# Rapid Online Estimation of Astrophysical Source Category and Compact Binary Parameters


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## Introduction

The detection of GW170817 during O2 made **multi-messenger** astronomy with gravitational waves a reality. A challenge for **low-latency searches** is to rapidly estimate the probabilities of a candidate event source to contain neutron star or black hole components. This **source classification** enables observatories to prioritize followup searches for electromagnetic or neutrino counterparts. We present a **chirp mass based** Rapid Source Classification method developed for **PyCBC Live** during O3 [1].

## Motivation

- Pipelines usually accurately recover the **chirp mass** $\mathcal{M}$ of the event, but not component masses or spins

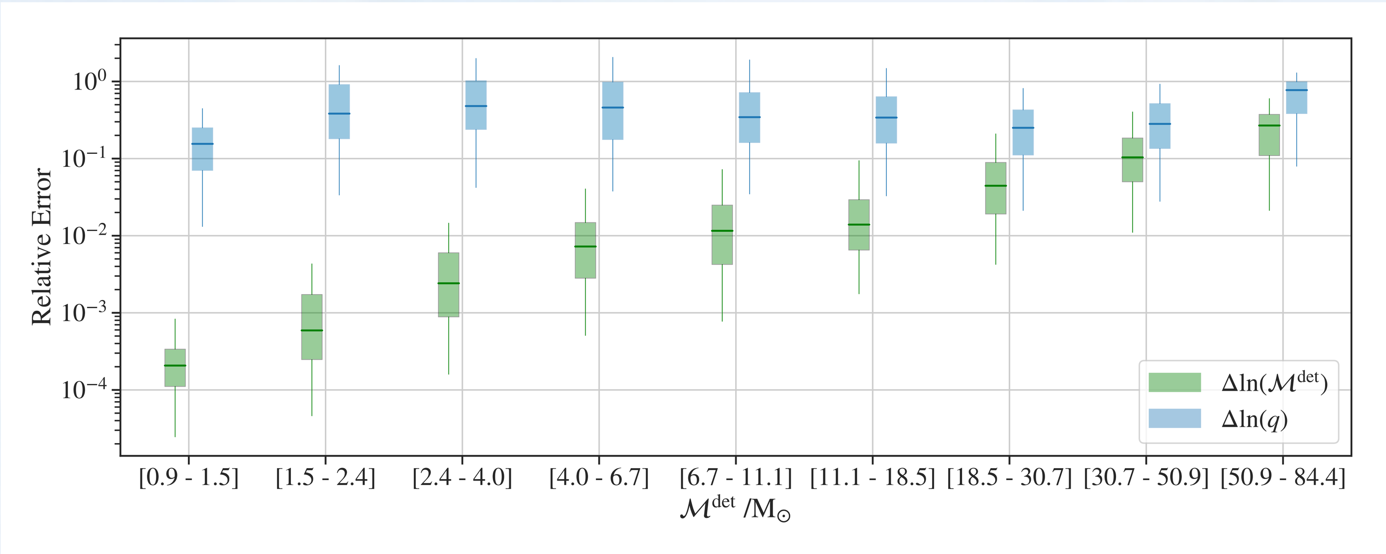


**Figure 1:** Boxplot comparison of chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$ and mass ratio $q = m_2/m_1$ relative errors for different chirp mass intervals.

- Previous method uses *hard-cuts* on $m_1$,$m_2$:
  - Assigns "0" or "1" to the different source types - no multi-component classification
  - Neglects uncertainty in $m_1$, $m_2$ - more than 10%
  - Does not account for **redshift** bias

## Main features of the method

- Classification between BNS, NSBH, BBH ($m_{\rm NS} \in$ [1-3] $M_\odot$, $m_{\rm BH} > 5\,M_\odot$) and MassGap (at least one of the masses $\in$ [3-5] $M_\odot$).
- Uses trigger **chirp masses** and **effective distances** from PyCBC Live
- Assumes a **uniform density prior** of candidate signals over the $m_1 m_2$ plane
- Assumes a $\Delta\mathcal{M}$ of 1% and combines it with uncertainty from redshift
- Estimates source probabilities to be **proportional to the area** of each CBC region inside contour

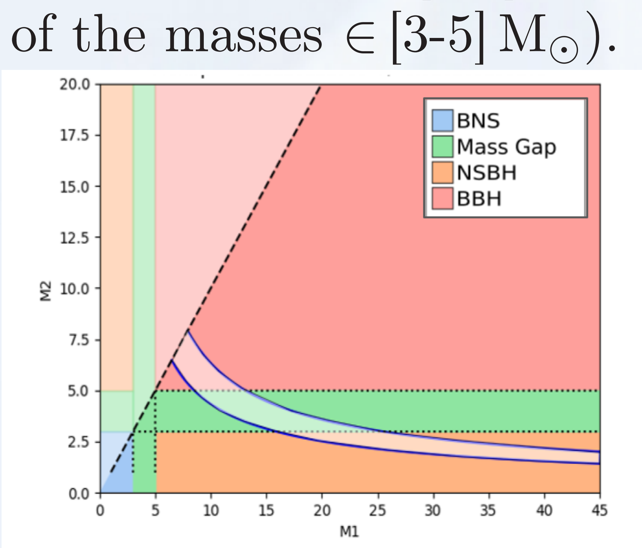


**Figure 2:** Contour of constant $\mathcal{M} \pm \Delta\mathcal{M}$ over $m_1 m_2$ plane

## Source redshift estimation

- Pipeline template is redshifted compared to source chirp mass
- $z = z(D_{\rm L})$, but PyCBC Live does not estimate $D_{\rm L}$ - this is calculated later by external processes.
- We fit a relationship between estimated $D_{\rm L}$ and effective distances $D_{\rm eff}$:

$$\tilde{D}_{\rm L} = C_D \cdot \min(D_{\rm eff})$$

- We estimate uncertainty on $D_{\rm L}$ using SNR $\rho$: $\tilde{\sigma}_{D_{\rm L}} = {\rm e}^{-0.516} \cdot \tilde{D}_{\rm L} \cdot \rho^{-0.322}$ and combine it with $\Delta\mathcal{M}$

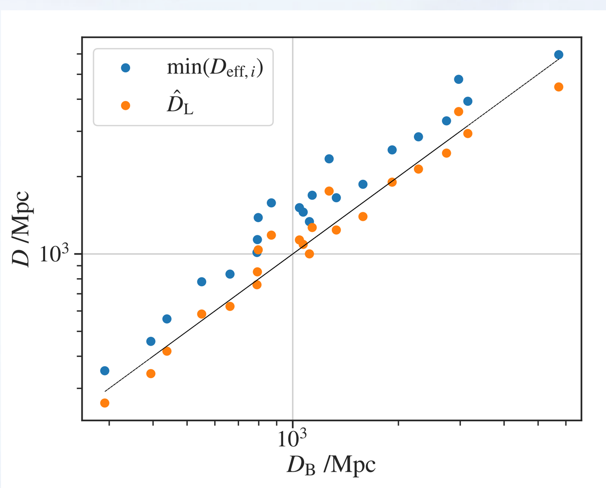


**Figure 3:** Fitting plot for luminosity distance $\tilde{D}_{\rm L}$

## Check with simulated signals

- Simulated signals injected into O3a data recovered with PyCBC Live: $m_{\rm NS} \in$ [1-3] $M_\odot$, $m_{\rm BH} \in$ [3-97] $M_\odot$, uniform in *chirp distance*

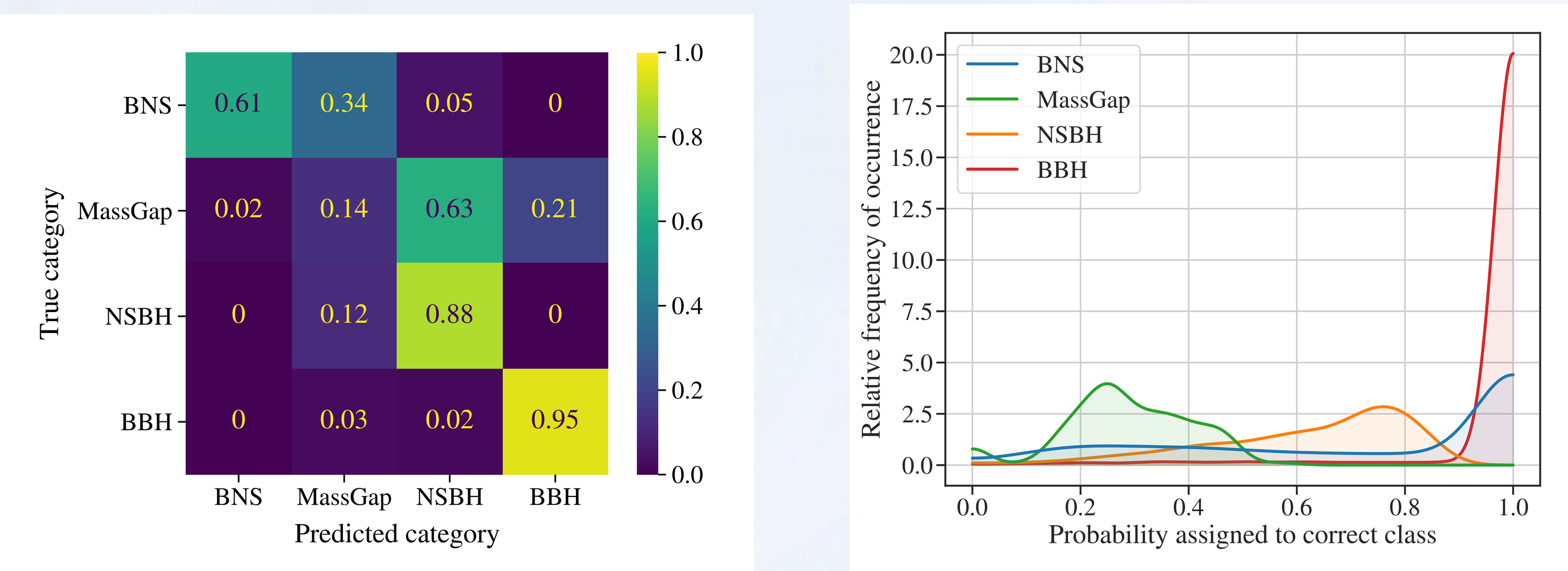


**Figure 4:** Confusion matrix comparing the true categories of the injected signals versus the category found with highest probability in each event (*left*) and KDE plot showing distribution of probabilities for correct classification (*right*)

## Results for low chirp mass O3 events

- We present results for O3 events sent in LVC Public Alerts with chirp masses less than 9 $M_\odot$.
- We compare probabilities (%) computed with our method with the ones sent on LVC Public Alerts and the ones from PE results for catalogs GWTC-2 and GWTC-3 [2, 3]

[a] Initial GCN, [b] Preliminary PE

| Event Name | Our method | | | | Public Alerts | | | | GWTC-2&3 PE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BNS | MG | NSBH | BBH | BNS | MG | NSBH | BBH | BNS | MG | NSBH | BBH | $\mathcal{M}(M_\odot)$ |
| GW190425 | 100 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | > 99 | < 1 | 0 | 0 | 1.4 |
| GW190426_152155 | 6 | 40 | 54 | 0 | 57<br>15 | 28<br>25 | 15<br>60 | 0 [a]<br>0 [b] | 1 | 29 | 64 | 0 | 2.4 |
| GW190707_093326 | 0 | 46 | 7 | 47 | 0 | 0 | 0 | 100 | 0 | < 1 | 0 | > 99 | 8.5 |
| GW190720_000836 | 0 | 47 | 4 | 49 | 0 | 0 | 0 | 100 | 0 | < 1 | 0 | > 99 | 8.9 |
| GW190814 | 0 | 31 | 52 | 17 | 0<br>0 | 100<br><1 | 0<br>>99 | 0 [a]<br>0 [b] | 0 | 0 | 100 | 0 | 6.1 |
| GW190924_021846 | 0 | 30 | 56 | 14 | 0 | 100 | 0 | 0 | 0 | 45 | 4 | 51 | 5.8 |
| GW190930_133541 | 0 | 44 | 14 | 42 | 0 | 100 | 0 | 0 | 0 | 8 | < 1 | 92 | 8.5 |
| GW200115_042309 | 7 | 41 | 52 | 0 | 0 | 100 | 0 | 0 | < 1 | 28 | 71 | 0 | 2.4 |
| GW200316_215756 | 0 | 46 | 3 | 51 | 0 | 100 | 0 | 0 | 0 | 5 | < 1 | 95 | 8.8 |

## Conclusions

- Previous *hard-cuts* classification can be completely wrong, asigning 0% probability to the correct source (e.g., GW190814 first Public Alert), while our new classification method always gives some probability to the correct source.
- Great majority of BNS and BBH events are assigned **high or very high** (>80%) correct class probabilities.
- Only for MassGap events this probability is mainly below 50%, but since the method usually assigns them to be NSBH this can be considered as a **conservative outcome**.

## Future work

- To obtain a more accurate classification, we could include information on the **binary mass ratio** $q$ and account for **component spins**.
- For that we would consider a higher dimensional parameter space, as in [4].

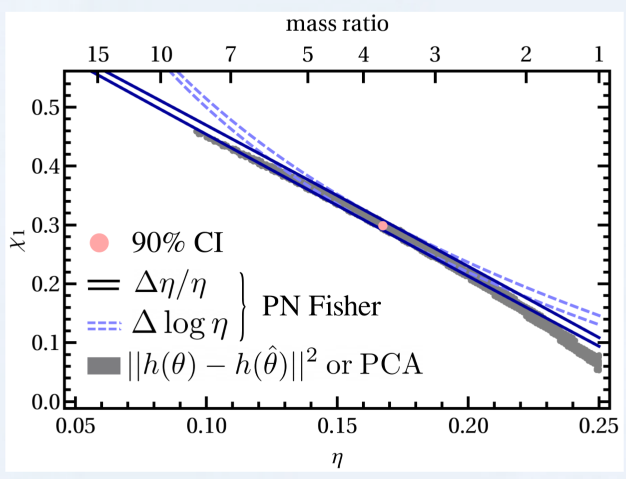


**Figure 5:** Correlation of errors in $q$ and BH spin $\chi_1$ for NSBH system (edited from [4])

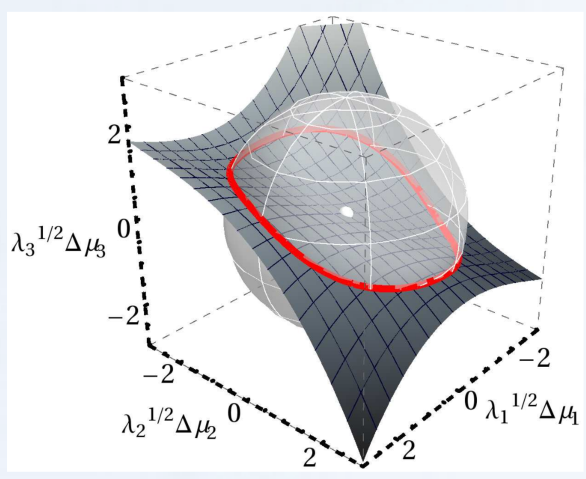


**Figure 6:** Consider space of PN parameters - Fisher matrix is constant. Surface represents physical points in higher parameter space [4]

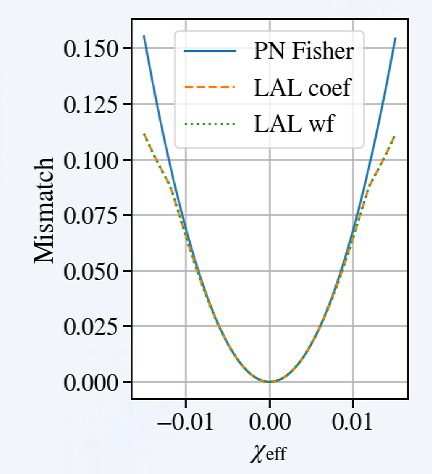


**Figure 7:** Demonstrate that mismatch from PN-space distance is consistent with direct method

## References


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[2] R. Abbott *et al.*, "GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run," *Phys. Rev. X*, vol. 11, p. 021053, 2021.

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