GRASS Padova 2022
GRAvitational-wave Science&technology Symposium

UNIVERSITÀ DI TRENTO

GRASS 2022 conference

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TIFPA Trento Institute for Fundamental Physics and Applications

An unmodeled search for echoes: probing the post-merger phase of a binary black hole coalescence.

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LSC LIGO Scientific Collaboration

LIGO VIRGO

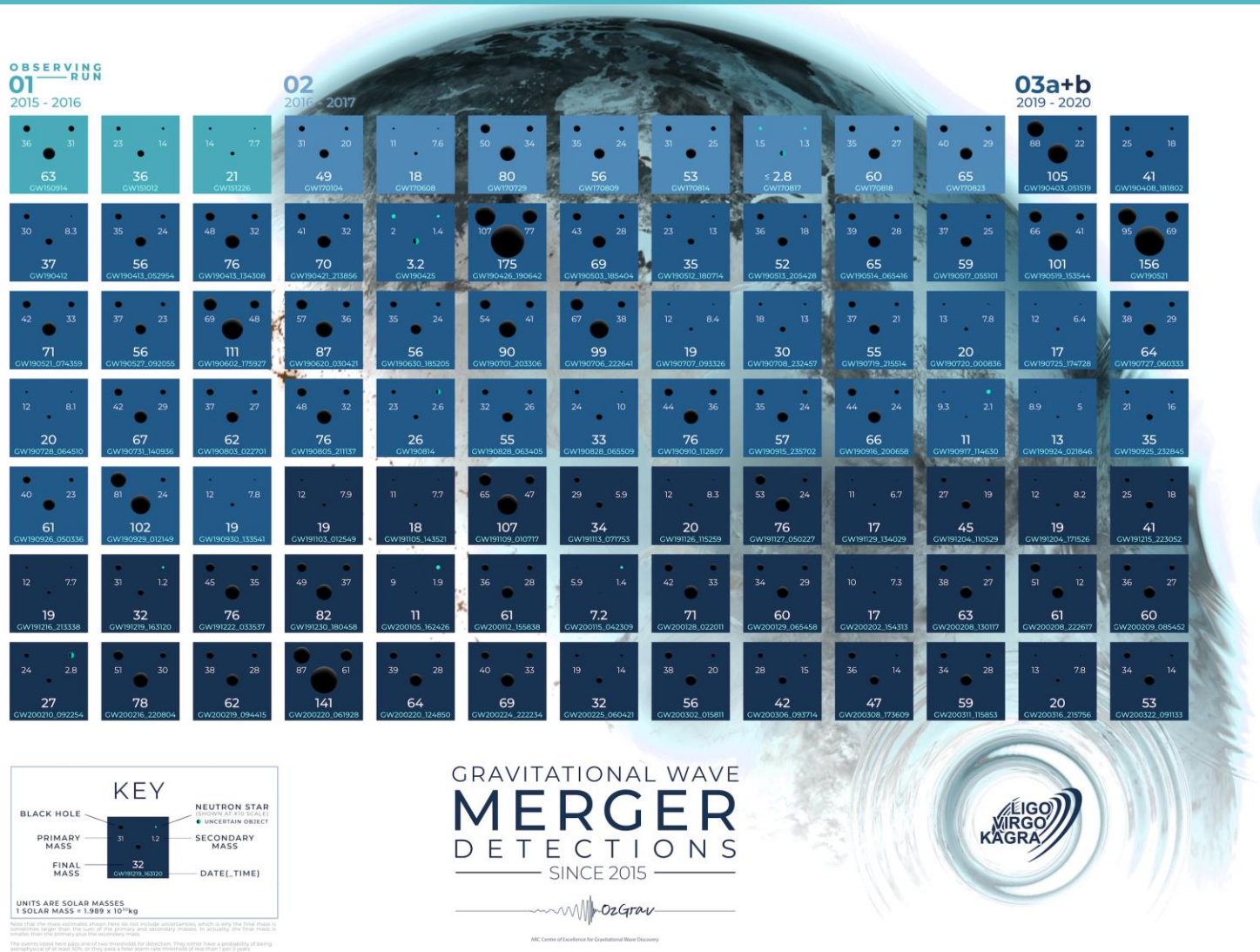
VIRGO

Outline of the presentation

1. Echoes search, WHY?
2. Echoes: state of the art.
3. Echoes: an unconstrained search.
4. Echoes: results of the search.
5. Conclusions.

1.1 - Echoes search, WHY?

- 2015, September 14 th: detection of the first gravitational wave (GW), GW150914.
- Several GW detection by LIGO-Virgo-KAGRA organisation:
  - GWTC-1 (O1, O2 runs);
  - GWTC-2 (O3a run);
  - GWTC-3 (O3b run);
- 83 (+6?) out of 89 detections are labelled as binary black hole (BBH) coalescences. **Are we sure of it?**



Credit: LIGO/Virgo/KAGRA/C. Knox/H. Middleton

1.2 - Echoes search, WHY?

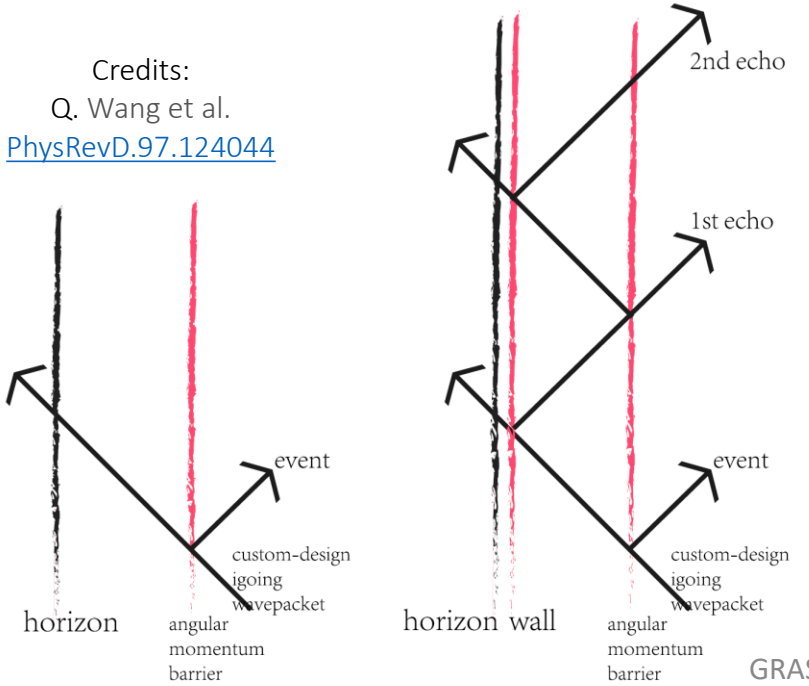
Alternative models to BH: **exotic compact objects** (**ECO**).

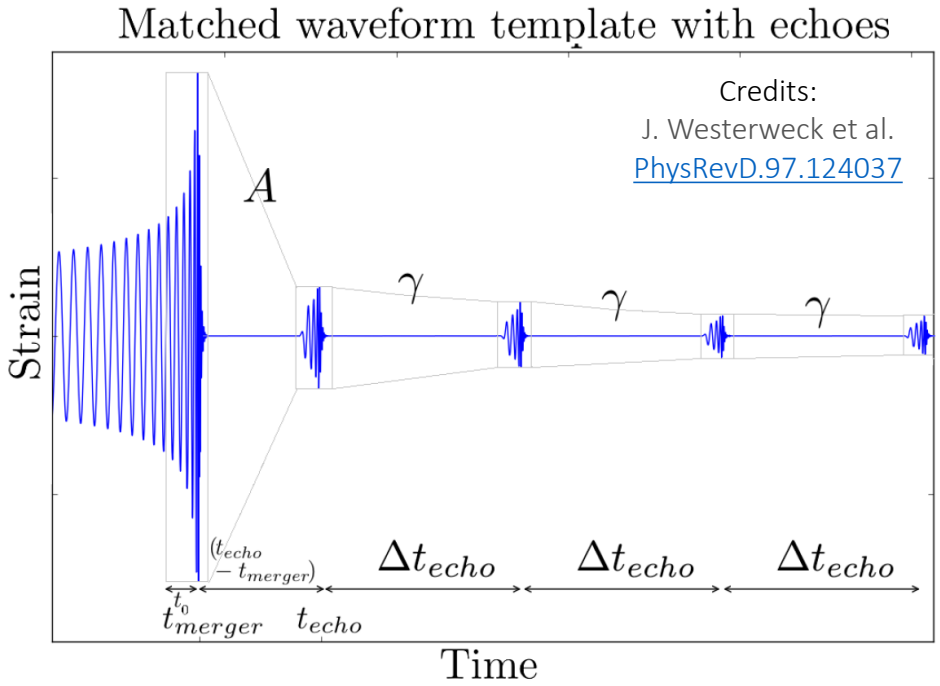
(ex: Gravastars or Firewalls)

ECOs share a common feature.

Emission of GW pulses, called echoes, in the post-merger ringdown phase of the coalescence.

Credits:
Q. Wang et al.
PhysRevD.97.124044





WHY searching ECHOES?

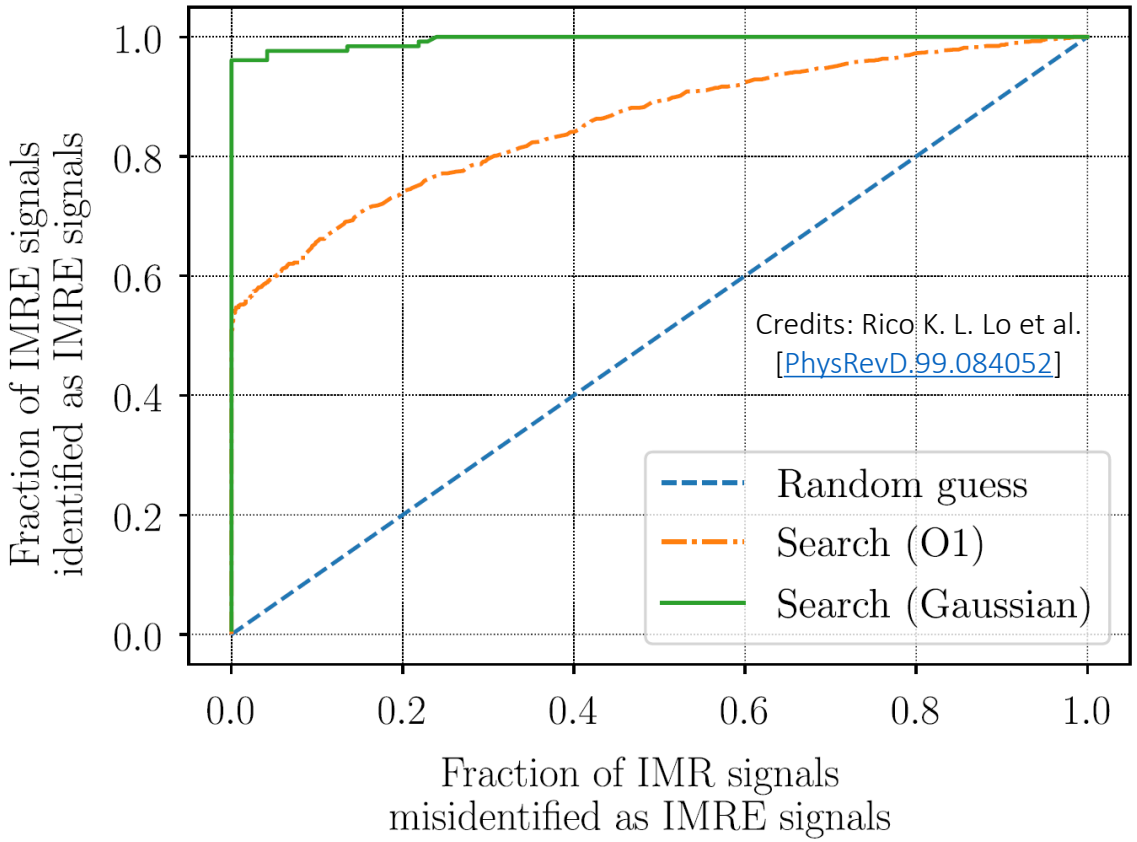
- **Probe the general relativity (GR) theory.**
- **Investigate exotic state of matter.**

2 - Echoes: state of the art

Several echoes searches were performed in past years

- **template searches**;
  - Julian Westerweck et al. [PhysRevD.97.124037];
    - Injections' faithfull reconstruction for strain $\geq 10^{-22}$;
  - Rico K. L. Lo et al. [PhysRevD.99.084052];

- **unmodeled searches**;
  - Ka Wa Tsang et al. [PhysRevD.98.024023];
    - signal decomposed using sine-Gaussian wavelets: confident detection for snr ≥ 12.

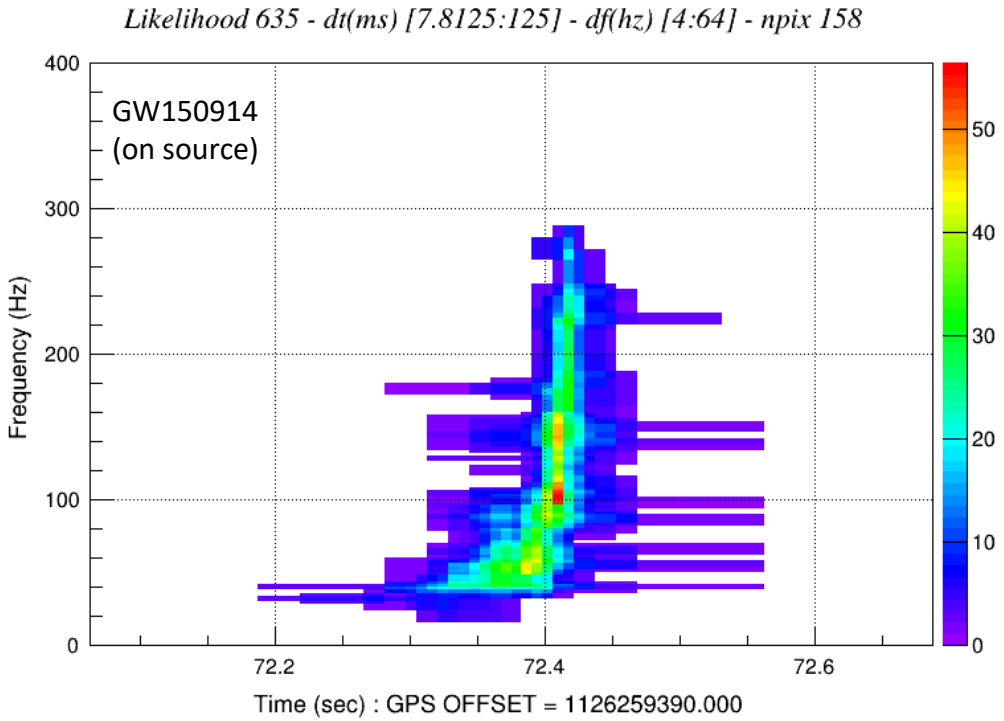


IMR : Inspiral-Merger-Ringdown
IMRE : Inspiral-Merger-Ringdown-Echoes

3.1 - Echoes: an unconstrained search

Coherent Wave Burst (cWB) pipeline

- **Unmodeled coherent search**:
  - no assumptions on the signal morphology.
- **Constrained maximum likelihood approach**



cWB flowchart

- Data conditioning
- Whitening of the data ($\mathbf{x}[\mathbf{i}]$)

} Single detector

$$\mathbf{x}[\mathbf{i}] = \mathbf{h}[\mathbf{i}] + \mathbf{n}[\mathbf{i}];$$

- Pixels selection
- Likelihood maximization ($\mathbf{L}$)
- Post production cuts

} Combined network

$$\mathbf{L} = \log\left(\frac{\mathbf{P}(\mathbf{x}|\mathbf{H_1})}{\mathbf{P}(\mathbf{x}|\mathbf{H_0})}\right);$$

$\mathbf{P}(\mathbf{x}|\mathbf{H_1})$: probability of having a signal.

$\mathbf{P}(\mathbf{x}|\mathbf{H_0})$: probability of the null hypothesis.

3.2 - Echoes: an unconstrained search

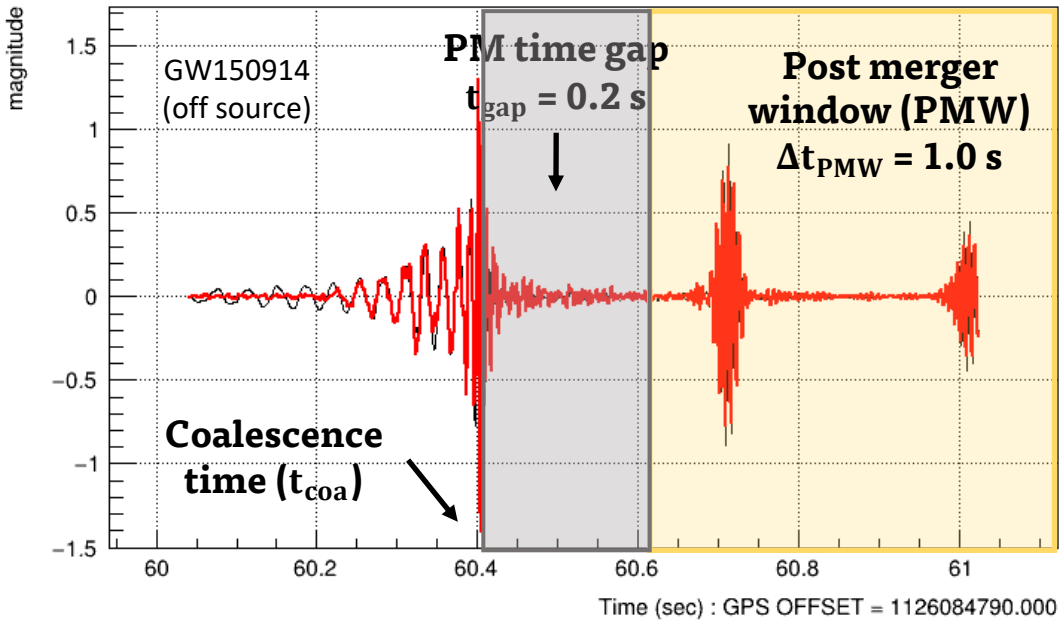
Method, science case: ECHOES

CBC event detection

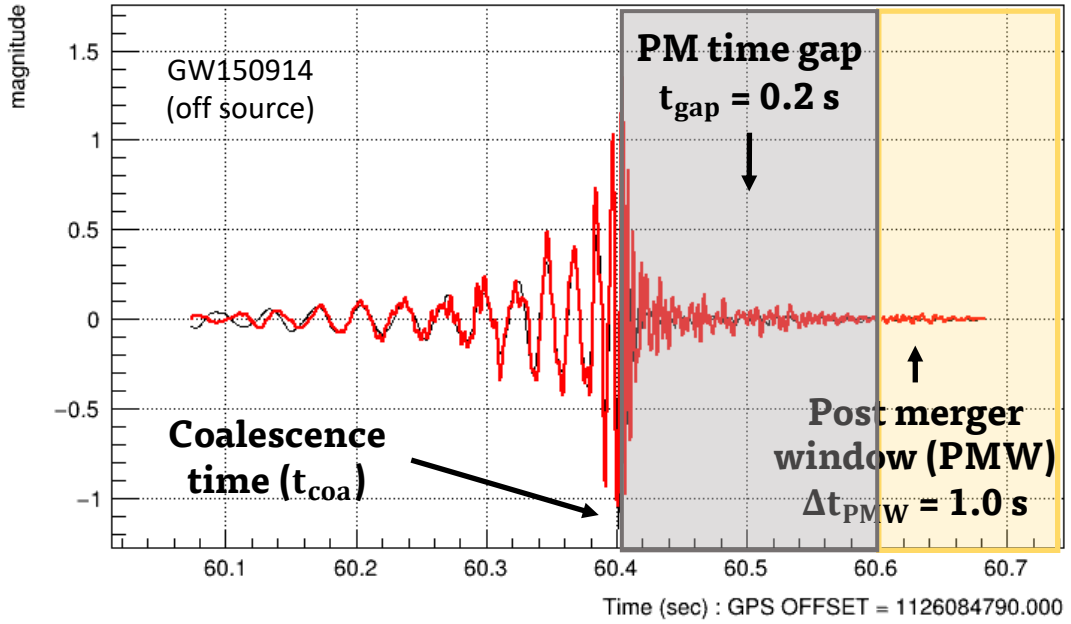
Follow-up search

Injections for target GW signal

Low Energy Signal (LES) study



Background (BGK) study



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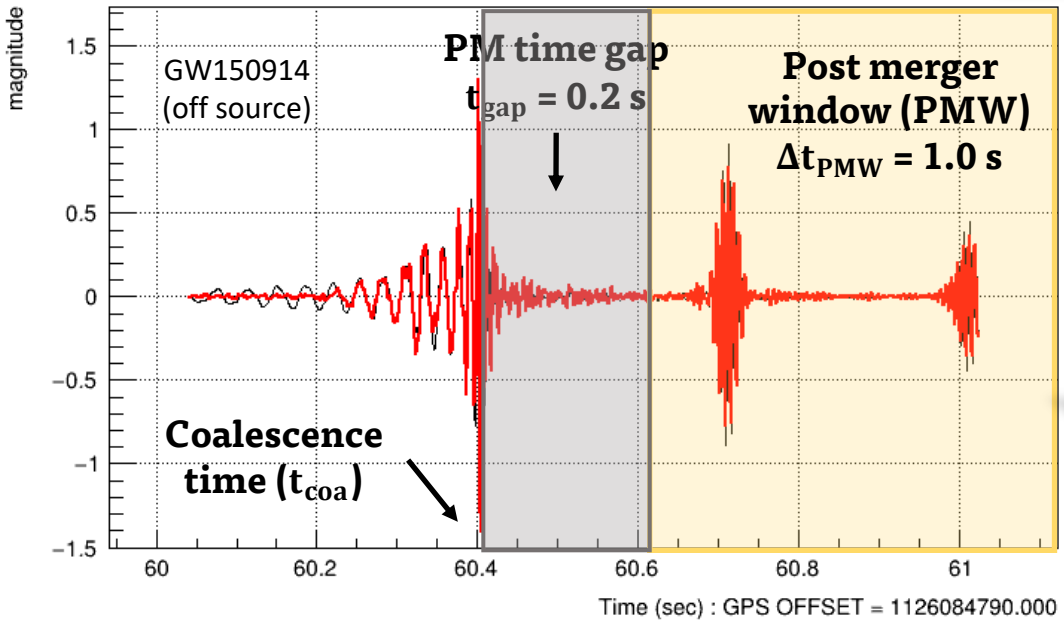
Method, science case: ECHOES



CBC event detection

Follow-up search

Injections for target GW signal

LVC: O3 all-sky burst search

arXiv:2107.03701v1

Lower internal cWB thresholds

Different whitening setup

Unmodeled triggered search for sub-threshold «features»

3.4 - Echoes: an unconstrained search

Main statistical parameters of the analysis:

Reconstructed energy: $\mathrm{E}^{\mathrm{PMW}} = \sum_K^{det.} \sum_i^{pixels} x_K[i]^2$

Coherence: $\mathrm{cc}^{\mathrm{PMW}} = \frac{\mathrm{E}_{\mathrm{coh}}^{\mathrm{PMW}}}{(\mathrm{E}_{\mathrm{coh}}^{\mathrm{PMW}} + \mathrm{E}_{\mathrm{null}}^{\mathrm{PMW}})}$

Detection efficiency:

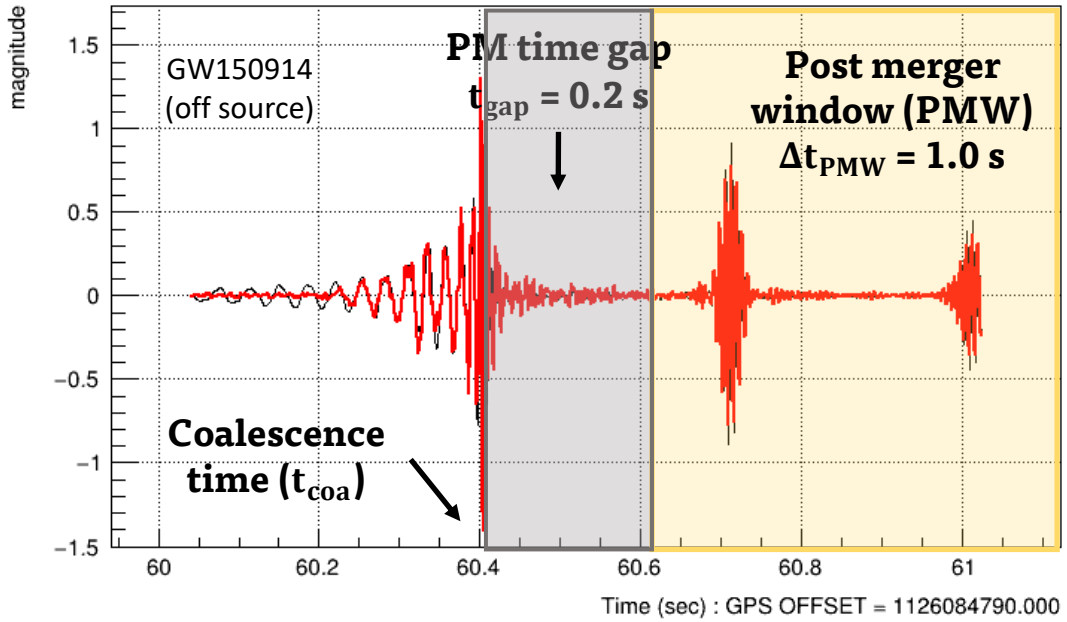
fraction of reconstructed events with

$\sqrt{\boldsymbol{E^{PMW}}} > \sqrt{\boldsymbol{E_{th}}}$ in the LES study.

False alarm probability (FAP):

fraction of reconstructed events with

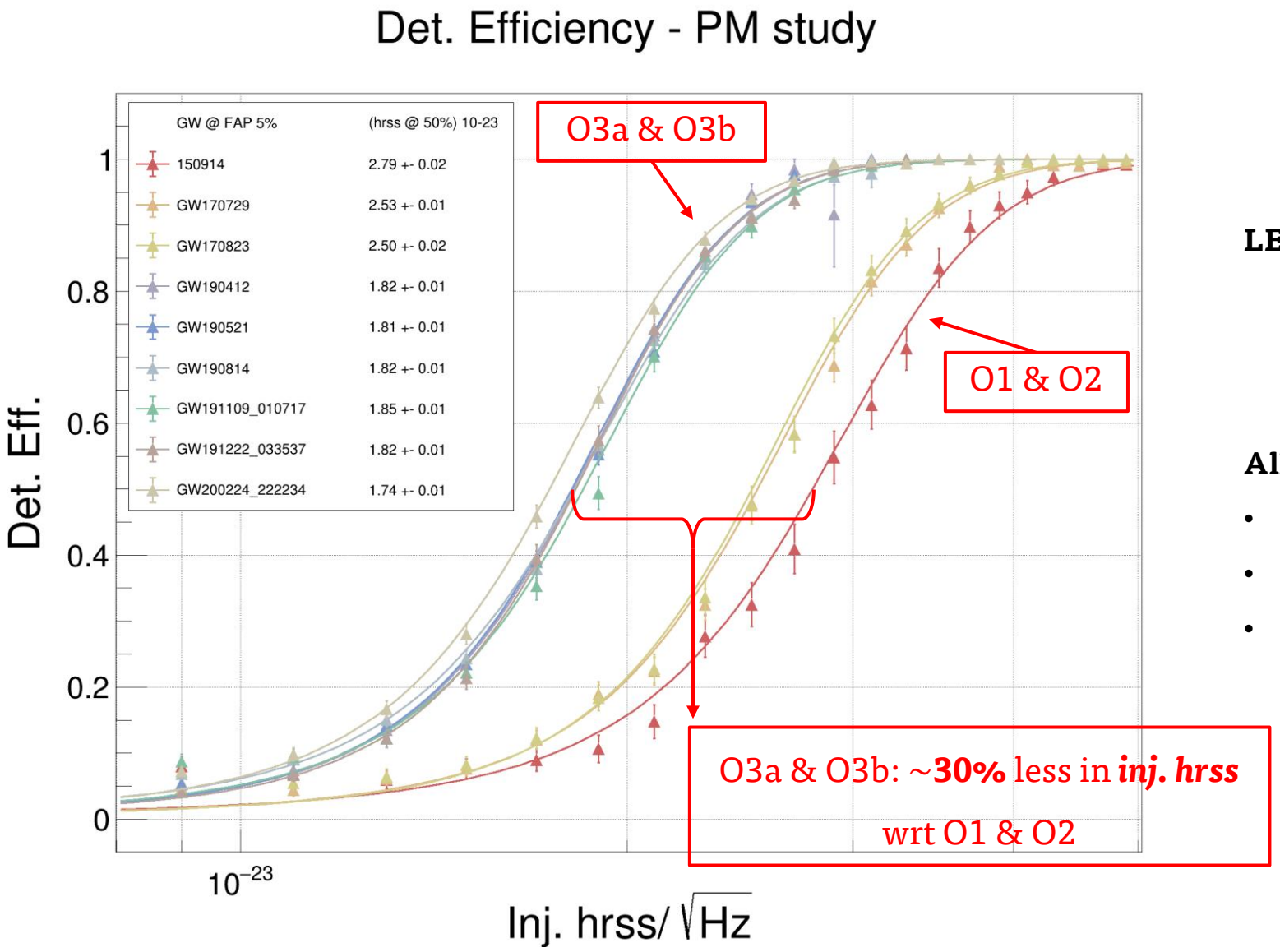
$\sqrt{\boldsymbol{E^{PMW}}} > \sqrt{\boldsymbol{E_{th}}}$ in the BGK study.



Mimikers for echoes:

- double Sine Gaussian (eliptical) pulses
- frequency = 140 Hz,
- Q = 8.8,
- $snr \in [0, \sim 10]$,
- damping factor γ = 0.5.

4.1 - Echoes: results of the search



GWTC-1,2,3 results :

hrss @50% det. Eff. in PMW

LES search for O3:

- **hrss @ 50% det.Eff. =** $\sim 1.85 \cdot 10^{-23} Hz^{-1/2}$

  requiring a FAR = 18/year.

All-sky short burst search O3:

- single Sine Gaussian (circular) with
- frequency = 235 Hz,
- Q = 100
  - **hrss @ 50% det.Eff. =** $0.8 \cdot 10^{-22} Hz^{-1/2}$

    requiring a FAR = 0.01/year.

GWTC-1,2,3 results – hrss @50% det. Eff. in PMW

$$\frac{\#\ \text{rec events with}\ \sqrt{E^{PMW}} > \sqrt{E_{th}}}{\#\ \text{total rec events}}$$

GW event – O1 & O2	$(\text{hrss}^{PMW})\ 10^{-23}$ @50% det. Eff. & 5% FAP.
GW150914	(2.79 ± 0.02)
GW151012	(2.57 ± 0.03)
GW151226	(2.70 ± 0.03)
GW170104	(2.52 ± 0.01)
GW170608	(2.63 ± 0.01)
GW170729	(2.53 ± 0.01)
GW170809	(2.40 ± 0.02)
GW170814	(2.51 ± 0.02)
GW170823	(2.50 ± 0.02)

O1, O2 and O3a & O3b

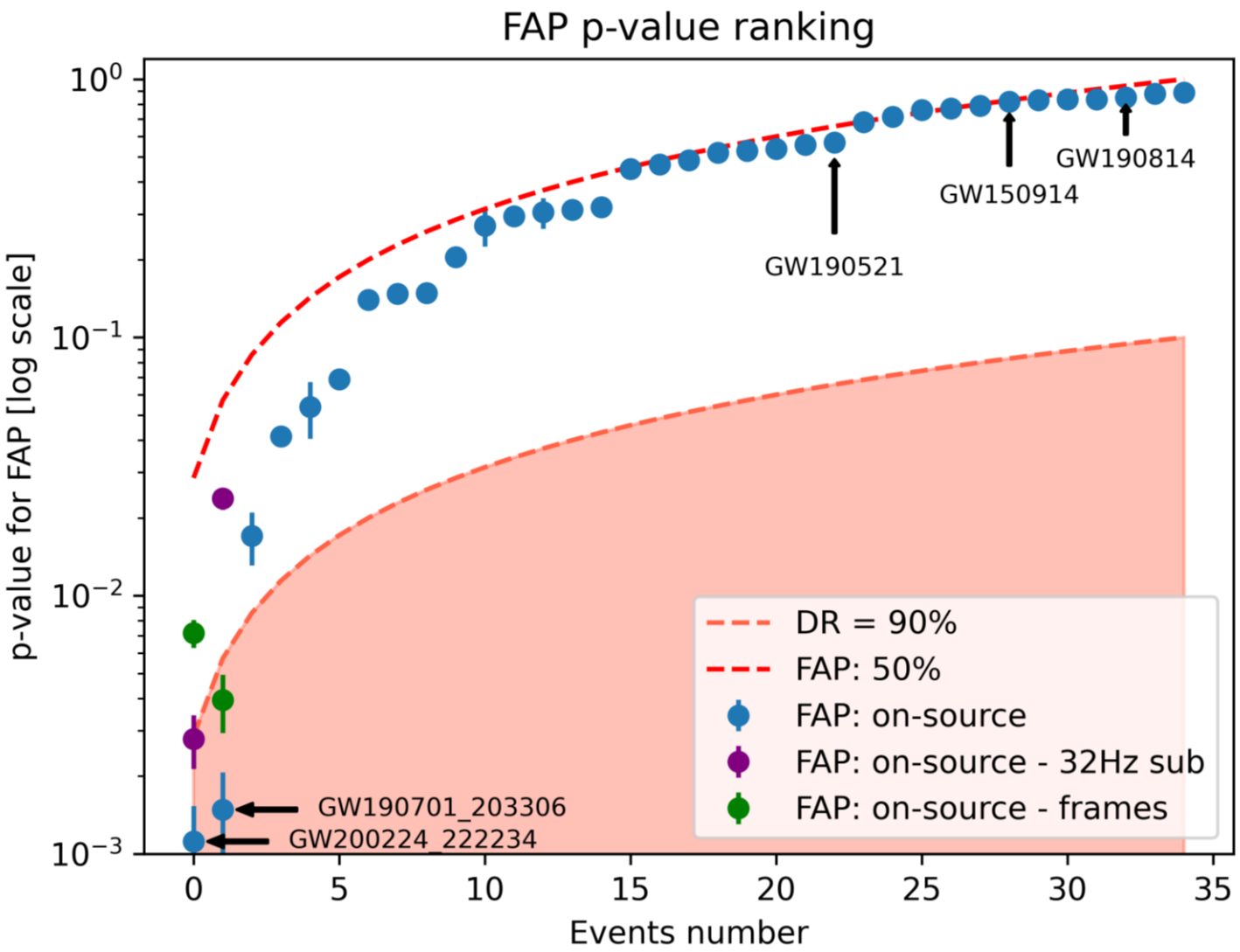
- Analysed events: detectable by cWB.
- Little improvment in $\mathbf{hrss}^{PMW}$ between O1 and O2 for @50% detection efficiency with a FAP of 5%.
- Evident improvment in $\mathbf{hrss}^{PMW}$ between O2 and O3 for @50% detection efficiency with a FAP of 5%.
- CBC PE waveform model based on GWTC-2 and GWTC-3 catalog to simulate CBC signals' properties.

GWTC-1,2,3 results – hrss @50% det. Eff. in PMW

GW event – O3a	$(\mathrm{hrss}^{PMW})\ 10^{-23}$ @50% det. Eff. & 5% FAP.
GW190408_181802	(1.82 ± 0.01)
GW190412	(1.82 ± 0.01)
GW190512_180714	(1.69 ± 0.02)
GW190513_205428	(1.83 ± 0.02)
GW190517_055101	(1.80 ± 0.02)
GW190519_153544	(1.84 ± 0.01)
GW190521	(1.81 ± 0.01)
GW190521_074359	(1.73 ± 0.01)
GW190602_175927	(1.98 ± 0.4)
GW190701_203306	(1.84 ± 0.01)
GW190706_222641	(1.82 ± 0.01)
GW190828_063405	(1.82 ± 0.01)
GW190915_235702	(1.88 ± 0.02)
GW190929_012149	(1.86 ± 0.02)
GW190814	(1.82 ± 0.01)

GW event – O3b	$(\mathrm{hrss}^{PMW})\ 10^{-23}$ @50% det. Eff. & 5% FAP.
GW191109_010717	(1.85 ± 0.01)
GW191204_171526	(2.05 ± 0.05)
GW191215_223052	(1.69 ± 0.02)
GW191222_033537	(1.82 ± 0.02)
GW191230_180458	(1.77 ± 0.08)
GW200219_094415	(1.75 ± 0.07)
GW200224_222234	(1.74 ± 0.01)
GW200225_060421	(1.89 ± 0.04)
GW200311_115853	(1.80 ± 0.01)

4.2 - Echoes: results of the search



On-source (OS) GW events' p-value ranking for the H_0 null hypothesis:

$$\textbf{p-value } H_0 = \frac{\#\text{ rec events with } \sqrt{E^{PMW}} > \sqrt{E_{OS}^{PMW}}}{\#\text{ total rec events}}$$

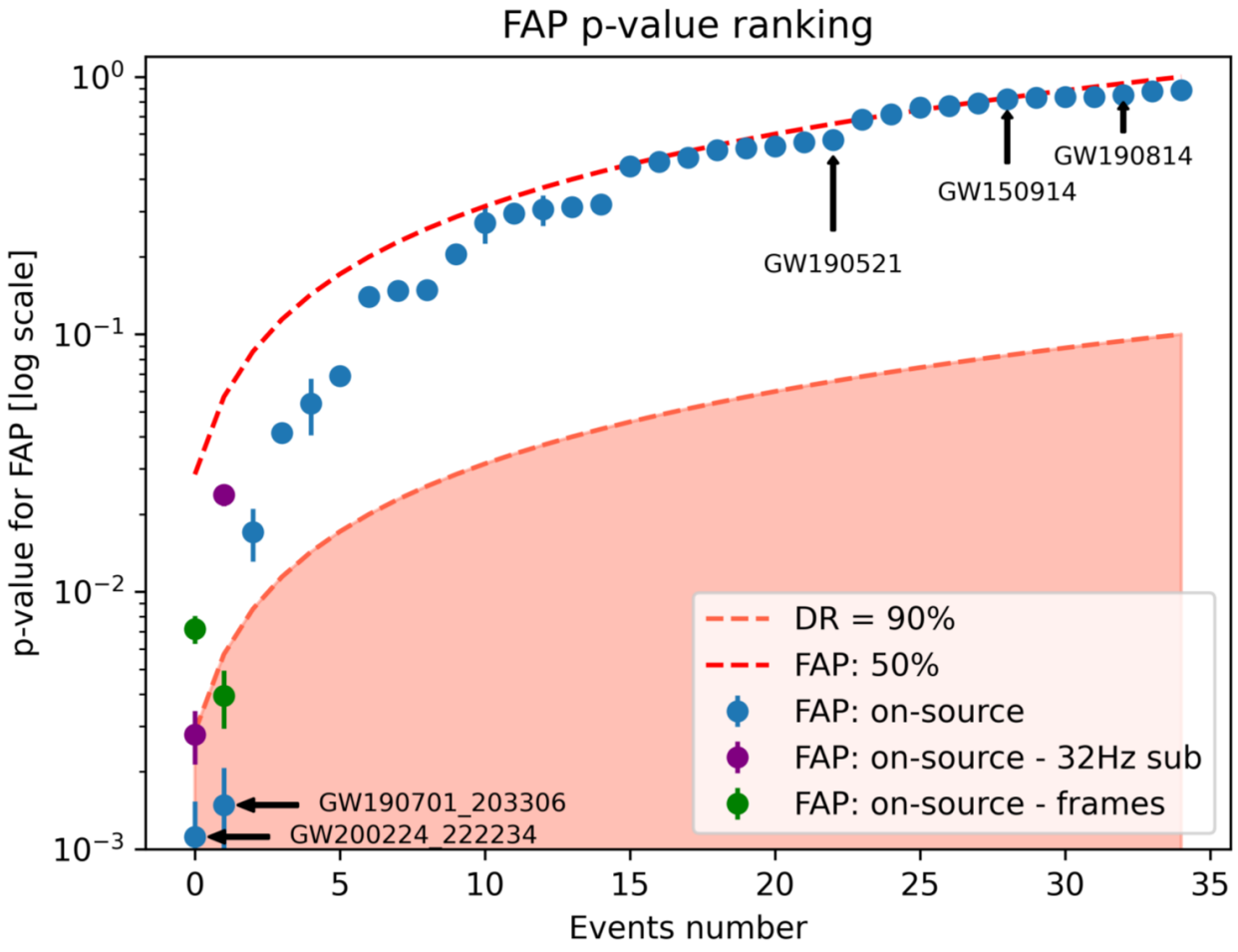
evaluated over the BGK study distribution.

Results:

- **Suspicious events**.
  - GW190701
  - GW200224
  - No other candidates provide warnings.

- **Green dots**: only 4096s around GW event.
- **Violet dots**: using the 32Hz mitigation plugin.

4.3 - Echoes: results of the search



GWTC-2:
R. Abbott et al. Phys. Rev. D 103, 122002

TABLE X. Results of search for GW echoes. A positive value of the log Bayes factor $\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$ 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	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$	Event	$\log_{10} \mathcal{B}^{\mathrm{IMRE}}_{\mathrm{IMR}}$
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		

GWTC-3:
arXiv:2112.06861v1

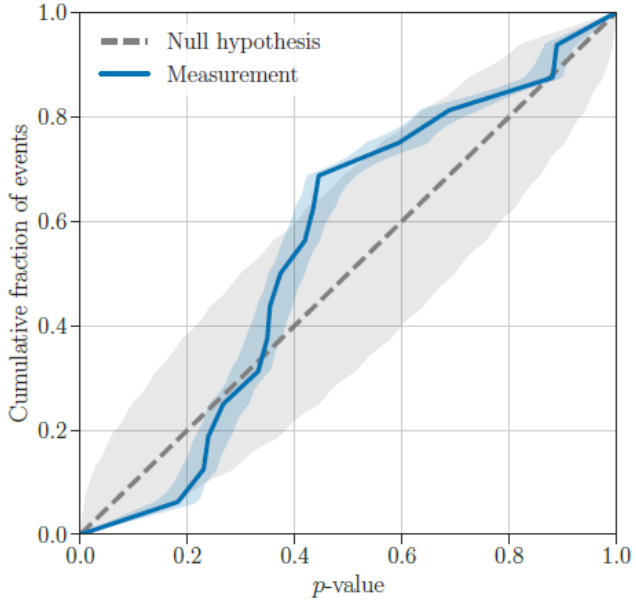
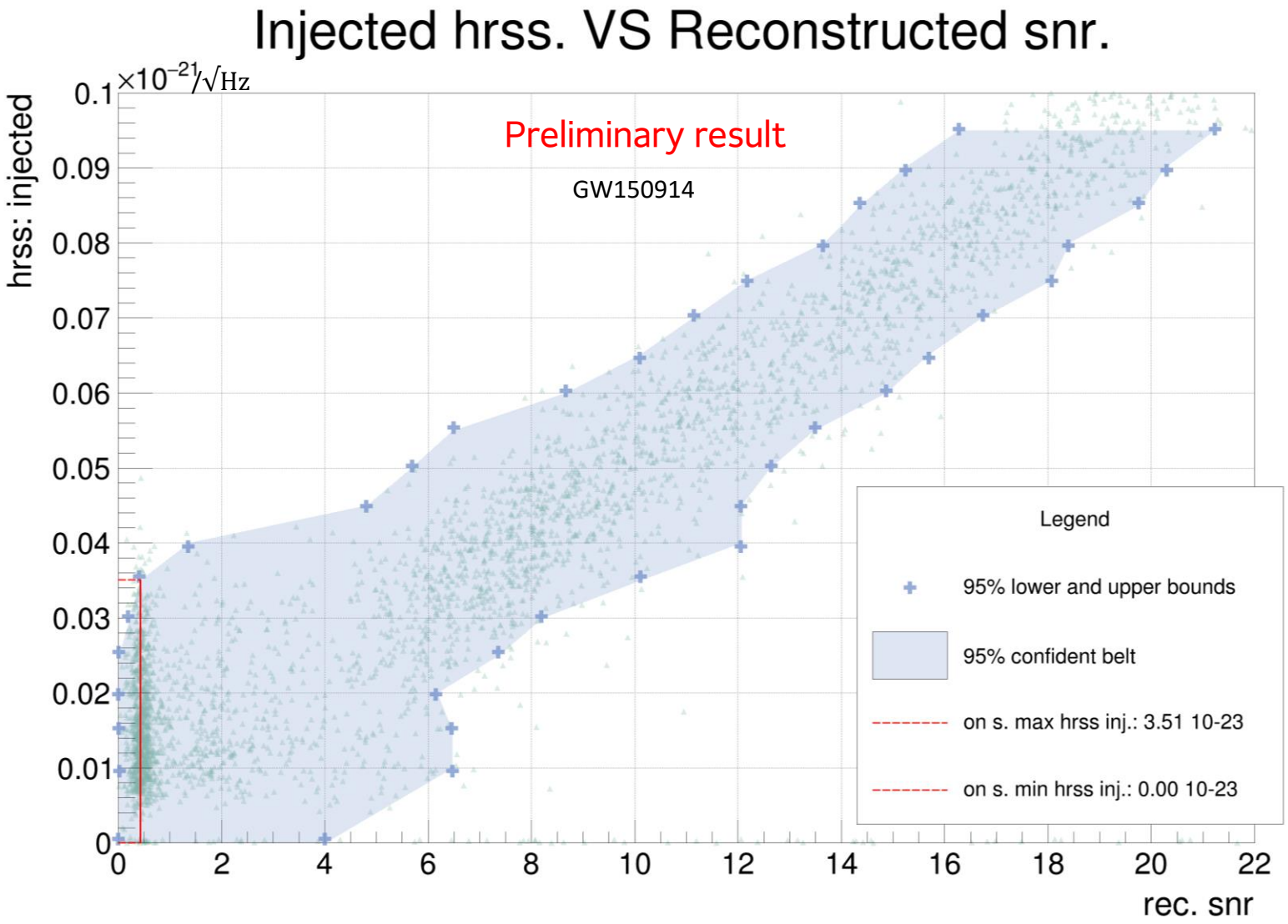


FIG. 15. Results of the echoes analysis (Sec. VIII B). Plot of fraction of events for which the echoes signal-to-noise p-value is less than or equal to the abscissa. The light-blue band represents the 90% credible interval of the observed p-values, while the diagonal dashed line is expectation from the null hypothesis. The light-gray band around the diagonal line represents the 90% uncertainty band of the null hypothesis.

Agreement with LIGO-Virgo testing GR results

4.4 - Echoes: results of the search



95% confident belt

- Preliminary result for GW150914.
- Reconstructed snr: -> define the interval of $hrss_{inj}$ @ 95% confidence and set constraints over A or γ parameters.
- On source snr -> compatible with null hypothesis.

GWTC-2 and 3

Threshold snr^{PMW} for a FAP = 5%

$\in [\sim 2, \sim 3]$

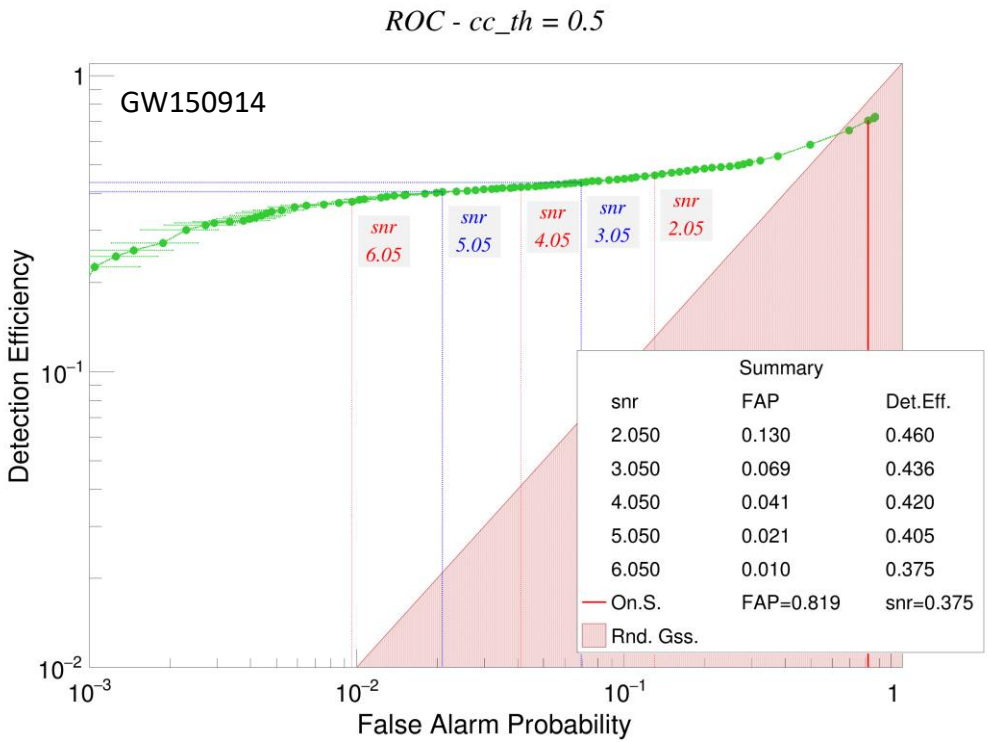
5 - Conclusions

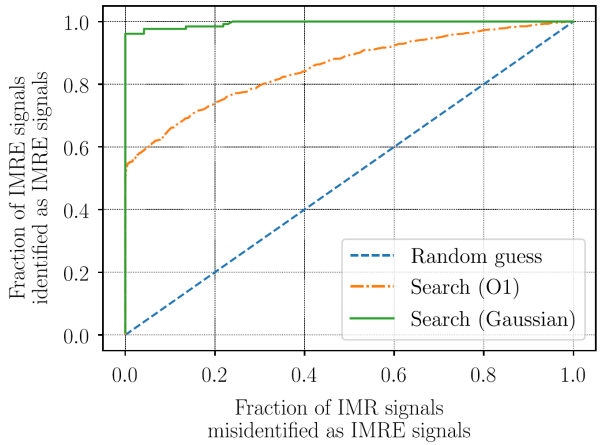
- Capability to detect sub-thresholds burst signals with FAP < 5%.

Threshold $\mathrm{snr}^{\mathrm{PMW}}$ for a FAP = 5% $\in [\sim 2, \sim 3]$

- Detection efficiency even at very low **SNR** values.
- Capability to recover fundamental echo morphological parameters $(\mathbf{A}, \mathbf{t_{echo}}, \mathbf{\Delta t_{echo}}, \boldsymbol{\gamma})$.

- **GW190701**: its PMW energy excess can be classified as a **noise feature** in the data.
  - With the 32Hz plugin p-value noise well above the discovery rate (DR) of 90%.
- **GW200224:** its PMW energy excess can be classified as a **noise feature** in the data.
  - Inconsistent p-values from the standard and the 4096s LES searches are pointing to systematic errors in the cWB background estimation when on-source time includes such peculiar noise features.





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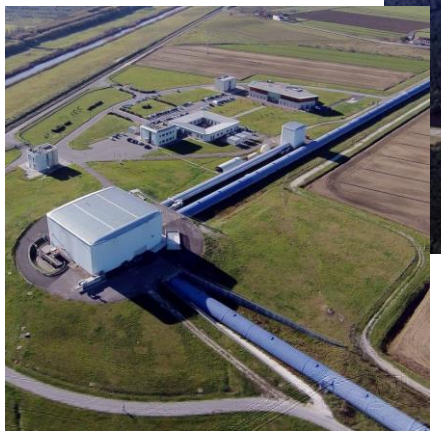
Sergey Klimenko
Marco Drago
Edoardo Milotti
Agata Trovato

Credits: C. Gray

Credits: J. Giaime



Credits: Virgo Collaboration

Thank you

for the attention!

Contact.

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END

Backup slides

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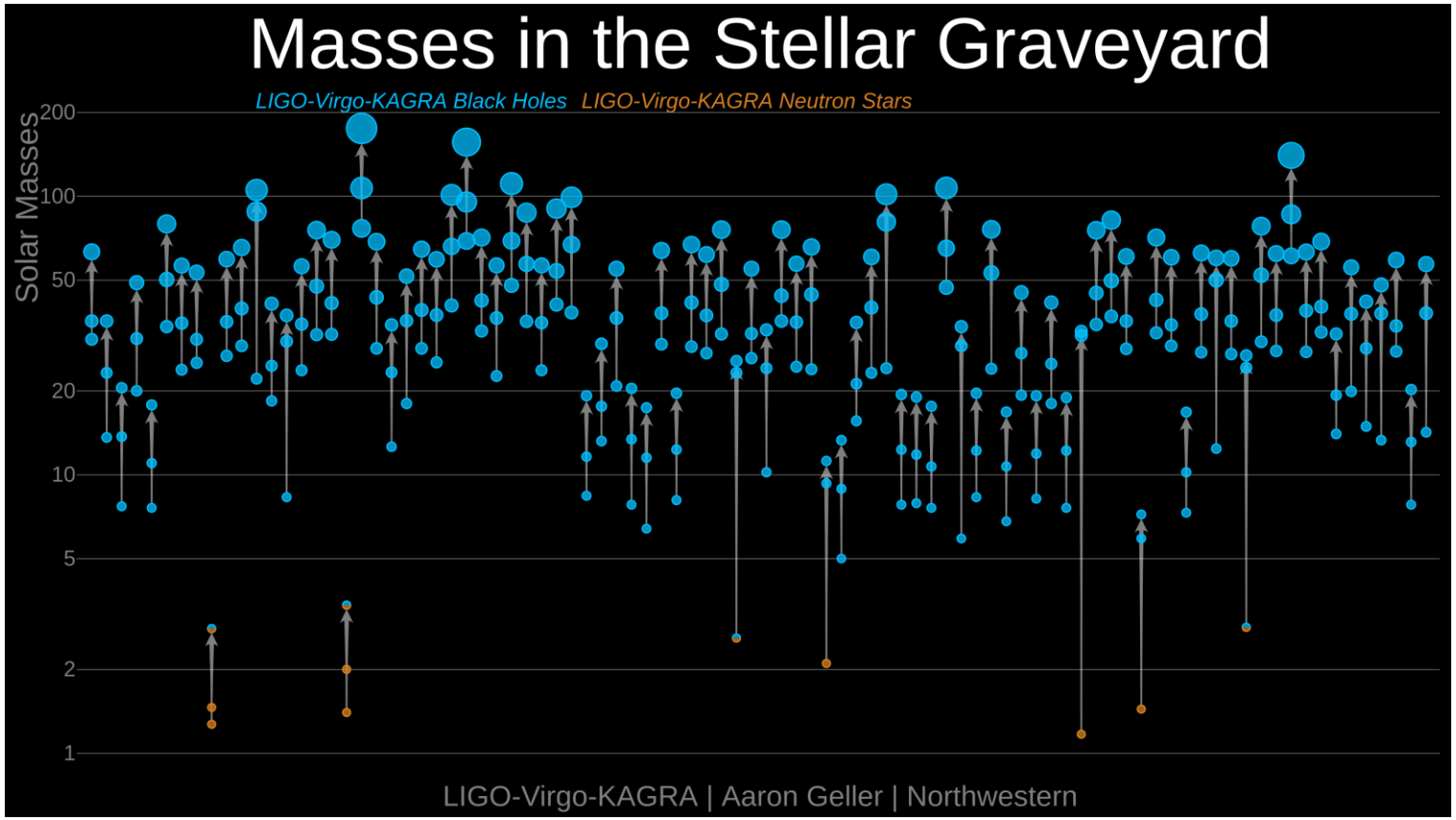


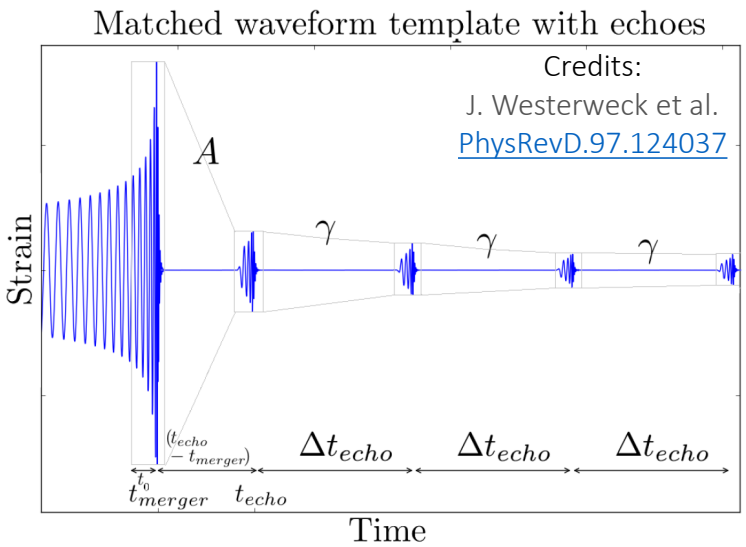
Credit: LIGO-Virgo/Aaron Geller/Northwestern

1.2 - Echoes search, WHY?

Several alternative models to BH, generally referred as **exotic compact objects** (ECO), such as Gravastars or Firewalls.

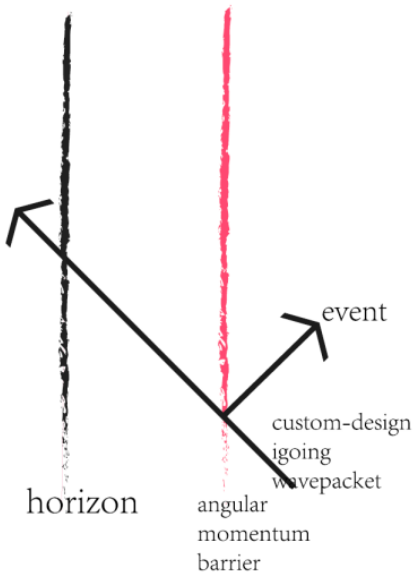
ECOs share a common feature.

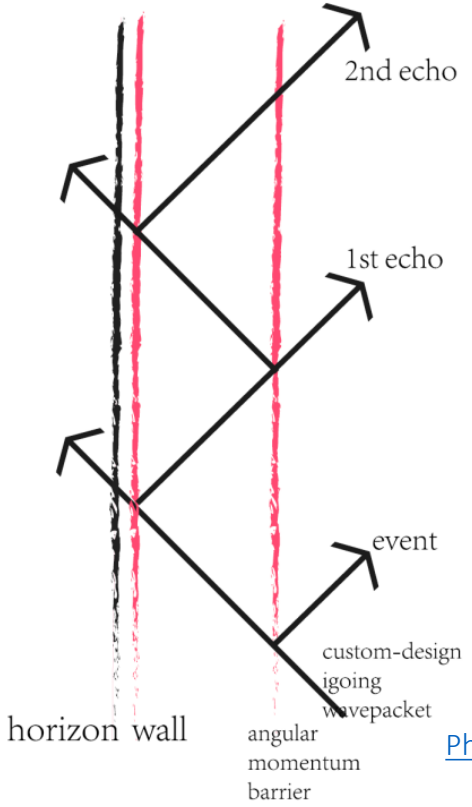
Emission of GW pulses, called echoes, in the post-merger ringdown phase of the coalescence.



Credits:
J. Westerweck et al.
PhysRevD.97.124037

- Multiple reflection of ingoing GW signal.
- Horizon replaced by a surface of different nature.





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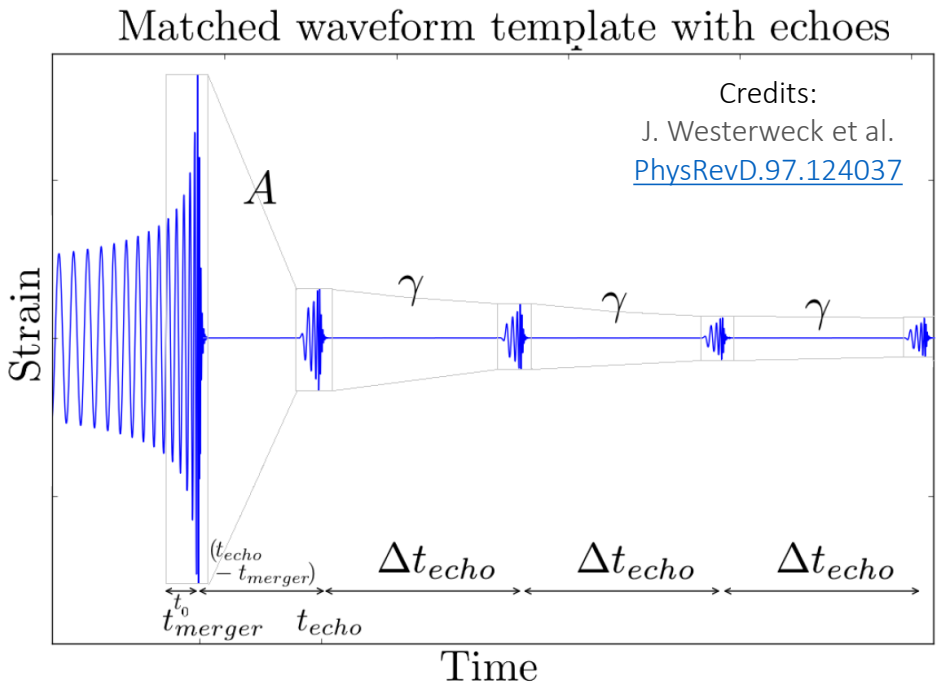
Emission of GW pulses, called echoes, in the post-merger ringdown phase of the coalescence.

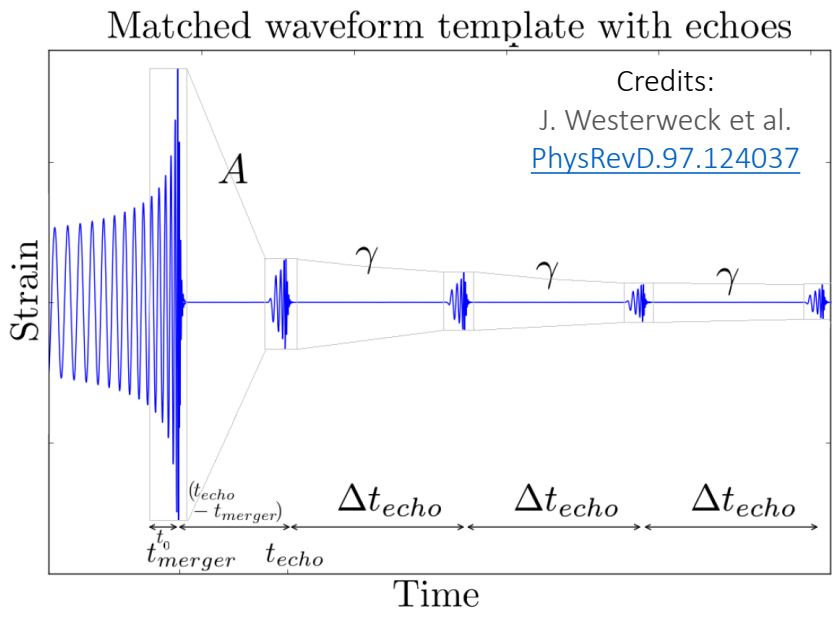
Parameter	Description
Δt_{echo}	time delay between subsequent echoes • n -> related to the nature of the ECO; • M -> remnant mass of the final ECO; • l -> radius lengh correction to the BH horizon;
t_{echo}	time of the first echo signal
γ	amplitude damping factor of echoes
A	relative amplitude of the first echo wrt the CBC signal.



WHY searching ECHOES?

- **Probe the general relativity (GR) theory.**
- **Investigate exotic state of matter.**

1.3 - Echoes search, WHY?



$$\Delta t_{echo} \sim n\, M \log\left(\frac{l}{M}\right), \qquad l \ll M, \qquad c = G = 1 \qquad [1]$$

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WHY searching ECHOES?

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[1] V. Cardoso et al. PhysRevD.94.084031

2 - Echoes: state of the art

Several echoes searches were performed in past years

- **template searches**;
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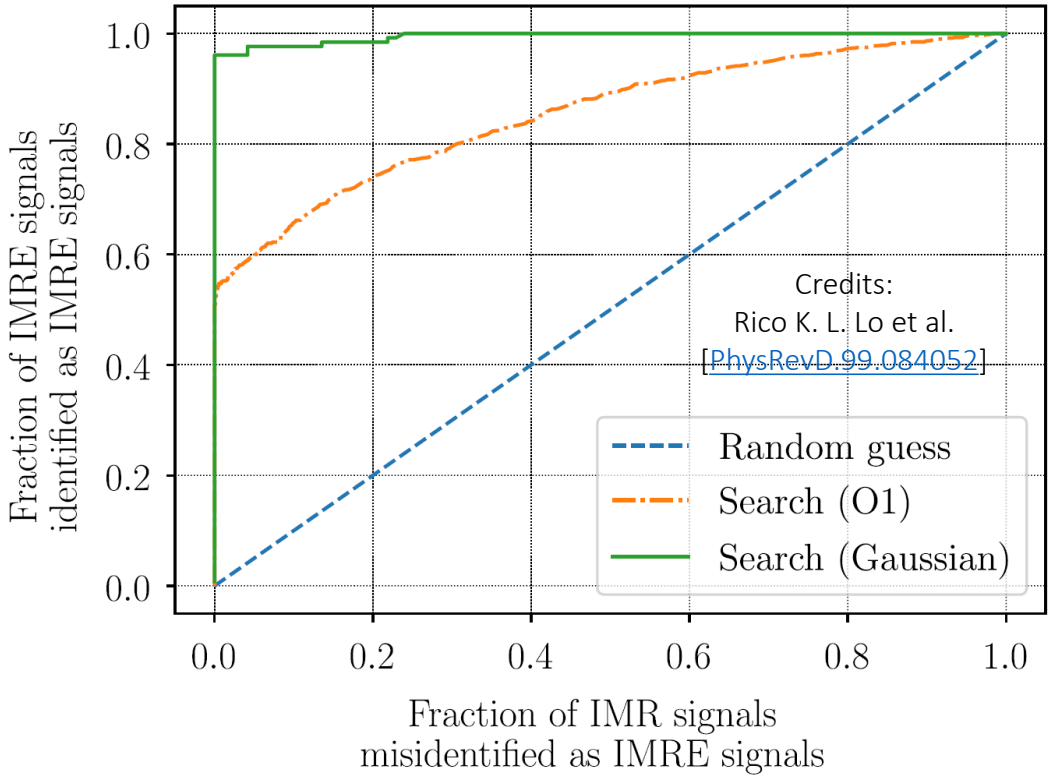

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Coherent Wave Burst (cWB) pipeline

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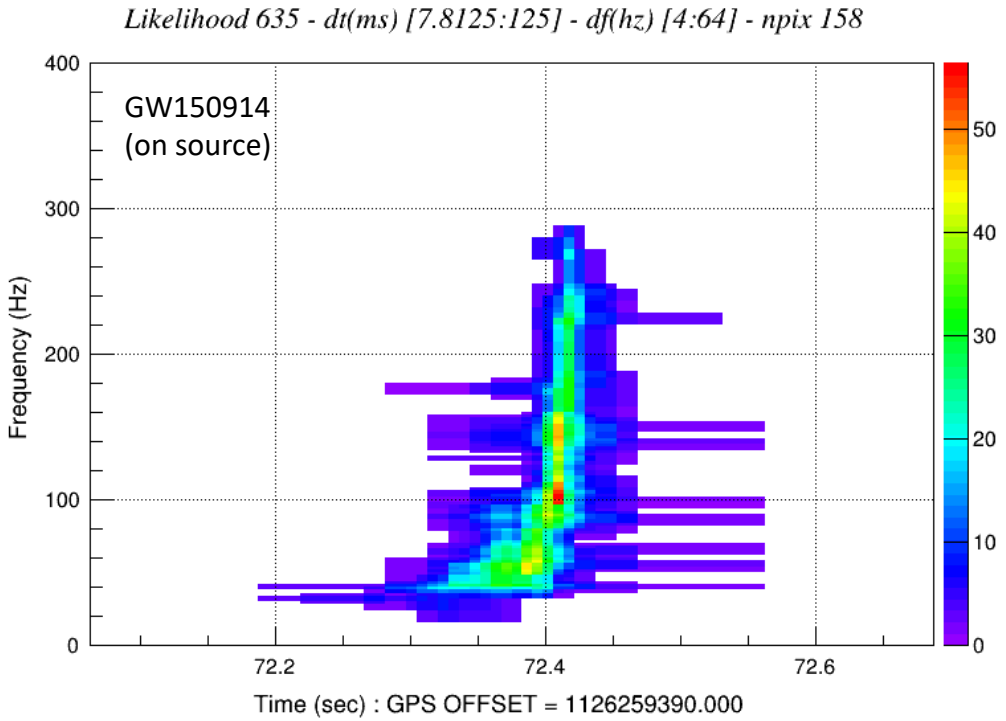


cWB flowchart

- Data conditioning
- Whitening of the data ($\mathbf{x[i]}$)

} Single detector

- Pixels selection
- Likelihood maximization ($\mathbf{L}$)
- Post production cuts

} Combined network

$$\mathbf{x[i] = h[i] + n[i]};$$

$$\mathbf{L = \log\left(\frac{P(x|H_1)}{P(x|H_0)}\right)};$$

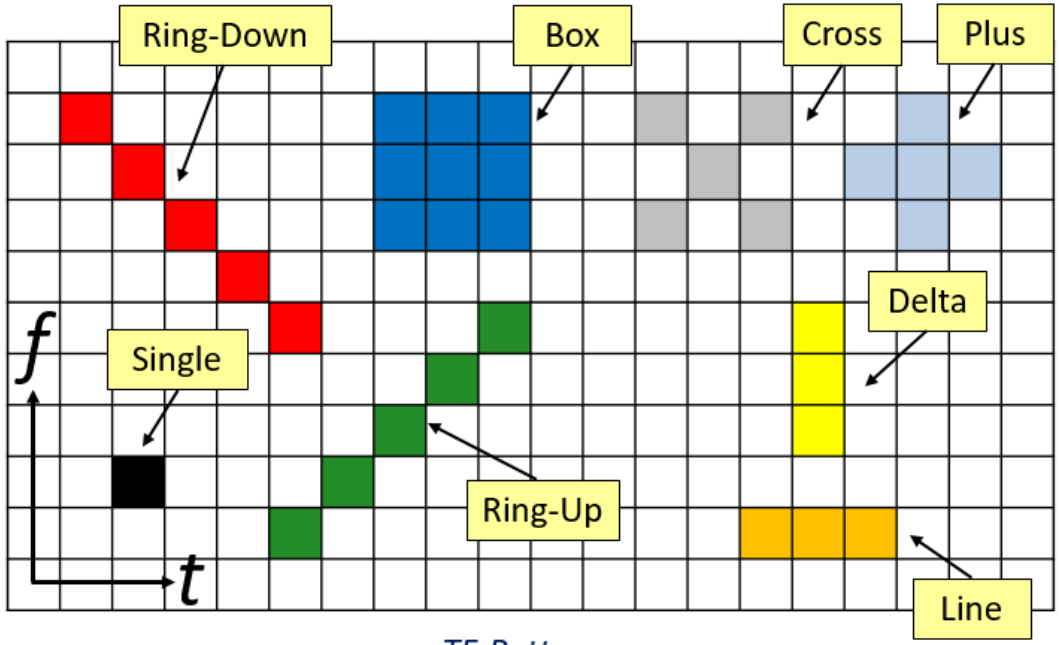
$\mathbf{P(x|H_1)}$: probability of having a signal.

$\mathbf{P(x|H_0)}$: probability of the null hypothesis.

6.1 – Appendix: cWB likelihood

CoherentWaveBurst (cWB) pipeline:

- **Unmodelled coherent search**:
  - no assumptions on the signal morphology.
- **Maximum likelihood approach**



TF-Patterns

$$x[i] = h[i] + n[i];$$

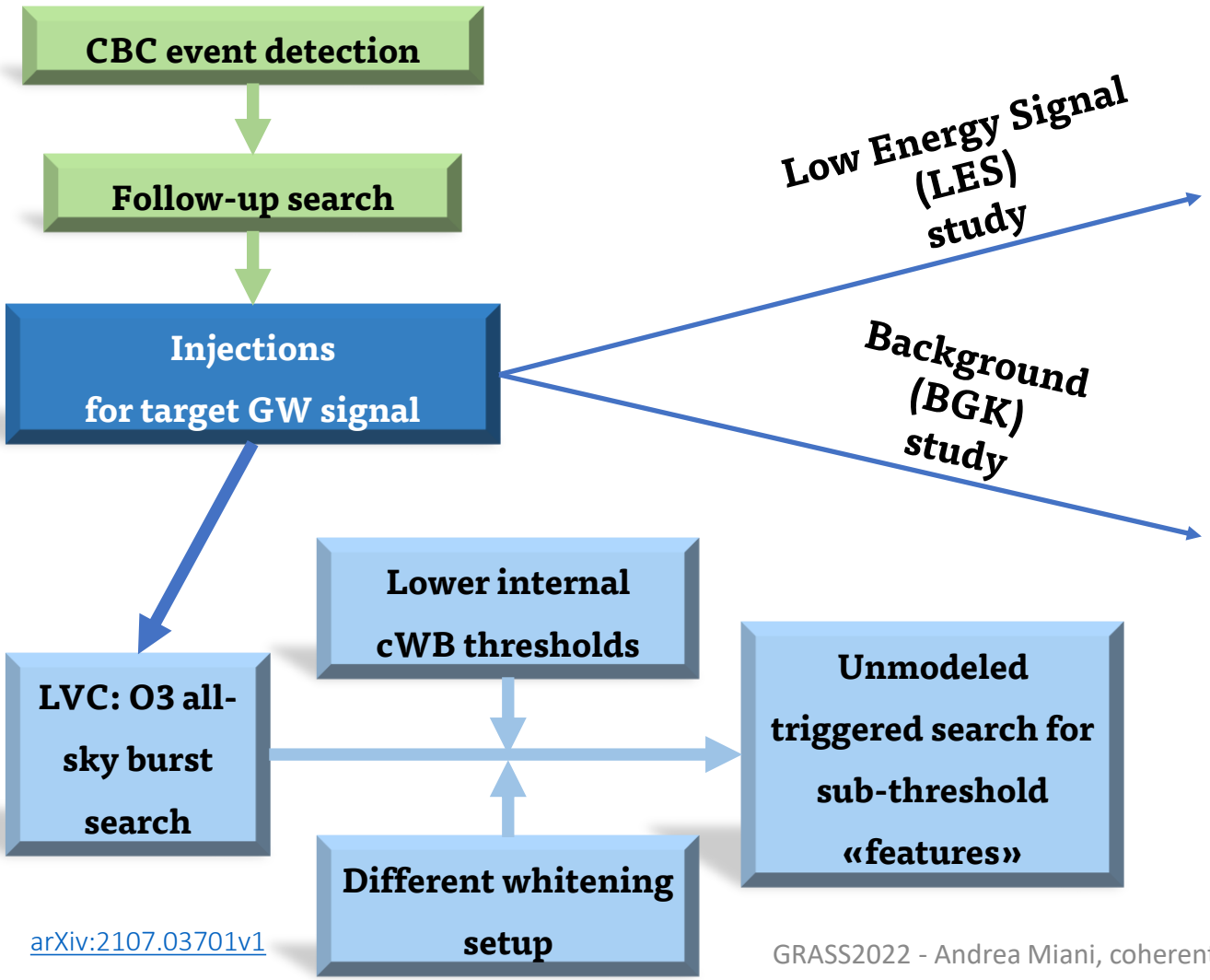
$$P(x|H_1) = \prod_{i=1}^{M} \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{(x[i]-\xi[i])^2}{2\sigma^2}\right)$$

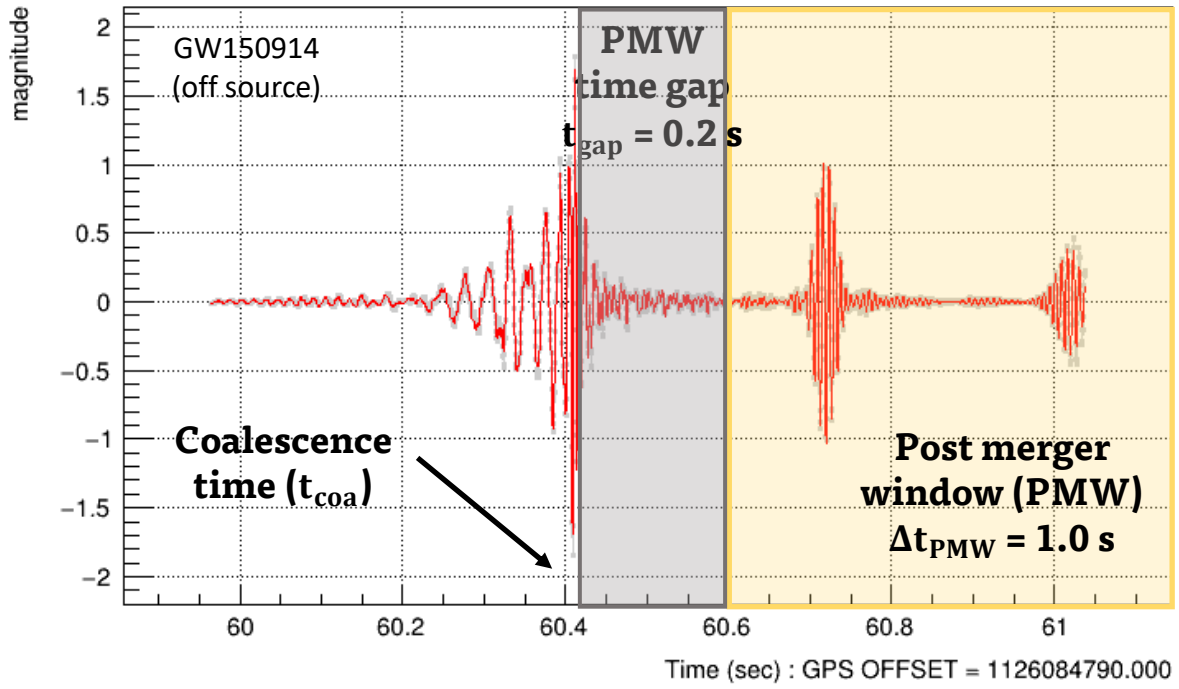
$$P(x|H_0) = \prod_{i=1}^{M} \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{x[i]^2}{2\sigma^2}\right)$$

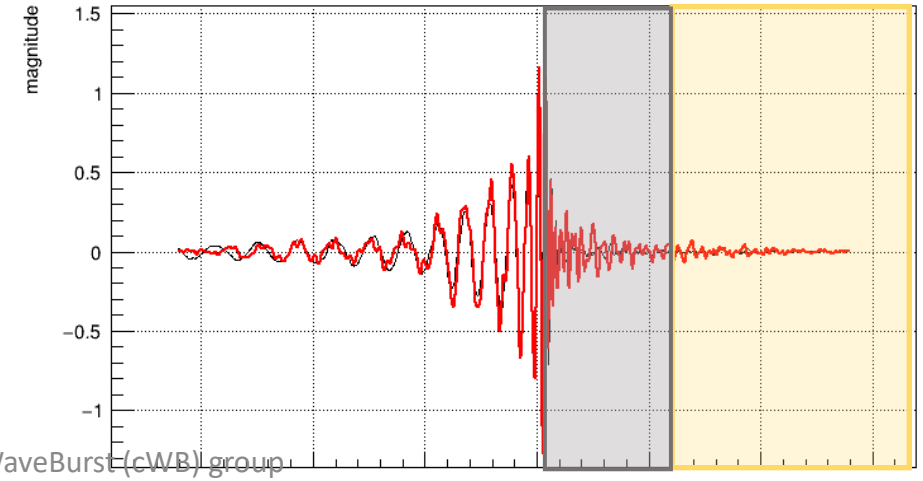
$$\mathrm{L} = \log\left(\frac{P(x|H_1)}{P(x|H_0)}\right) = \sum_{k=1}^{N} \sum_{i\in\Omega_{TF}} \left(\frac{x_k^2[i]}{\sigma_k^2[i]} - \frac{(x_k[i]-\xi_k[i])^2}{\sigma_k^2[i]}\right);$$

cWB method: CBC follow-up

Method, science case: ECHOES

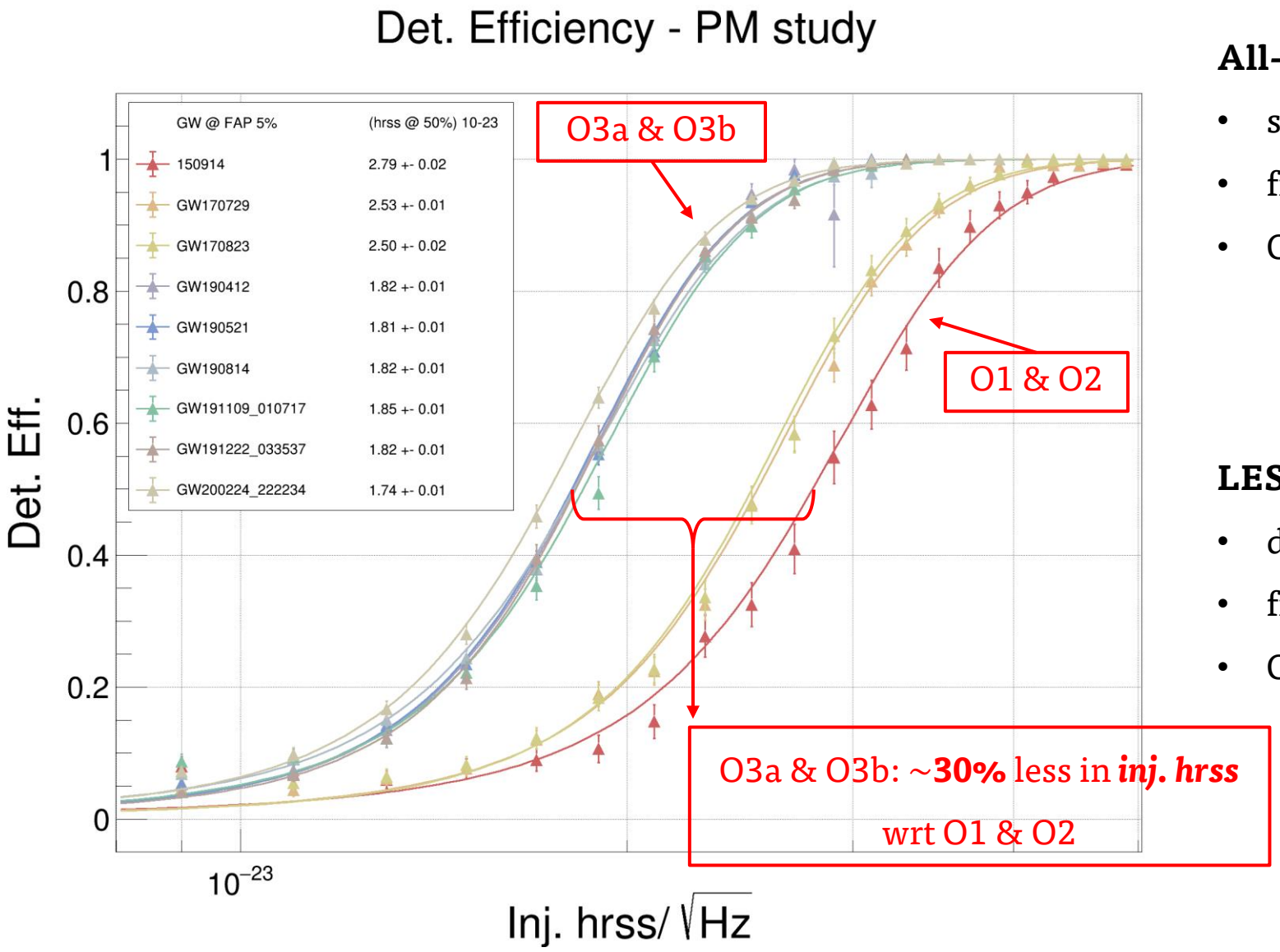






arXiv:2107.03701v1

GWTC-1,2,3 results – hrss @50% det. Eff. in PMW



All-sky short burst search O3:

- single Sine Gaussian (circular) with
- frequency = 235 Hz,
- Q = 100
  - **hrss @ 50% det.Eff. =** $\mathbf{0.8 \cdot 10^{-22} Hz^{-1/2}}$

    requiring a FAR = 0.01/year.

LES search for O3:

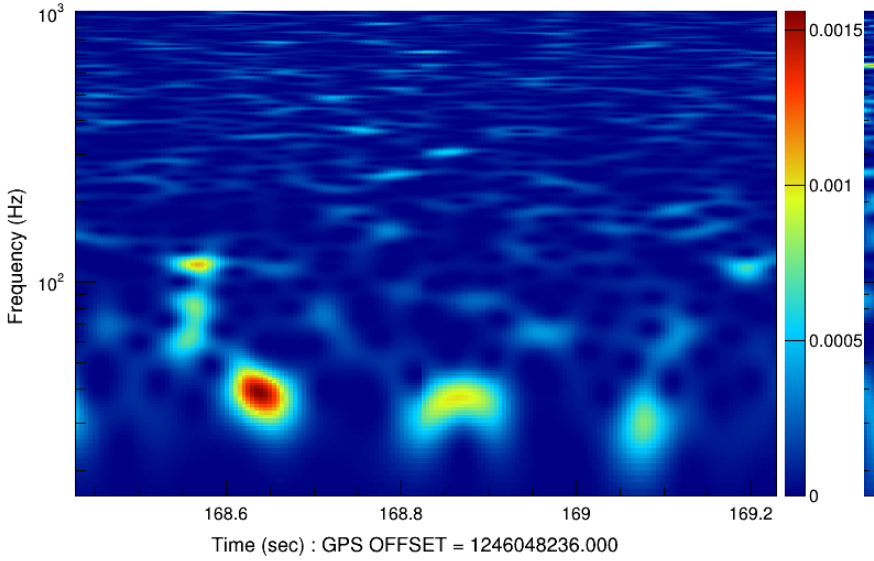
- double Sine Gaussian (eliptical) with
- frequency = 140 Hz,
- Q = 8.8
  - **hrss @ 50% det.Eff. =** $\mathbf{\sim 1.85 \cdot 10^{-23} Hz^{-1/2}}$

    requiring a FAR = 18/year.

Case of GW190701 – LH network

On-source (OS) event

L1 – Spectrogram (y-log scale)



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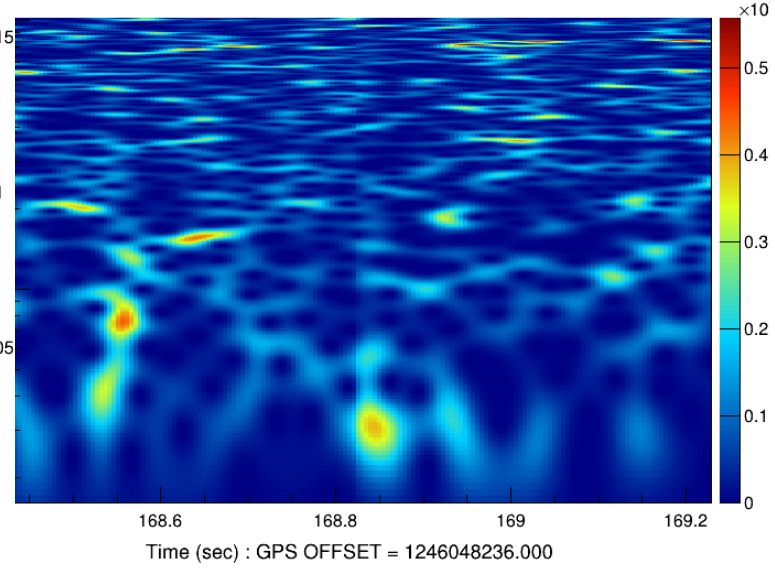
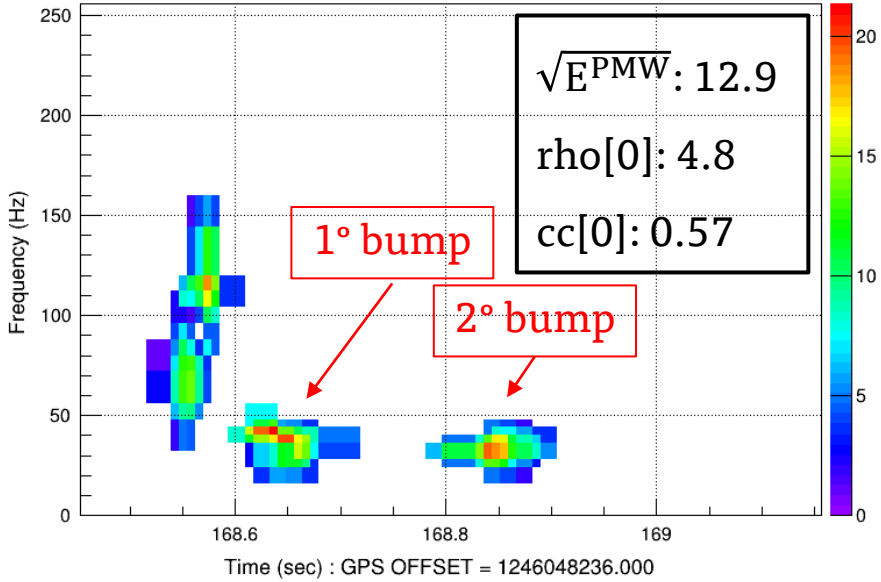
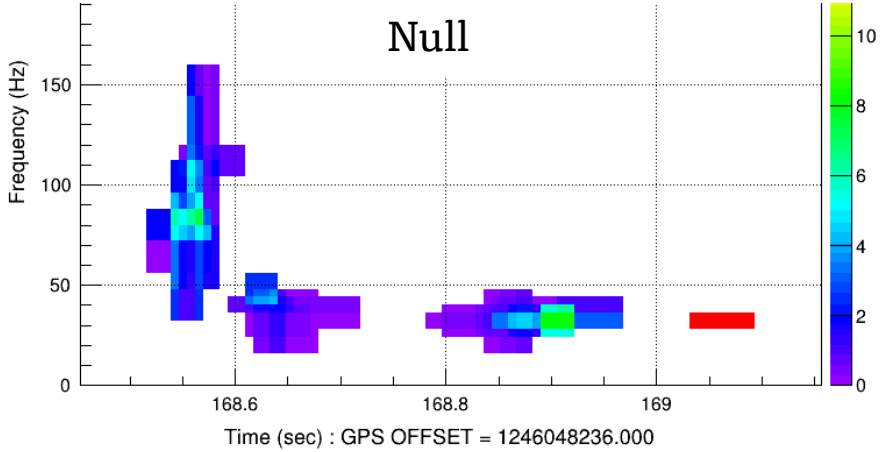


Likelihood





LES **standard** search

-> p-value = 0.0015 ± 0.0006

LES **4096s search**

-> p-value = 0.004 ± 0.001

LES **32Hz plugin search**

-> p-value = 0.024 ± 0.002

OS - LH - cc^{PMW}:

Without subtracting GW190701:

- all = 0.73;
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- On-source (OS) LH analysis with best CBC PE subtracted (sub).
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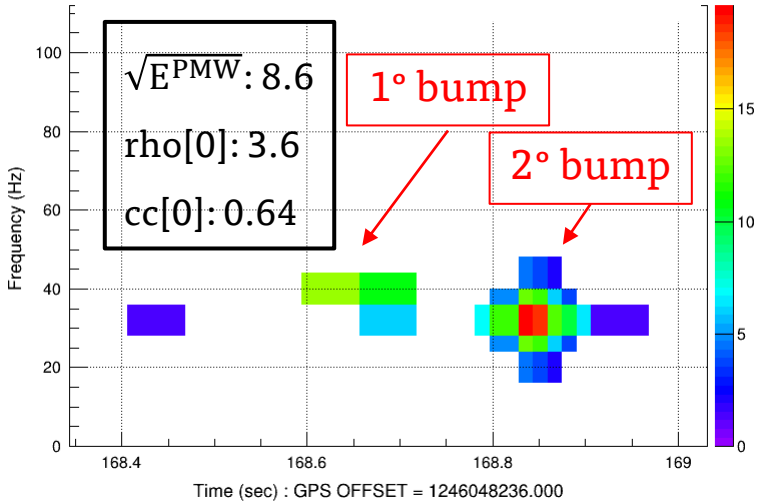
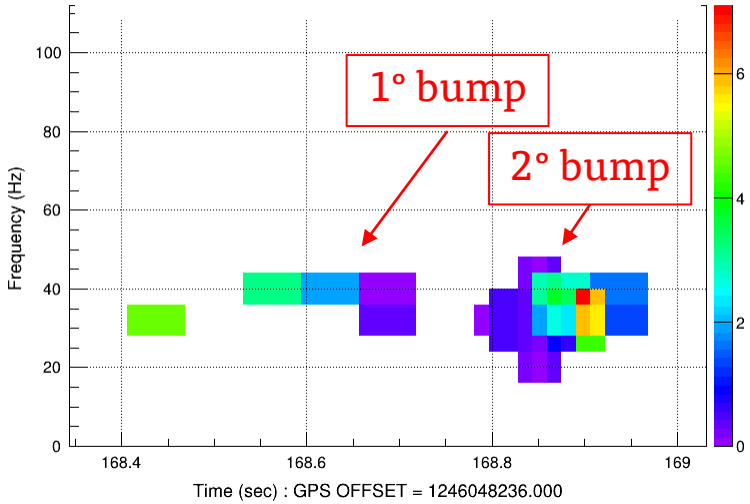
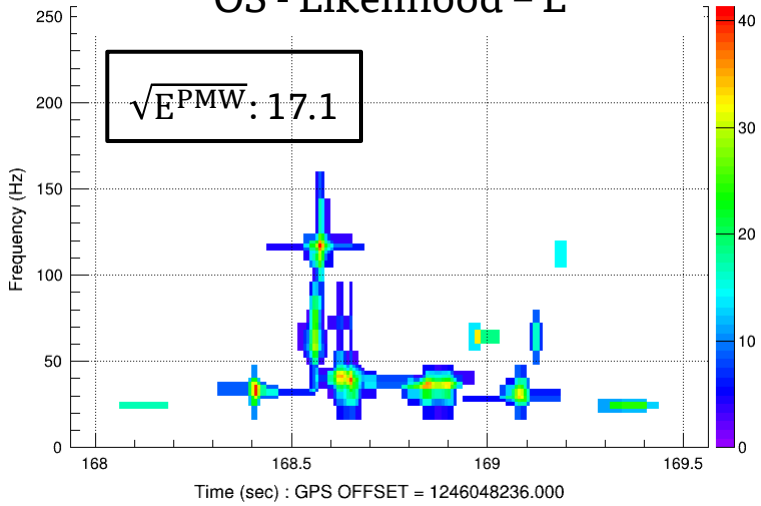


OS sub. – Null - LH



OS - Likelihood – L



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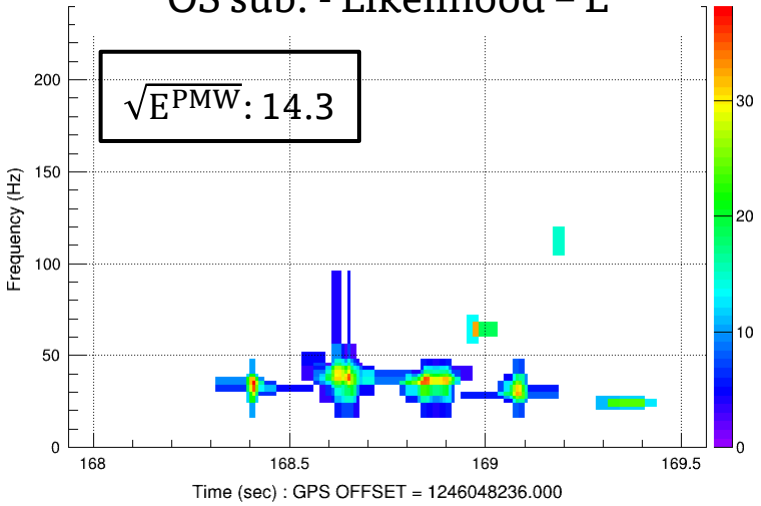

The PMW excess of energy in GW190701 can be classified as a **noise feature** in the data. With the 32Hz plugin its p-value noise is well above the discovery rate (DR) of 90%.

Case of GW200224 – LH network

On-source event

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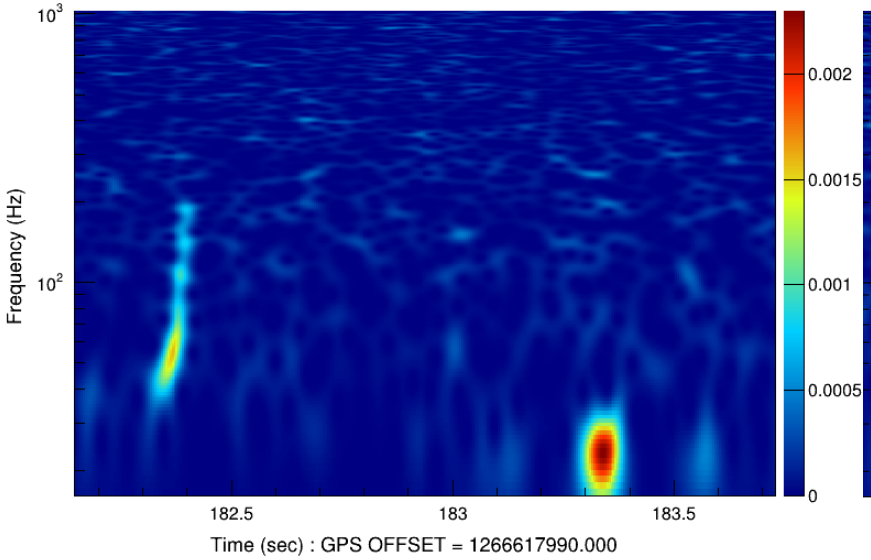

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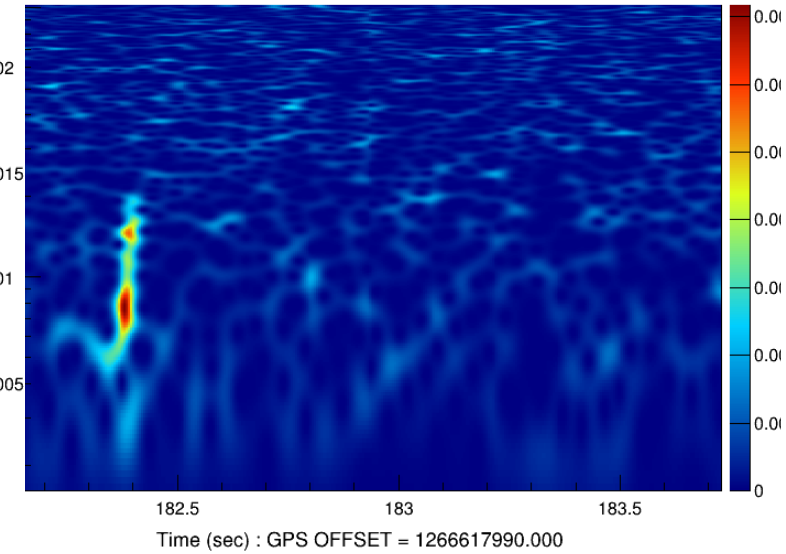
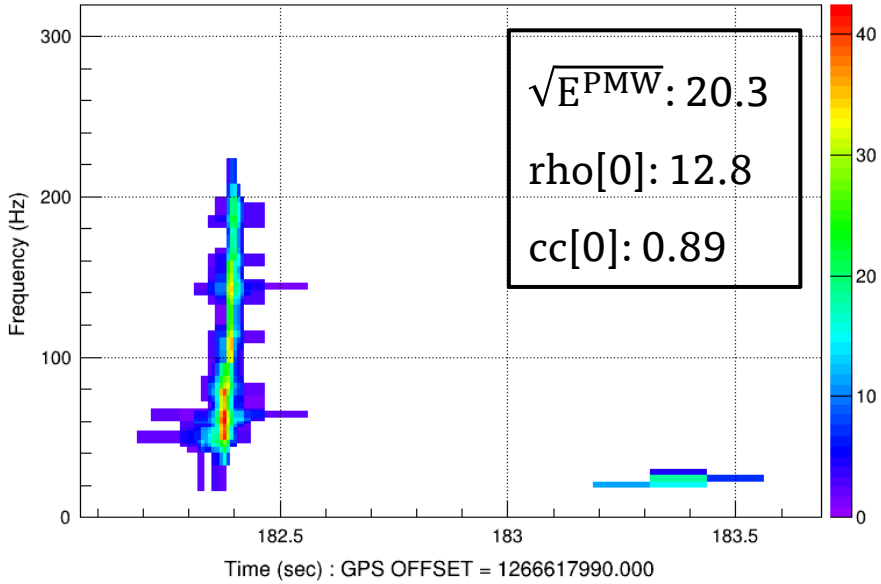
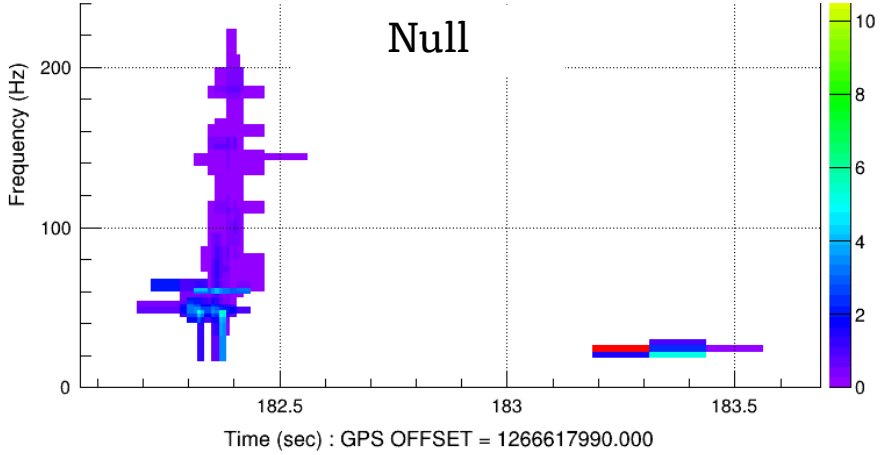


Likelihood





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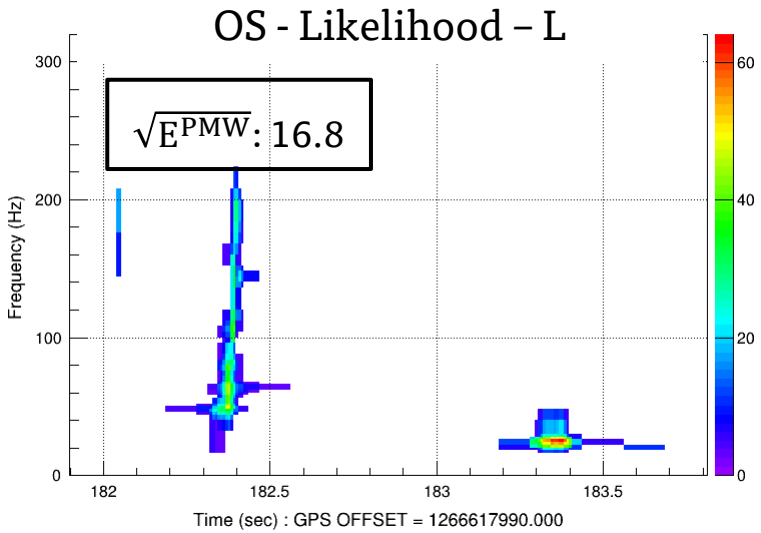

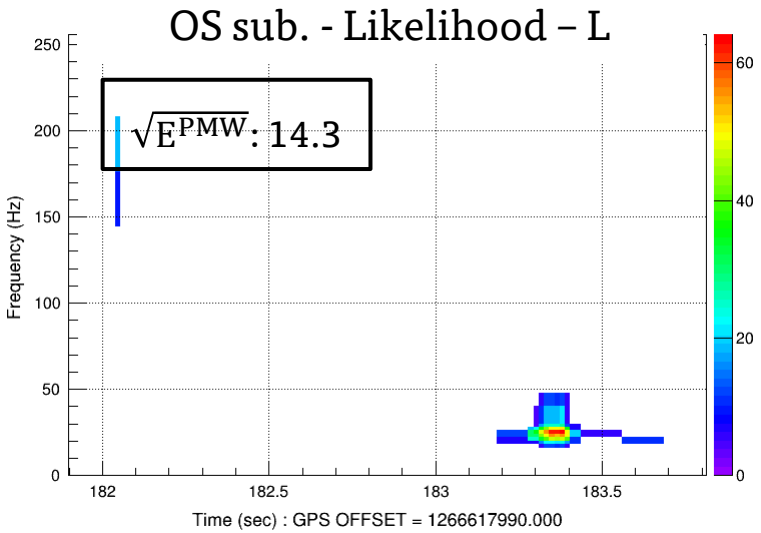

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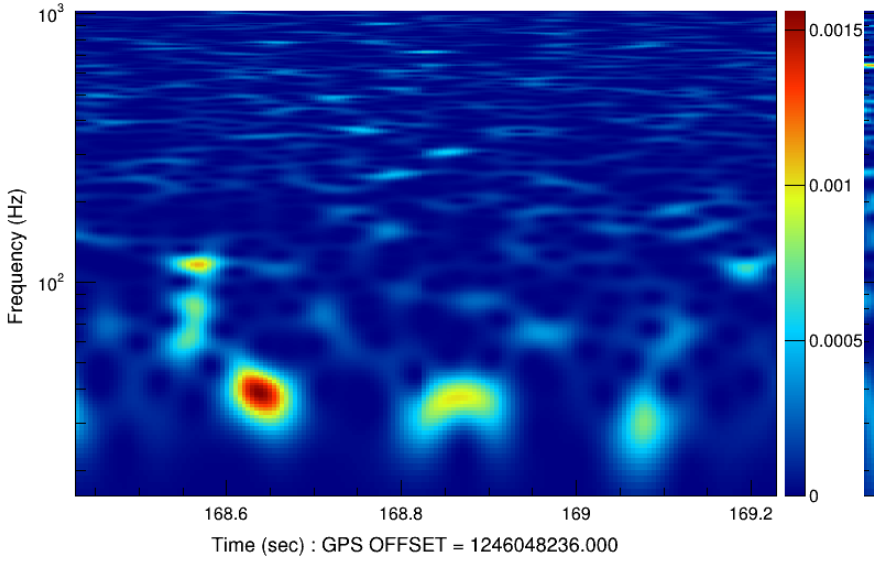

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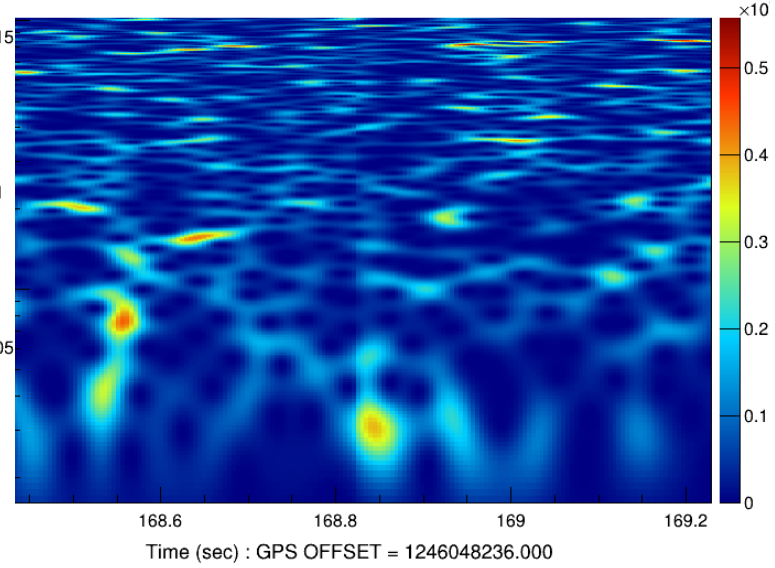

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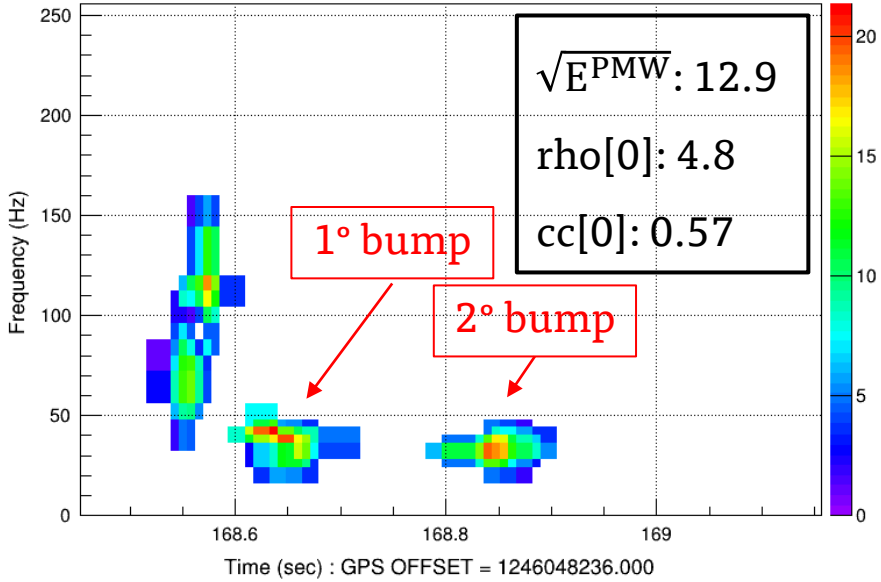

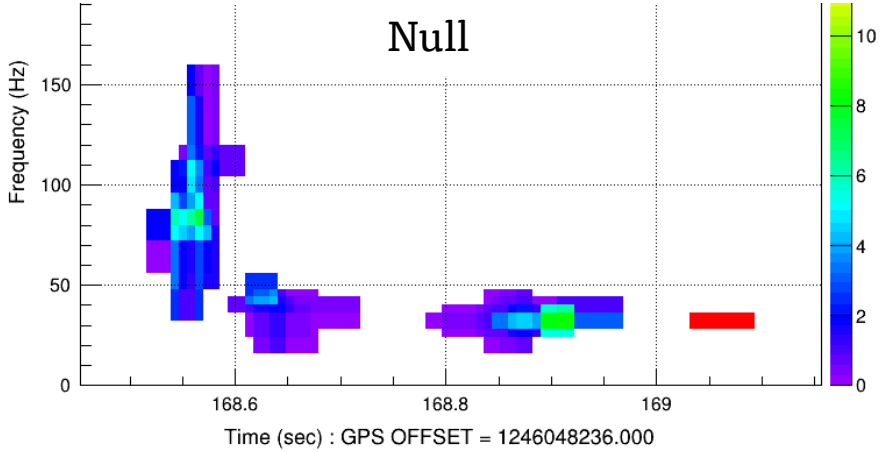

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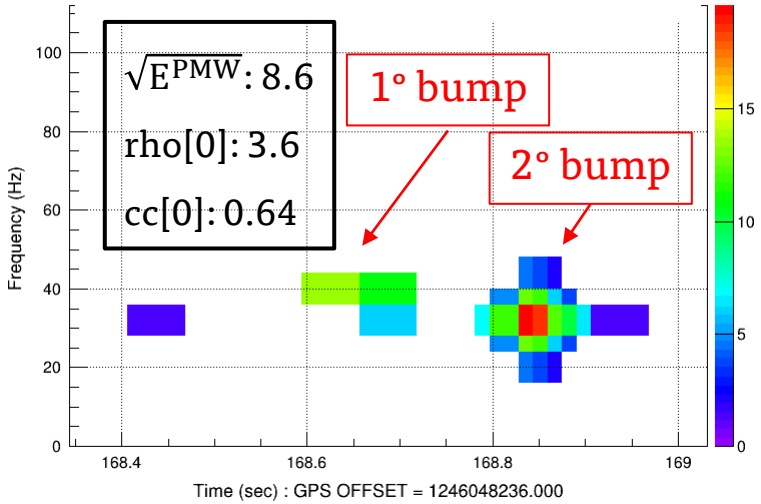

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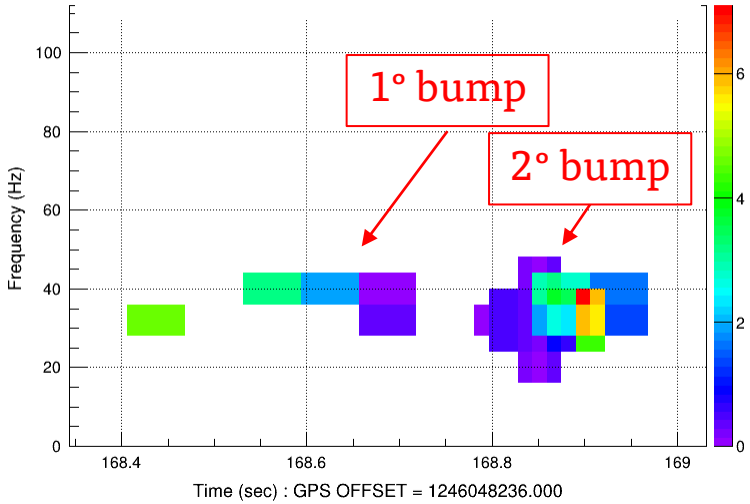

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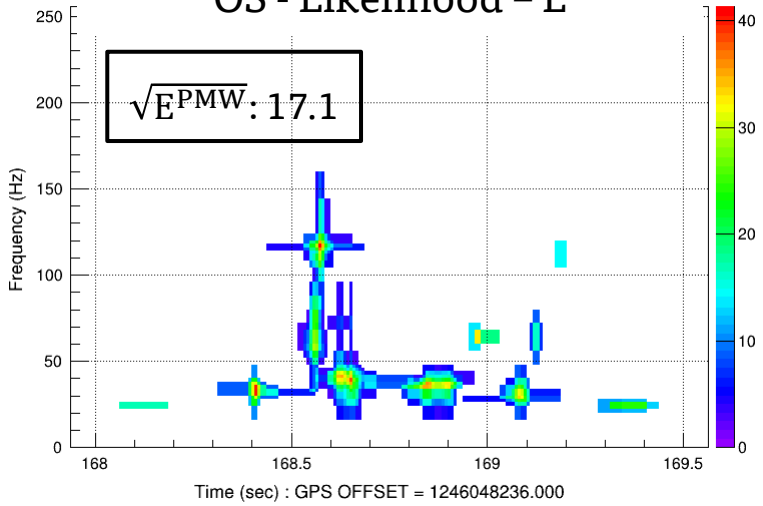

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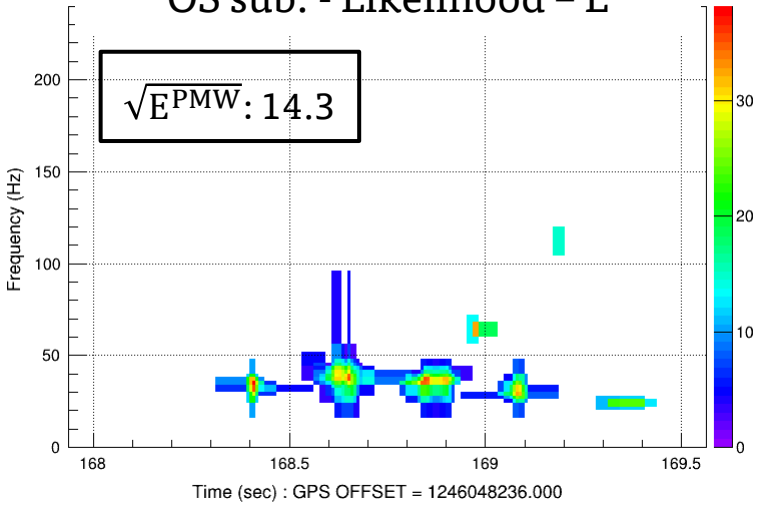

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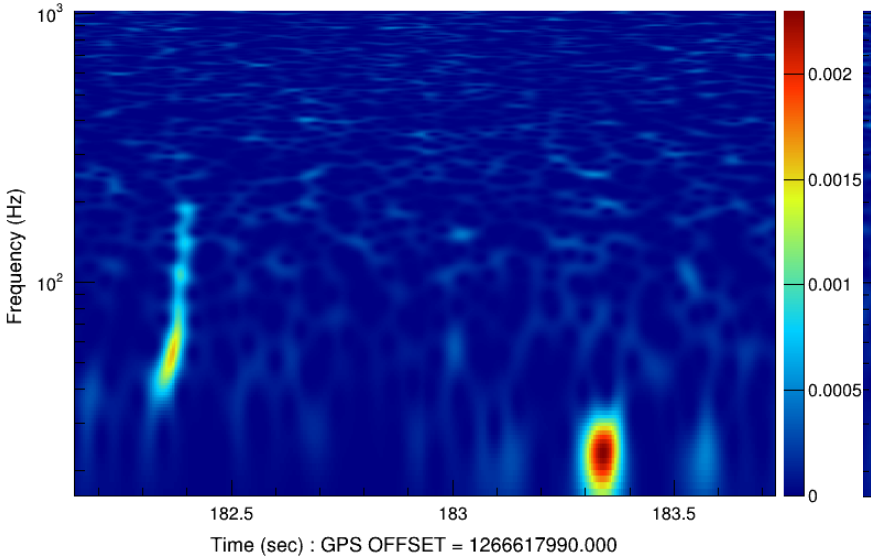

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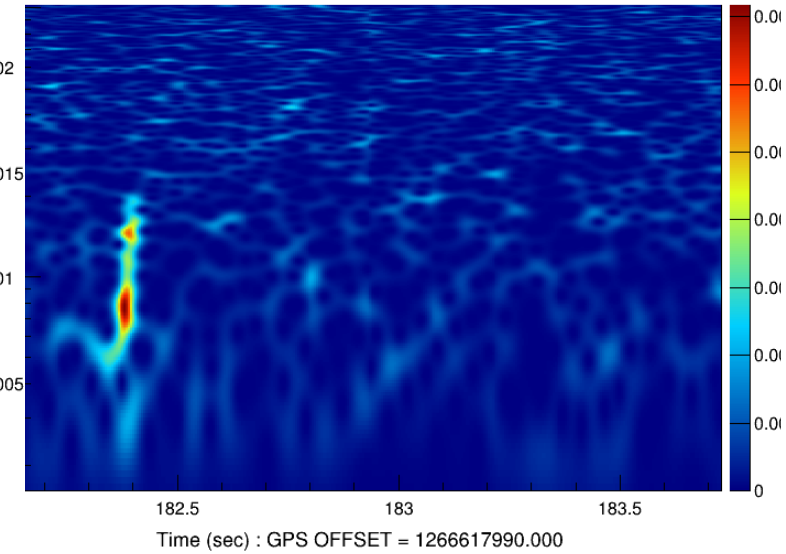
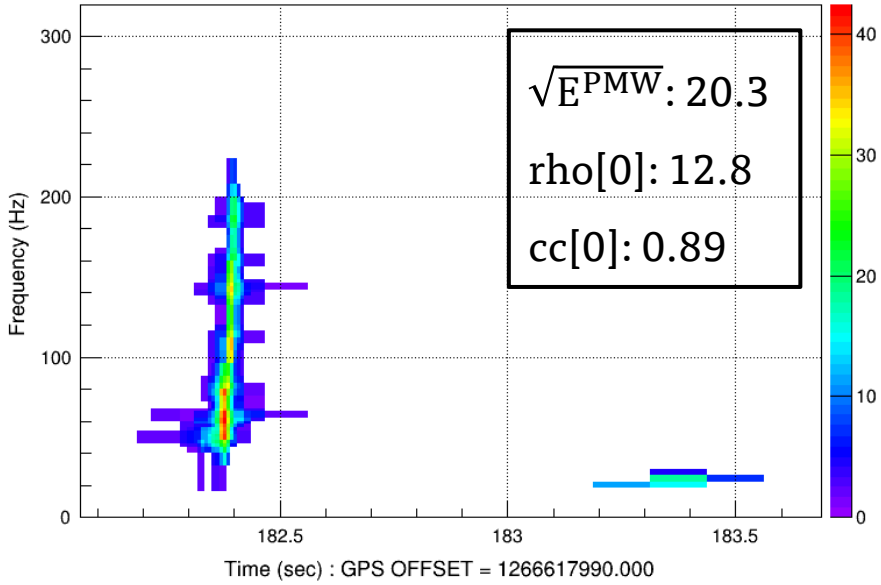
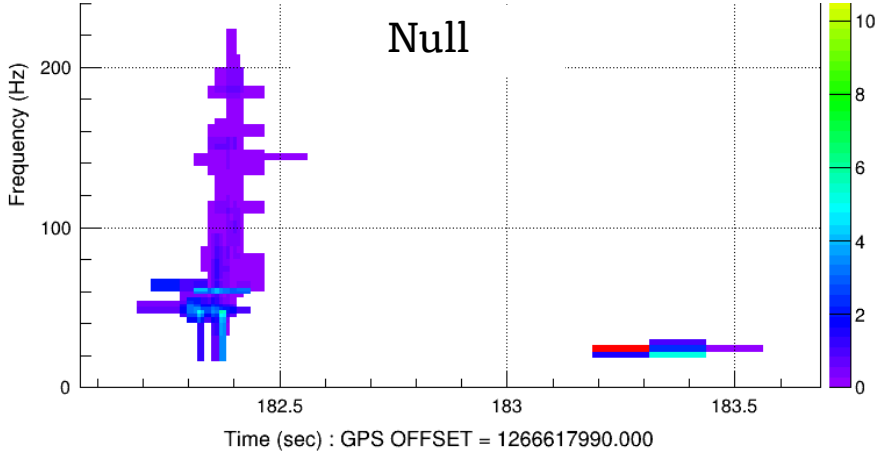


Likelihood





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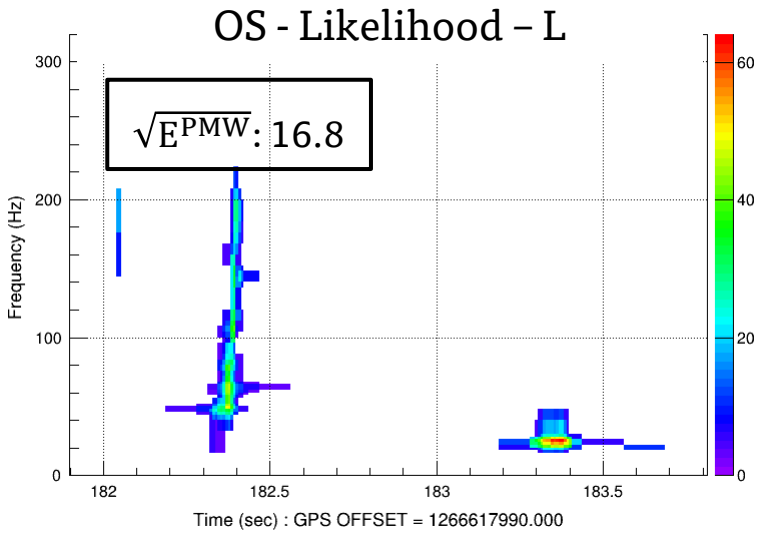

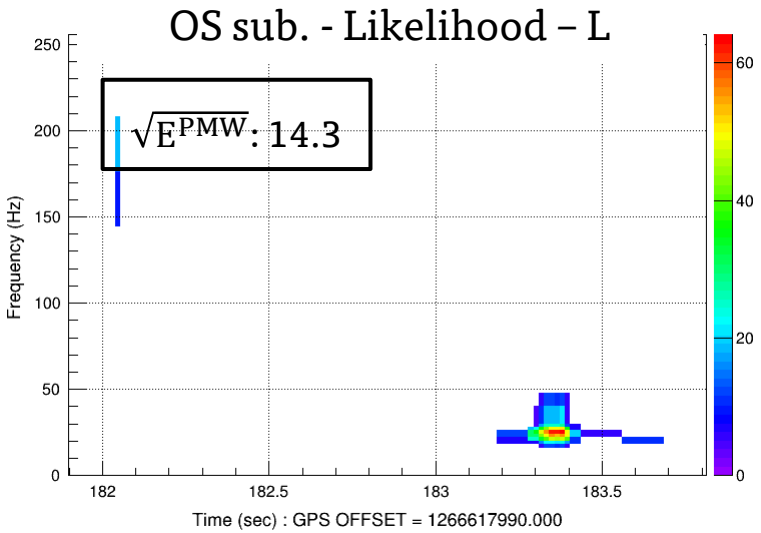

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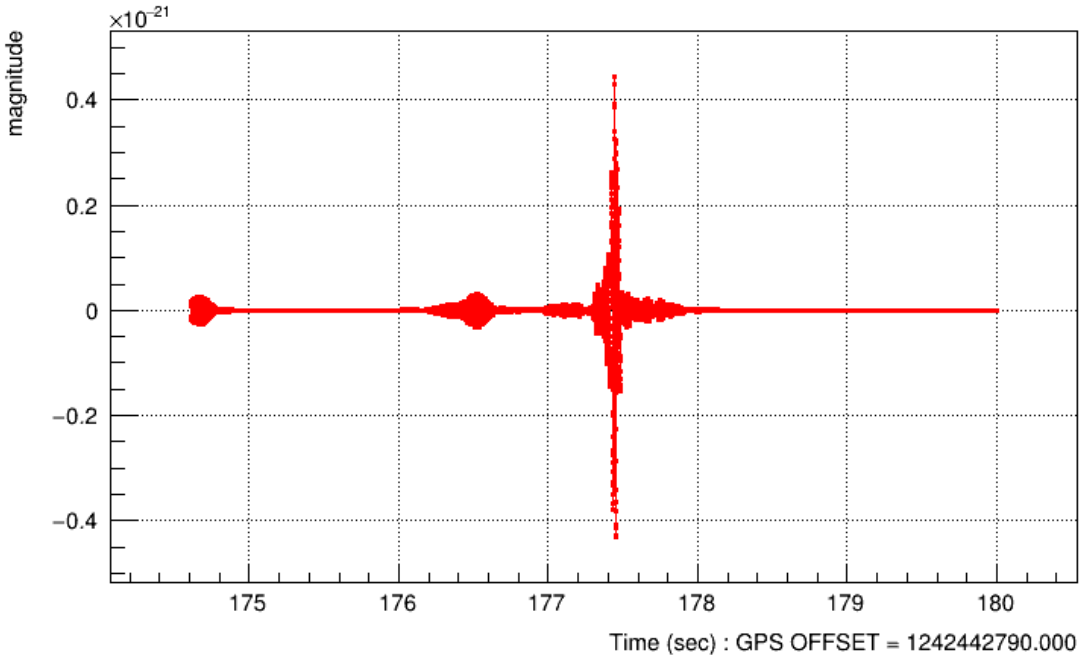
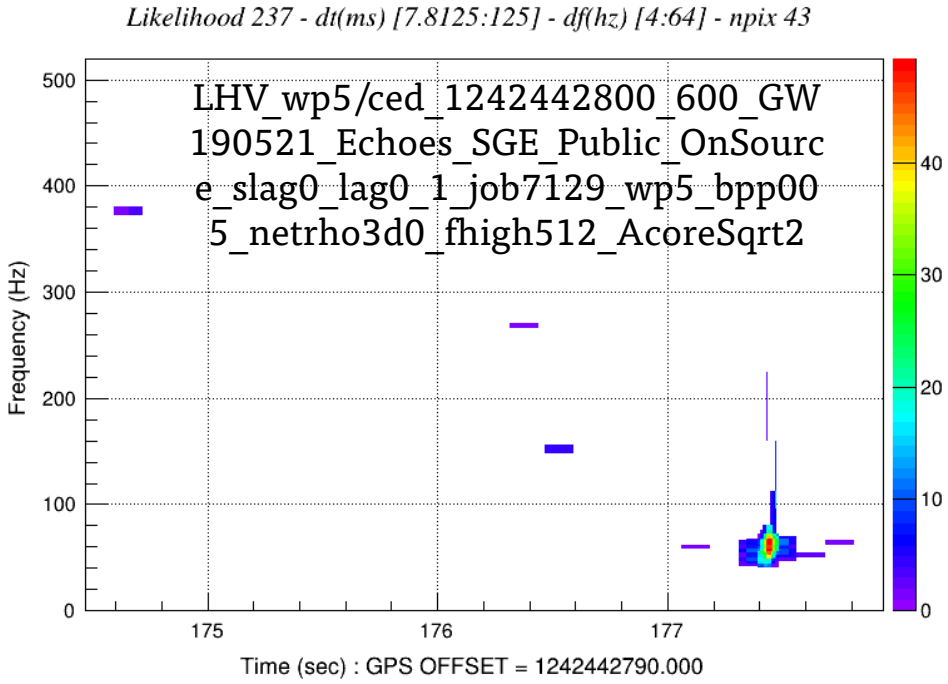
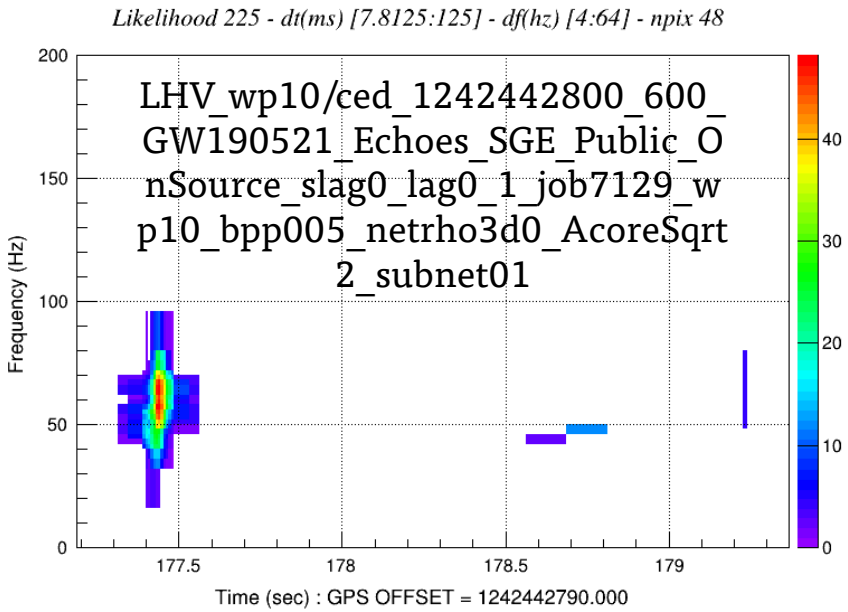
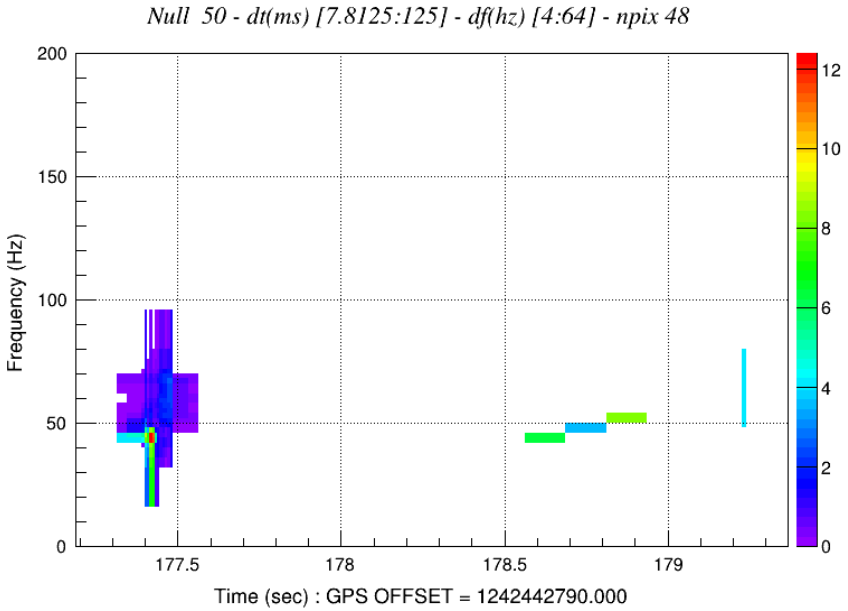

×10^-21
magnitude
0.4
0.2
0
−0.2
−0.4
175
176
177
178
179
180
Time (sec) : GPS OFFSET = 1242442790.000


Likelihood 237 - dt(ms) [7.8125:125] - df(hz) [4:64] - npix 43
LHV_wp5/ced_1242442800_600_GW190521_Echoes_SGE_Public_OnSource_slag0_lag0_1_job7129_wp5_bpp005_netrho3d0_fhigh512_AcoreSqrt2
Frequency (Hz)
500
400
300
200
100
0
175
176
177
Time (sec) : GPS OFFSET = 1242442790.000
40
30
20
10
0


Likelihood 225 - dt(ms) [7.8125:125] - df(hz) [4:64] - npix 48
LHV_wp10/ced_1242442800_600_GW190521_Echoes_SGE_Public_OnSource_slag0_lag0_1_job7129_wp10_bpp005_netrho3d0_AcoreSqrt2_subnet01
Frequency (Hz)
200
150
100
50
0
177.5
178
178.5
179
Time (sec) : GPS OFFSET = 1242442790.000
40
30
20
10
0


Null 50 - dt(ms) [7.8125:125] - df(hz) [4:64] - npix 48
Frequency (Hz)
200
150
100
50
0
177.5
178
178.5
179
Time (sec) : GPS OFFSET = 1242442790.000
12
10
8
6
4
2
0