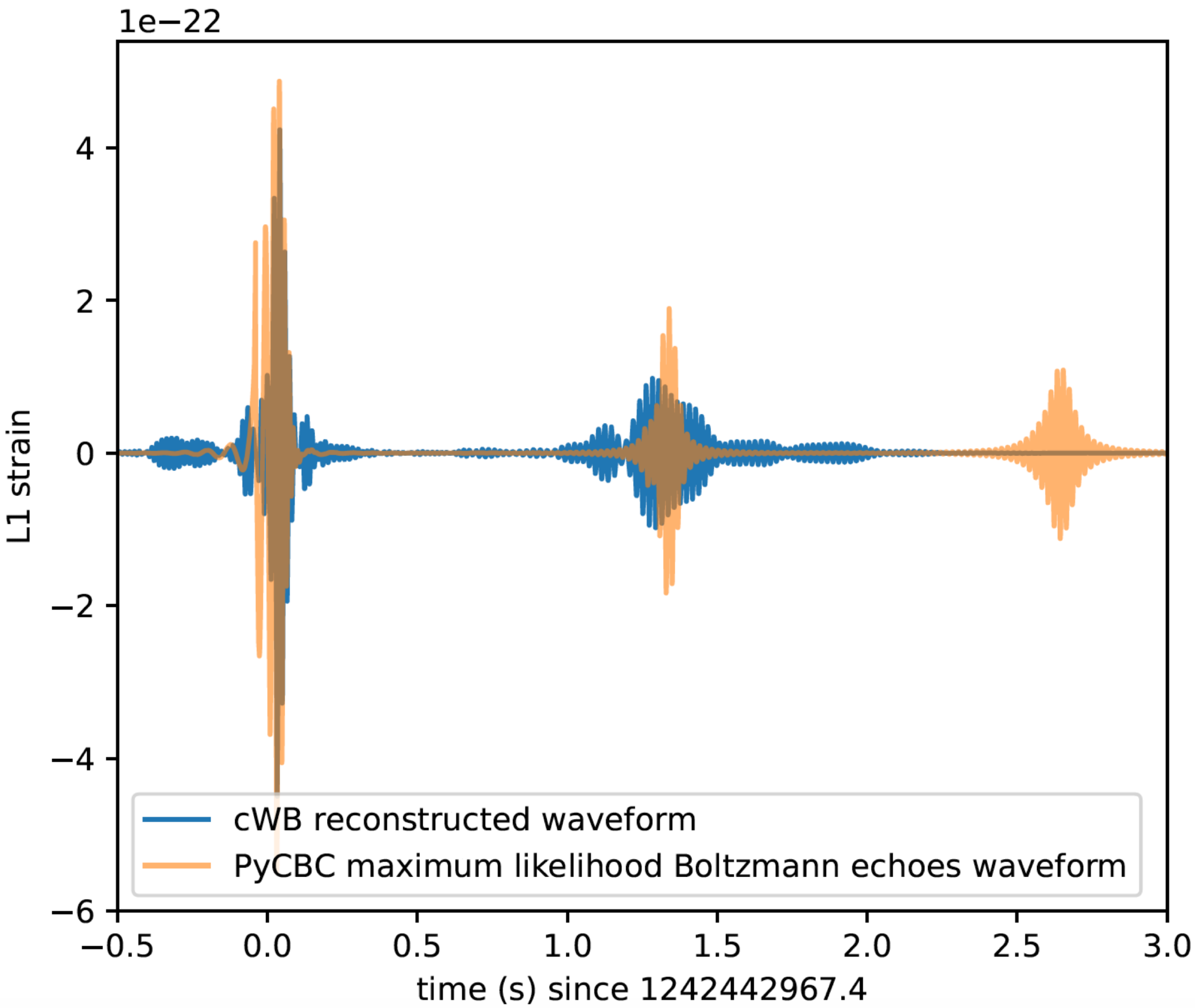
Preference for echoes

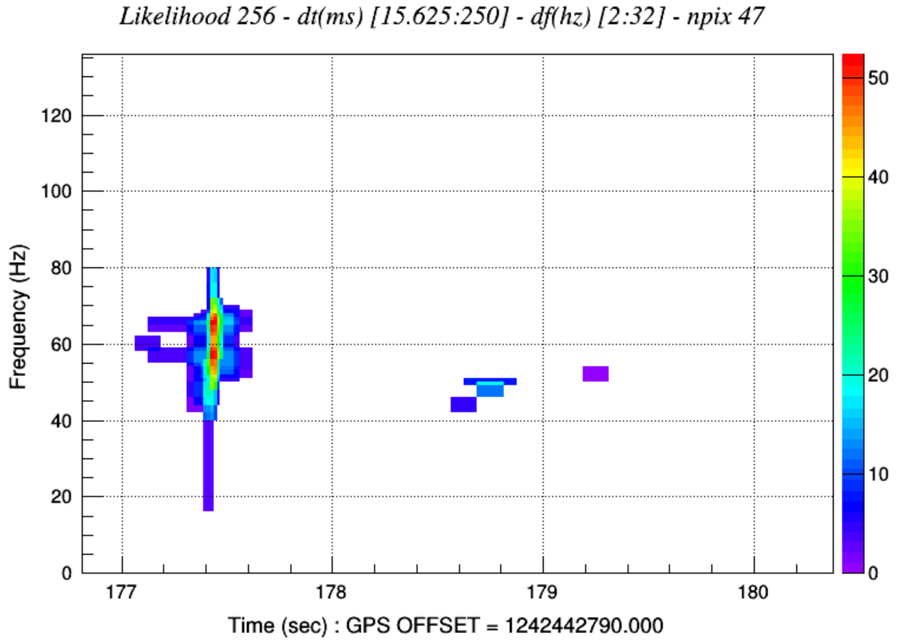
$$l_P \rightarrow l_P/\Lambda$$

$$-12 < log\Lambda < 12$$



Reconstructed waveform from **cWB** and **PyCBC** pipline





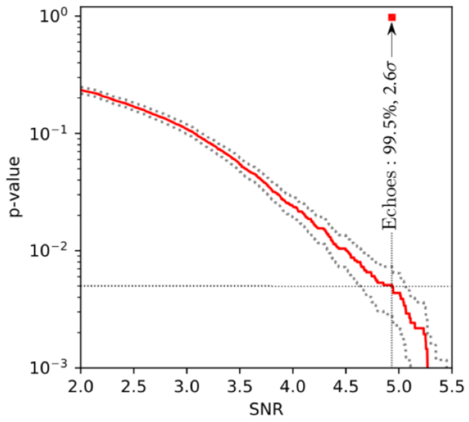
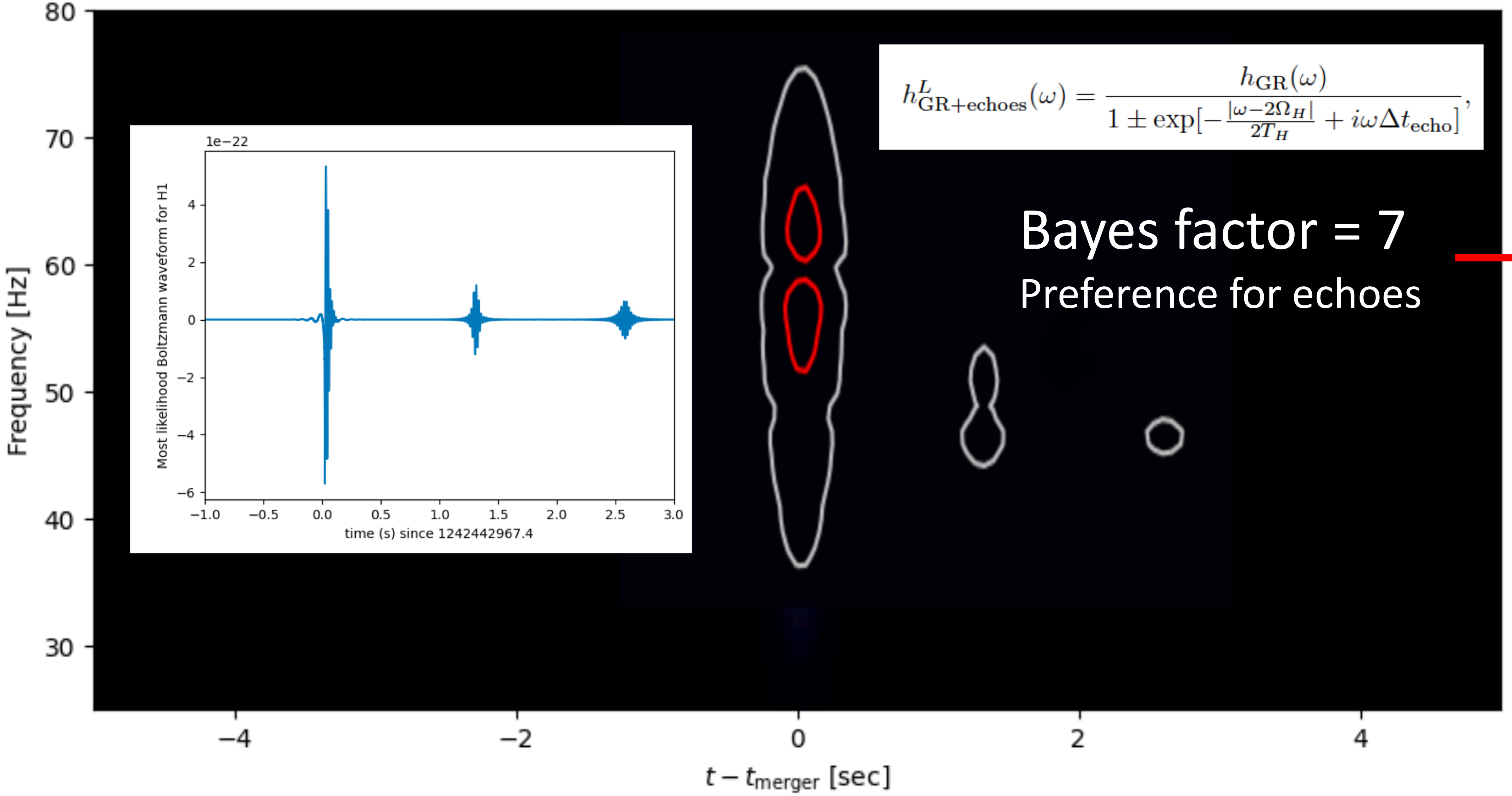


FIG. 5: cWB p-value estimation postmerger signal vs its signal-to-noise ratio and its Poisson error using injection approach.

PyCBC: contour plot
cWB: density plot



PyCBC

PyCBC: contour plot
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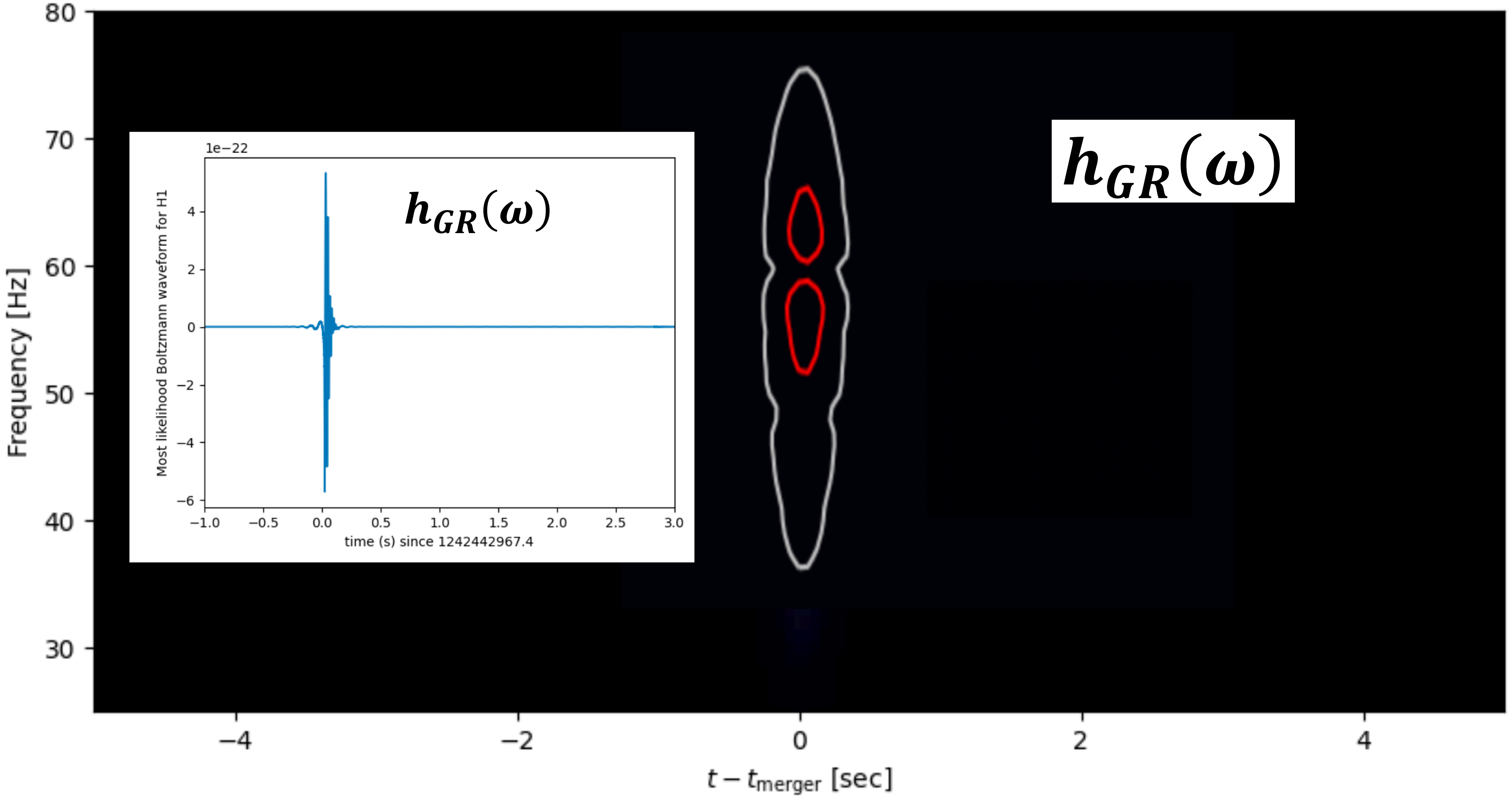

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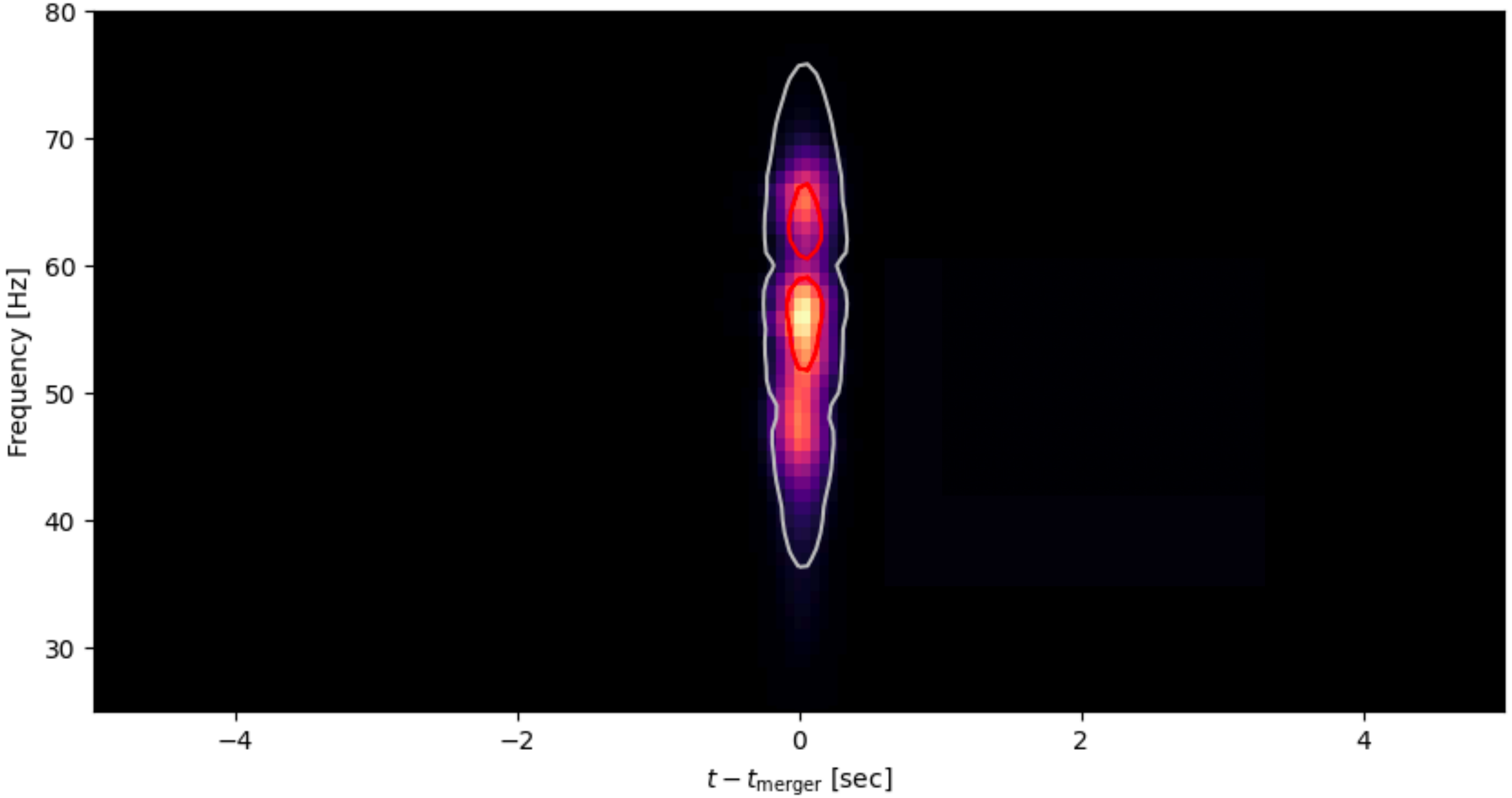
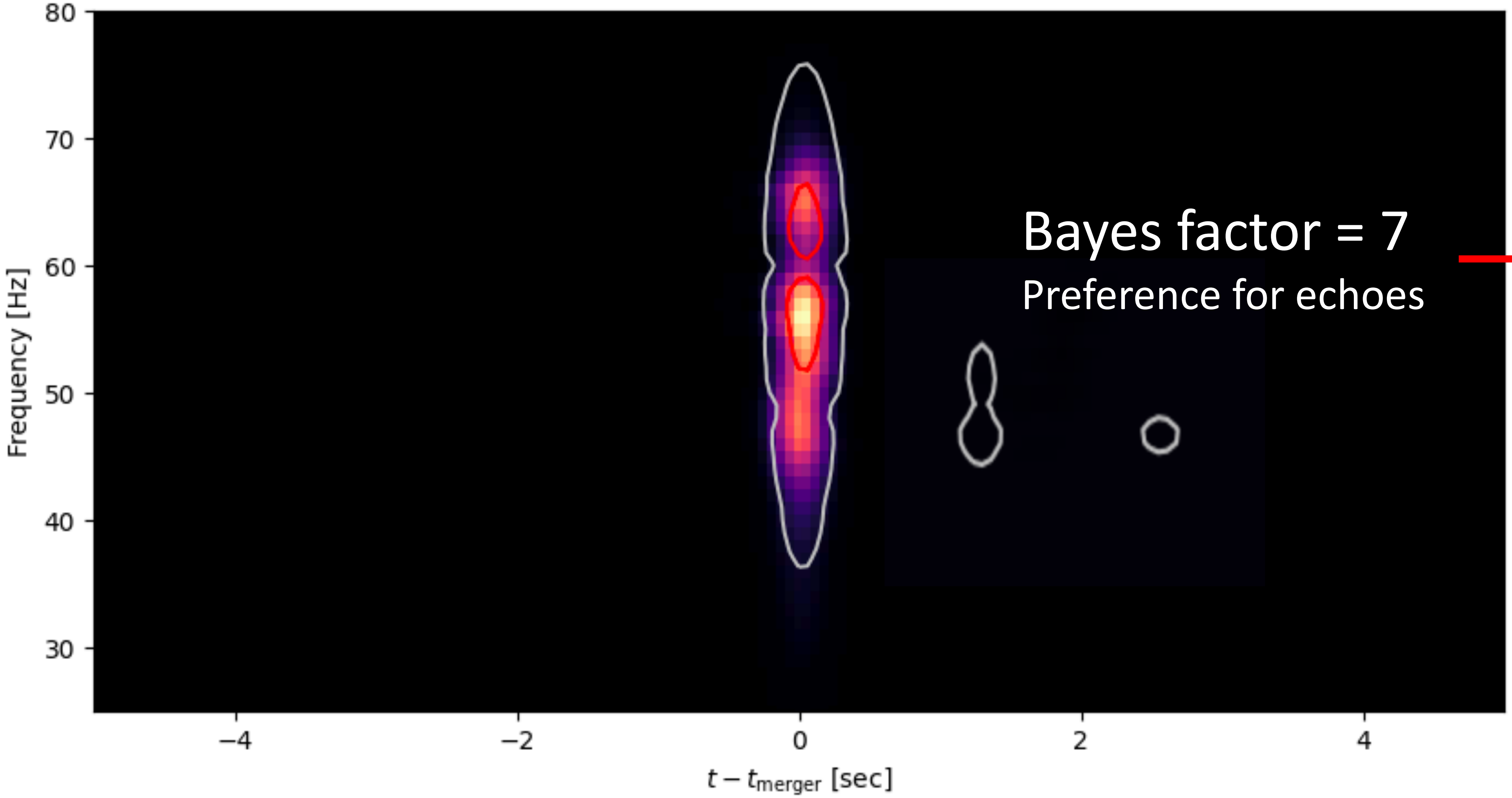
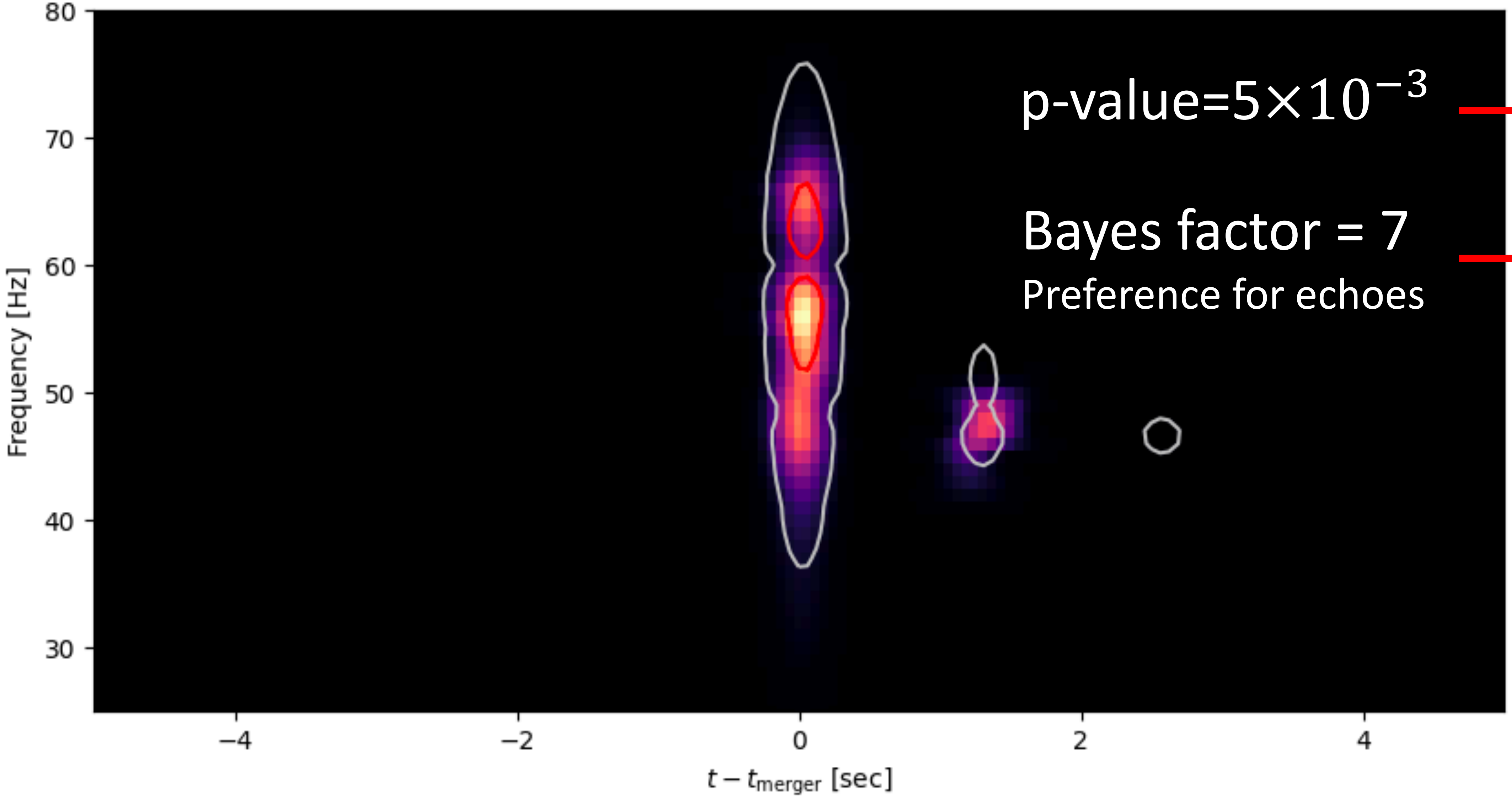


PyCBC: contour plot
cWB: density plot



PyCBC

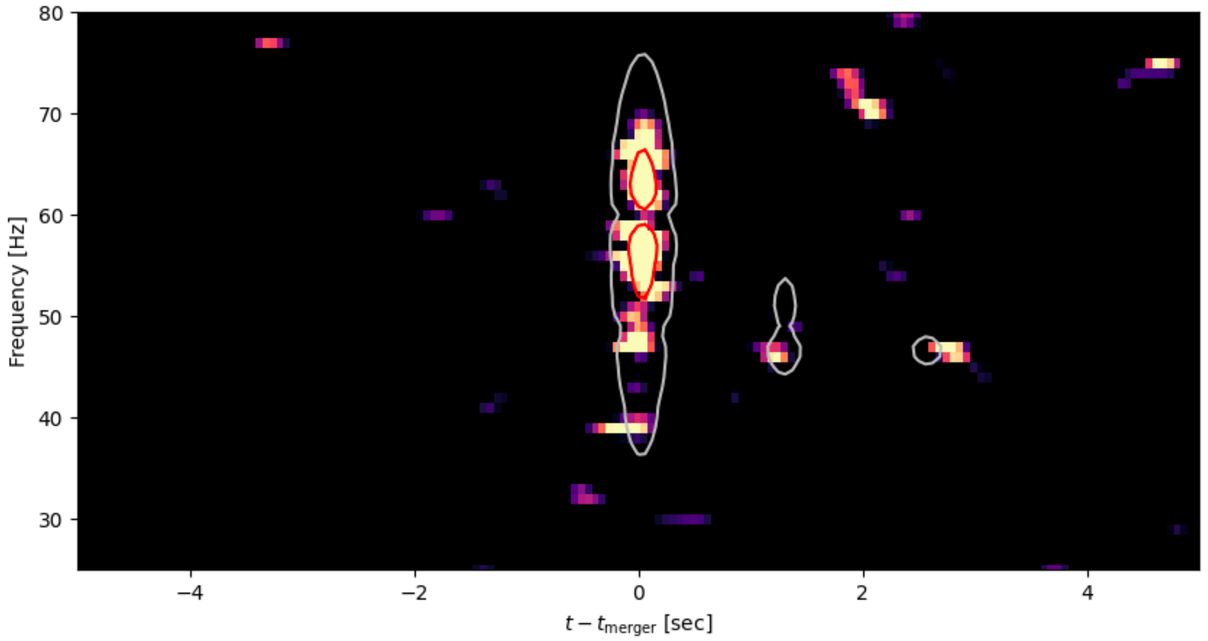
PyCBC: contour plot
cWB: density plot



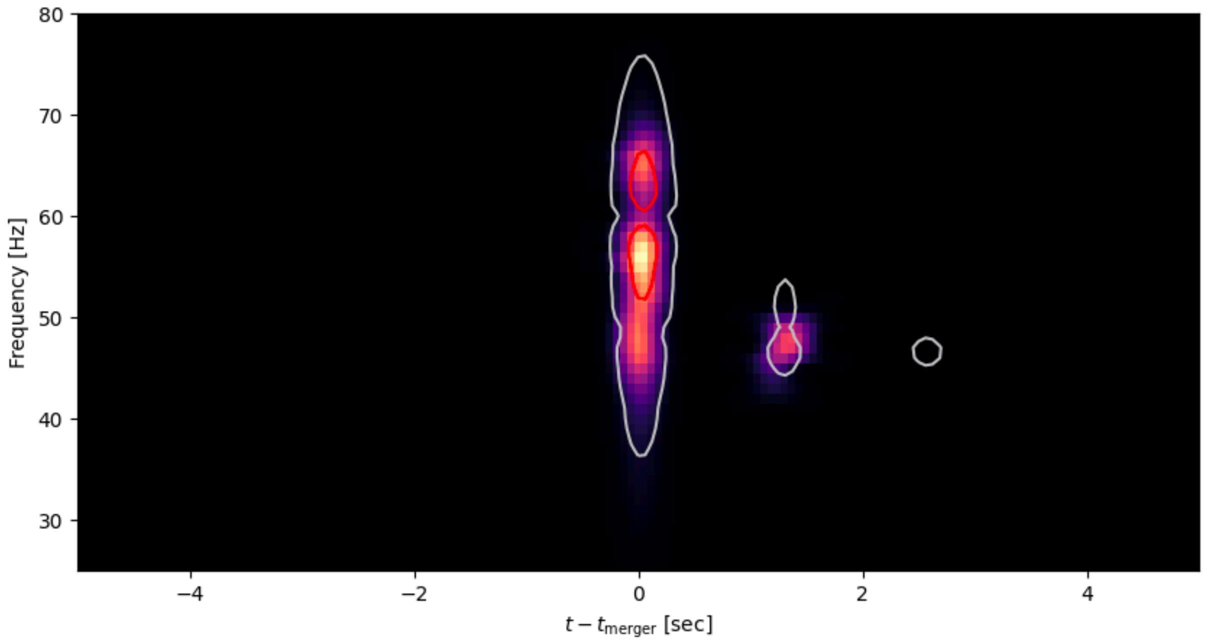
CWB

PyCBC

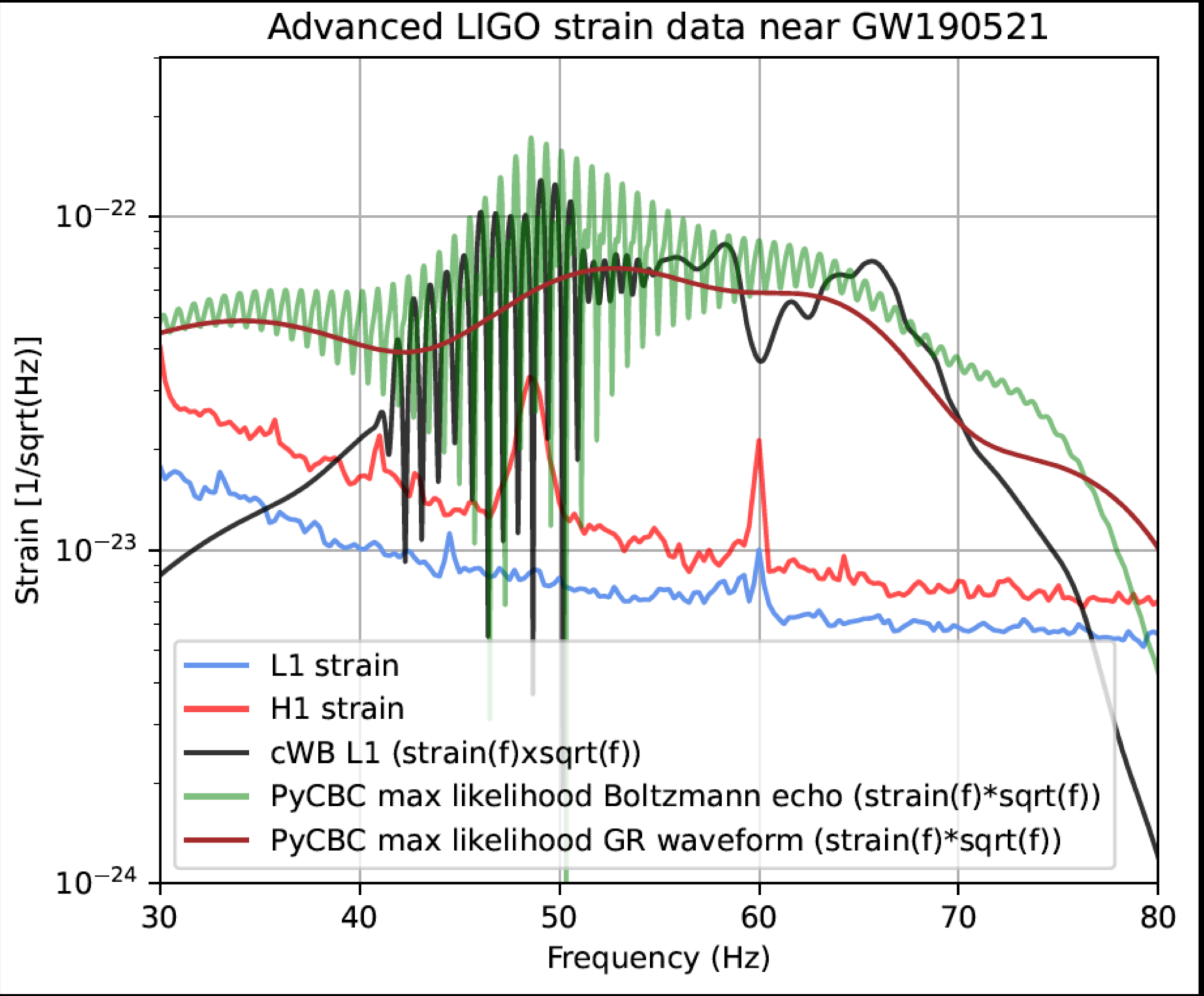
PyCBC: contour plot
Hanford x Livingston: density plot

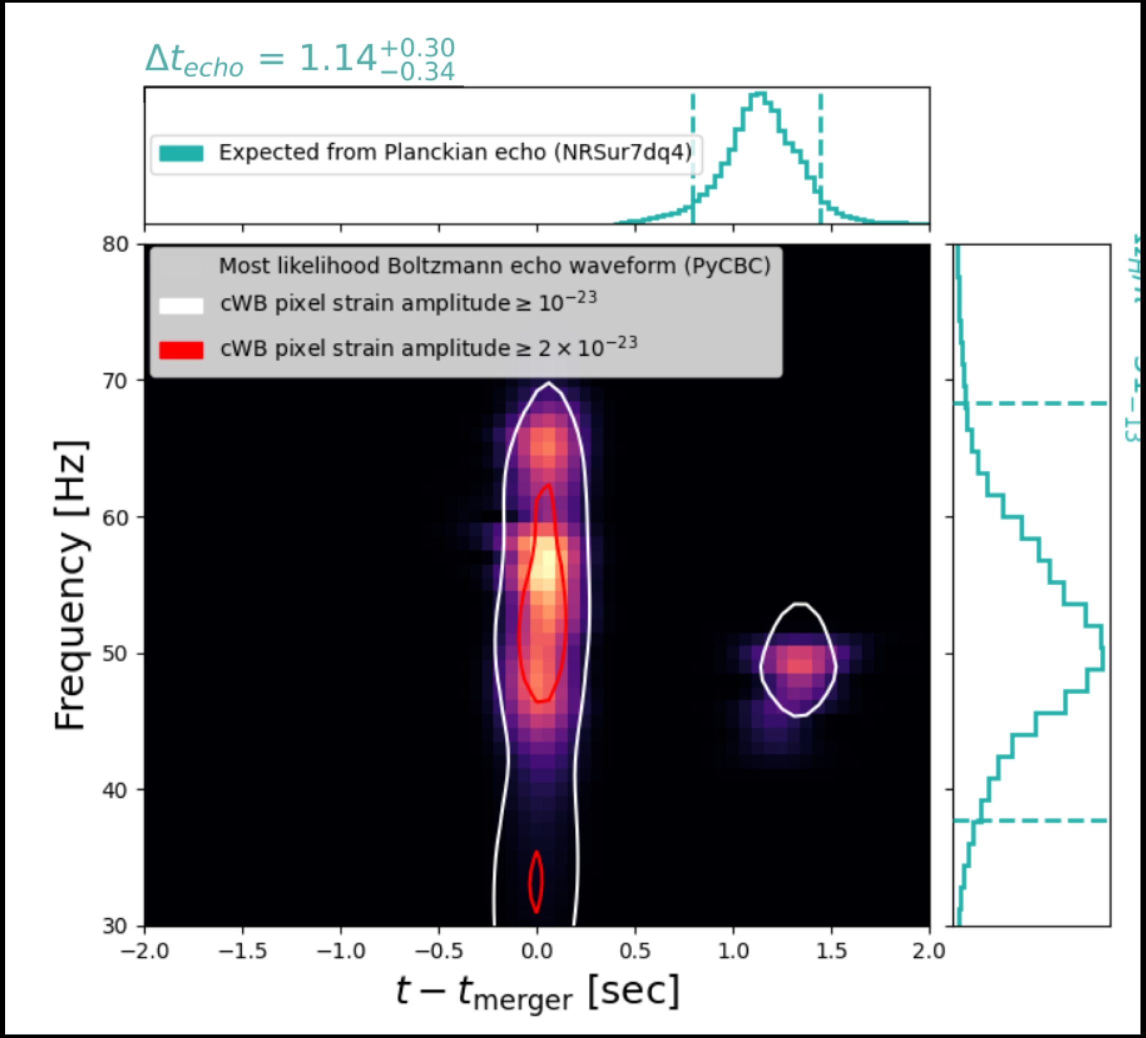


PyCBC: contour plot
cWB: density plot



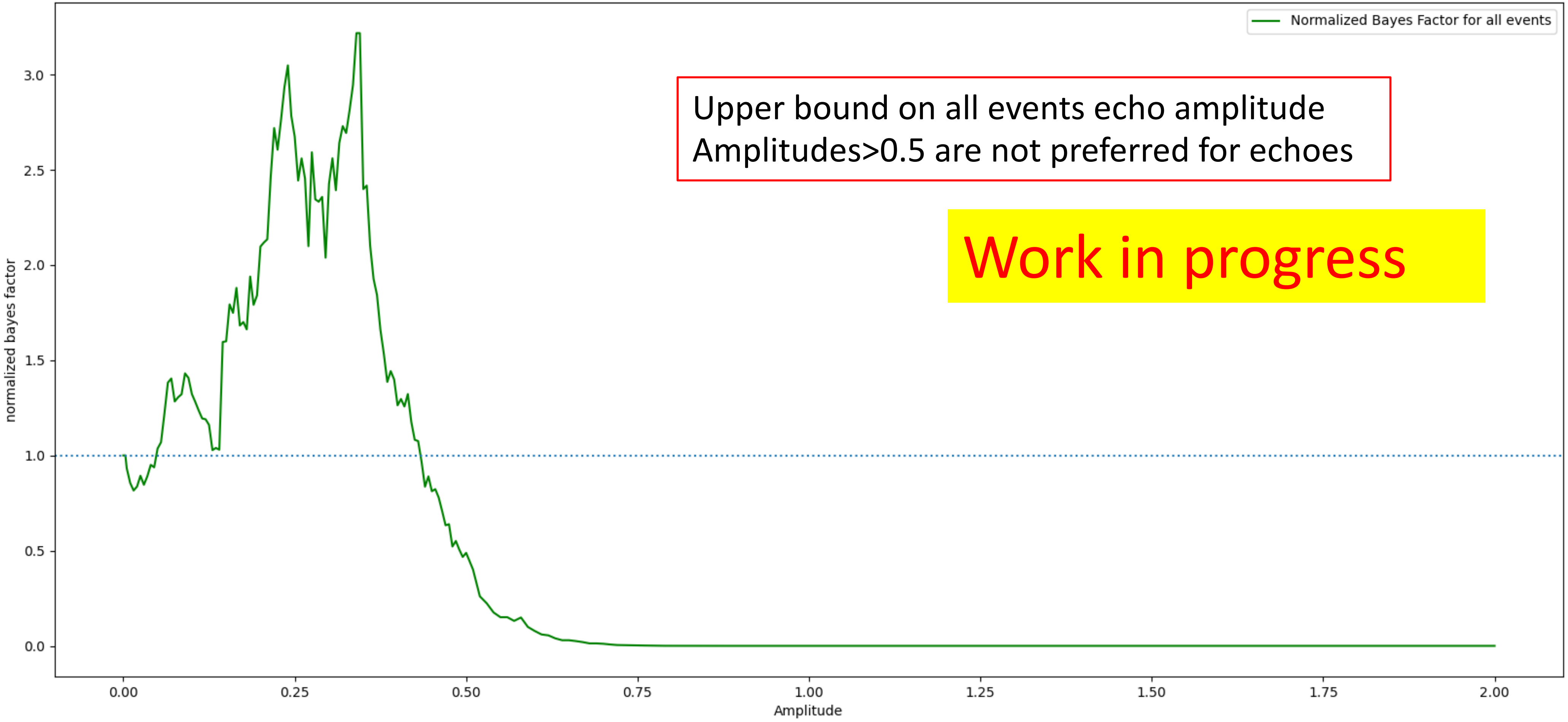
PyCBC vs cWB





$E^{\text{Echoes}}_{\text{MainEvent}}$	L1	H1	V1	Mean
cWB	15.3%	10.8%	6.6%	13.4%
PyCBC	$10.3^{+9.2}_{-7.4}\%$	$10.3^{+9.2}_{-7.4}\%$	$10.3^{+9.2}_{-7.4}\%$	$10.3^{+9.2}_{-7.4}\%$

Combining 65 events



Upper bound on all events echo amplitude
Amplitudes>0.5 are not preferred for echoes

Work in progress

- **Summary**
- Although no clear and widely-accepted observational signs of echoes (or deviations from vacuum GR) have been observed in GW detectors to date, we might be close!
- The fact that independent methods find similar signals from possibly the most massive event suggests that echoes should be one of prime targets for the next generation of GW detectors.
- GW190521 which is the most massive event observed to date has a loud echo signal (Possible first measurement of stimulated Hawking radiation)
- We also argue that previous searches (by the LIGO/Virgo and KAGRA collaboration) have missed this signal due to a nonphysical prior range, notably missing the expected $t_{echo} = 1.14^{0.30}_{-0.34}$ sec for GW190521, with their choice of $0.05 \text{ sec} < t_{echo} < 0.5$ sec prior or miss this event.

Thank you

GW150914

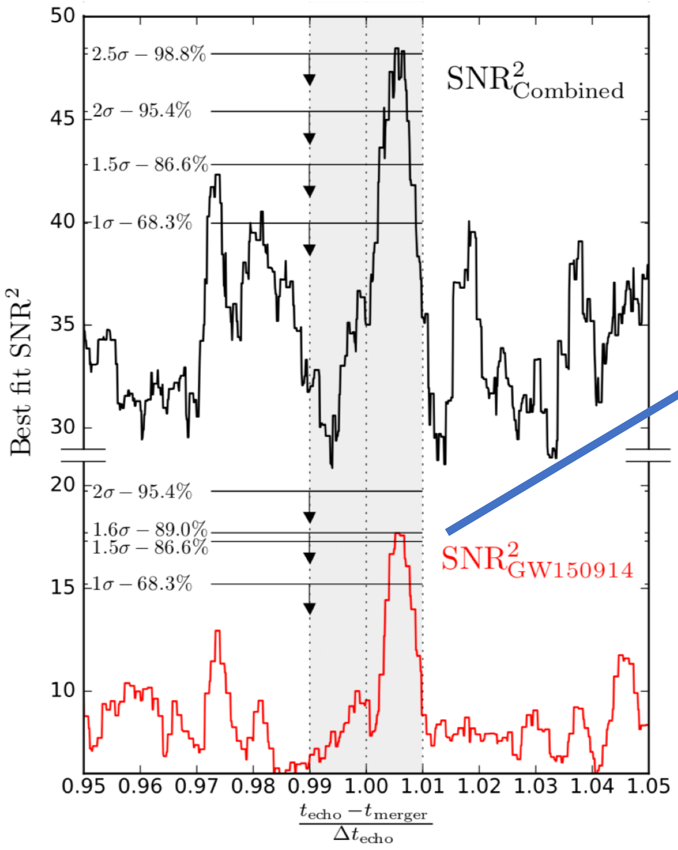
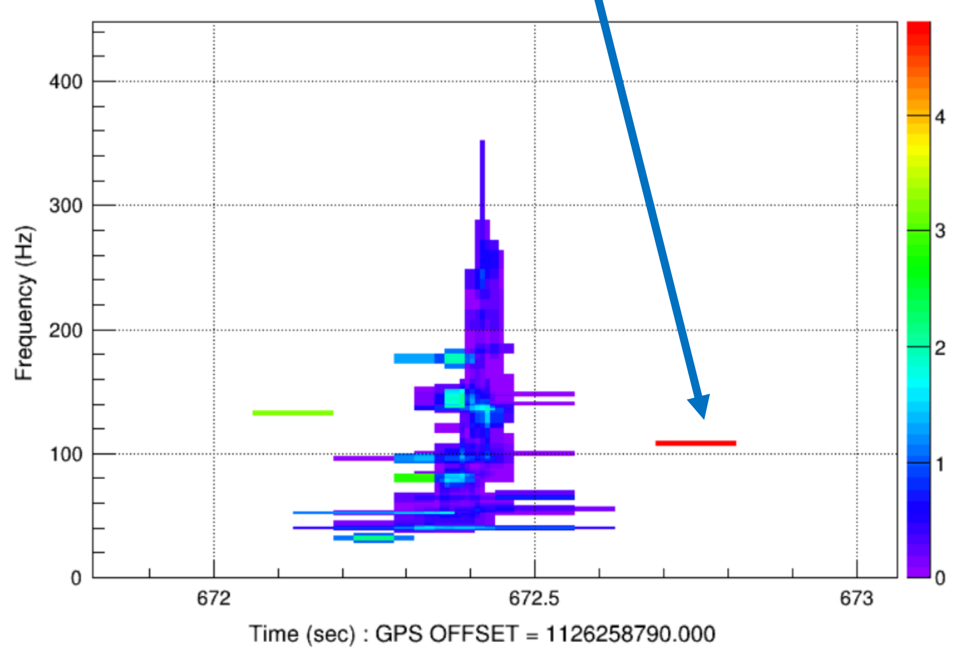


FIG. 4: Best fit (or maximum) SNR^2 near the expected time of merger echoes (Eq's. 1 and 6), for the combined (top) and GW150914 (bottom) events. The significance of the peaks is quantified by the p-value of their SNR_{max} within the gray rectangle (see Appendix E for detail of calculation).

Abedi et al (Oct 2017)

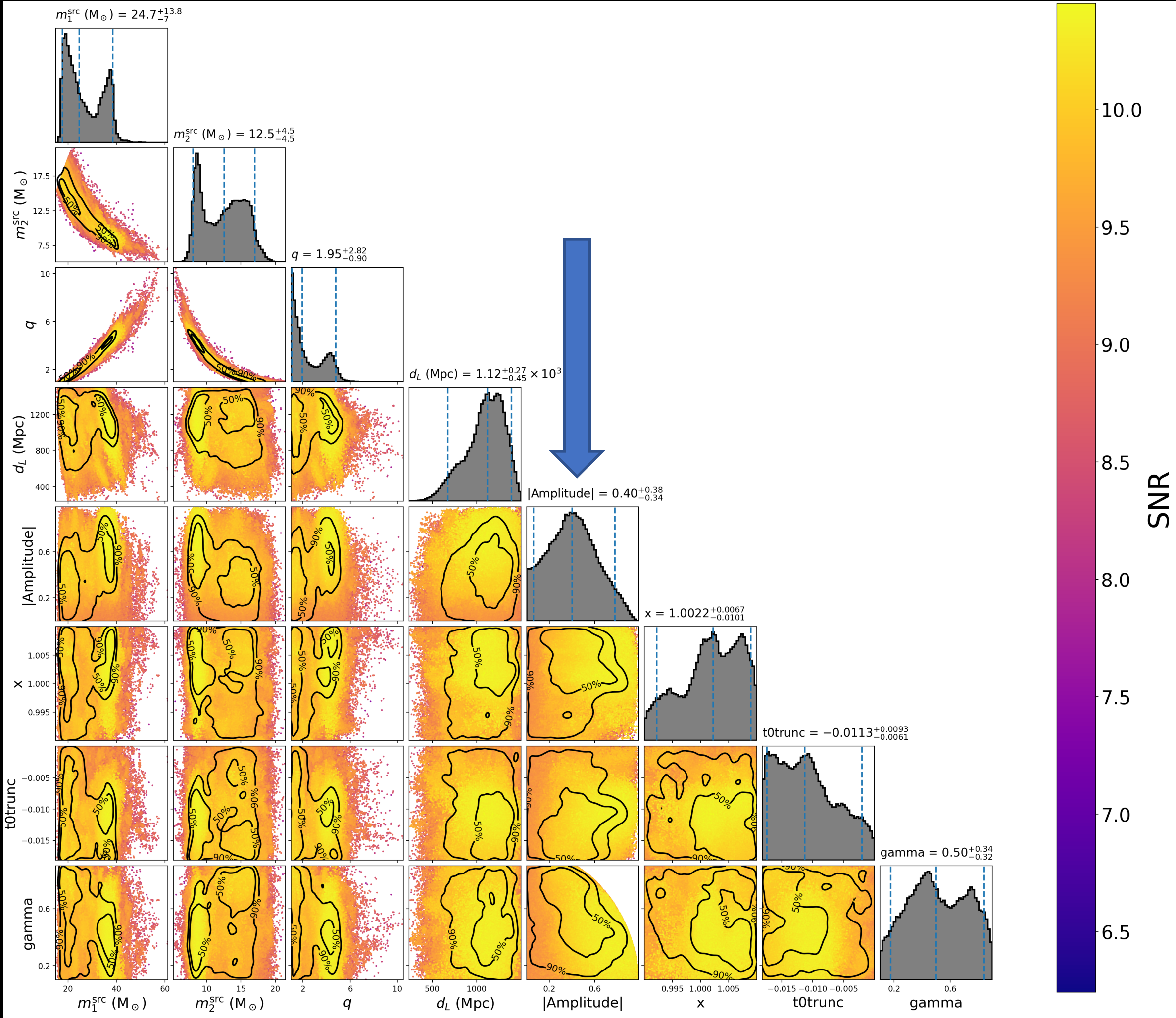
	GW150914	GW151226	LVT151012
$\Delta t_{echo,pred}$ (sec)	0.2925 $\pm$ 0.00916	0.1013 $\pm$ 0.01152	0.1778 $\pm$ 0.02789
$\Delta t_{echo,best}$ (sec)	0.30068	0.09758	0.19043
$\lvert A_{best,I} \rvert$	0.091	0.33	0.34
$SNR_{best,I}$	4.13	3.83	4.52

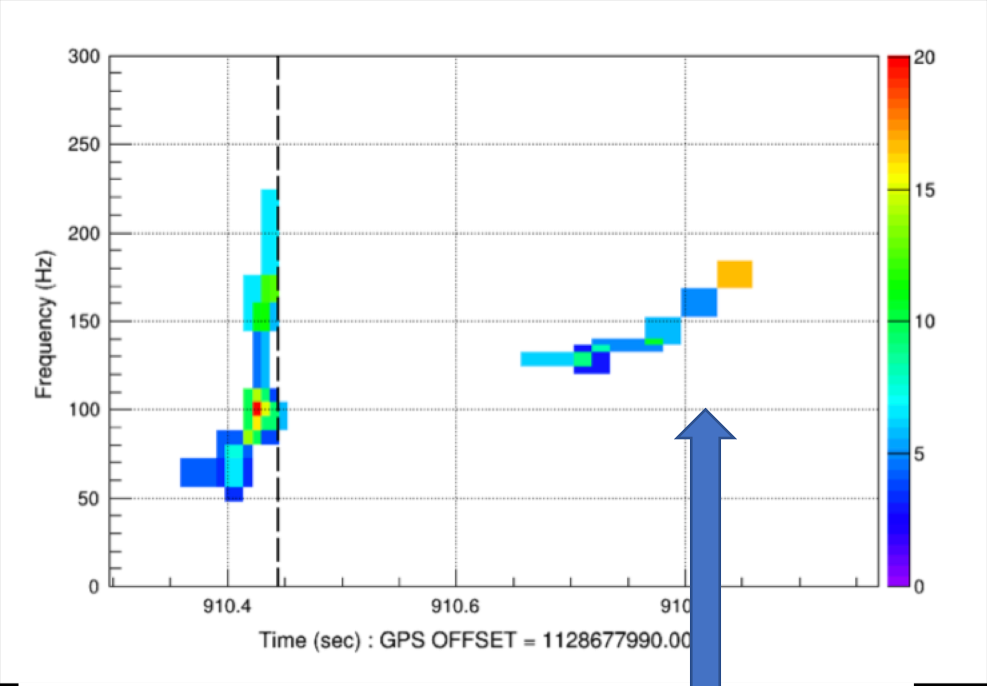
TABLE II: Theoretical expectations for Δt_{echo}'s of each merger event (Eq. 6), compared to their best combined fit within the 1σ credible region, and the contribution of each event to the joint SNR for the echoes (Eq. 10).

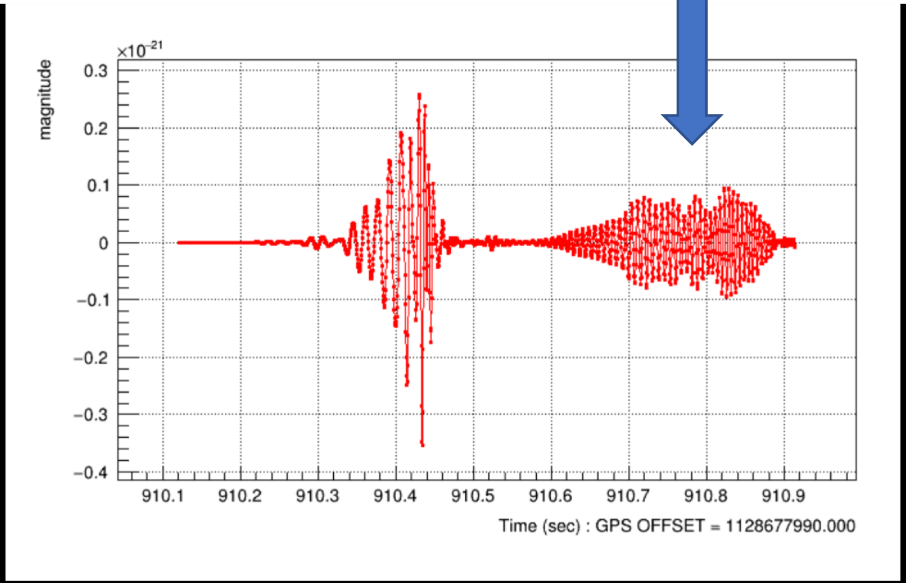


Credit: Salemi et al, 2019

GW151012

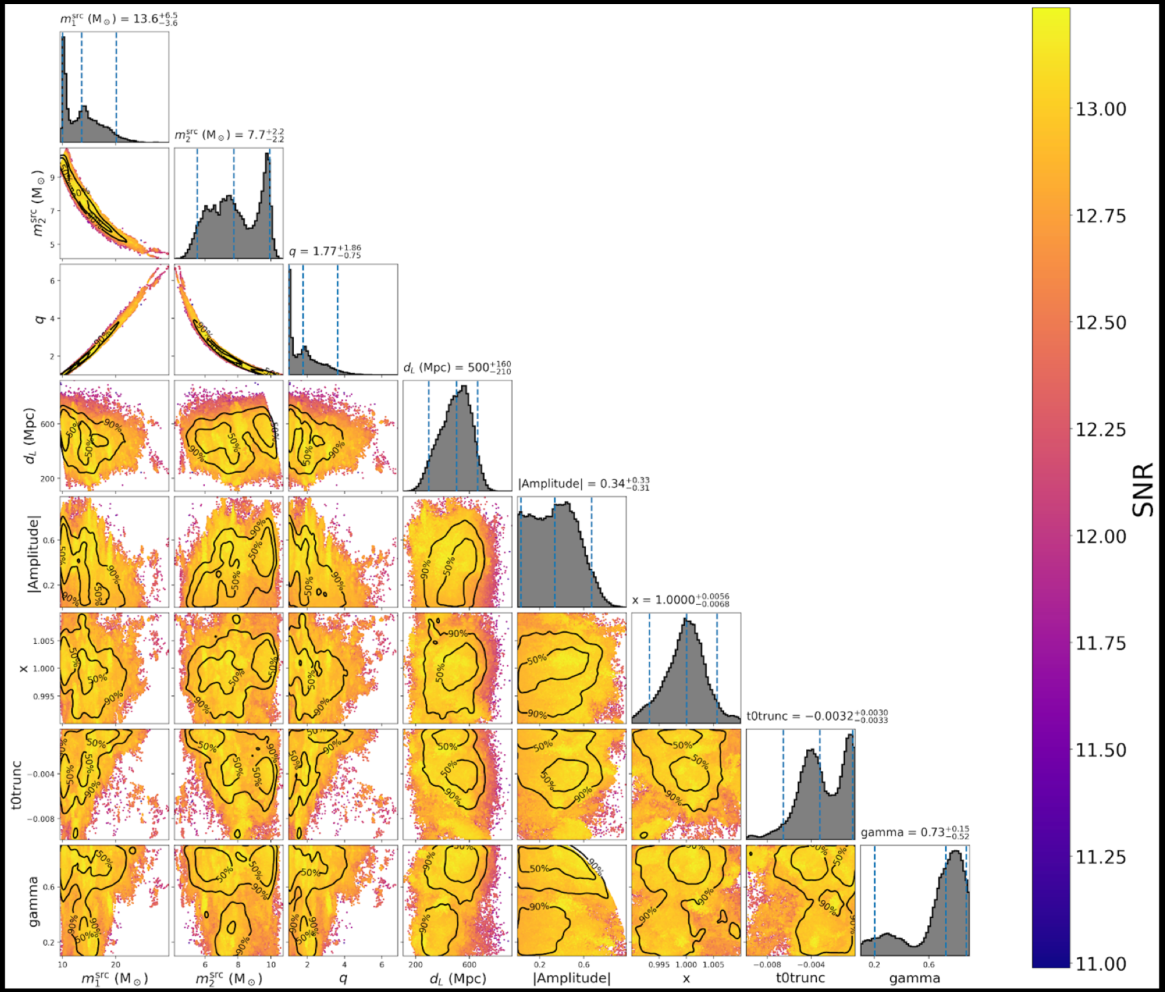




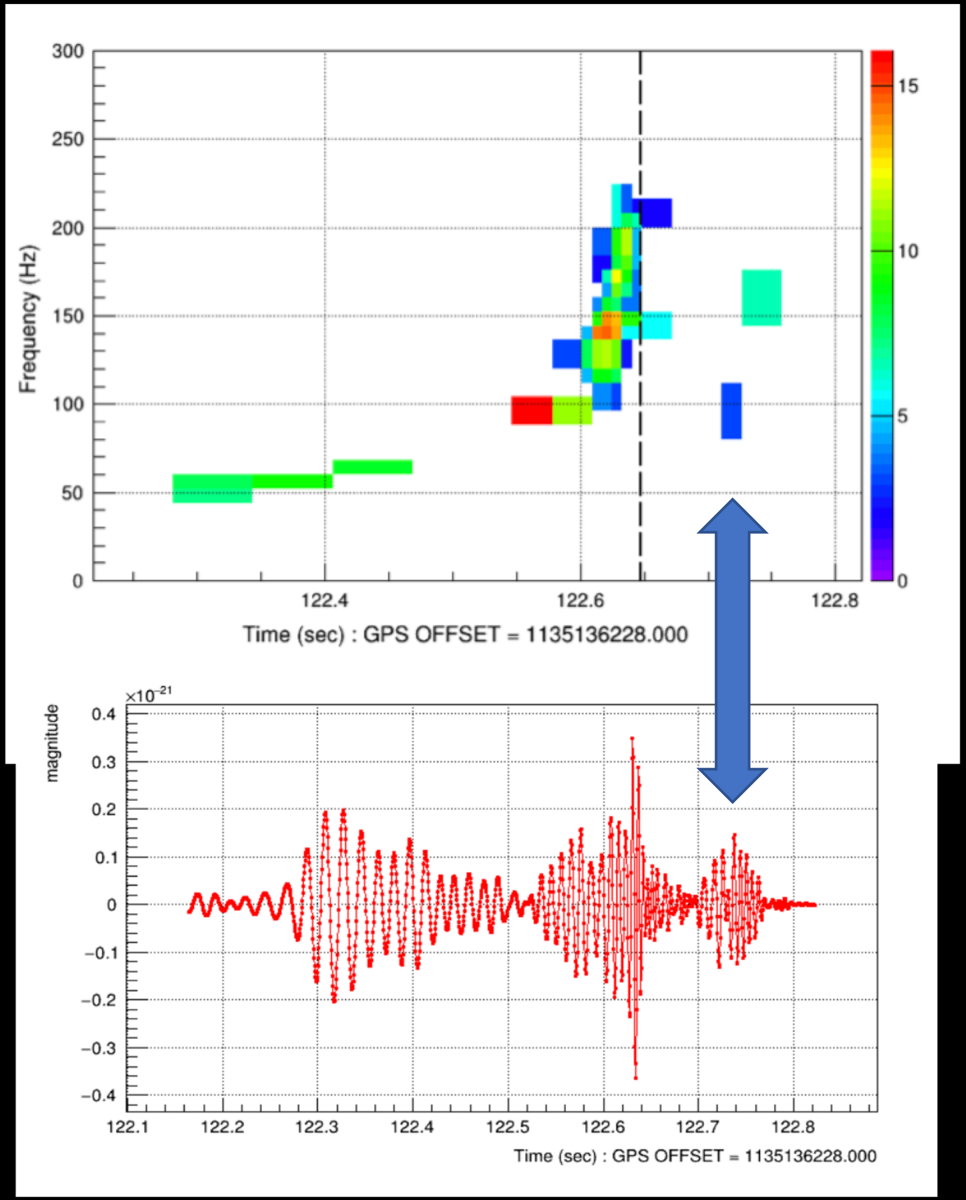


Credit: Salemi et al, 2019

GW151226

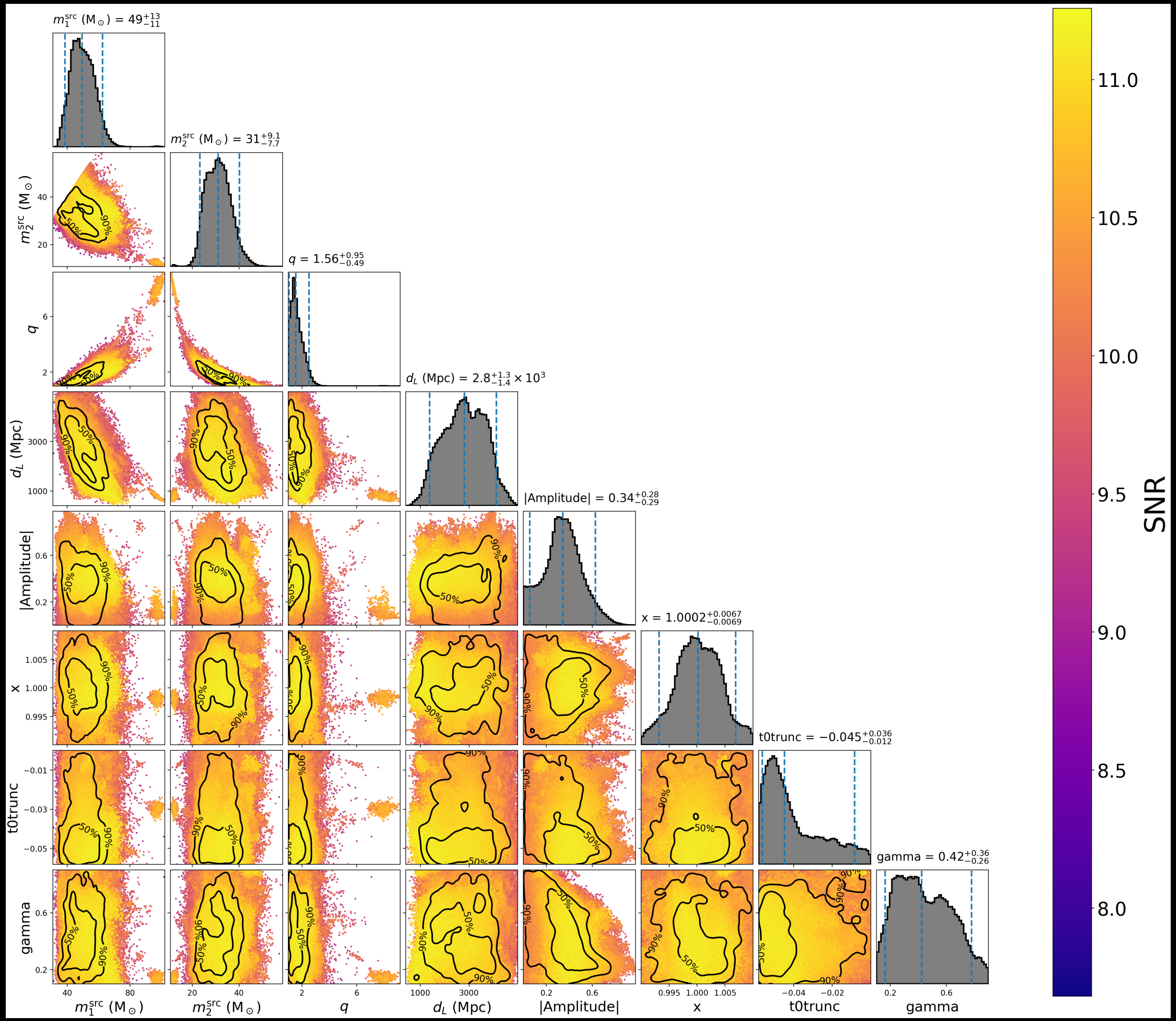


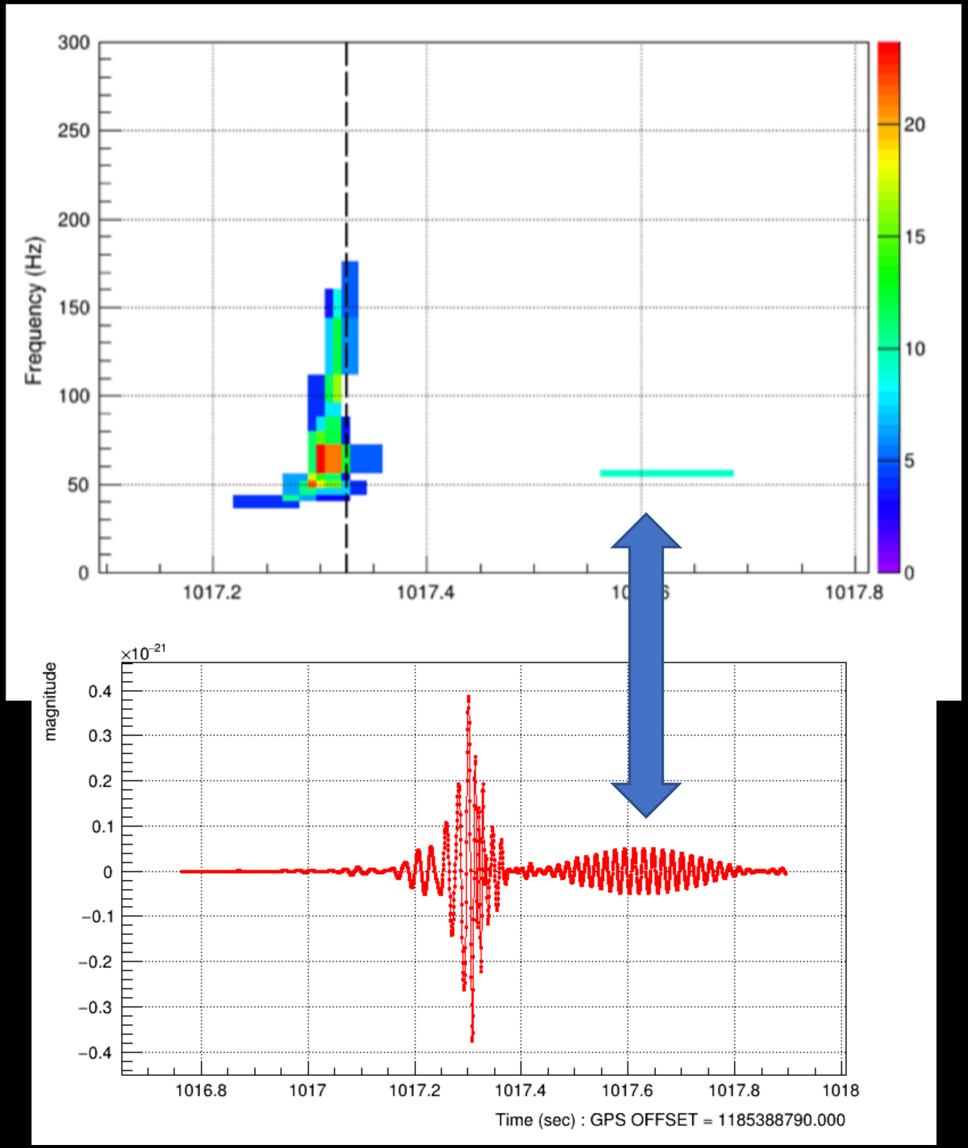
LogB = +1.18



Credit: Salemi et al, 2019

GW170729





LogB = +0.45

Credit: Salemi et al, 2019

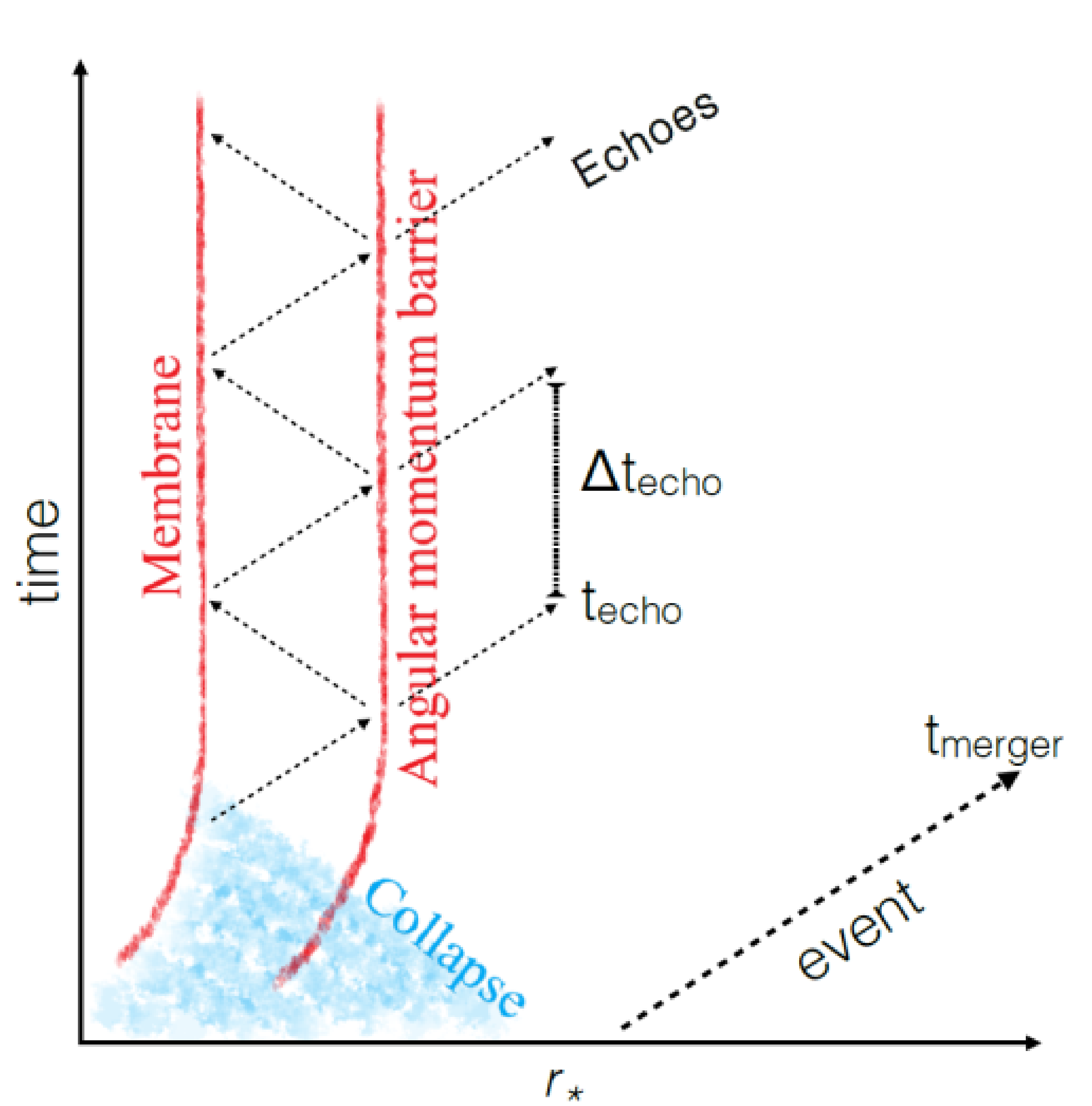
In nature, a BNS merger can develop in four possible ways:

1. A black hole forms immediately after merger.
2. A hypermassive NS is formed, then within $\leq$ 1sec it collapses into a black hole.
3. A supermassive NS is formed that collapses to a black hole on timescales of $10 - 10^4$sec.
4. A stable neutron star is formed.

$$\Delta t_{\text{echo}} \simeq \frac{4GM_{\text{BH}}}{c^3}\left(1+\frac{1}{\sqrt{1-a^2}}\right)\times \ln\left(\frac{M_{\text{BH}}}{M_{\text{planck}}}\right)$$
$$\simeq 4.7 \text{ msec}\left(\frac{M_{\text{BH}}}{2.7\ M_{\odot}}\right)\left(1+\frac{1}{\sqrt{1-a^2}}\right),$$

from LIGO/Virgo (90% CL)

$$0.0109 < \Delta t_{\text{echo}}(\text{sec}) < 0.0158$$
$$63 \leq f_{\text{echo}}(\text{Hz}) \leq 92$$



Expected regions