EPS-HEP2021 conference

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Methods and results on the search for gravitational wave echoes in the post-merger phase after binary black hole coalescences.

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Outline of the presentation

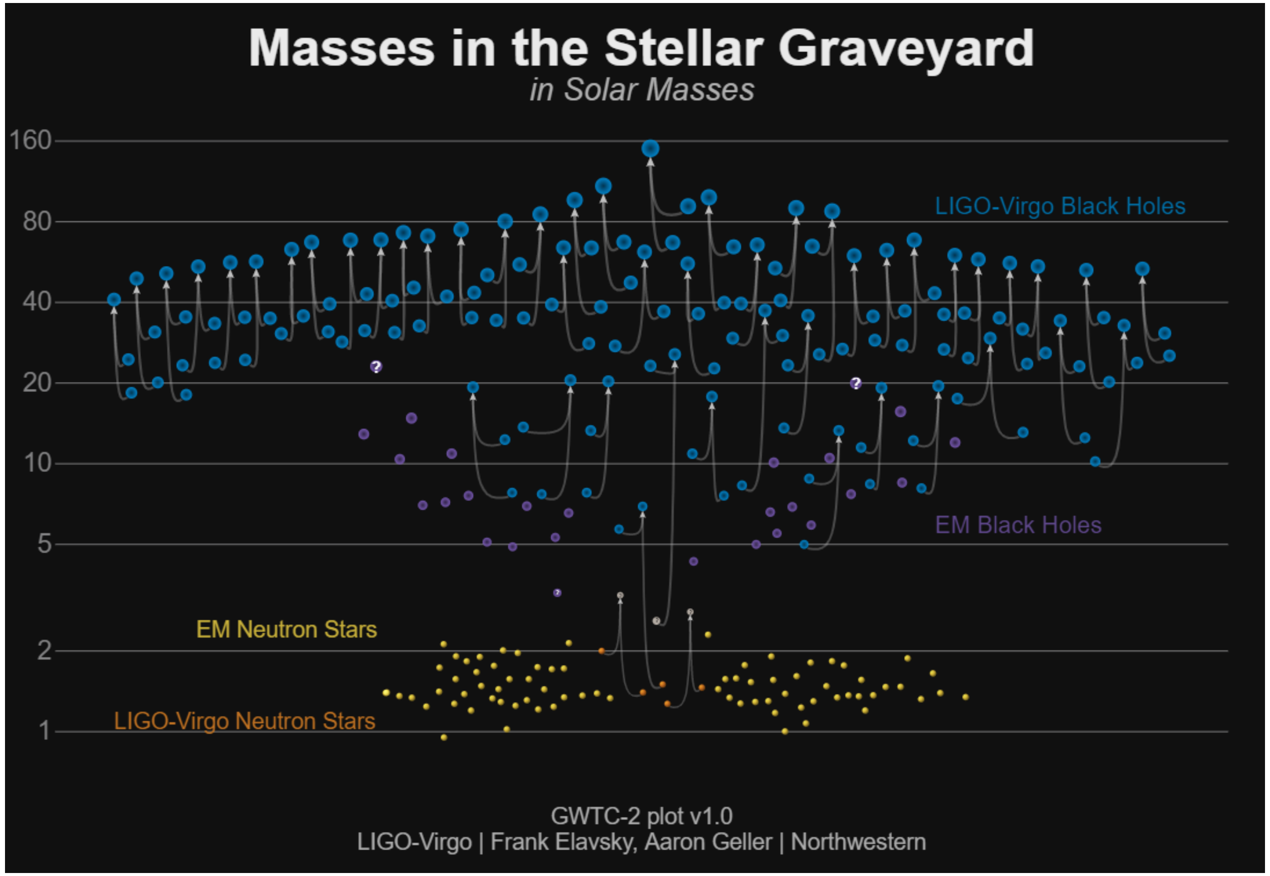
1. Echoes search, WHY?
2. Echoes: state of the art.
3. Echoes: an unconstrained search.
4. Echoes: results of the search.
5. Conclusions.

1.1 - Echoes search, WHY?

- 2015, September 14 th: detection of the first gravitational wave (GW), GW150914.

- LIGOs and Virgo interferometers had detected several GW signals in the past six years. GWTC-1 (O1, O2 runs) and GWTC-2 (O3a run).

- 45 (+3?) out of 50 detections are labelled as binary black hole (BBH) coalescences. **Are we sure of it?**



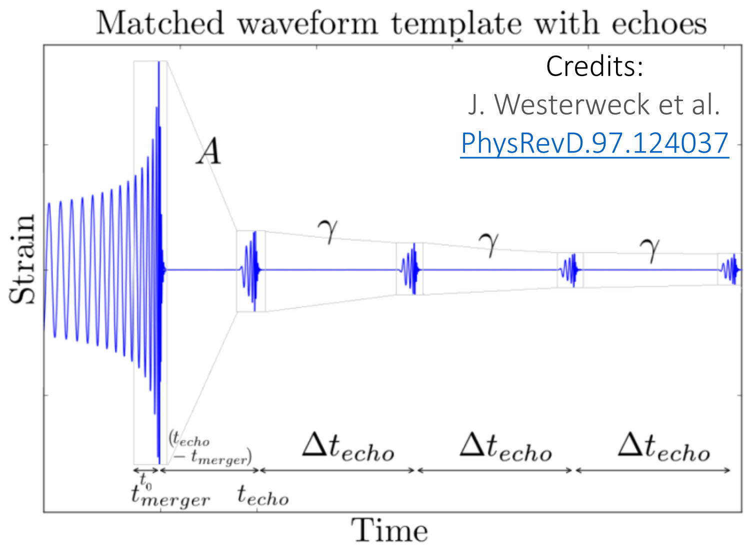
Credit: Visualization: LIGO -Virgo / Frank Elavsky, Aaron Geller / Northwestern

1.2 - Echoes search, WHY?

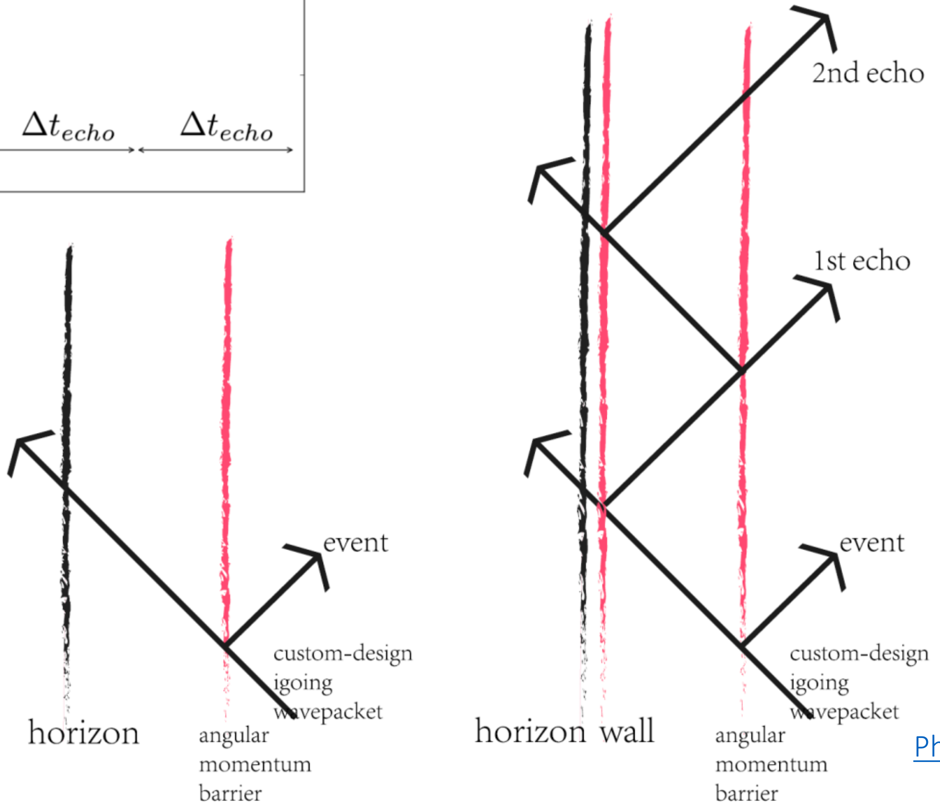
Several alternative models to BH, generally referred as **exotic compact objects** (ECO), such as Gravastars or Firewalls.

ECOs share a common feature.

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

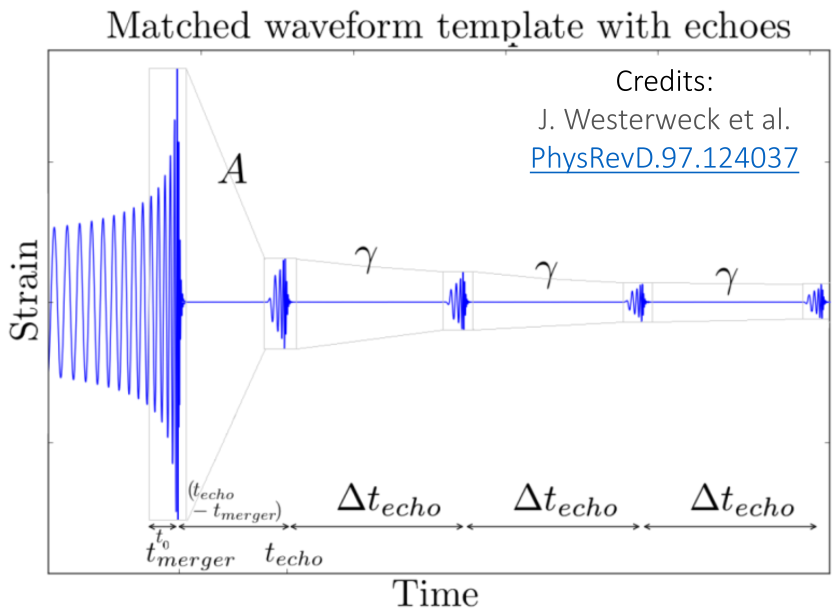


- Multiple reflection of ingoing GW signal.
- Horizon replaced by a surface of different nature.



Credits:
Q. Wang et al.
PhysRevD.97.124044

1.3 - Echoes search, WHY?



WHY searching ECHOES?

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

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

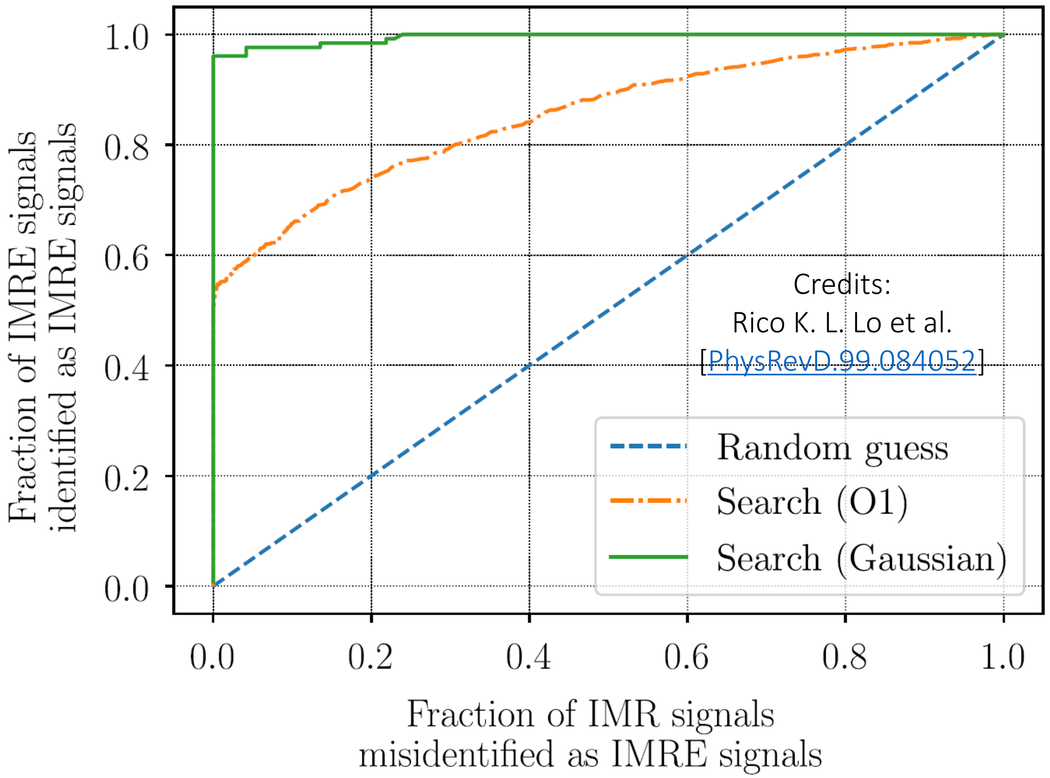
Parameter	Description
Δt_{echo}	time delay between subsequent echoes • n -> related to the nature of the ECO; • M -> remnant mass of the final ECO; • l -> radius lengh correction to the BH horizon;
t_{echo}	time of the first echo signal
γ	amplitude damping factor of echoes
A	relative amplitude of the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

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

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 ≥ 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.

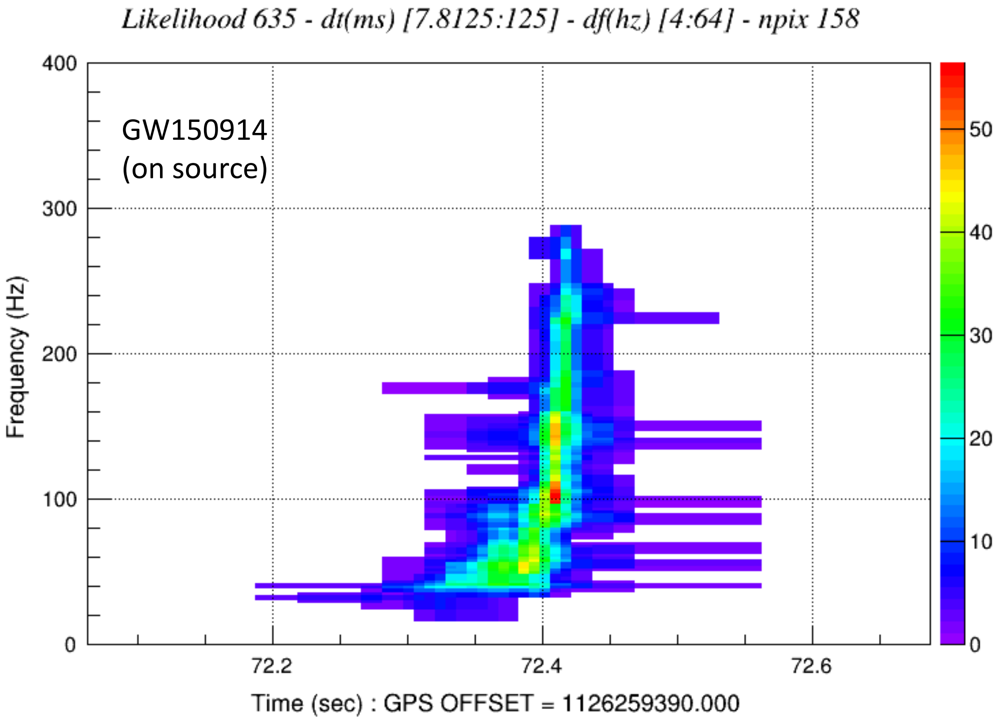


IMR : Inspiral-Merger-Ringdown
IMRE : Inspiral-Merger-Ringdown-Echoes

3.1 - Echoes: an unmodeled 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 ($\mathbf{x[i]}$)

} Single detector

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

} Combined network

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

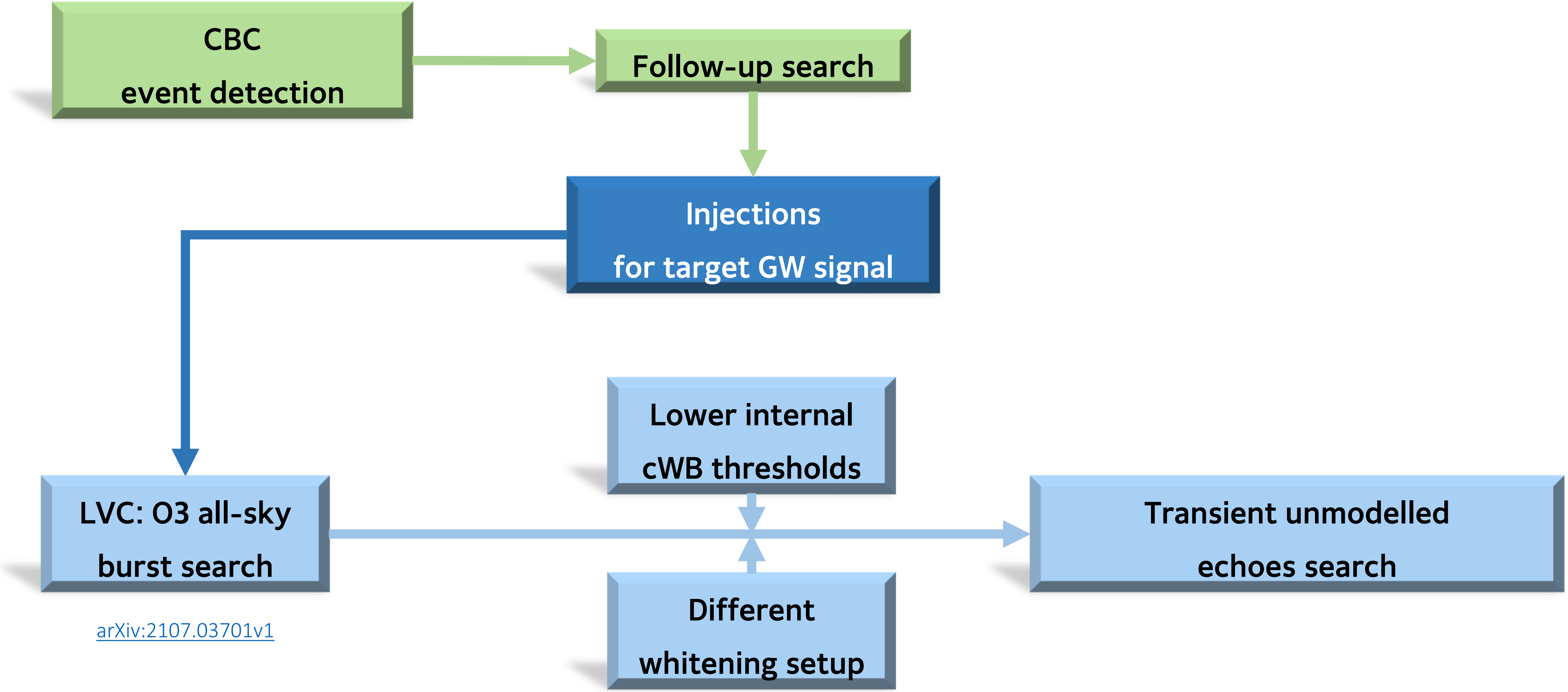
$$\mathbf{L = \log\left(\frac{P(x|H_1)}{P(x|H_0)}\right)};$$

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

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

3.2 - Echoes: an unmodeled search

Method:

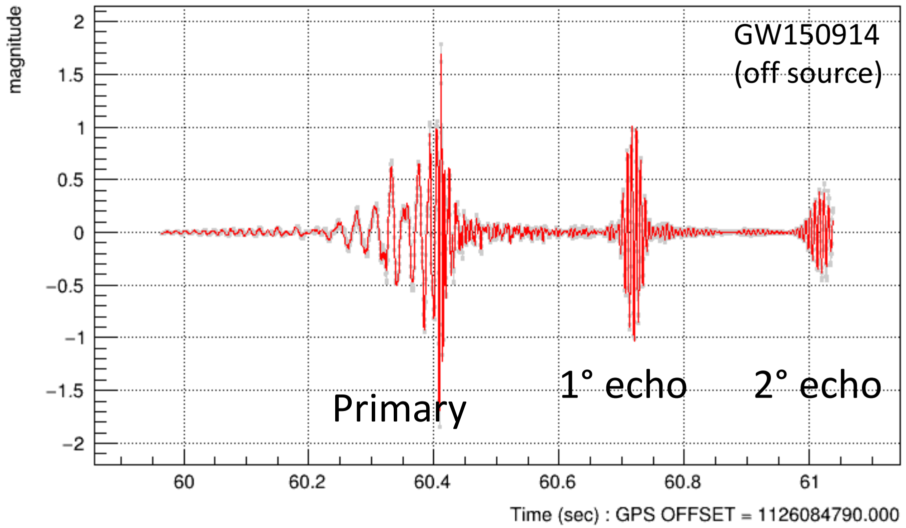


3.3 - Echoes: an unmodeled search

Injections for target GW signal

Selected randomly from posterior waveforms (LAL inference).

Waveform model: IMRPhenomPv2



Only Primary injections - [P]

- one injection every 600s;
- real noise (O1 and O2);

Primary + ≪Echoes≫ injections - [P+E]

- same as [P] injections;
- echoes model = Eliptical sine-Gaussian (SGE);
- two echoes injected;
- $t_{echo} = 0.3s$ after binary coalescence time;
- $\Delta t_{echo} = 0.3s$;
- $\gamma = 0.5$;
- $A \in [0.05 - 1.0]$ relative to primary signal amplitude;
  - random uniform log amplitude distribution.

3.4 - Echoes: an unmodeled search

Statistic estimators for echoes detection:

Reconstructed energy: $E^{PMW} = \sum_K \sum_i x_k[i]^2$

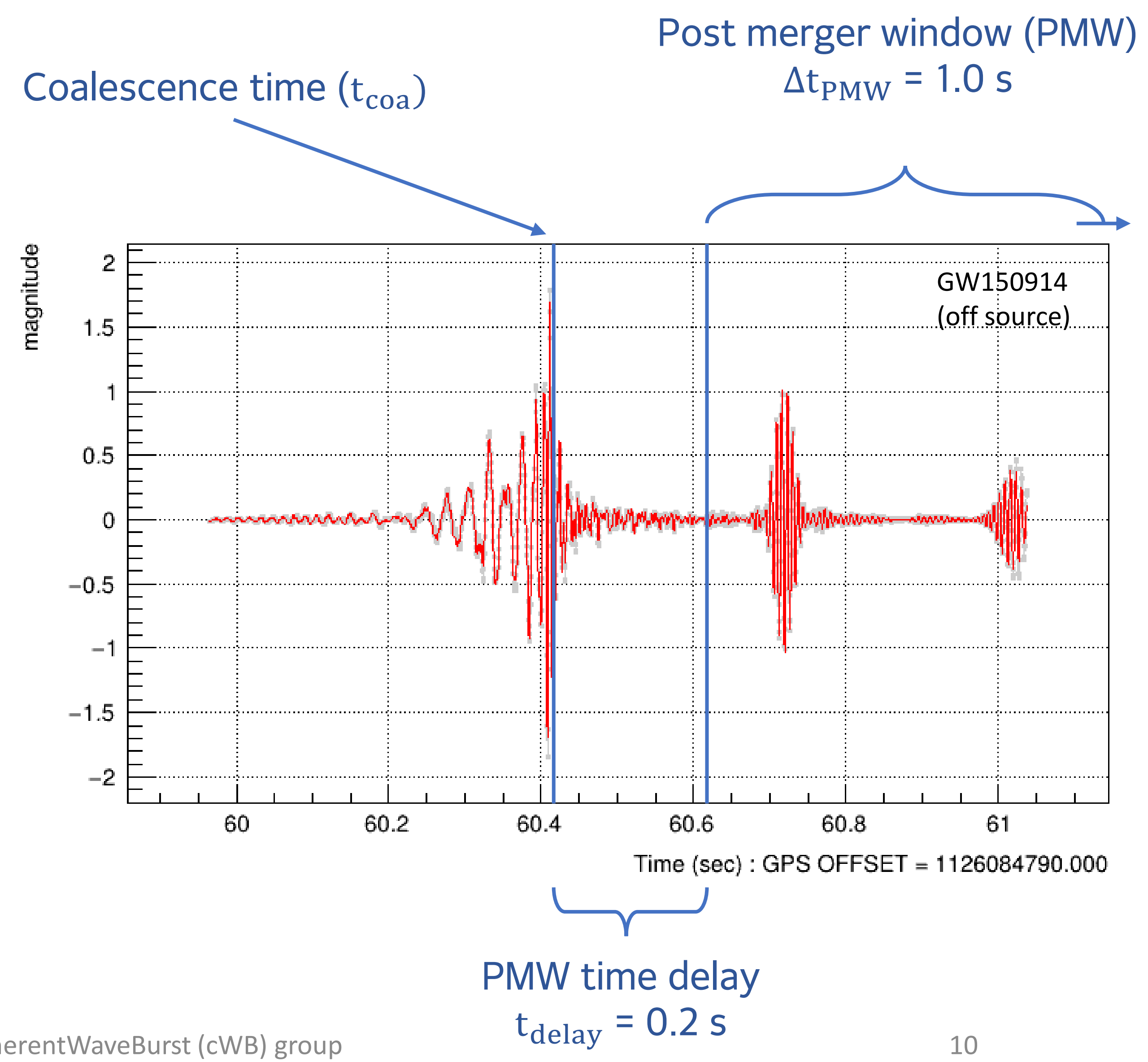
Coherence: $cc^{PMW} = E_{coh}^{PMW} / (E_{coh}^{PMW} + E_{null}^{PMW})$

Echoes detection efficiency:

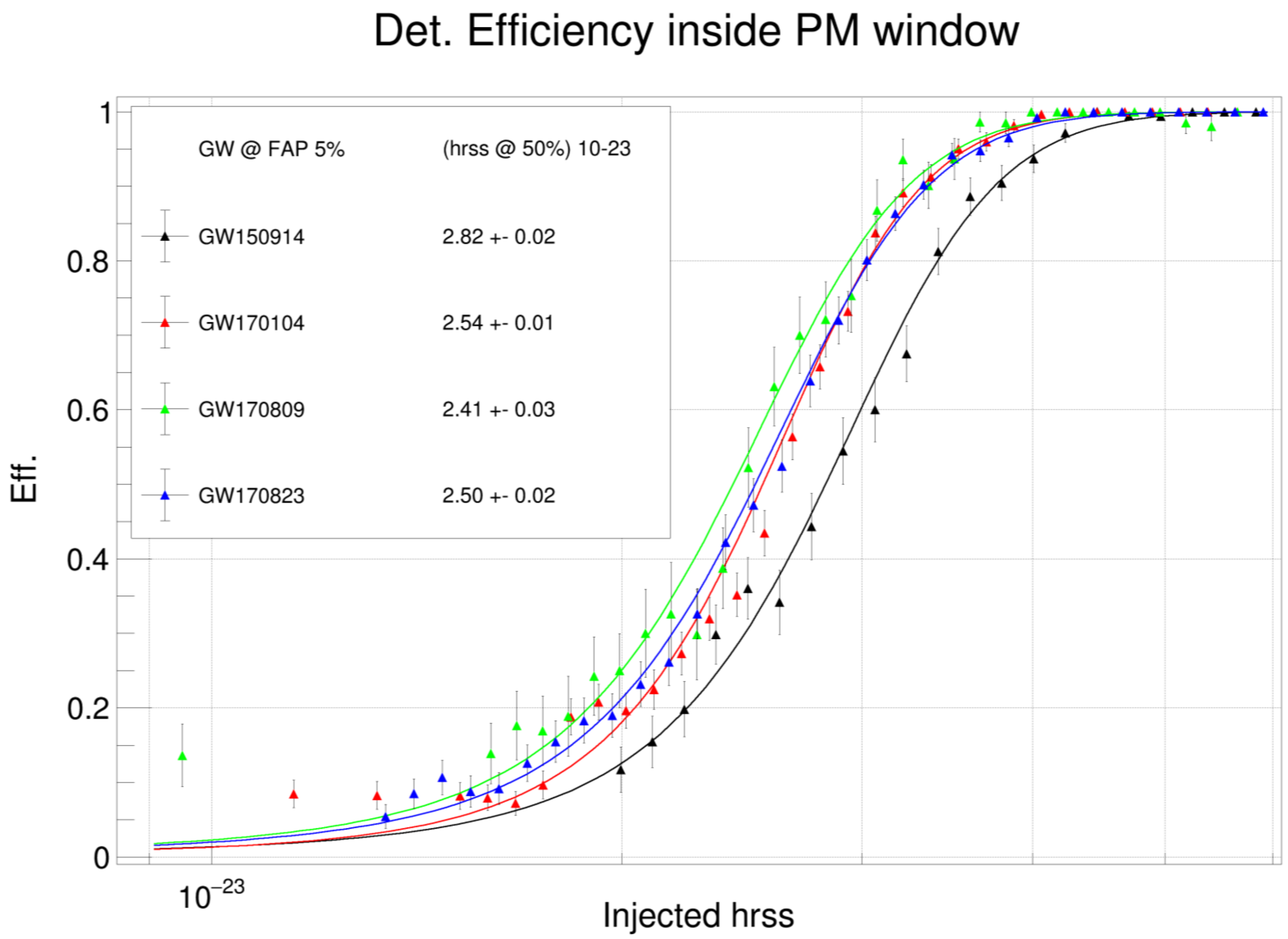
fraction of reconstructed events with $\mathbf{snr^{PMW}} > \mathbf{th.\,snr^{PMW}}$ in [P+E] injections.

False alarm probability (FAP):

fraction of reconstructed events with $\mathbf{snr^{PMW}} > \mathbf{th.\,snr^{PMW}}$ in [P] injections.



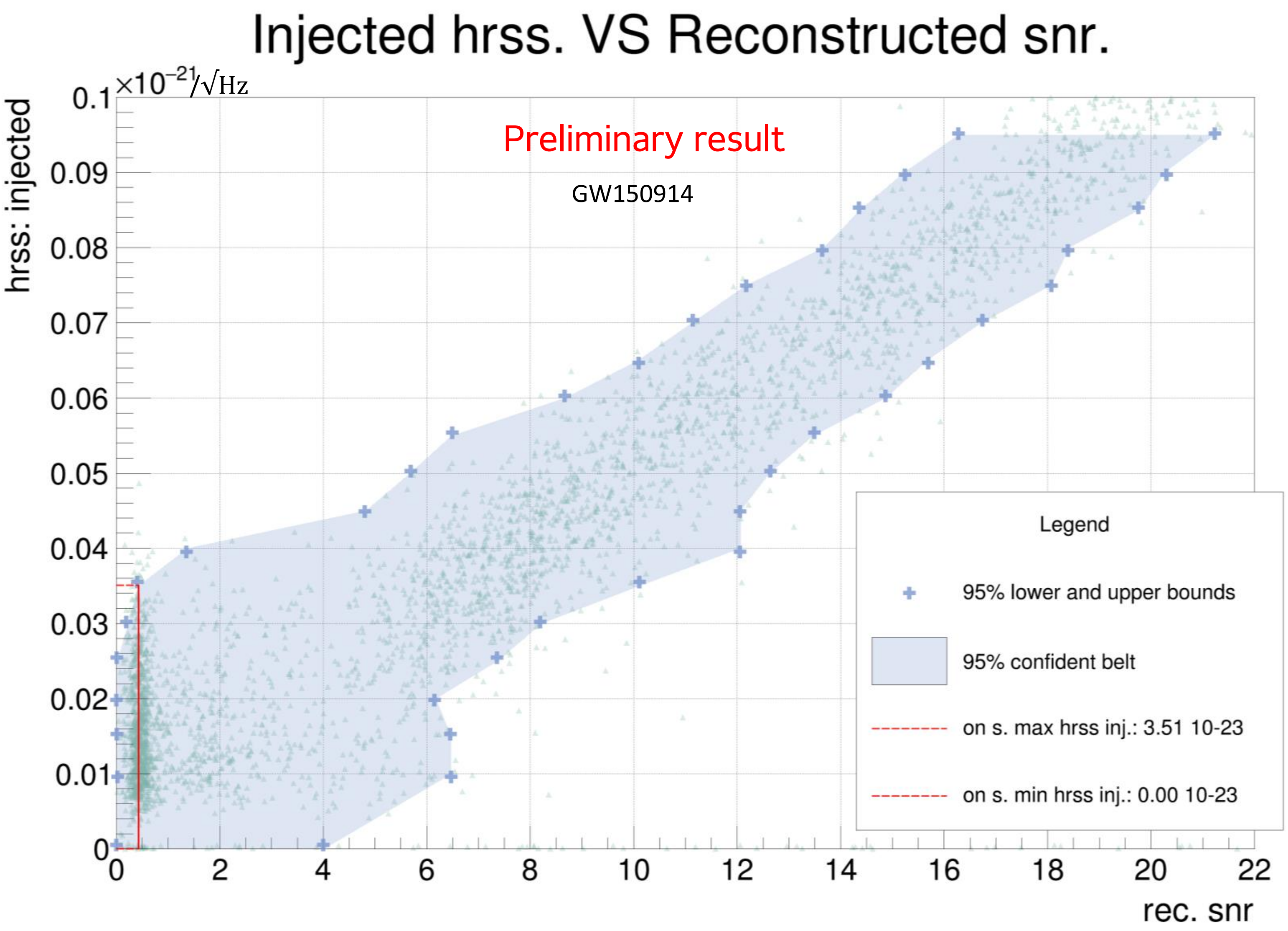
4.1 - Echoes: result of the search



$$\frac{\#\ \text{rec events with}\ \sqrt{E^{PMW}} > snr_{thr}}{\#\ \text{total rec events}}$$ [P+E]

GW event	$hrss_w^{PM}$ @50% det. Eff. for 5% FAP.
GW150914	$(2.82 \pm 0.02) \cdot 10^{-23}$
GW151012	$(2.60 \pm 0.03) \cdot 10^{-23}$
GW151226	$(2.72 \pm 0.03) \cdot 10^{-23}$
GW170104	$(2.54 \pm 0.01) \cdot 10^{-23}$
GW170608	$(2.63 \pm 0.01) \cdot 10^{-23}$
GW170729	$(2.53 \pm 0.01) \cdot 10^{-23}$
GW170809	$(2.41 \pm 0.03) \cdot 10^{-23}$
GW170814	$(2.53 \pm 0.02) \cdot 10^{-23}$
GW170823	$(2.50 \pm 0.02) \cdot 10^{-23}$

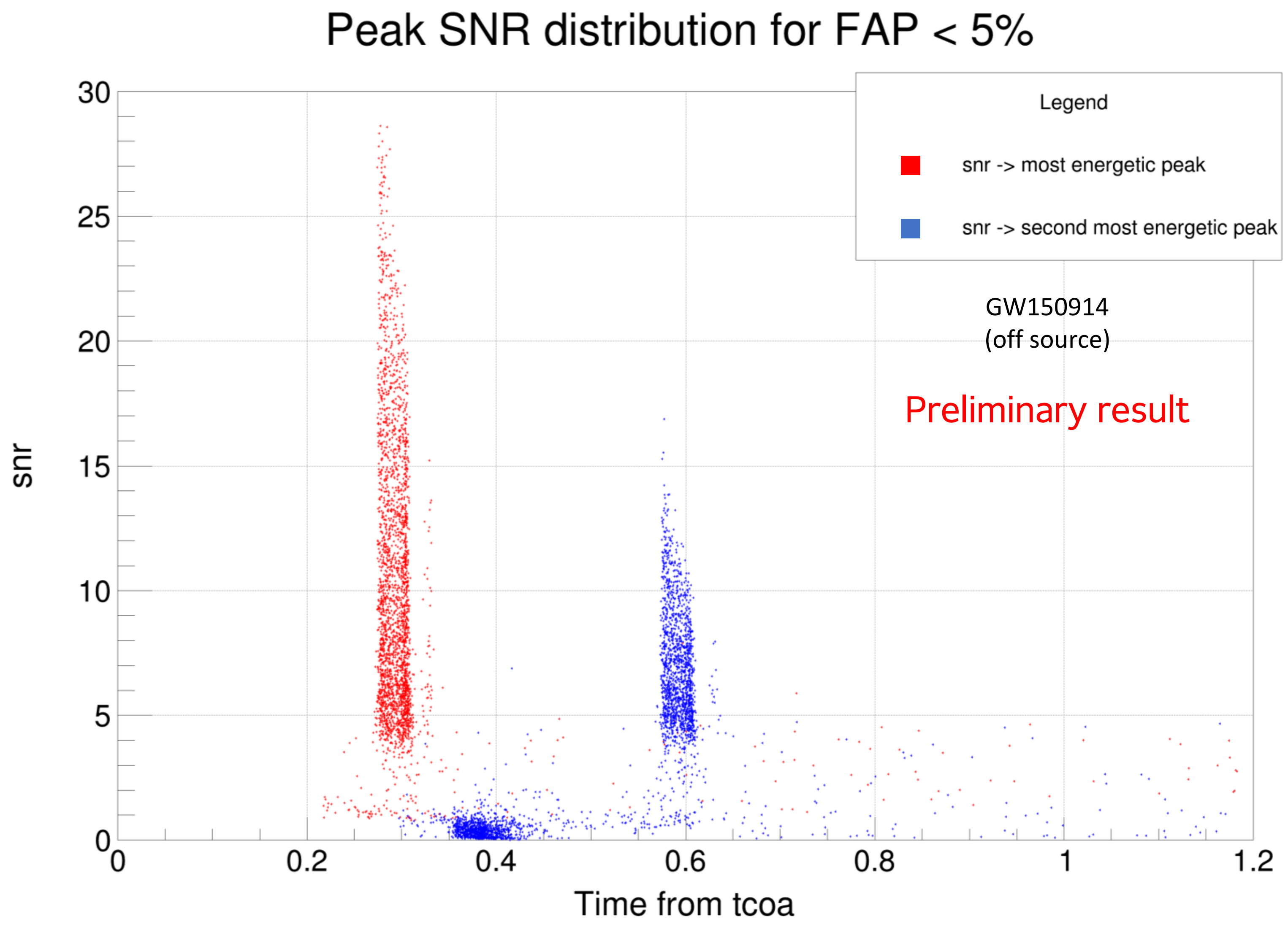
4.2 - Echoes: result of the search



95% confident belt

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

4.3 - Echoes: result of the search



Reconstructed SNR(t) inside a moving time interval, in PMW data segment.

The first two highest SNR(t) in PMW are plotted.

Echo's parameters that can be recovered and constrained:

- study: $\mathbf{\Delta t_{echo}}$;
- study: $\mathbf{t_{echo}}$ and $\mathbf{A}$;
- study: $\boldsymbol{\gamma}$;

5 - Conclusions

TAKE HOME:

- Capability to recover fundamental echo morphological parameters ($\mathbf{A}, \mathbf{t}_{\mathbf{echo}}, \mathbf{\Delta t}_{\mathbf{echo}}, \boldsymbol{\gamma}$).
- Capability to detect sub-thresholds burst signals with FAP < 5%.

Threshold $\mathbf{snr}^{\mathbf{PMW}}$ for a FAP = 5% $\in [\sim \mathbf{1.3}, \sim \mathbf{2.7}]$

- Detection efficiency even at very low $\mathbf{SNR}$ values.

TO DO:

- Extending the analysis to O3 events.
- Perform calibrated echo injections for each BBH GW events of GWTC-1 and GWTC-2.

FUTURE PLANS:

- Possibility to use the same searching procedure to study hyperbolic encounters and capture, memory effect, ecc.

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Credits: C. Gray

Credits: J. Giaime

Credits: Virgo Collaboration

Thank you

for the attention!

LIGO Scientific Collaboration

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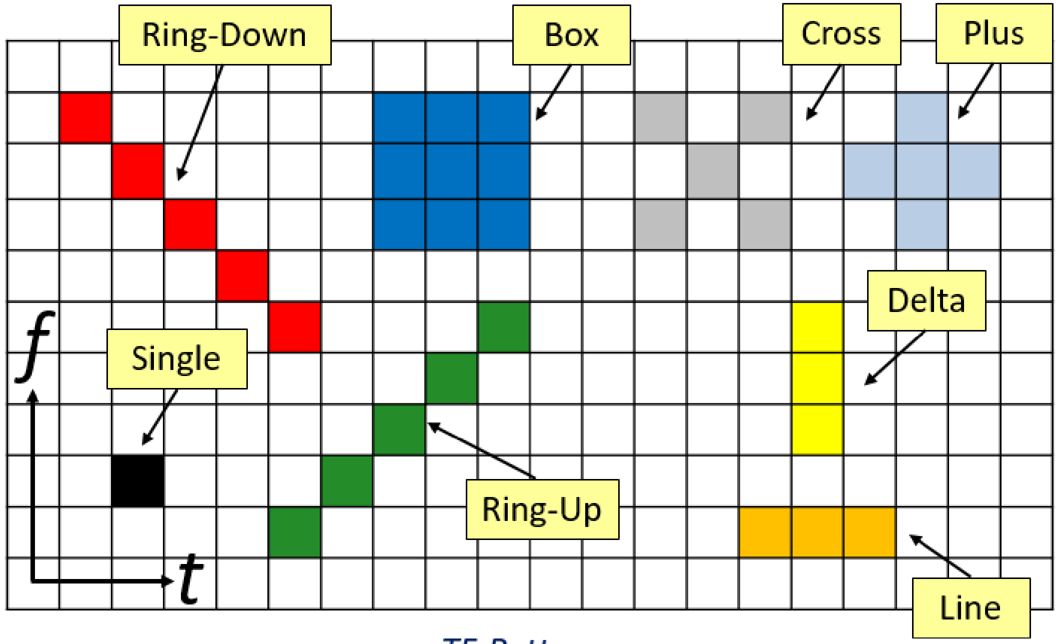
VIRGO

Backup Slides

CoherentWaveBurst (cWB) pipeline:

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



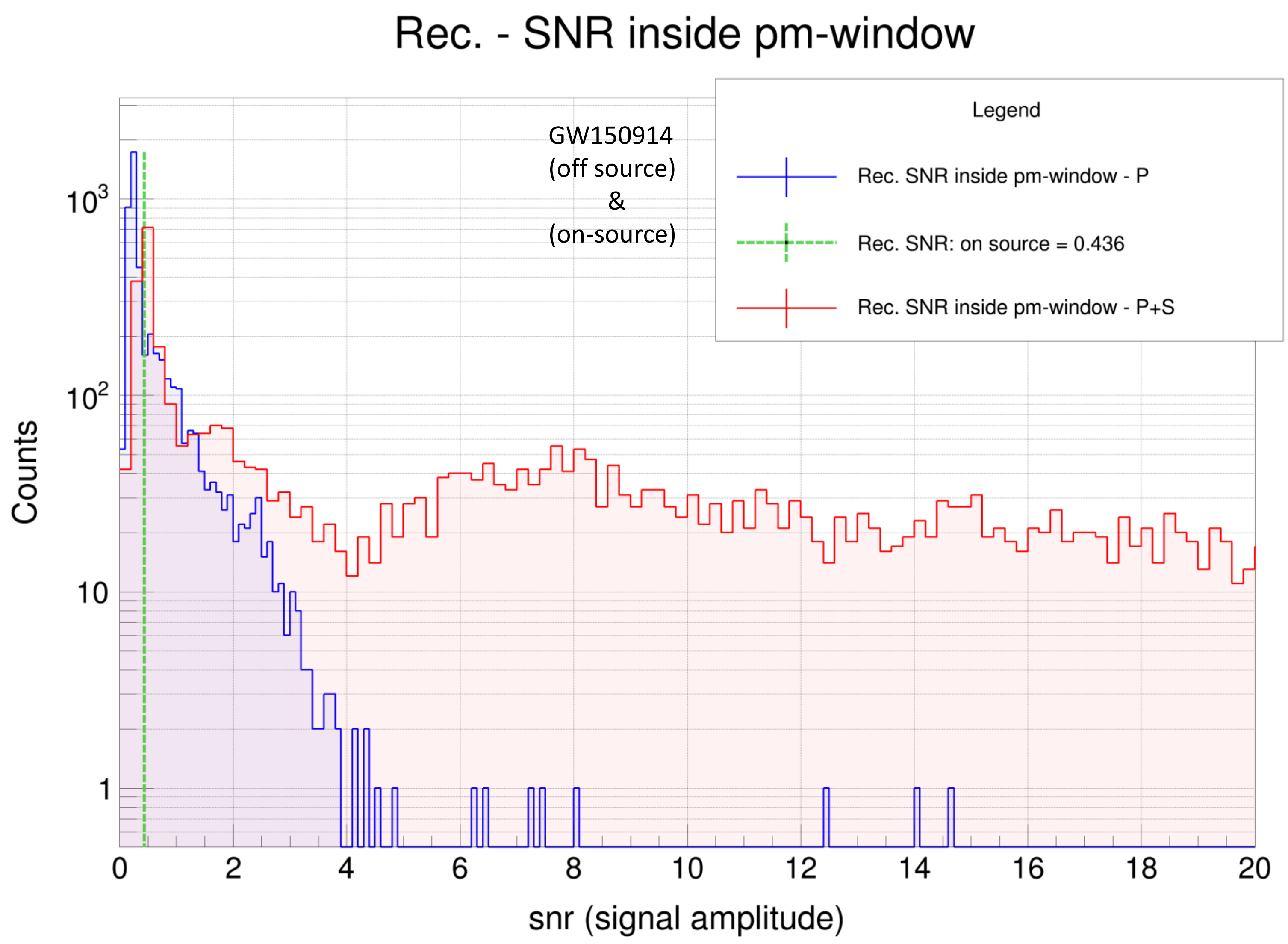
TF-Patterns

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

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

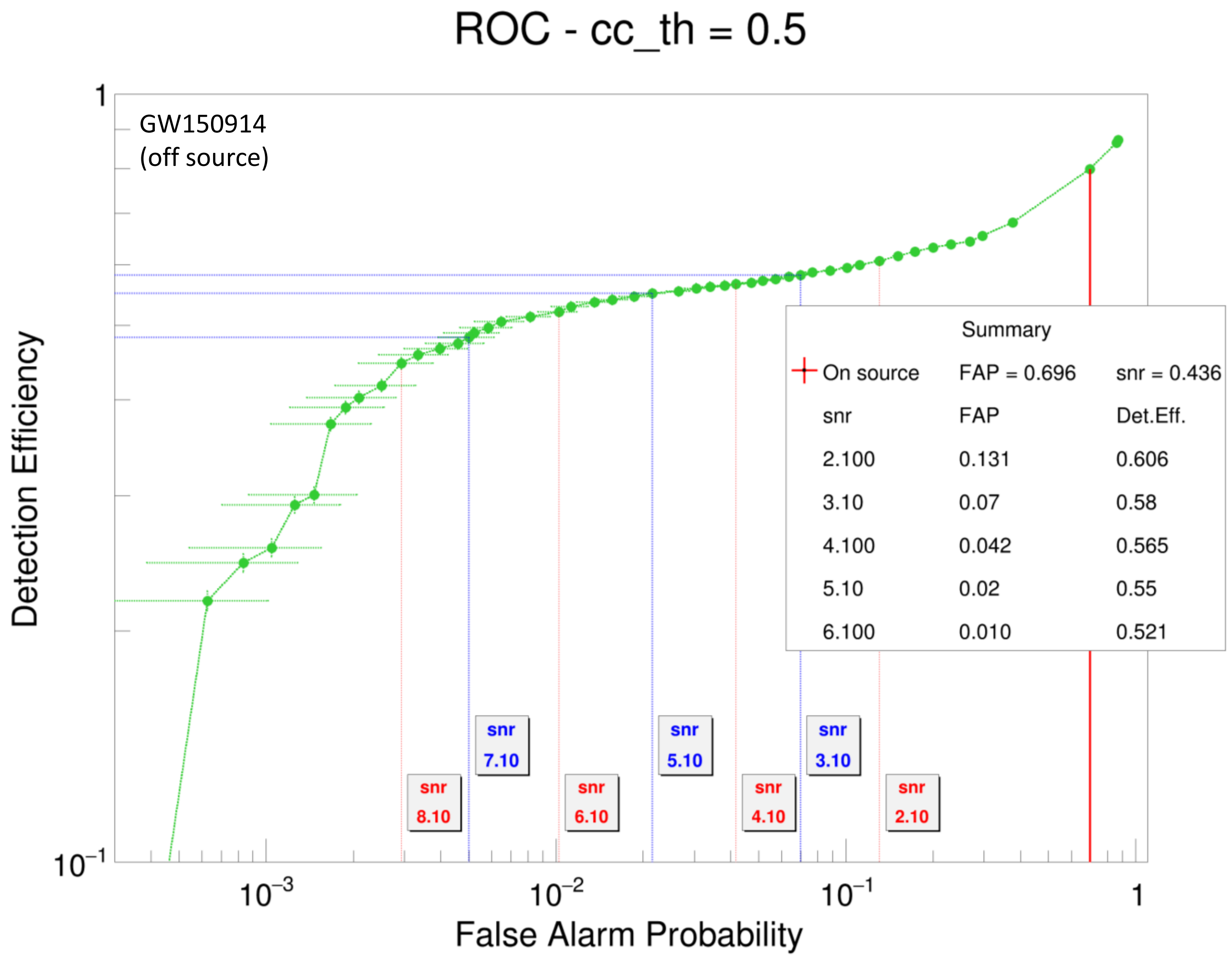
$$P(x|H_0) = \prod_{i=1}^{M} \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{x[i]^2}{2\sigma^2}\right)$$

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



Reconstructed snr inside the PM window

- **Blue distribution**: referred to results for “only primary” [P] injection.
- **Red distribution**: referred to results for “primary + echoes” [P+E] injection.
- **Green line**: snr value of the on-source event.



ROC

(Receiver Operating Characteristic)

- **False Alarm Probability**: fraction of events with SNR in PM window above SNR threshold for “only primary” [P] injection.
- **Detection Efficiency**: fraction of events with SNR in PM window above SNR threshold for “primary + echoes” [P+E] injection.

6.4 – Appendix: O1 & O2 on source results

GW event	snr^{PMW}	snr^{PMW} @ FAP5%	p-value H_0 (FAP)
GW150914	0.47	3.7	0.696
GW151012	7.87	1.3	0.001
GW151226	0.19	2.3	0.790
GW170104	0.07	2.5	0.888
GW170608	1.84	1.7	0.046
GW170729	2.99	1.7	0.035
GW170809	0.03	0.5	0.557
GW170814	0.27	2.7	0.450
GW170818			
GW170823	0.01	1.7	0.835

Here:

$\text{snr}^{\text{PMW}} > \text{snr}^{\text{PMW}}@\text{FAP5\%}$

Cannot be compared: require a different pipeline setup.

- Agreement with: F. Salemi et al. PhysRevD.100.042003