EM-MBTA: Low Latency Ranking of Galaxies within a Gravitational-wave Sky Localization

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Introduction

- Success of the observational campaign following GW170817 originates also from some lucky coincidences: closest GW event and highest SNR.
- Skymap limited the 90% probability area to just $28\,\mathrm{deg}^2$.
- Skymaps typically cover $\mathcal{O}(100-1000)\ \mathrm{deg}^2$.
- Ranking galaxies **using gravitational information only** could be helpful to astronomers.

Online Pipelines

Modeled Search

- Search for specific signals from Compact Binary Coalescense
- GstLAL, MBTA, PyCBCLive, SPIIR
- matched-filtering based analysis

Unmodeled Search

- Core-collapse of massive stars, magnetar star-quakes, cosmic strings and others
- cWB, oLIB
- Excess power algorithms

Matched Filtering

Given a signal $s(t) = n(t) + h(t)$, assuming Gaussian noise the log likelihood is given by

$$\ln \Lambda_h(t) = (s|h)(t) - \frac{1}{2}(h|h)(t)$$

where $(a|b)(t) = 4\Re \int_0^\infty df \, \frac{\tilde{a}(f)\tilde{b}^*(f)}{S_n(f)} e^{-i2\pi f t}$. Then, SNR time series for the single interferometer is

$$\rho_h^2(t) = 2 \ln \Lambda_h(t)$$

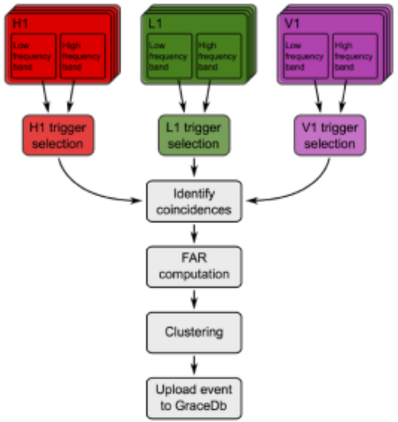
.

Coincident SNR:

$$\rho_{coinc}^2 = \rho_i^2(t_i) + \rho_j^2(t_j)$$

MBTA: Multi-Band Template Analysis

- Parameters space divided in 3 regions (approximately BNS, NSBH, BBH).
- Low-f and high-f bands with approximately equal SNR.
- Clusters triggers associated to the same event.



Coherent SNR

Generalizing to many detectors[1], $\ln \Lambda_h(t) = (\mathbf{s}|\mathbf{h}) - \frac{1}{2}(\mathbf{h}|\mathbf{h})$ where $(\mathbf{s}|\mathbf{h}) := \sum_{i=ifo}(s^i|h^i)$ and $h^i(t) = \sum_{\mu=1}^{4} \mathcal{A}^\mu(D, \psi, \phi_0, \iota) h^i_\mu(t)$,

$$
\begin{aligned}
h^i_1(t) &= F^i_+(\theta^i,\, \phi^i,\, \chi^i) h_0(t)\,, \\
h^i_2(t) &= F^i_\times(\theta^i,\, \phi^i,\, \chi^i) h_0(t)\,, \\
h^i_3(t) &= F^i_+(\theta^i,\, \phi^i,\, \chi^i) h_{\frac{\pi}{2}}(t)\,, \\
h^i_4(t) &= F^i_\times(\theta^i,\, \phi^i,\, \chi^i) h_{\frac{\pi}{2}}(t)\,.
\end{aligned}
$$

Then,

$$\ln \Lambda_h(t) = \mathcal{A}^\mu (\mathbf{s}|\mathbf{h}_\mu) - \frac{1}{2}\mathcal{A}^\mu \mathcal{M}_{\mu\nu} \mathcal{A}^\nu$$

with $\mathcal{M}_{\mu\nu} := (\mathbf{h}_\mu|\mathbf{h}_\nu)$. Coherent SNR:

$$\rho^2_{coh}(t) = (\mathbf{s}|\mathbf{h}_\mu)\mathcal{M}^{\mu\nu}(\mathbf{s}|\mathbf{h}_\nu)$$

[1] I. Harry, S. Fairhurst, *Phys. Rev, D* **83** 084002 (2011)

Sky Localization and parameters estimation

- BAYESTAR: rapid CBC sky localization algorithm.
  - Coherently modeling the response of the gravitational-wave detector network.
  - **Fixed** masses and spins.
  - Computes the **posterior probability distribution** over the sky location and distance of the source.
  - Latency: $\mathcal{O}(10)$ seconds.
- LALInference: full CBC parameter estimation algorithm.
  - Explores a greatly **expanded parameter space** (masses, spins...) with MCMC and nested sampling.
  - Performs **full forward modeling** of the gravitational-wave signal and the **strain calibration** of the gravitational-wave detectors.
  - Latency: $\mathcal{O}(1)$ hours.

Strategy

- Extract galaxies coordinates from Bayestar skymap.
- Select $\mathcal{O}(10)$ templates that triggered in MBTA.
- Matched filtering of the two polarization already performed for online analysis.
- Compute the coherent SNR for each galaxy and for each template in the bank.
- Galaxy with higher cohSNR is the most likely to be the host.

Querying galaxies with GWsky

- **84** gravitational-wave sky localizations from the "First Two Years" paper[2] are selected (HLV).
- The **90% confidence level** for each probability skymap is build using the MOC (Multi Order Coverage map) implemented in GWsky/Aladin.
- We query databases for retrieving objects whose position falls within this MOC map at 90% confidence level using the **GLADE** catalog.
- We compute the sky position of the **maximum probability pixel**.
- See **G. Greco's talk** for more details.

[2] Singer et al. arXiv:1404.5623 [astro-ph.HE]

Calculating the coherent SNR

- LALSuite code **lalapps_cohPTF_inspiral** looping over the selected galaxies from the GLADE catalog cutting at 1-sigma distance.
- Component masses of the **template with highest coincident SNR** are passed to a script that prepares a single-template bank that is used for the analysis.
- The template bank and the GPS times related to the each event are input of the function that computes the coherent SNR.

Large FoV telescopes

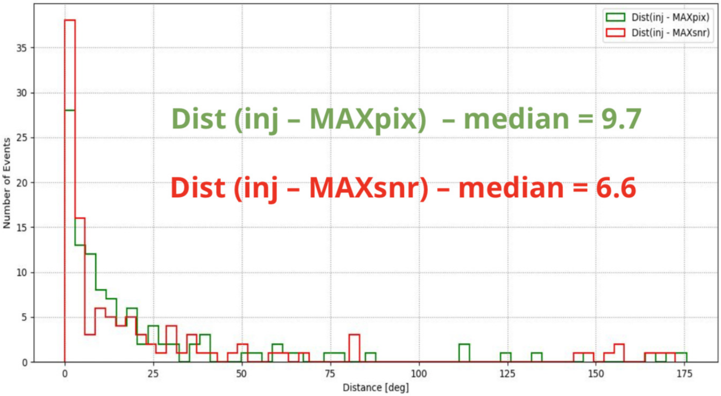


Figure: Distributions of the **angular distances** between the true location of the injection and the pixel of maximum probability (green) or the galaxy with greatest coherent SNR (red). There is a mild indication of a better performance of our method.

Small FoV telescopes

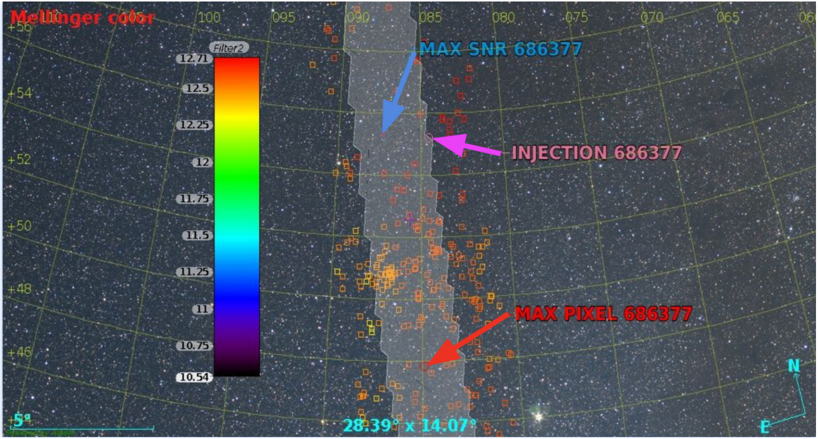


Figure: Here the injection is ranked **3rd** using cohSNR while it is at the 41% c.l. that contains **285** galaxies.

Small FoV telescopes

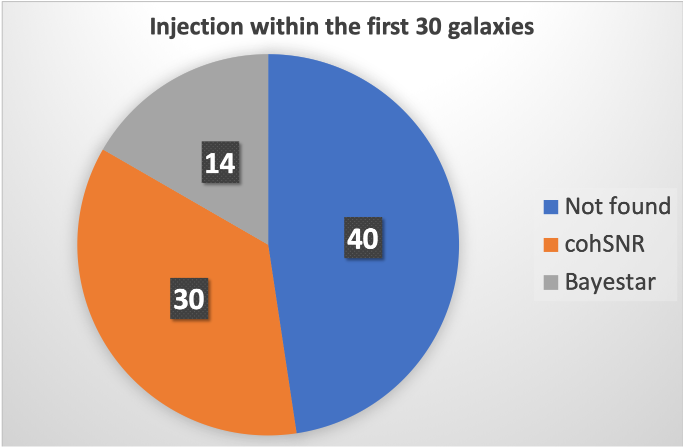
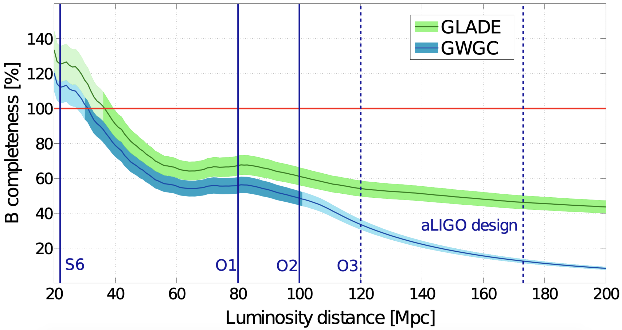


Figure: In **44/84** cases, either cohSNR or Bayestar capture the injection within the **first 30 galaxies**. In **15/44** cases both cohSNR and Bayestar rank the injection within the first 30 galaxies. **cohSNR** finds it in a **higher ranking 11/15** times, and Bayestar 4/15 times.

Conclusions & outlook

- Small template bank improved the results.
- Results are very **preliminary but intriguing** and motivate further investigation.
- More statistic is required.
- lalapps_cohPTF_inspiral is not optimised for our scope.
- EM-MBTA.py takes advantage of MBTA matched filtering output, computed for online detection.
- Expected **latency of few minutes**.

GLADE



B-band completeness.png

Coincident and coherent SNR

coincident SNR

- Single IFO triggers in compatible time window

$$\rho^2_{coinc} = \rho^2_i(t_i) + \rho^2_j(t_j)$$

- computationally cheap
- less information

coherent SNR

- coherence of phases and amplitudes in all IFOs

$$\rho^2_{coh}(t) = (\mathbf{s}|\mathbf{h}_\mu)\mathcal{M}^{\mu\nu}(\mathbf{s}|\mathbf{h}_\nu)$$

- computationally expensive
- more information