Source classification of compact-binary mergers for candidates from the MBTA pipeline

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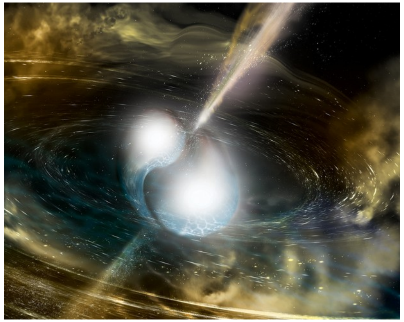
Why do we need a source classification?

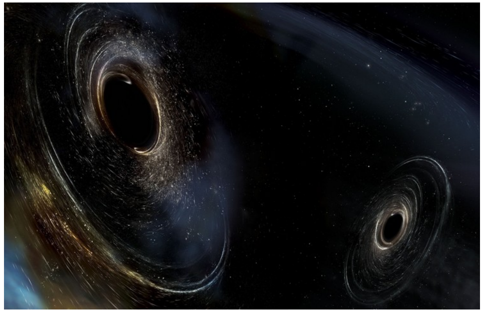
Compact-binary coalescences divided in 3 categories:

Binary Neutron Stars (BNS)



Neutron Star Black Hole (NSBH)

Binary Black Hole (BBH)



In low-latency:

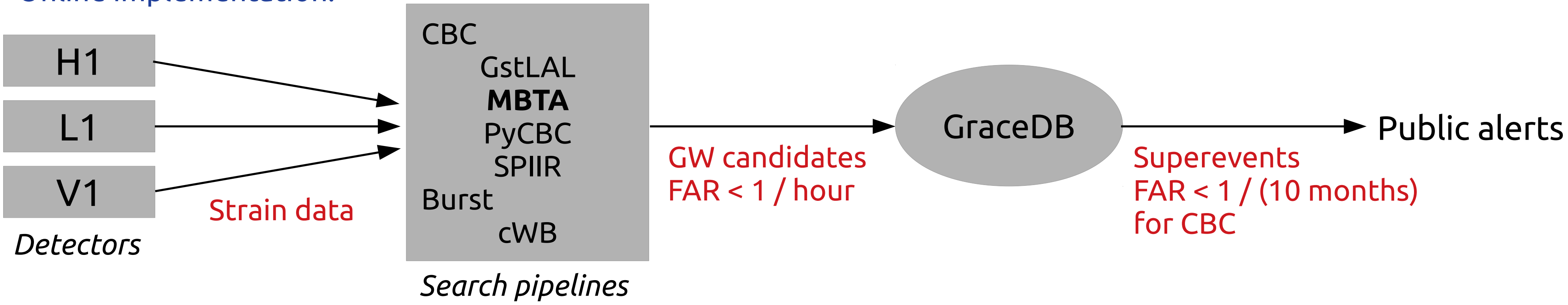
- Help astronomers to decide whether to undertake a follow-up or not of the gravitational-wave candidates broadcast via public alerts

In archival data:

→ Sub-threshold triggers analysis with other messengers (electromagnetic, neutrinos…)
→ Compute binary merger rates of source specific compact objects
→ Inform the population synthesis of compact-binary systems

MBTA a CBC search pipeline

- Online implementation:



- **Multi-Band Template Analysis** pipeline developed in Virgo used in online/offline searches (*Class. Quantum Grav. 38 095004*)
- Offline implementation:
  - Add $\mathbf{p_{astro}}$ calculation with **source classification**
  - Results published in GWTC-2.1 (*R. Abbott et al. 2021*)

Name	Inst.	MBTA			GstLAL			PyCBC			PyCBC-BBH		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}
GW190403_051519	HL	– –	– –	– –	– –	– –	– –	– –	– –	– –	7.7	8.0	0.61
GW190408_181802	HLV	8.7×10^{-5}	14.4	1.00	$< 1.0 \times 10^{-5}$	14.7	1.00	2.5×10^{-4}	13.1	1.00	$< 1.2 \times 10^{-4}$	13.7	1.00
GW190412	HLV	$< 1.0 \times 10^{-5}$	18.2	1.00	$< 1.0 \times 10^{-5}$	19.0	1.00	$< 1.1 \times 10^{-4}$	17.4	1.00	$< 1.2 \times 10^{-4}$	17.9	1.00
GW190413_052954	HL	– –	– –	– –	– –	– –	– –	*170*	*8.5*	*0.13*	0.82	8.5	0.93

Probability of astrophysical origin: p_{astro}

$$p_{astro} = \frac{\text{foreground}}{\text{background} + \text{foreground}} = \frac{\Lambda_1 f(x)}{\Lambda_0 b(x) + \Lambda_1 f(x)}$$

- **b(x) background density** estimated from MBTA process
- Λ_0 expected number of background triggers
- **f(x) astrophysical foreground density** estimated from astrophysical population
- Λ_1 expected number of astrophysical triggers
- Bayesian analysis using a Poisson mixture formalism to determine Λ_0 and Λ_1: *(Kapadia et al. 2020)*
  → $p(\Lambda_0, \Lambda_1|\vec{x}) \propto \pi(\Lambda_0, \Lambda_1)\ \mathcal{L}(\vec{x}|\Lambda_0, \Lambda_1)$

Name	MBTA				GstLAL				PyCBC				PyCBC-BBH		
	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{astro}
GW190425_081805	–	–	–	–	0.00	0.00	0.78	0.78	–	–	–	–	–	–	–
GW190707_093326	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.93	0.07	0.00	1.00	0.93	0.07	1.00
GW190720_000836	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.95	0.05	0.00	1.00	1.00	0.00	1.00
GW190725_174728	0.59	0.00	0.00	0.59	–	–	–	–	0.79	0.17	0.00	0.96	0.58	0.24	0.82

GWTC-2.1

- Generalization to 3 categories of astrophysical triggers:
  → $\vec{\Lambda}_1 = \{\Lambda_{BNS}, \Lambda_{NSBH}, \Lambda_{BBH}\}$
- Perform a source classification by computing p_{BNS}, p_{NSBH} and p_{BBH}:

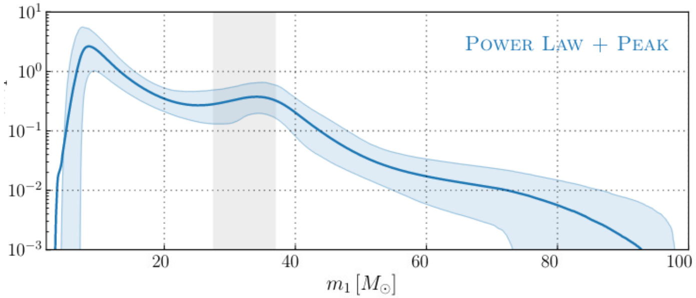
→ $p_\alpha(x|\vec{x}) = \int_0^\infty p(\Lambda_0, \vec{\Lambda}_1|\vec{x}) \frac{\Lambda_\alpha f_\alpha(x)}{\Lambda_0 b(x) + \vec{\Lambda}_1 . \vec{f}(x)} \mathrm{d}\Lambda_0\, \mathrm{d}\vec{\Lambda}_1 \qquad \Rightarrow p_{astro}(x|\vec{x}) = \sum_\alpha p_\alpha(x|\vec{x})$

Computing p_{astro}: key points

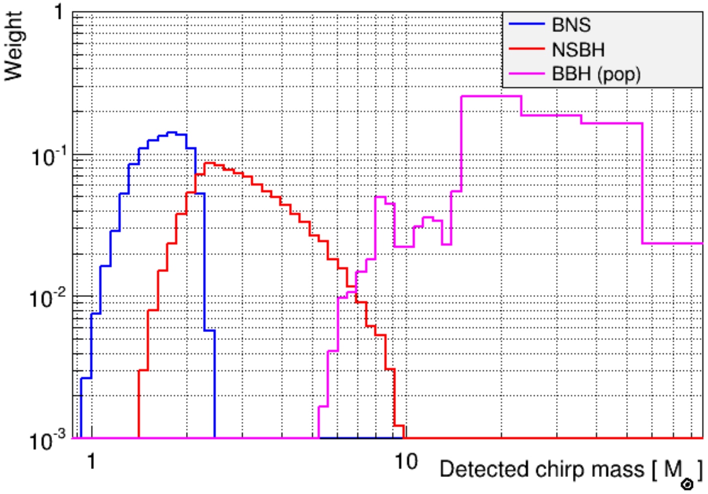
- Population models:

[R. Abbott et al 2021 ApJL 913 L7](#)

	Mass distribution	Mass range ($M_\odot$)	Spin range	Spin orientations	Redshift evolution	Maximum redshift
BBH (pop)	Power Law + Peak	$5 < m_1 < 80$ $5 < m_2 < 80$	$\lvert\chi_{1,2}\rvert < 0.998$	isotropic	$\kappa = 0$	1.9
NSBH	$p(m_1) \propto m_1^{-2.35}$ uniform	$2.5 < m_1 < 60$ $1 < m_2 < 2.5$	$\lvert\chi_1\rvert < 0.998$ $\lvert\chi_2\rvert < 0.4$	isotropic	$\kappa = 0$	0.25
BNS	uniform	$1 < m_1 < 2.5$ $1 < m_2 < 2.5$	$\lvert\chi_{1,2}\rvert < 0.4$	isotropic	$\kappa = 0$	0.15



- Binning of the search parameter space:
  - → Standard search is split into 3 "mass1 - mass2" regions "BNS", "NSBH", "BBH"
  - → For p_{astro} calculation we use a "chirp mass – mass ratio" space divided in 165 bins



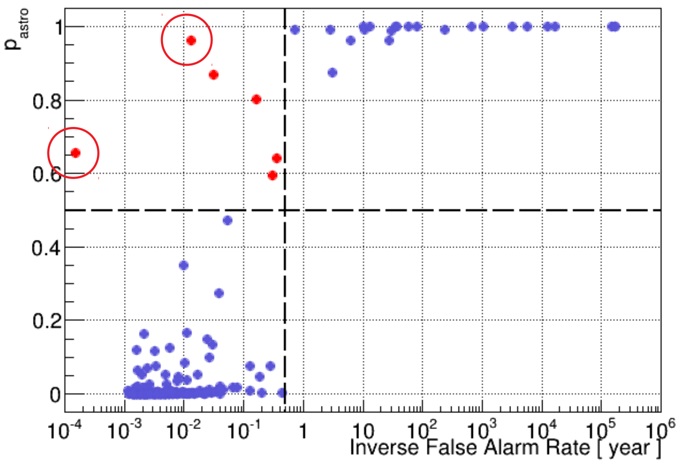
- Look at how injections of simulated GW signals in O3a data are recovered in MBTA template bank
  - → Build the foreground for the different astrophysical categories

Results in GWTC-2.1 (O3a period)

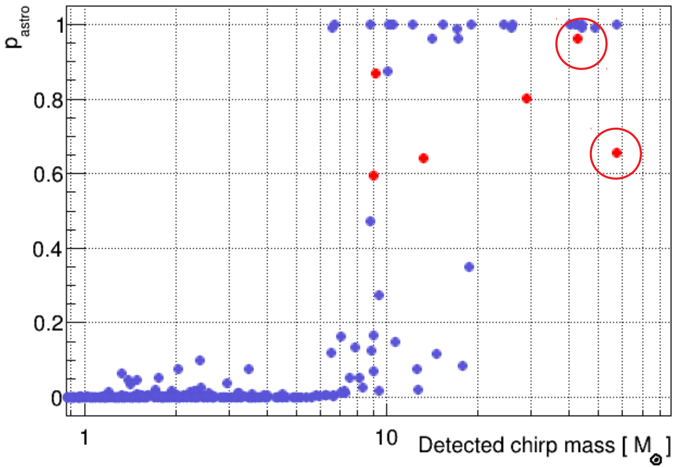
Number of events with p_astro > 0.5

MBTA	GstLAL	PyCBC All Sky	PyCBC BBH
29	34	23	35

MBTA



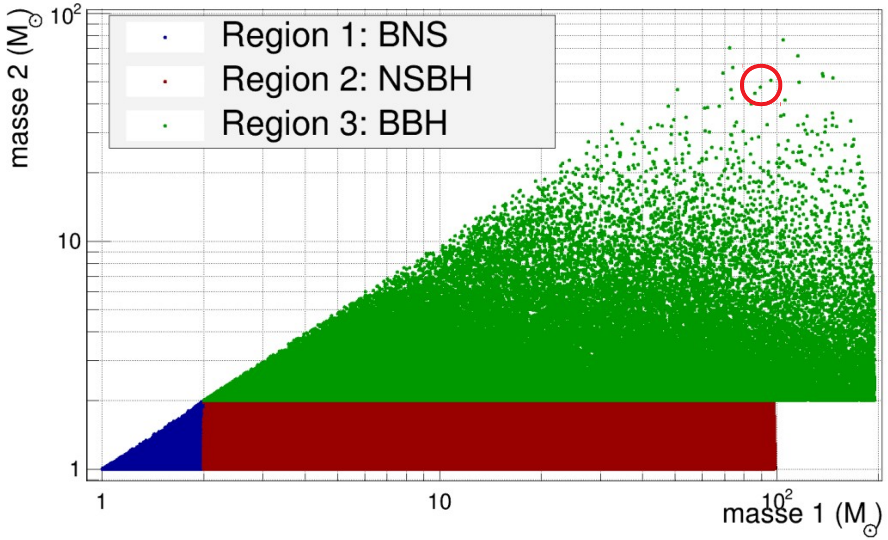
MBTA

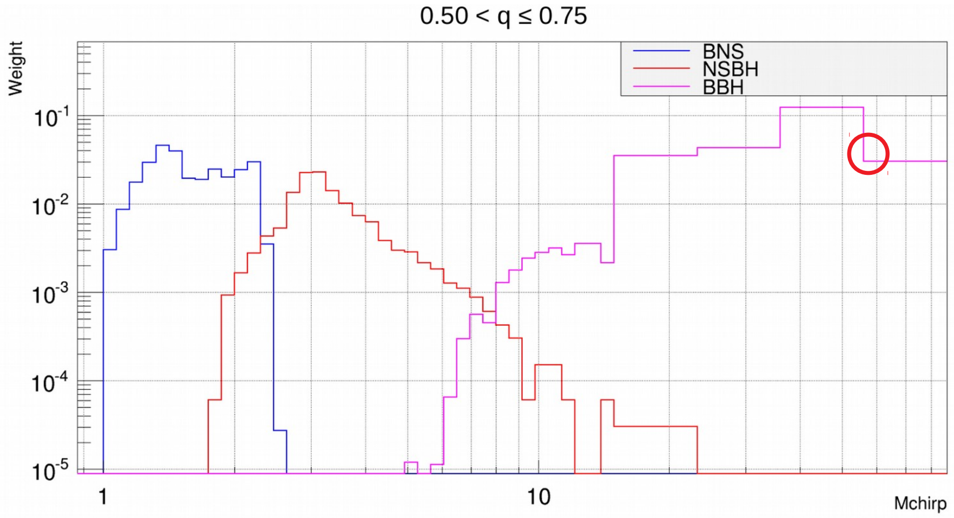


- Lowest IFAR candidates with $p_{astro} > 0.5$ occur at high chirp mass
  - ➔ The binning of the parameter space allows to construct a background for high-mass systems with a low number of templates → low background
  - ➔ The expected BBH population is high in that region → high foreground

Example of a high-mass candidate event: GW190916

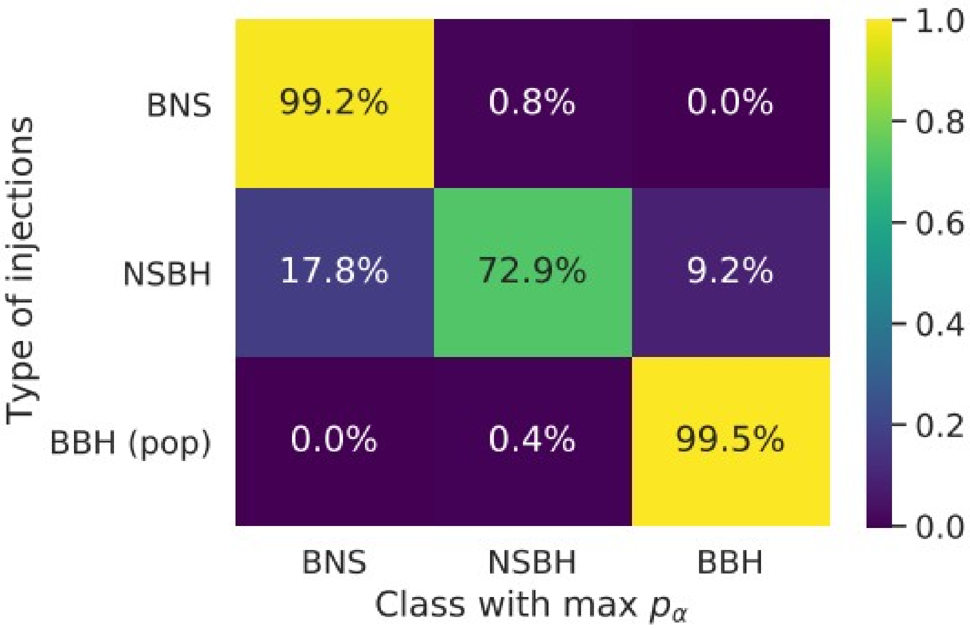
	pAstro	FAR [yr^{-1}]	SNR	Chirp mass $(m1.m2)^{3/5}/(m1+m2)^{1/5}$	Mass ratio (q=m2/m1)
GW190916 HL	**0.66**	**~ 6900**	8.2	57.6	0.55





Performance of the classification

- Simulated GW signals for the assumed compact-binary populations:
  - ➔ About 40 000 injections for each astrophysical category

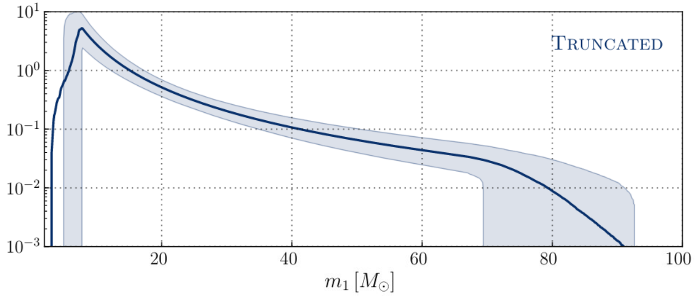


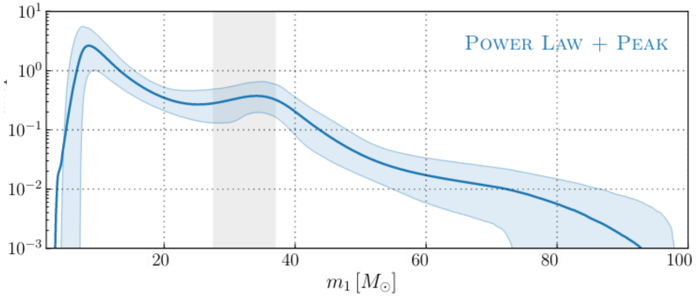
- Poor measurement of the mass ratio:
  - ➔ Overlap between some of the NSBH bins and the other categories

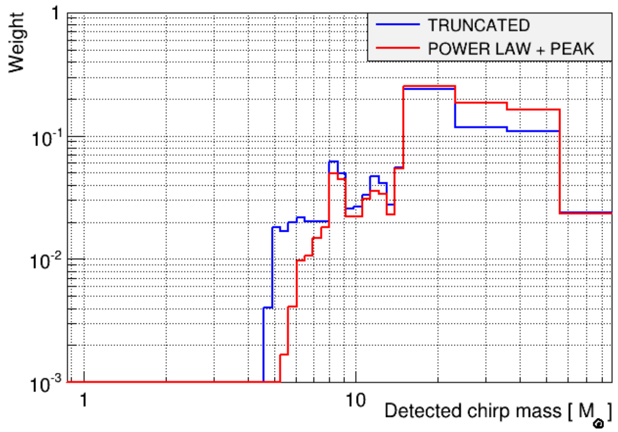
p_{astro} sensitivity to BBH population models

Truncated and Power Law + Peak models from: [*R. Abbott et al 2021 ApJL 913 L7*]

➔ Most disfavored model against preferred model

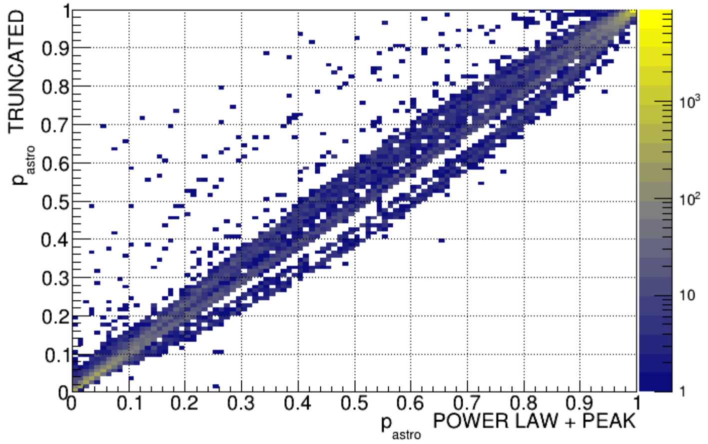


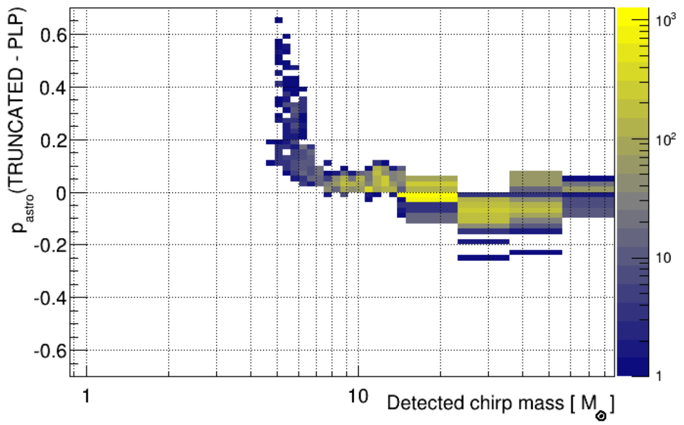




In the region $0.1 < p_{astro} < 0.9$

Median and 90% CI of absolute p_{astro} difference: 0.0 ± 0.1



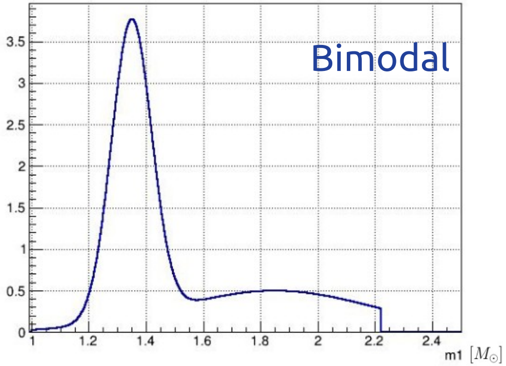


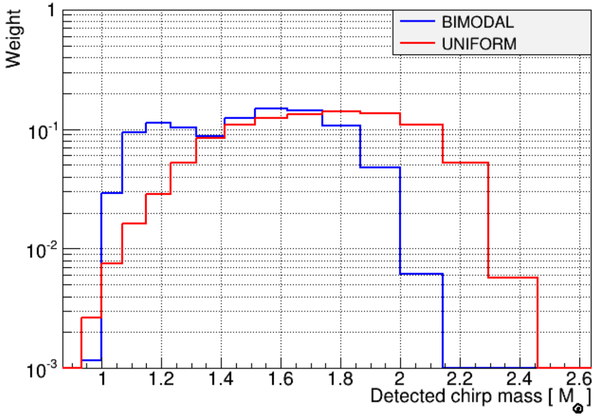
p_{astro} sensitivity to BNS population models

Bimodal model from: *Alsing et al. 2018*, *Chatziioannou, Farr 2020*, *Landry et al. 2020*

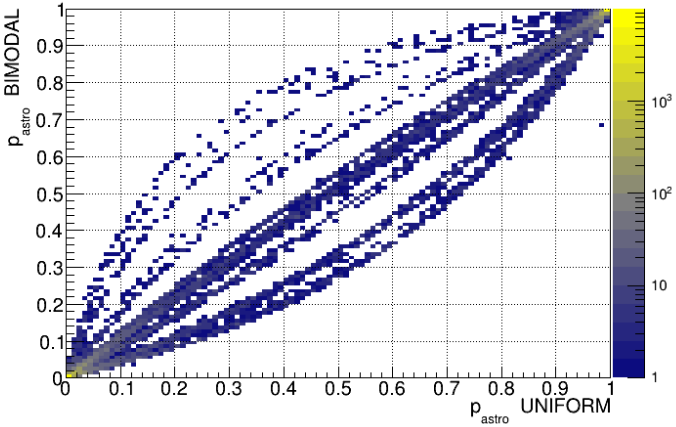
- Compatible with Galactic distribution of NS and GW NS

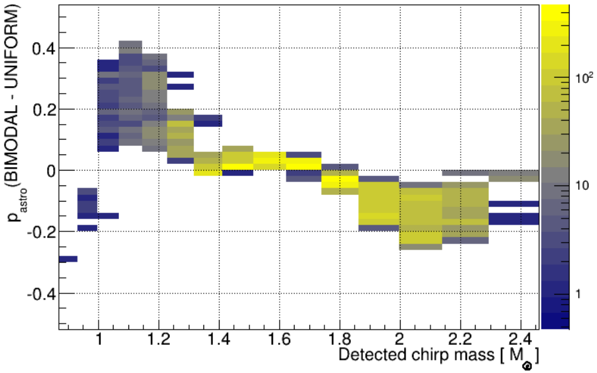
BNS	uniform	$1 < m_1 < 2.5$ $1 < m_2 < 2.5$





In the region $0.1 < p_{astro} < 0.9$
Median and 90% CI of absolute p_{astro} difference: 0.0 ± 0.2





Conclusion and perspectives

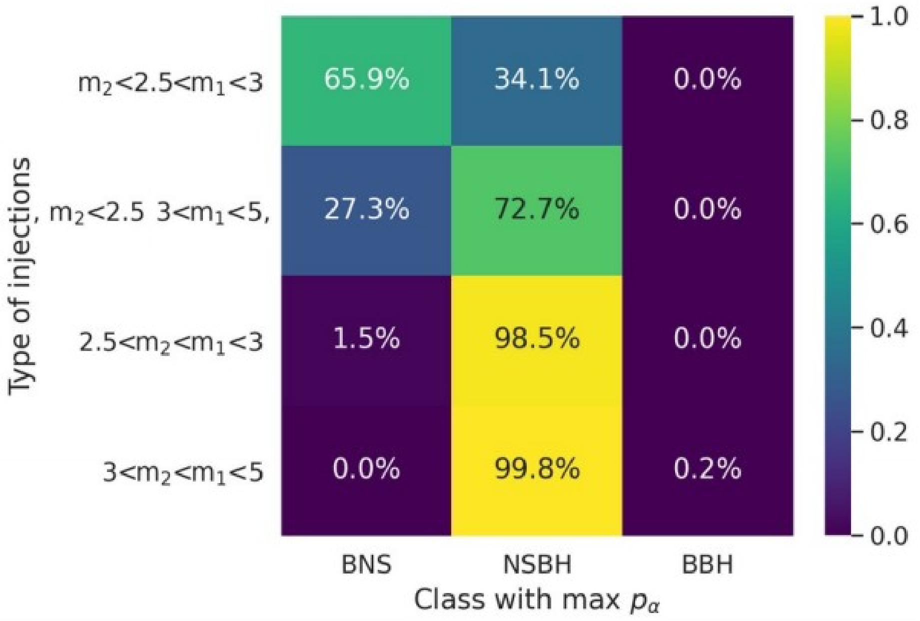
- Start to have a reasonable knowledge of BBH populations
  - ➔ Allow to go from FAR to p_{astro} to select candidate events
- BNS and NSBH populations are still uncertain:
  - ➔ Current p_{astro} of such candidate events will change with more detections

- Towards O4:
  - ➔ p_{astro} method used offline will be adapted to low-latency search
  - ➔ Fine tuning and updated population models
  - ➔ Make a source classification in terms of EM bright sources?

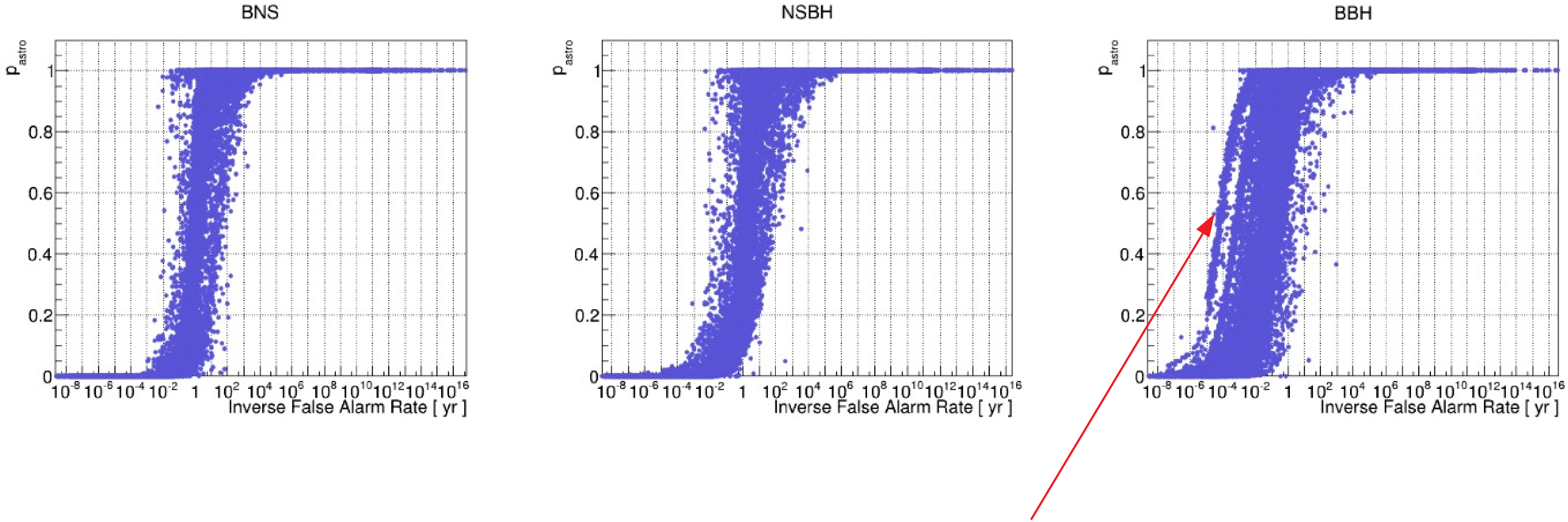
EXTRA SLIDES

Performance of the classification in the mass gap

Simulated GW signals in the assumed mass gap between BNS and BBH from 2.5 $M_\odot$ to 5 $M_\odot$



p_{astro} and IFAR on injections



High-mass injections