Rapid Online Estimation of Astrophysical Source Category and Compact Binary Parameters

arXiv: 2203.10080

Verónica Villa-Ortega[1], T.Dent, A.Curiel

IGFAE, University of Santiago de Compostela

12th Iberian GW Meeting, 7th June 2022

[1] veronica.villa@rai.usc.es

EXCELENCIA MARÍA DE MAEZTU

IGFAE Instituto Galego de Física de Altas Enerxías

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

XUNTA DE GALICIA

galicia

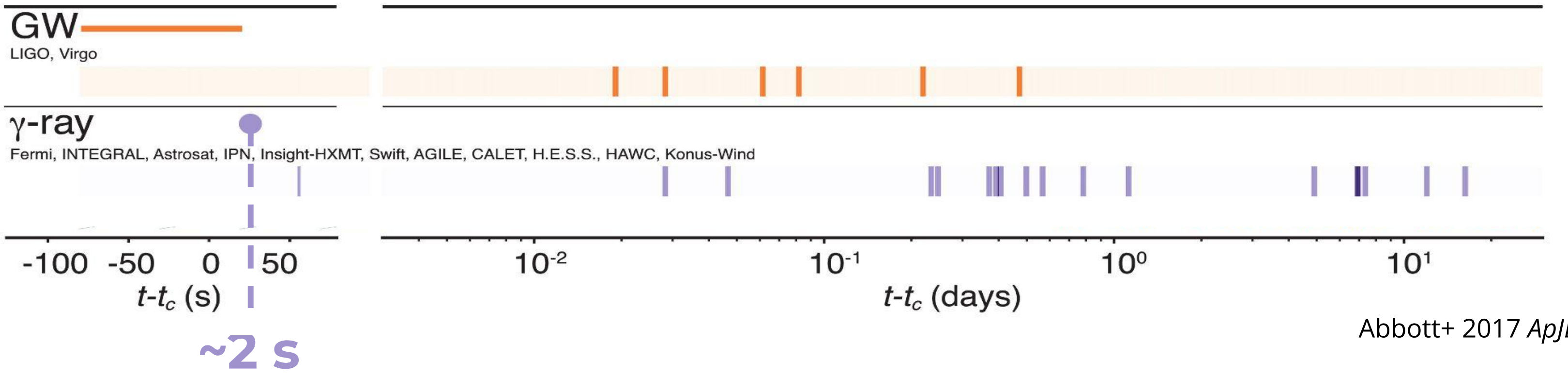
GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

Motivation: Rapid Follow-up

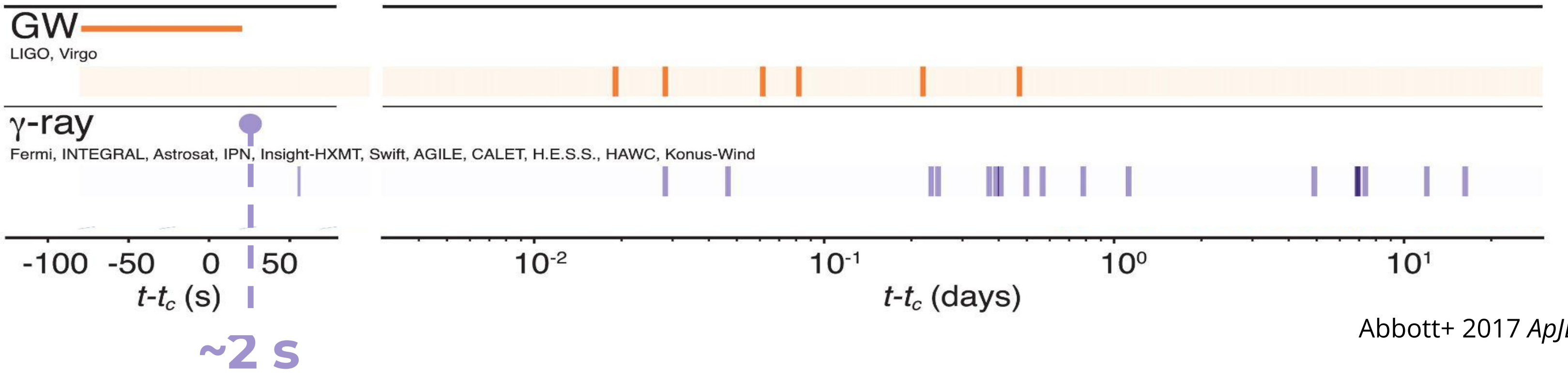
First EM counterpart - GW170817: γ-ray burst with ~2 s latency



Abbott+ 2017 *ApJL* 848 L12

Motivation: Rapid Follow-up

First EM counterpart - GW170817: γ-ray burst with ~2 s latency



Abbott+ 2017 *ApJL* 848 L12

Challenge

Look for events with potential EM or neutrino counterparts (high probability of containing a NS) in **very low-latency**

Candidates Identification

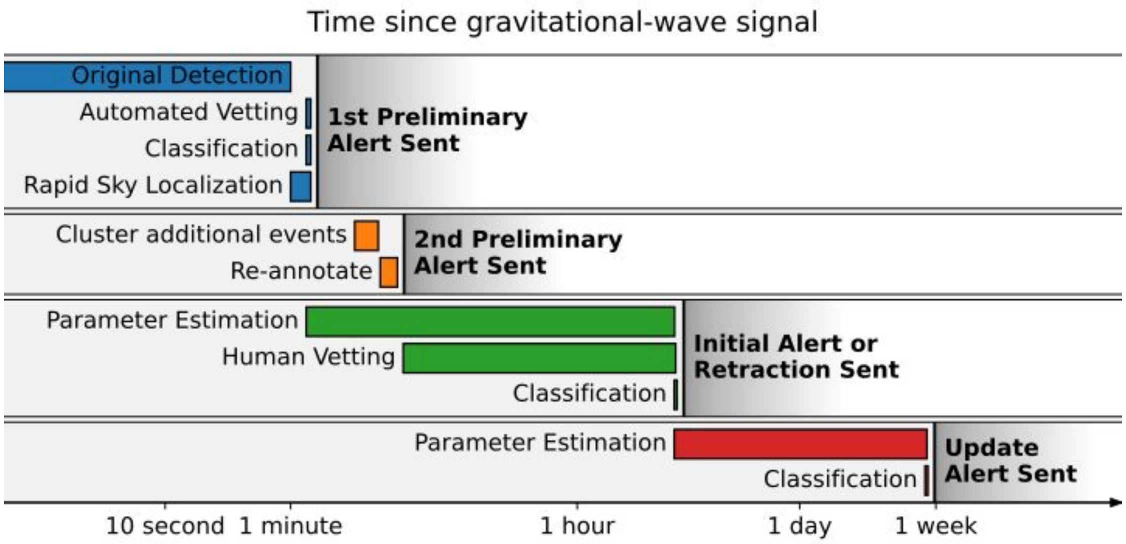
Searches perform candidate identification on two timescales:

- **Low-latency** → Generates public alerts within minutes
- **Offline** → - Reanalysis with better data quality and/or more detailed methods
  - Takes hours to weeks

Candidates Identification

Searches perform candidate identification on two timescales:

- **Low-latency** → Generates public alerts within minutes
- **Offline** → - Reanalysis with better data quality and/or more detailed methods
  - Takes hours to weeks



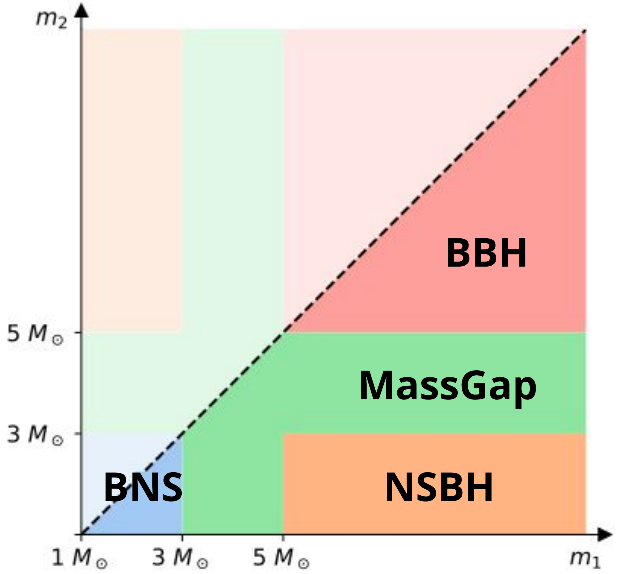
LVC Public Alerts User Guide

Source Classification of CBC

- **Source Classification:** probability that the source belongs to the different Astrophysical categories or is of Terrestrial origin

Source Classification of CBC

- **Source Classification:** probability that the source belongs to the different Astrophysical categories or is of Terrestrial origin
- Astrophysical Categories of CBC during O3: **BNS, NSBH, MassGap, BBH**

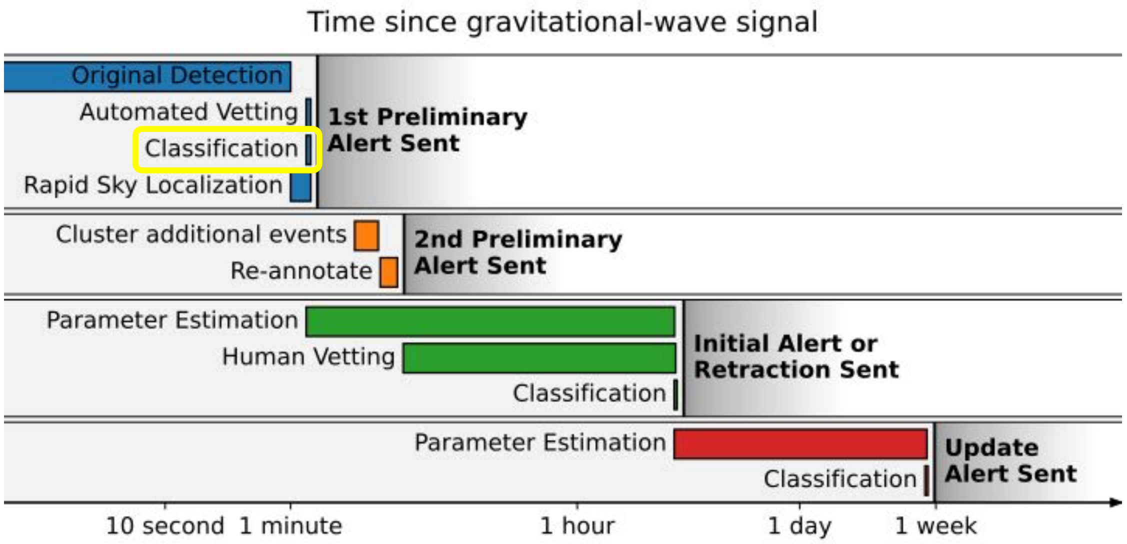


LVC Public Alerts User Guide

Candidates Identification

Searches perform candidate identification on two timescales:

- **Low-latency** → Generates public alerts within minutes
- **Offline** → - Reanalysis with better data quality and/or more detailed methods
  - Takes hours to weeks

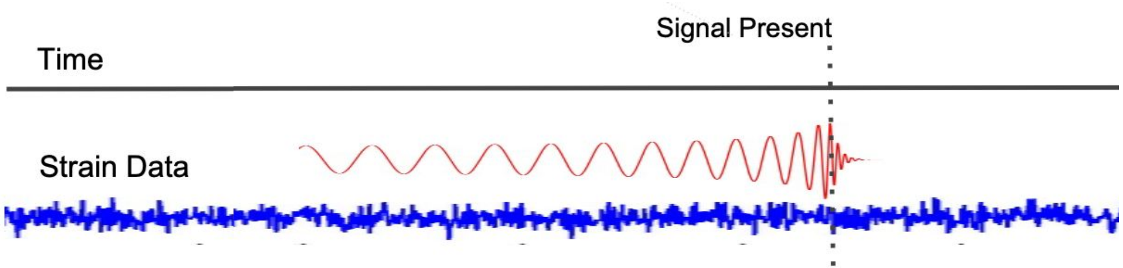


LVC Public Alerts User Guide

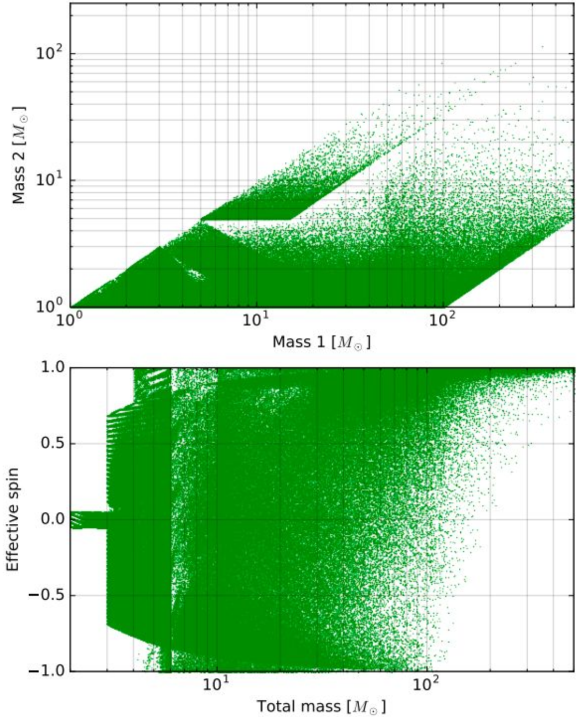
Source Classification in PyCBC Live

PyCBC Live:

- Online all-sky modelled search for CBC's
- Uses matched filtering with a bank of templates



- Each template has component masses and spins

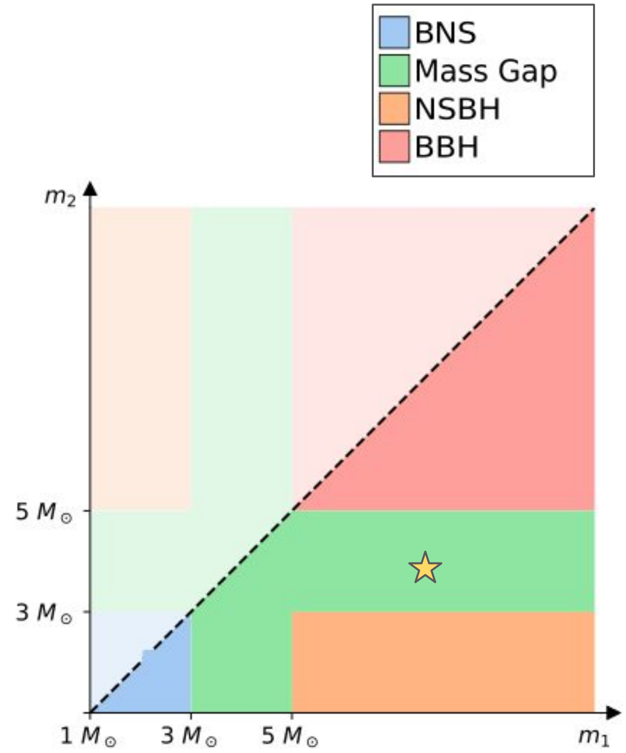


Nitz *et al.* 2018 *PRD* 98, 024050, Dal Canton *et al* arXiv:1705.01845

Source Classification in PyCBC Live during O3

“Hard-cuts” method:

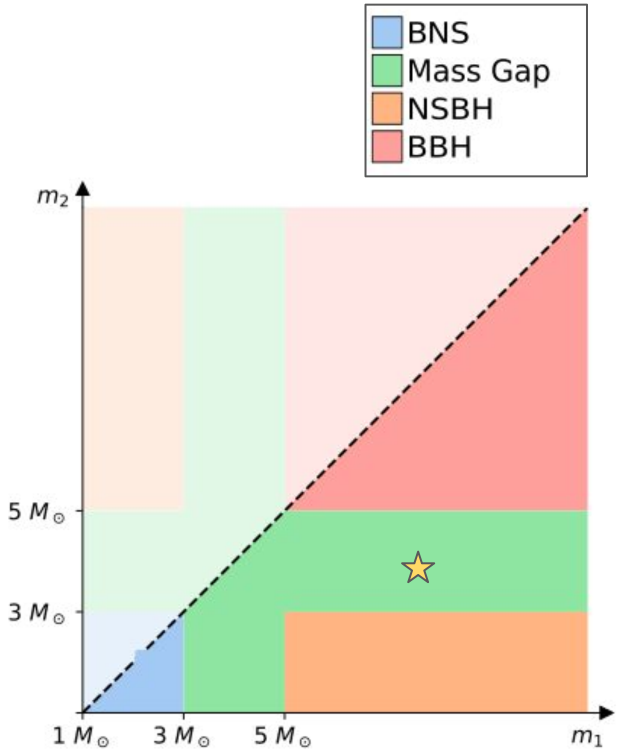
- Uses point (template) estimates of **component masses** m_1 m_2



Source Classification in PyCBC Live during O3

“Hard-cuts” method:

- Uses point (template) estimates of **component masses** m_1 m_2
- Assigns **100% to a single astrophysical class** and 0% to the others



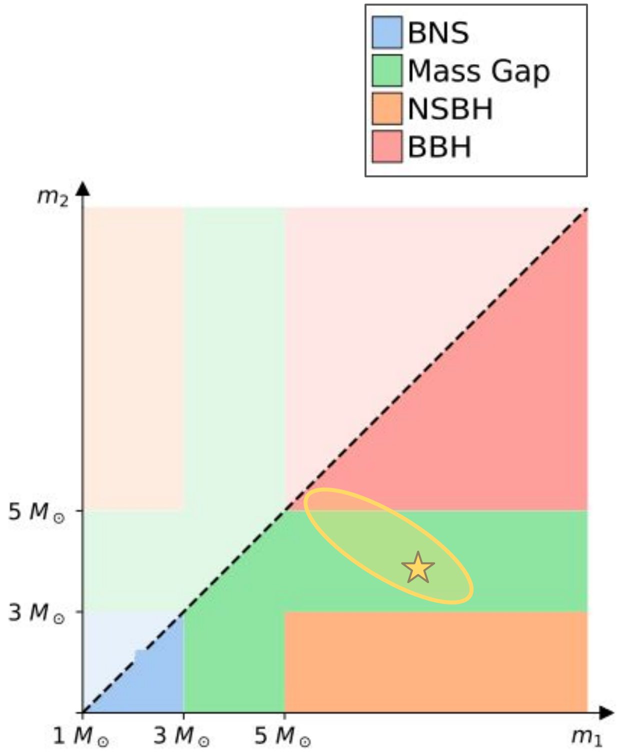
Source Classification in PyCBC Live during O3

“Hard-cuts” method:

- Uses point (template) estimates of **component masses** $m_1\, m_2$
- Assigns **100% to a single astrophysical class** and 0% to the others

Drawbacks:

- Component masses have **large uncertainties >10%**



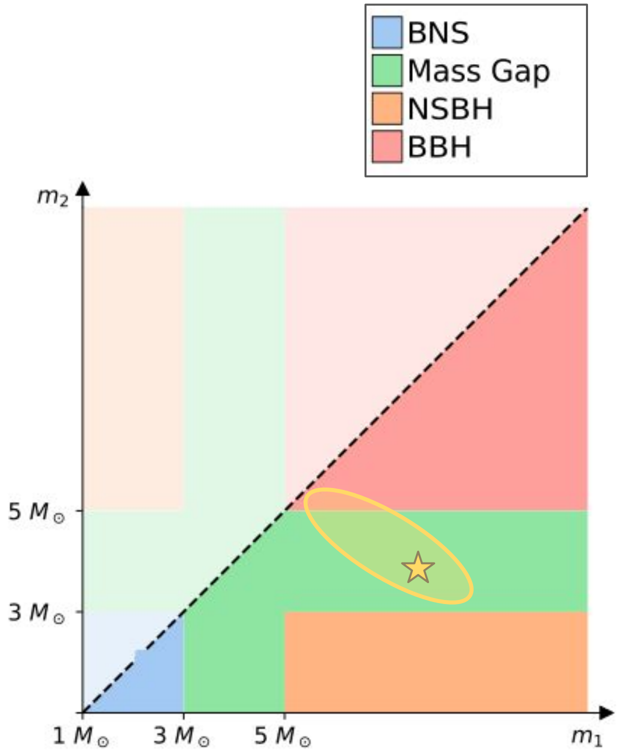
Source Classification in PyCBC Live during O3

“Hard-cuts” method:

- Uses point (template) estimates of **component masses** $m_1\ m_2$
- Assigns **100% to a single astrophysical class** and 0% to the others

Drawbacks:

- Component masses have **large uncertainties >10%**
- Does not account for **redshift bias**

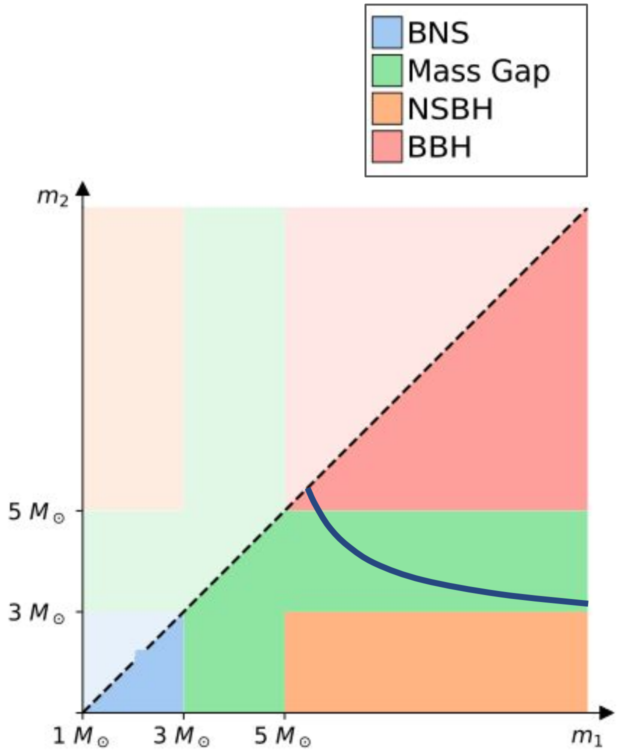


New Classification Method

“Chirp-mass based” method:

- Uses point estimates of **chirp mass**

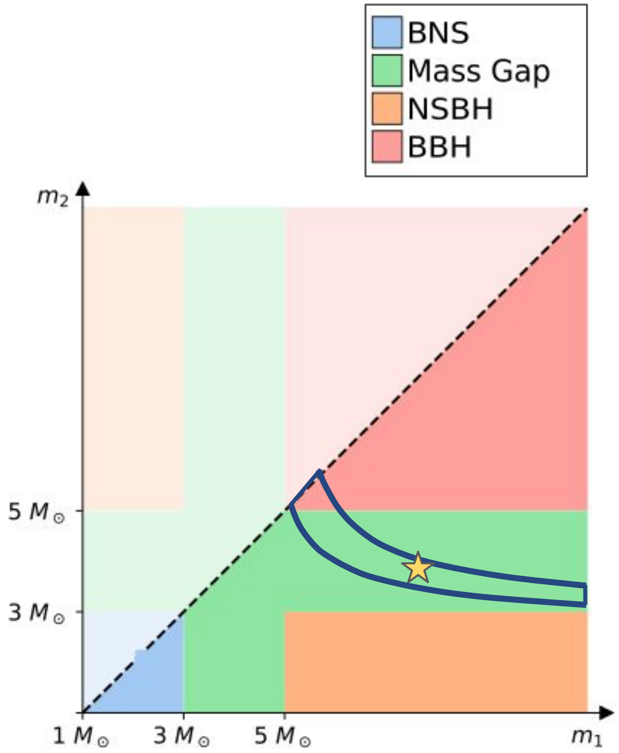
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



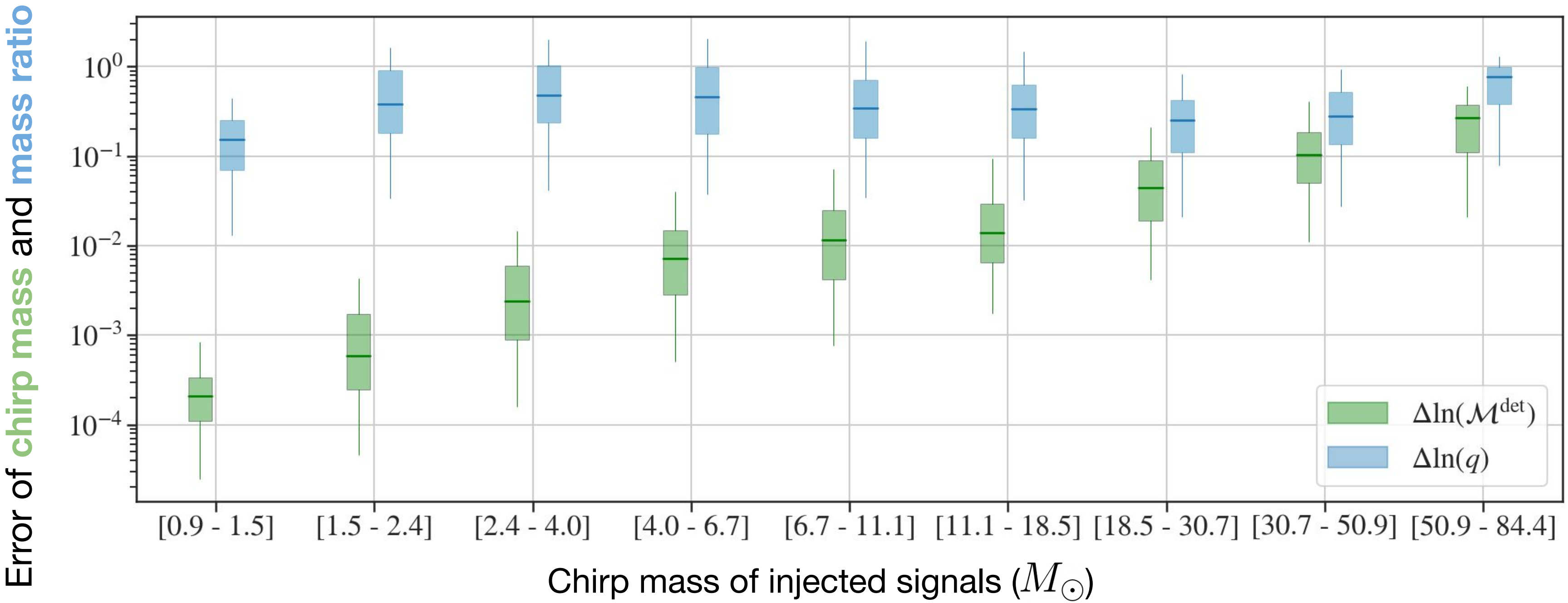
New Classification Method

“Chirp-mass based” method:

- Uses point estimates of **chirp mass** $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$
- Chirp mass is measured with **little uncertainty ~0.1-1%**
    - m_1 m_2 constrained to a interval of constant $\mathcal{M} \pm \Delta\mathcal{M}$
    - We assume $\Delta\mathcal{M} = 1\%$



Uncertainties on template masses

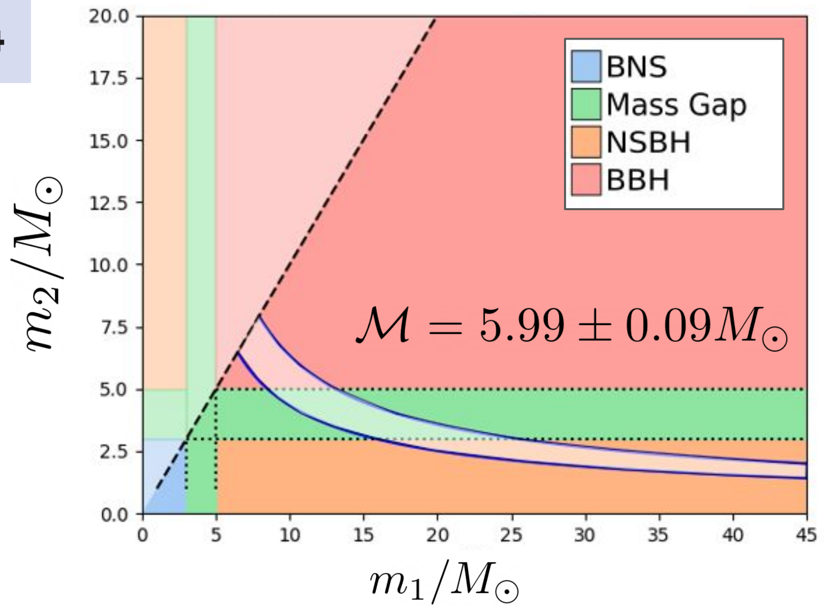


Source Probabilities from Chirp Mass

Assuming **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

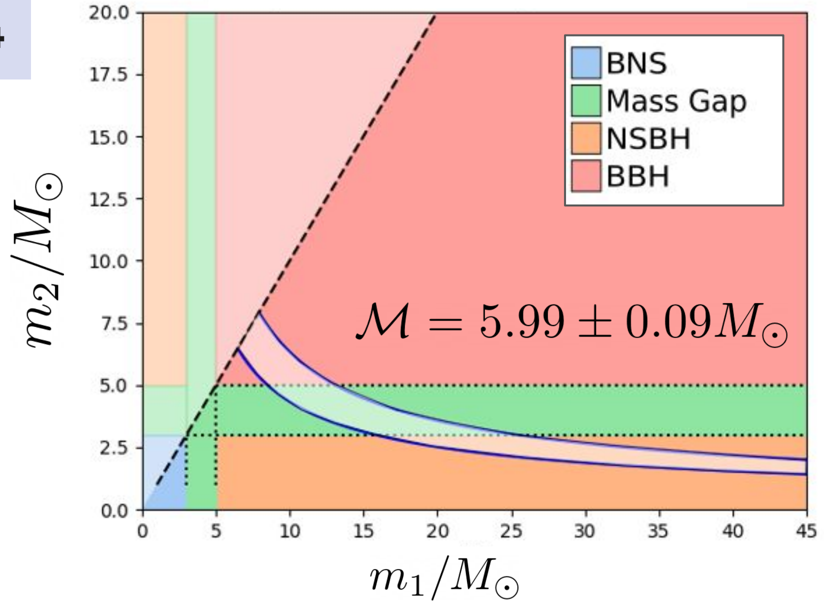


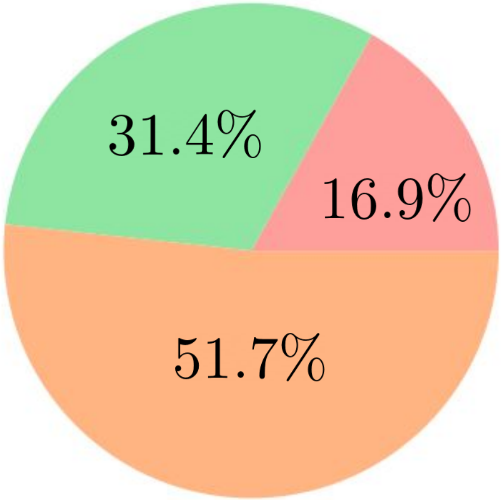
Source Probabilities from Chirp Mass

Assuming **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

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

Source Redshift Estimation

- Pipeline template is **redshifted** compared to source chirp mass $\mathcal{M}_{\rm tmpl} = \mathcal{M}_{\rm src} \cdot (1+z)$
- Redshift can be estimated from D_L (assuming a cosmology)

Source Redshift Estimation

- Pipeline template is **redshifted** compared to source chirp mass $\mathcal{M}_{\mathrm{tmpl}} = \mathcal{M}_{\mathrm{src}} \cdot (1 + z)$
- Redshift can be estimated from D_L (assuming a cosmology)
- **Problem:** PyCBC Live does not estimate D_L - is computed later during Sky Localization

Source Redshift Estimation

- Pipeline template is **redshifted** compared to source chirp mass $\mathcal{M}_{\mathrm{tmpl}} = \mathcal{M}_{\mathrm{src}} \cdot (1+z)$
- Redshift can be estimated from D_L (assuming a cosmology)
- **Problem:** PyCBC Live does not estimate D_L - is computed later during Sky Localization

PyCBC Live recovers **effective distances** to the source:

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

Source Redshift Estimation

- Pipeline template is **redshifted** compared to source chirp mass $\mathcal{M}_{\rm tmpl} = \mathcal{M}_{\rm src} \cdot (1+z)$
- Redshift can be estimated from D_L (assuming a cosmology)
- **Problem:** PyCBC Live does not estimate D_L - is computed later during Sky Localization

PyCBC Live recovers **effective distances** to the source:

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

- One for each detector i

Source Redshift Estimation

- Pipeline template is **redshifted** compared to source chirp mass $\mathcal{M}_{\mathrm{tmpl}} = \mathcal{M}_{\mathrm{src}} \cdot (1+z)$
- Redshift can be estimated from D_L (assuming a cosmology)
- **Problem:** PyCBC Live does not estimate D_L - is computed later during Sky Localization

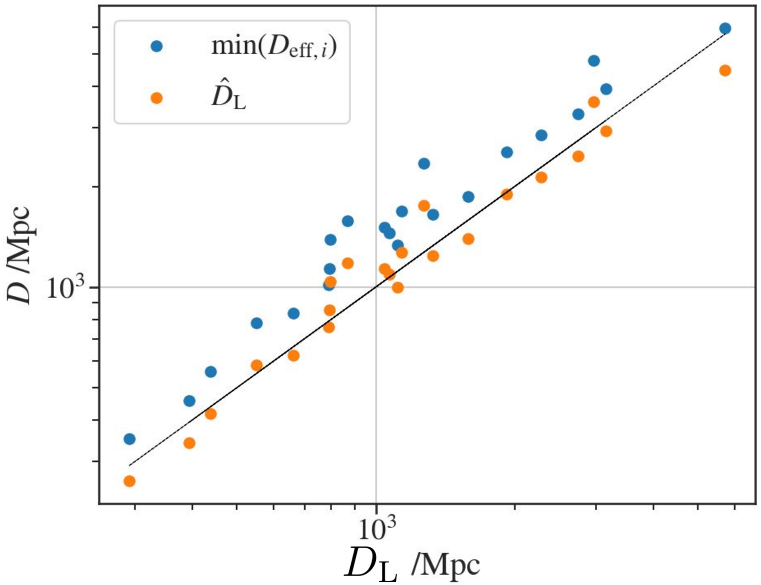
PyCBC Live recovers **effective distances** to the source:

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

- One for each detector i
- $D_{\mathrm{eff},i} \geq D_{\mathrm{L}}$ so we can take the minimum one

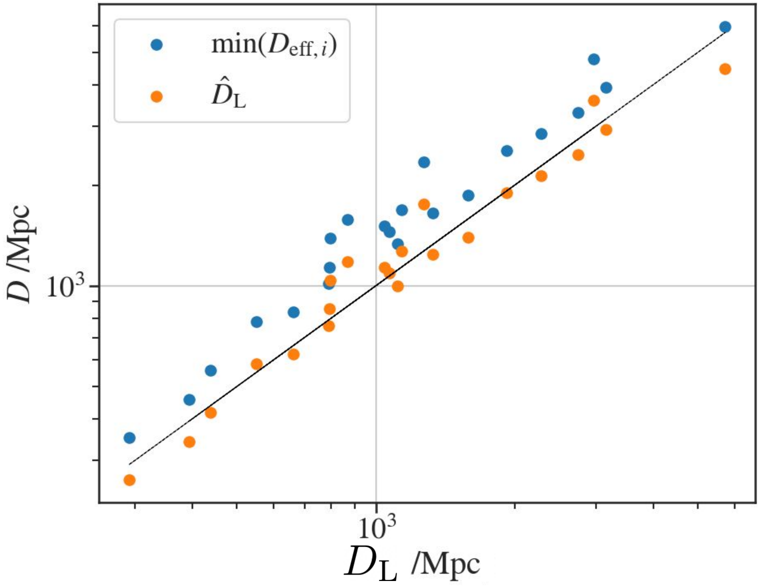
Luminosity Distance Estimation

- We fit a relationship between estimated D_L and minimum effective distances
  - $\tilde{D}_{\mathrm{L}} = C_D \cdot \min(D_{\mathrm{eff},i})$
  - Data from O3a events

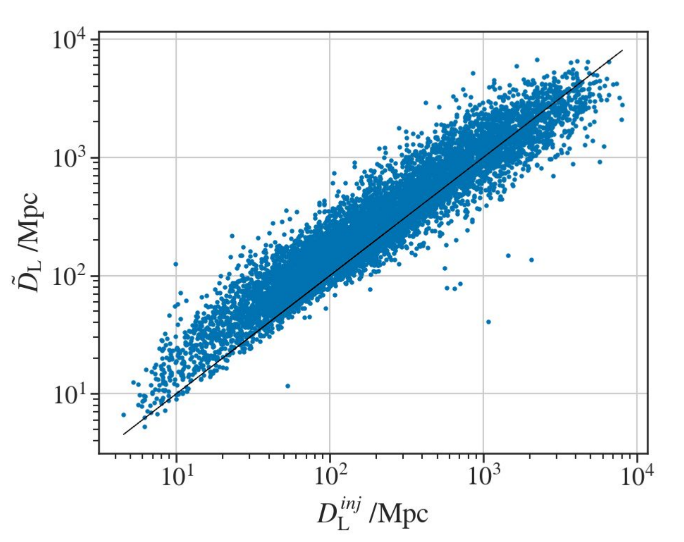


Luminosity Distance Estimation

- We fit a relationship between estimated D_L and minimum effective distances
  - $\tilde{D}_\mathrm{L} = C_D \cdot \min(D_{\mathrm{eff},i})$
  - Data from O3a events



Check with simulated signals

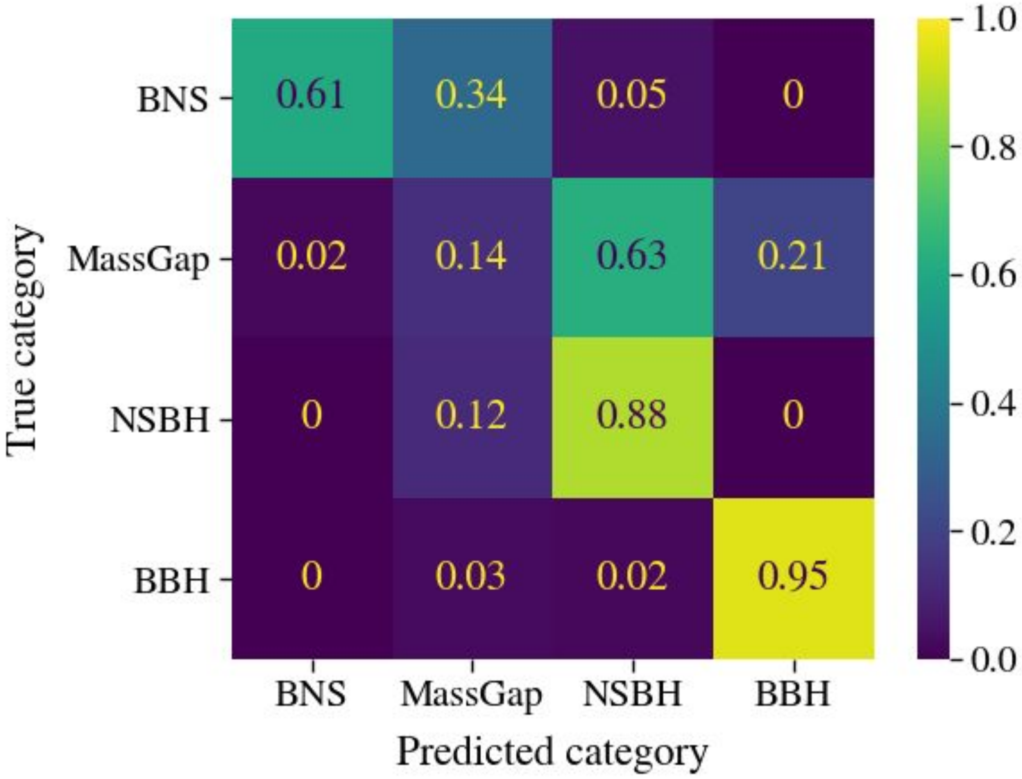


Method applied to simulated signals

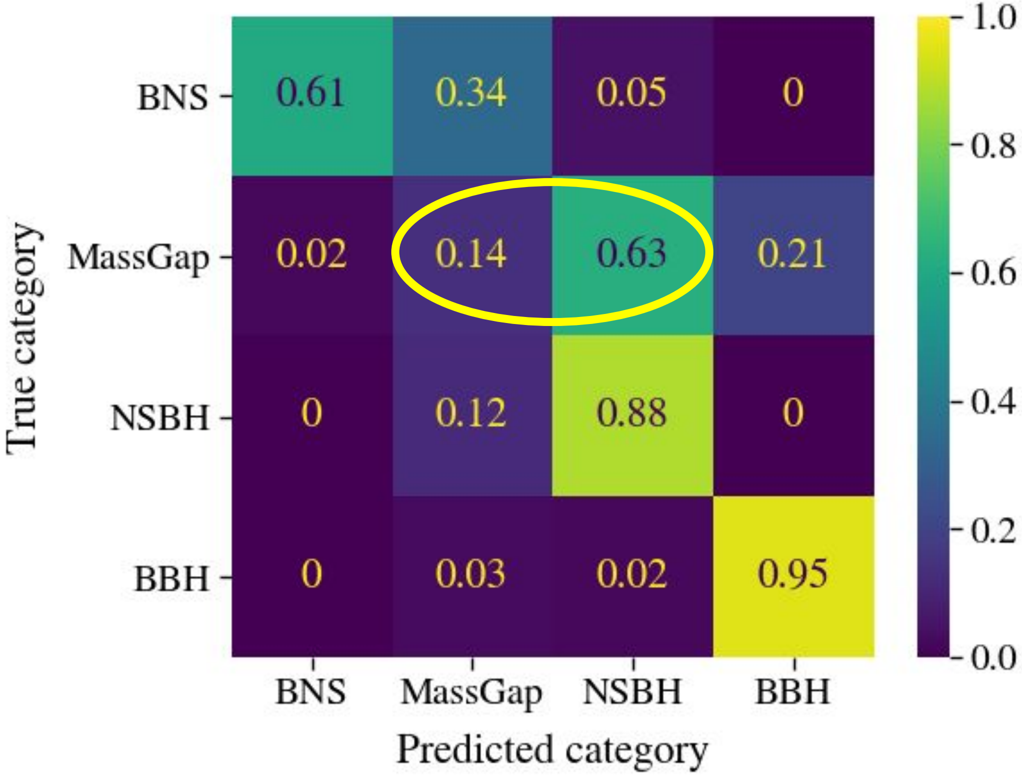
Simulated signals injected into O3a data recovered with PyCBC Live:

- m(NS) ∈ [1-3] $M_\odot$
- m(BH) ∈ [3-97] $M_\odot$
- Uniform in **chirp distance**

Confusion Matrix

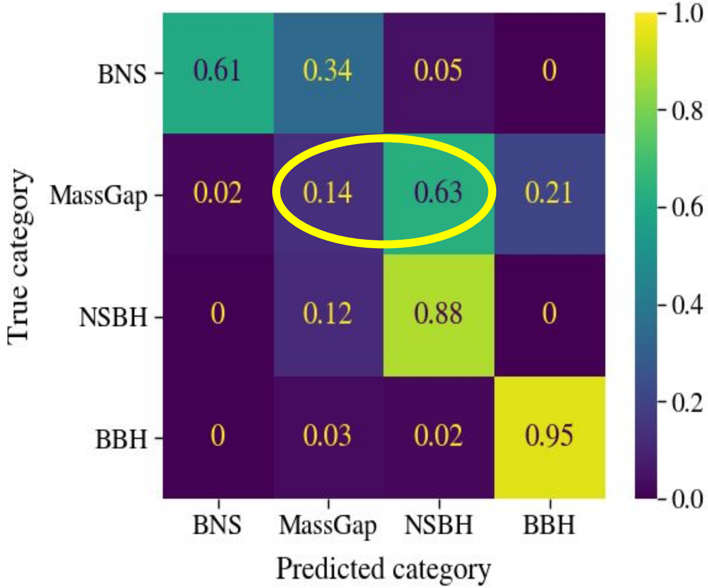


Confusion Matrix

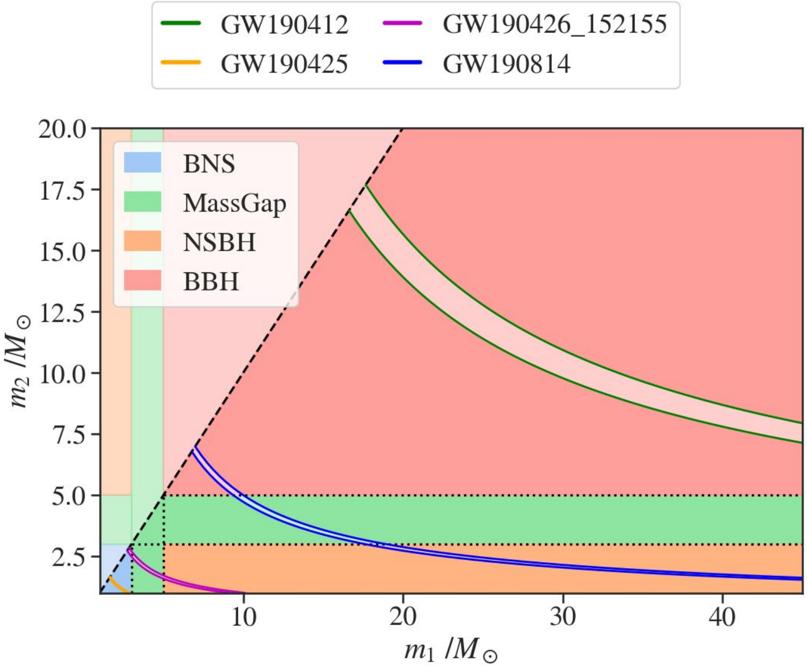


MassGap and NSBH always overlap with other regions

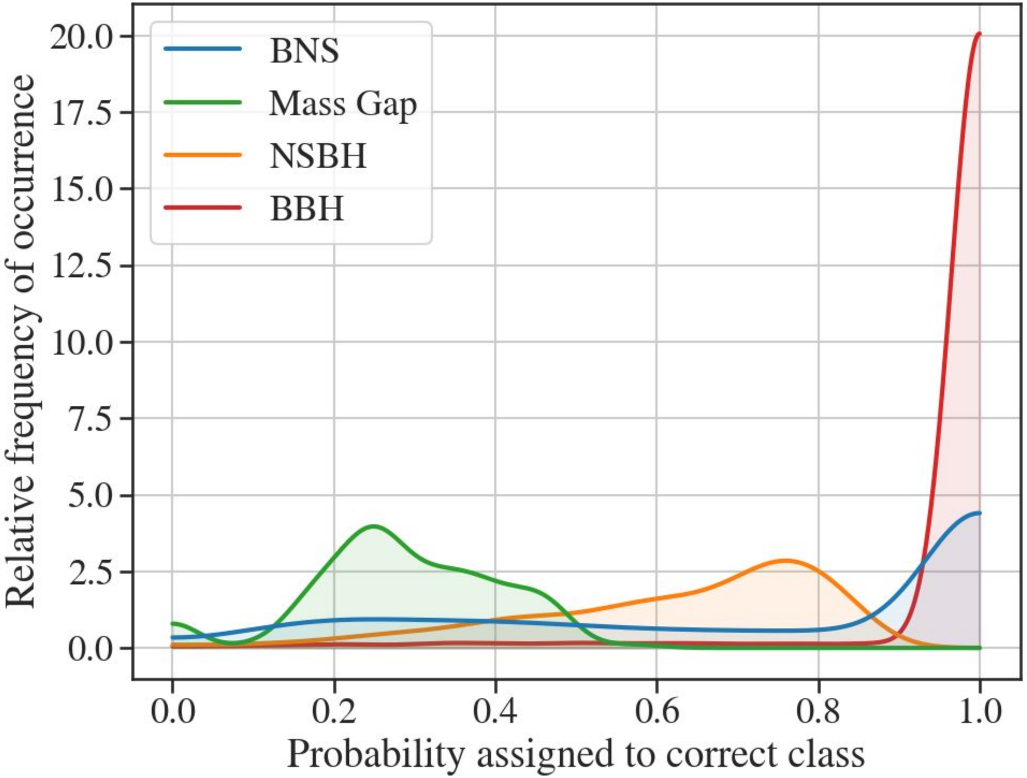
Confusion Matrix



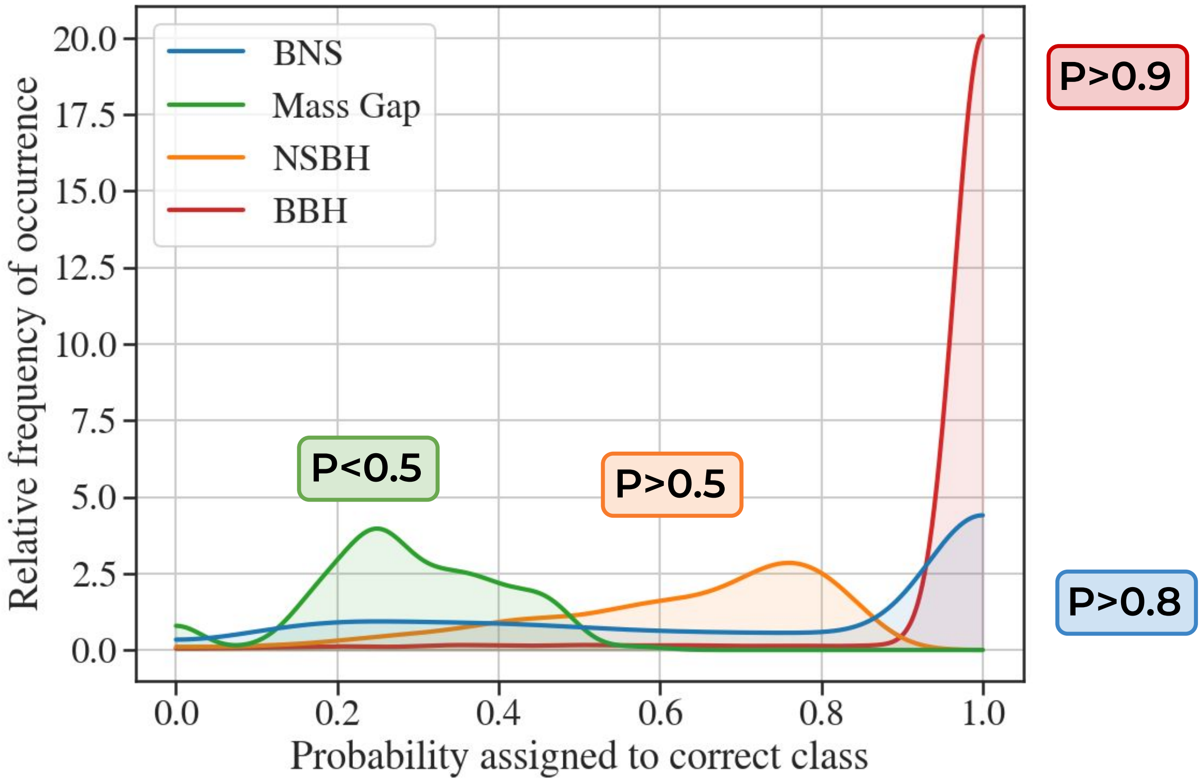
Overlap between regions



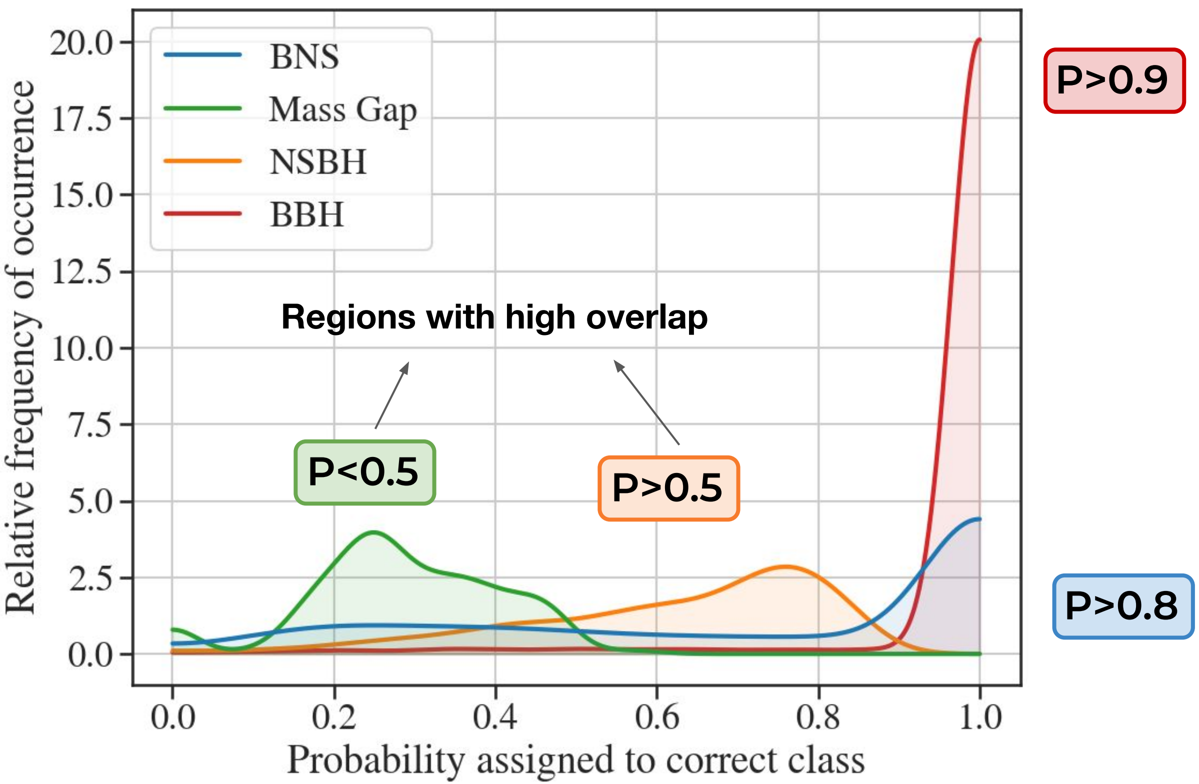
Kernel Density Estimation (KDE)



Kernel Density Estimation (KDE)



Kernel Density Estimation (KDE)



Results for low-mass O3 events

- 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**

Results for low-mass O3 events

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	28	15	0 [a]	1	29	64	0	2.4
					15	25	60	0 [b]					
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	100	0	0 [a]	0	0	100	0	6.1
					0	<1	>99	0 [b]					
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

[a] Initial Public Alert [b] Preliminary PE

Results for low-mass O3 events

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	28	15	0 [a]	1	29	64	0	2.4
					15	25	60	0 [b]					
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	100	0	0 [a]	0	0	100	0	6.1
					0	<1	>99	0 [b]					
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

[a] Initial Public Alert [b] Preliminary PE

Results for low-mass O3 events

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	28	15	0 [a]	1	29	64	0	2.4
					15	25	60	0 [b]					
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	100	0	0 [a]	0	0	100	0	6.1
					0	<1	>99	0 [b]					
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

[a] Initial Public Alert [b] Preliminary PE

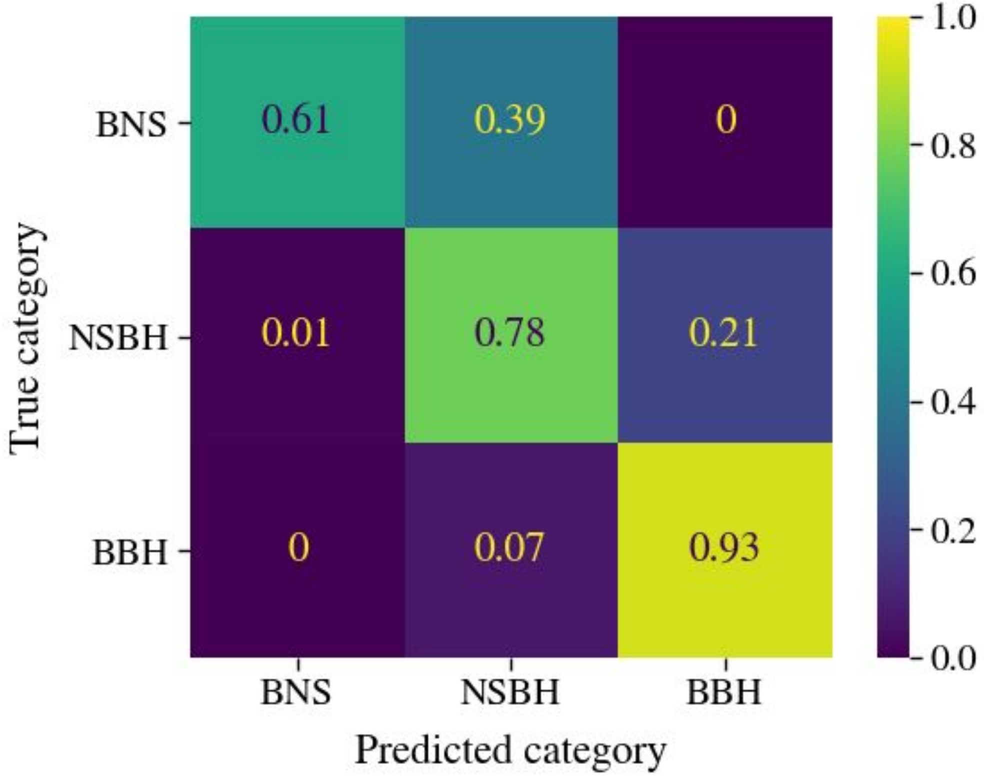
Summary

- We developed a new Source Classification method that improves the previous “hard-cuts”:
  - Offers a **spectrum of probabilities**
  - Accounts for **redshift bias** by estimating the **source distance**
- The method is **implemented in PyCBC Live** and it is available to run in O4
- Only adds **<50 ms** to the latency of the pipeline - **very low-latency**
- **Next step:**
  - To obtain a more accurate classification, we are investigating how to include information on the **binary mass ratio** q and account for **component spins**
  - For that we are considering a higher dimensional parameter space

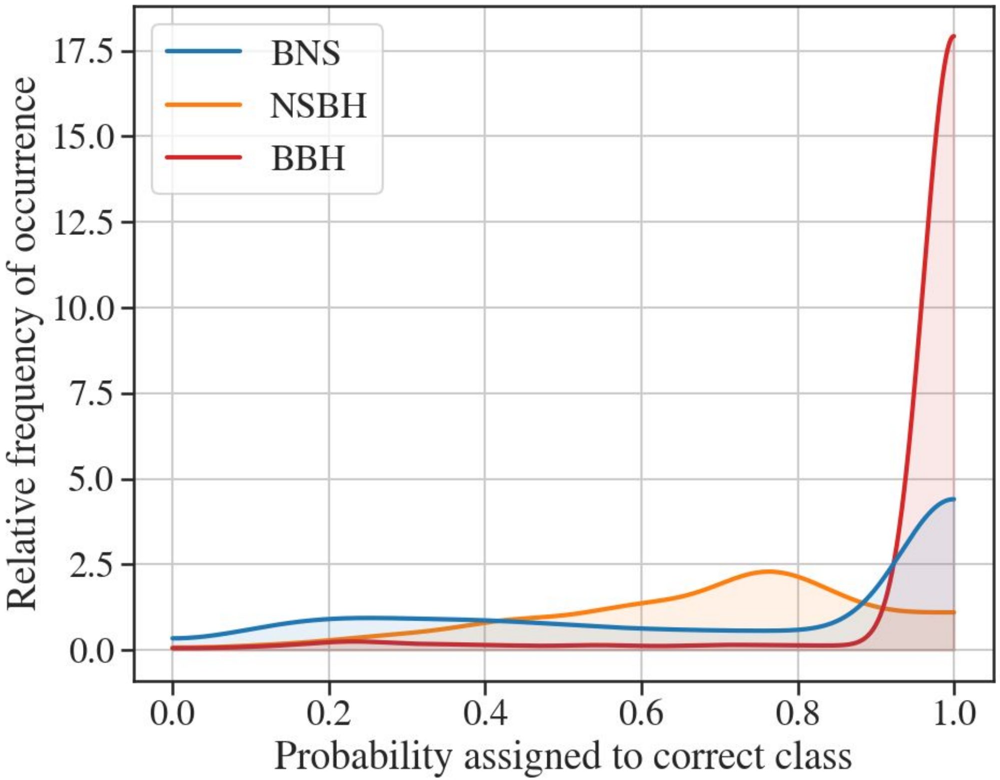
Thank you for your attention!

EXTRA SLIDES

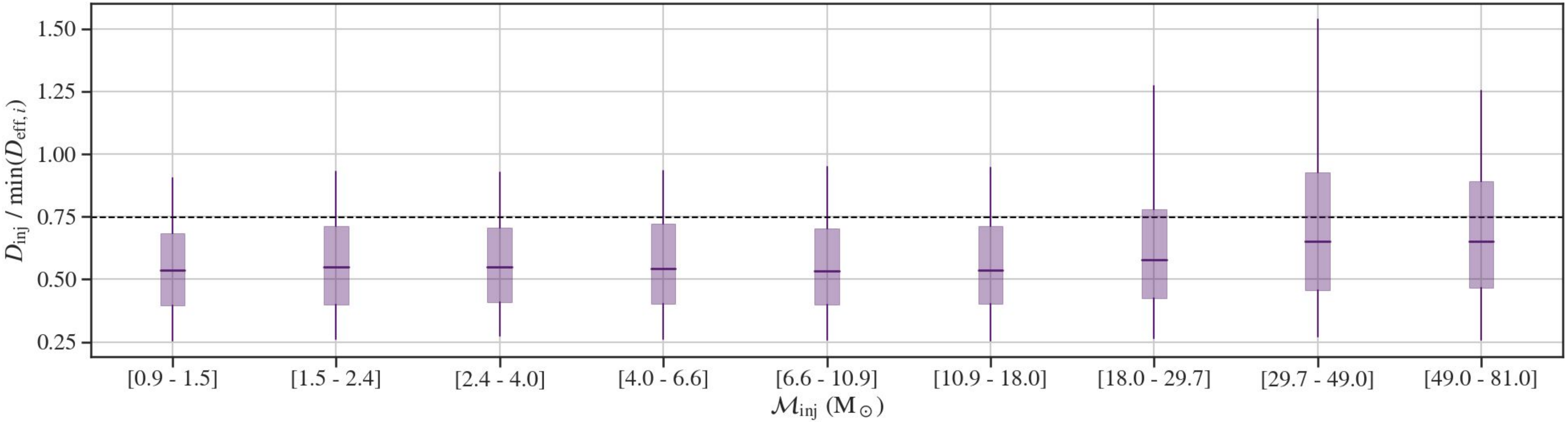
Results without MassGap



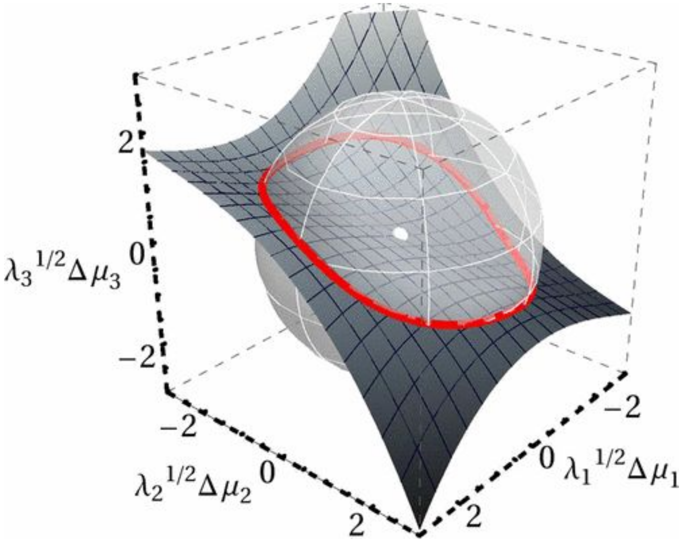
Results without MassGap

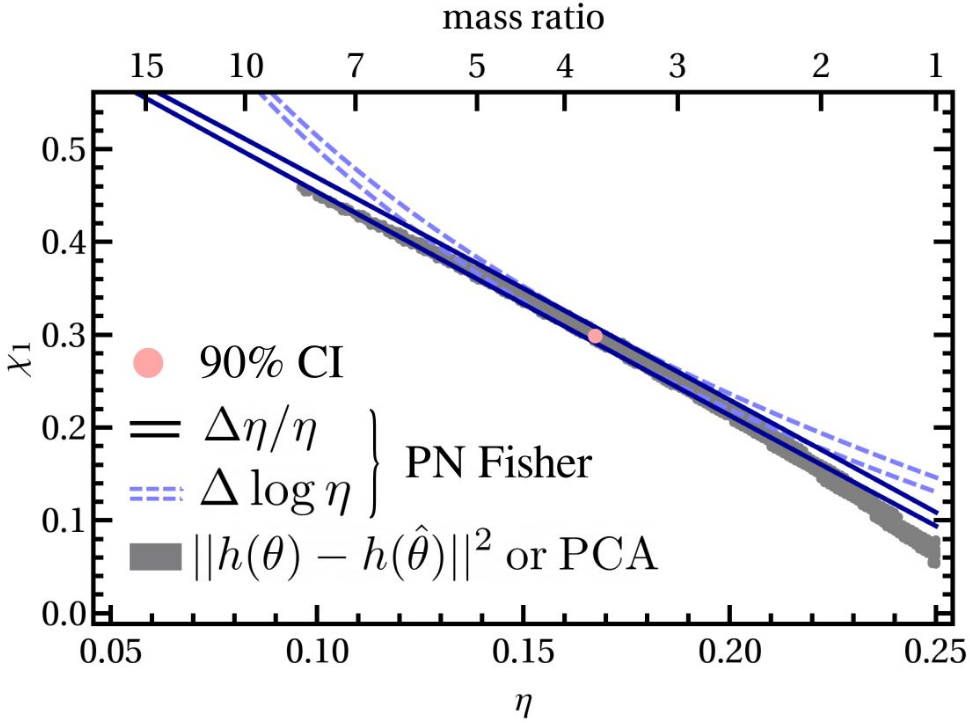


Check of distance fit with injections



Future Work





Expect to get better estimates of parameter errors by computing template mismatches in higher dimensional space
- (space based on PN coefficients)

Ohme *et al* 2013 *PRD* 88 042002