Rapid Online Estimation of GW Source Redshift and Astrophysical Source Category

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Source Classification for Rapid Follow-up

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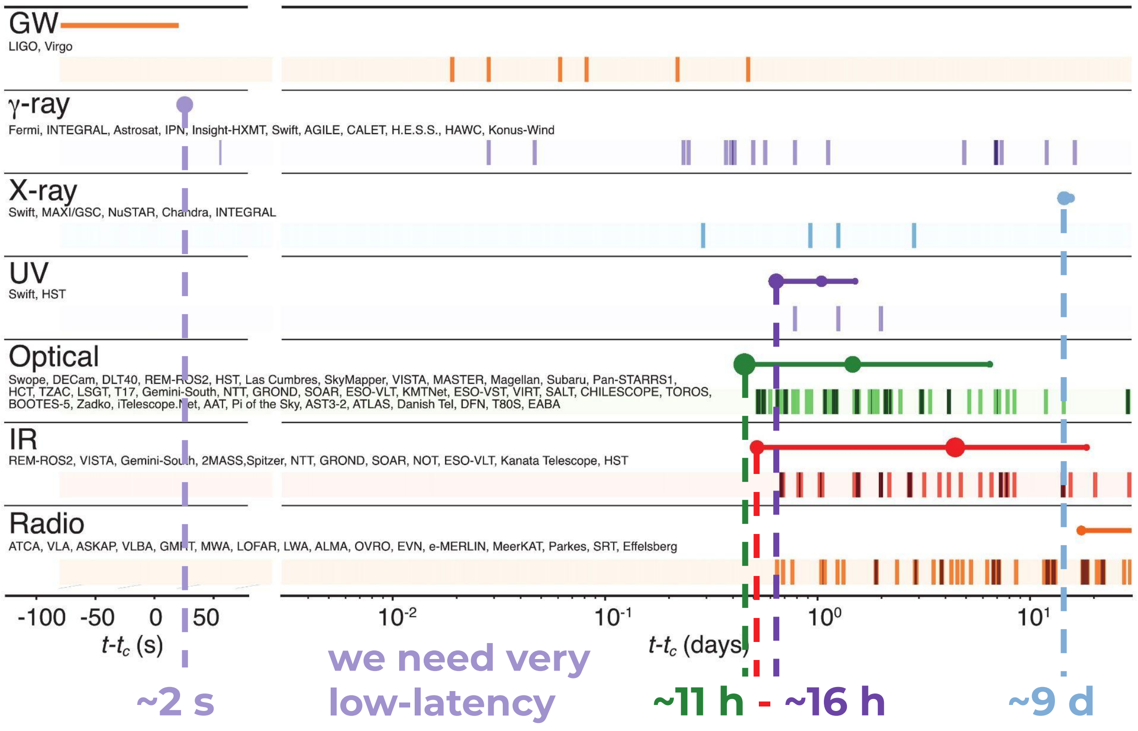
GW170817 + EM counterparts follow-up



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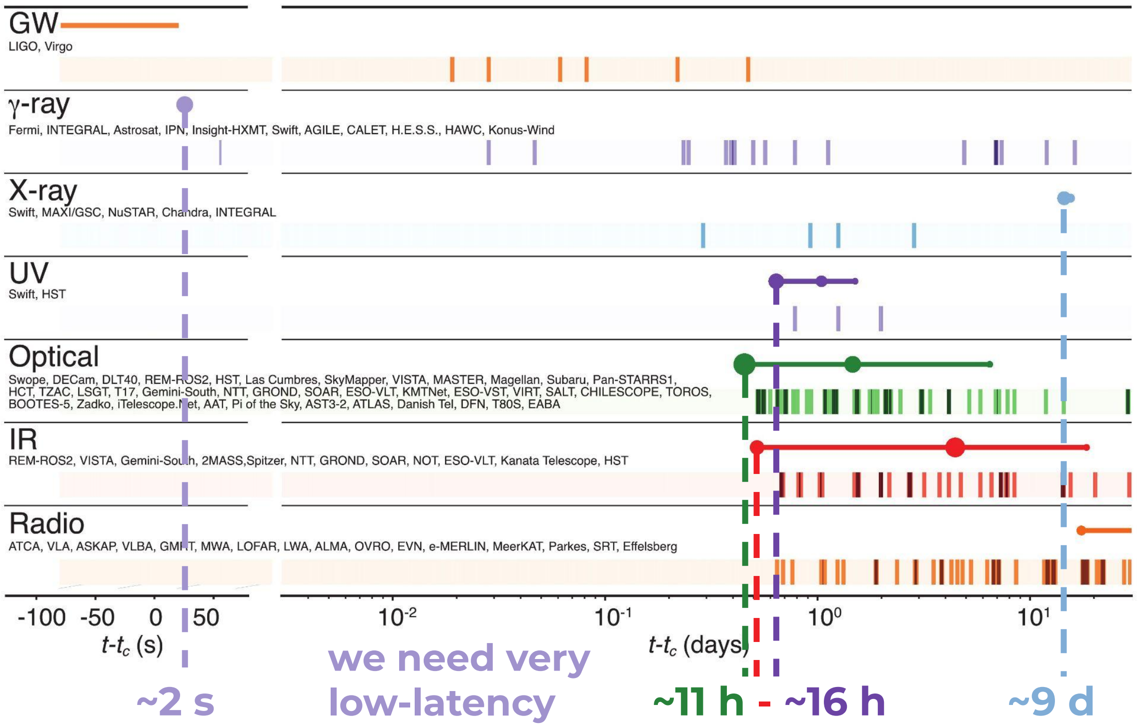
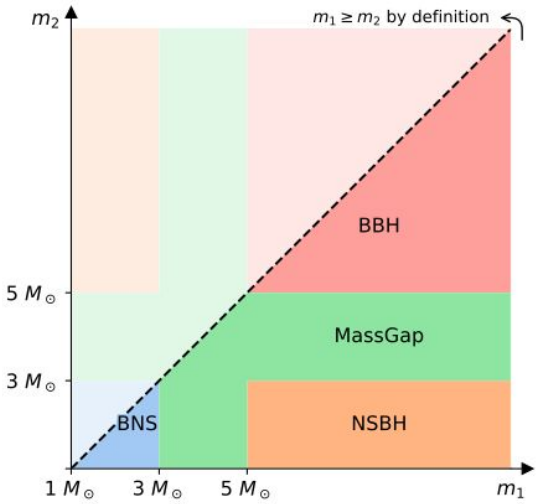


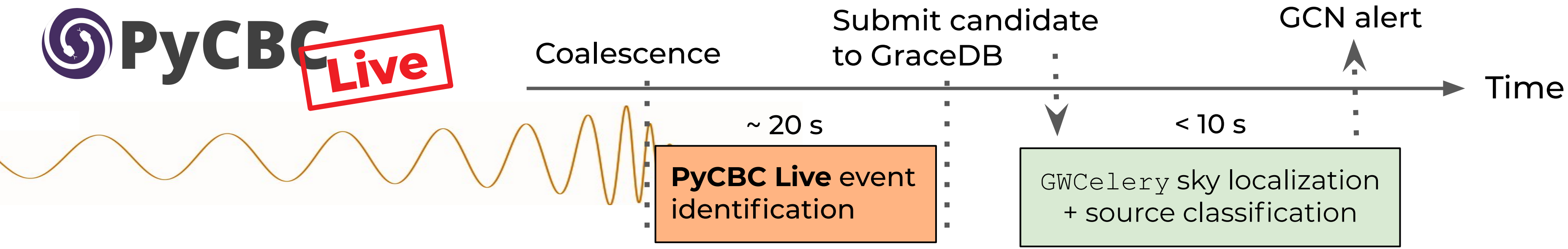


$\{ P_{BNS}, P_{MG}, P_{NSBH}, P_{BBH} \}$

*assuming the origin is astrophysical

PyCBC Live Alerts in O3

https://arxiv.org/pdf/1805.11174.pdf



Source classification based on "hard cuts" on component masses m_1 m_2

- Assigns Boolean 0 or 1 to the different CBC categories - just one final category
- Neglects uncertainties in component masses ~ 20-30%
- Does not account for redshift bias

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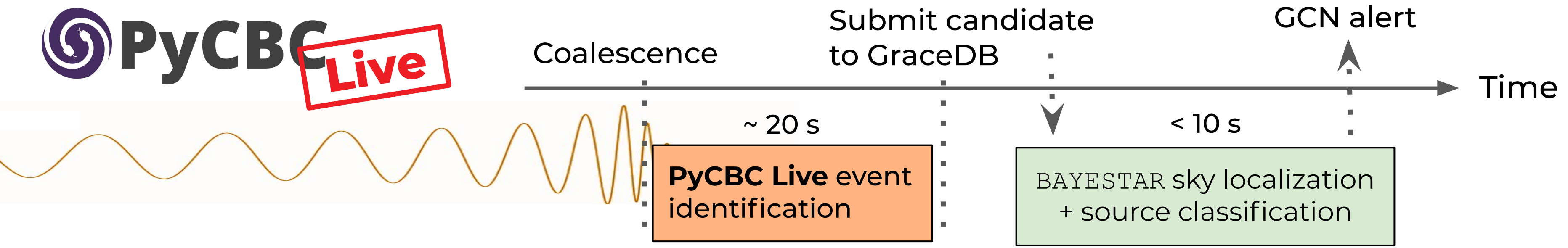

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- Assigns Boolean 0 or 1 to the different CBC categories - just one final category
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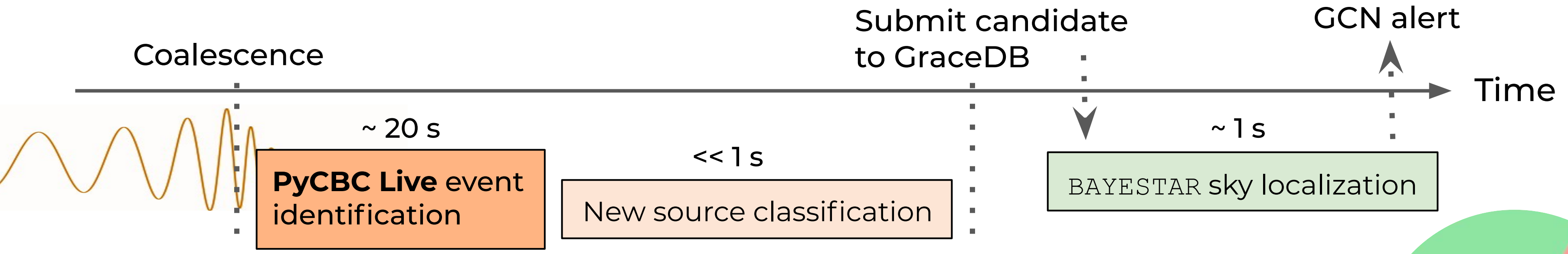
We can improve this

- Spectrum of probabilities
- Use a quantity with little uncertainty: chirp mass ~0.1-1%

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- Add redshift correction

New Classification Method

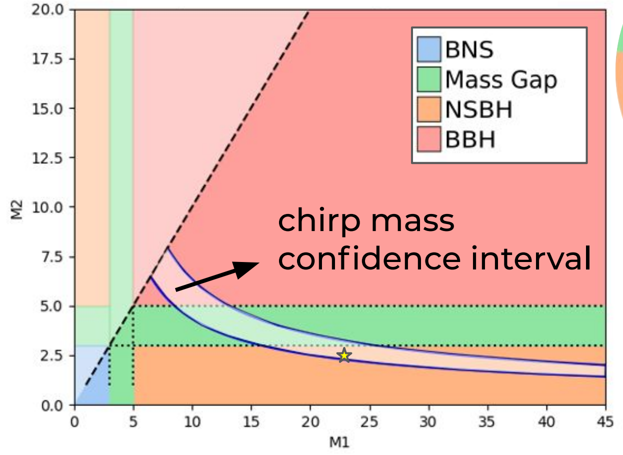


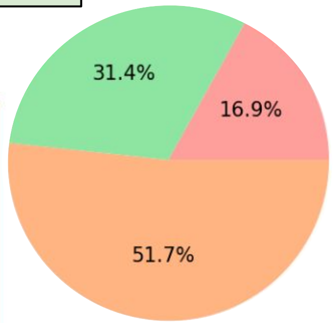
Use chirp mass from the search pipeline:

- m_1 m_2 constrained to a interval of constant $\mathcal{M} \pm \Delta\mathcal{M}$
- Assumed uncertainty of 1 %

Assume uniform density prior of candidate signals over $m_1 m_2$ plane:

- Probabilities proportional to the area of each region inside contour of chirp mass





GW190814

Source Redshift Estimation

PyCBC Live

Pipeline template is redshifted compared to source chirp mass $\mathcal{M}_{\rm tmpl} = \mathcal{M}_{\rm src} \cdot (1+z)$

- Redshift is a function of luminosity distance → computed by BAYESTAR once the event has been uploaded to GraceDB

Not available!

What do we have available?

- Effective distances to the source
  - Luminosity distance * antenna factor

$$D_{\rm eff} = D\left[F_+^2\left(\frac{1+cos^2\iota}{2}\right)^2 + F_\times^2 cos^2\iota\right]^{-1/2}$$

  - One effective distance for each detector
  - Estimate a numerical relation between distances
  - Since $D_{\rm eff} \geq D_{\rm lum}$ we can take the minimum effective distance

Source Redshift Estimation

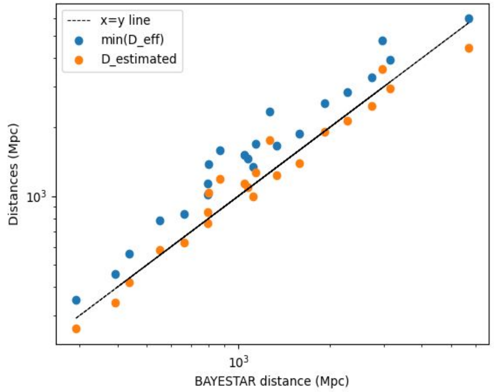
- Estimation of luminosity distance
  - Estimate a relation between distances using PyCBC Live and `BAYESTAR` data of O3a events

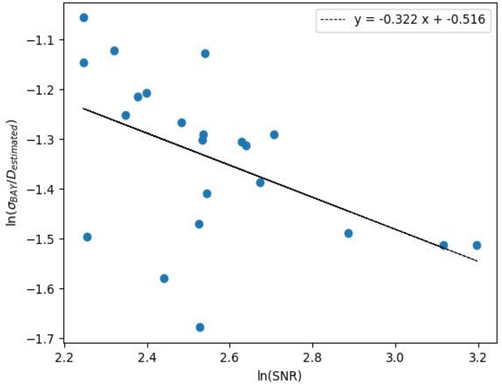
$$\tilde{D}_{\mathrm{lum}} = 0.749 \cdot min(D_{\mathrm{eff}})$$

- Estimation of the uncertainty of luminosity distance
  - Using the signal-to-noise ratio from the pipeline

$$\tilde{\sigma}_{\mathrm{lum}} = \tilde{D}_{\mathrm{lum}} \cdot \mathrm{e}^{-0.516} \cdot \rho_{\mathrm{coinc}}^{-0.322}$$

- We propagate the distance uncertainty into the redshift and chirp mass uncertainty
- This correction will be dominant over the assumed 1% uncertainty in chirp mass

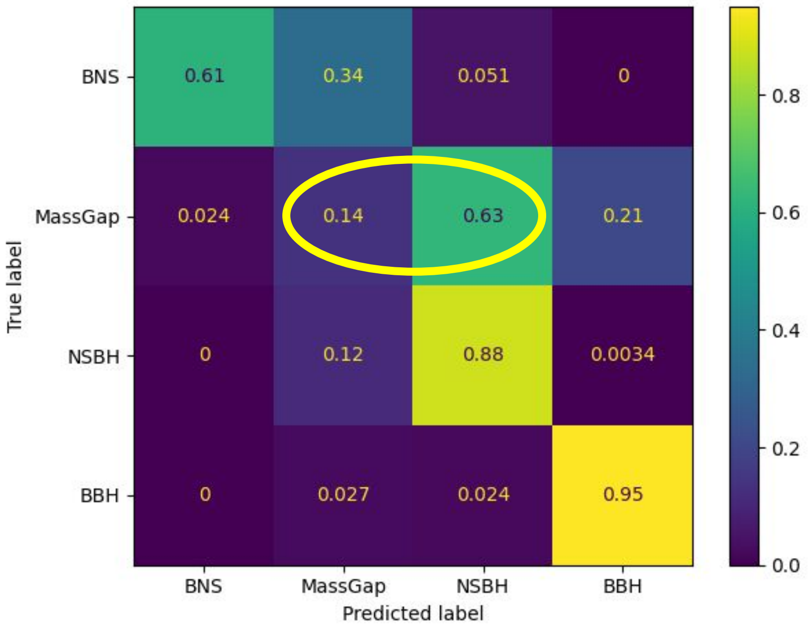




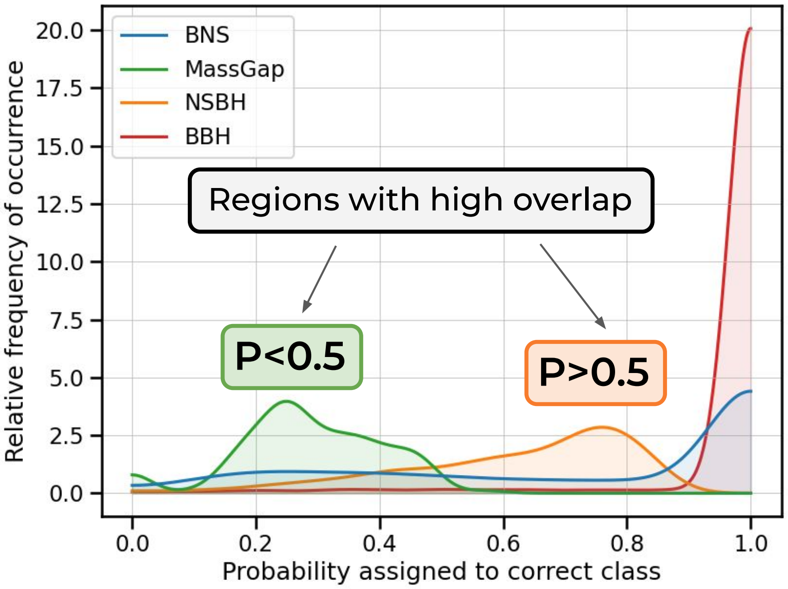
Results with simulated signals

PyCBC Live

To check the method we simulated a population of astrophysical signals, added them to real data from O3 and recovered them with PyCBC Live



[Highest probability]



Results with O3a data

GWTC-2:
https://arxiv.org/abs/2010.14527

PyCBC Live

We applied the method to PyCBC Live triggers of O3a

Events	Estimated Prob (%)	GCNs Prob(%)*	Catalog Masses + PE
GW190426_152155	NSBH 52, MG 41 BNS 7	**BNS 57** MG 27 NSBH 14 [(a)] NSBH 60 MG 25 BNS 15 [(b)]	m_1 5.7 m_2 1.5 **NSBH 64 MG 30**
GW190707_093326	BBH 47 MG 46 NSBH 6	BBH 100	m_1 11.6 m_2 8.4 **BBH 100**
GW190720_000836	BBH 49 MG 46 NSBH 4	BBH 100	m_1 13.4 m_2 7.8 **BBH 99**
GW190814	NSBH 52 MG 31 BBH 17	**MG 100**	m_1 23.2 m_2 2.59 **NSBH 100**
GW190924_021846	NSBH 55 MG 30 **BBH 15**	**MG 100**	m_1 8.9 m_2 5.0 **BBH 51 MG 45**
GW190930_133541	BBH 47 MG 46 NSBH 6	**MG 100**	m_1 12.3 m_2 7.8 **BBH 92**

* rescaled to sum to 100 % [(a)] Initial GCN, [(b)] Preliminary PE

Summary and Future Work

- Previous “hard-cuts” classification can be completely wrong, while the new classification method always give some probability to the correct source.
- The great majority of BNS and BBH events are assigned high or very high 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.
- As future work we will introduce some information about the populations of the sources in the prior of candidate events in the masses plane.
- We probably will say goodbye to MassGap category
- Investigation about binary mass ratio and spins in very low-latency
- We need more studies on biases and uncertainties

Thank you for your attention!

Results with O3a data

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PyCBC Live

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GW190930_133541	BBH 47 MG 46 NSBH 6	BBH 86 NSBH 14	m_1 12.3 m_2 7.8 **BBH 92**