Predicting GW candidates source properties in low-latency with MBTA during O4

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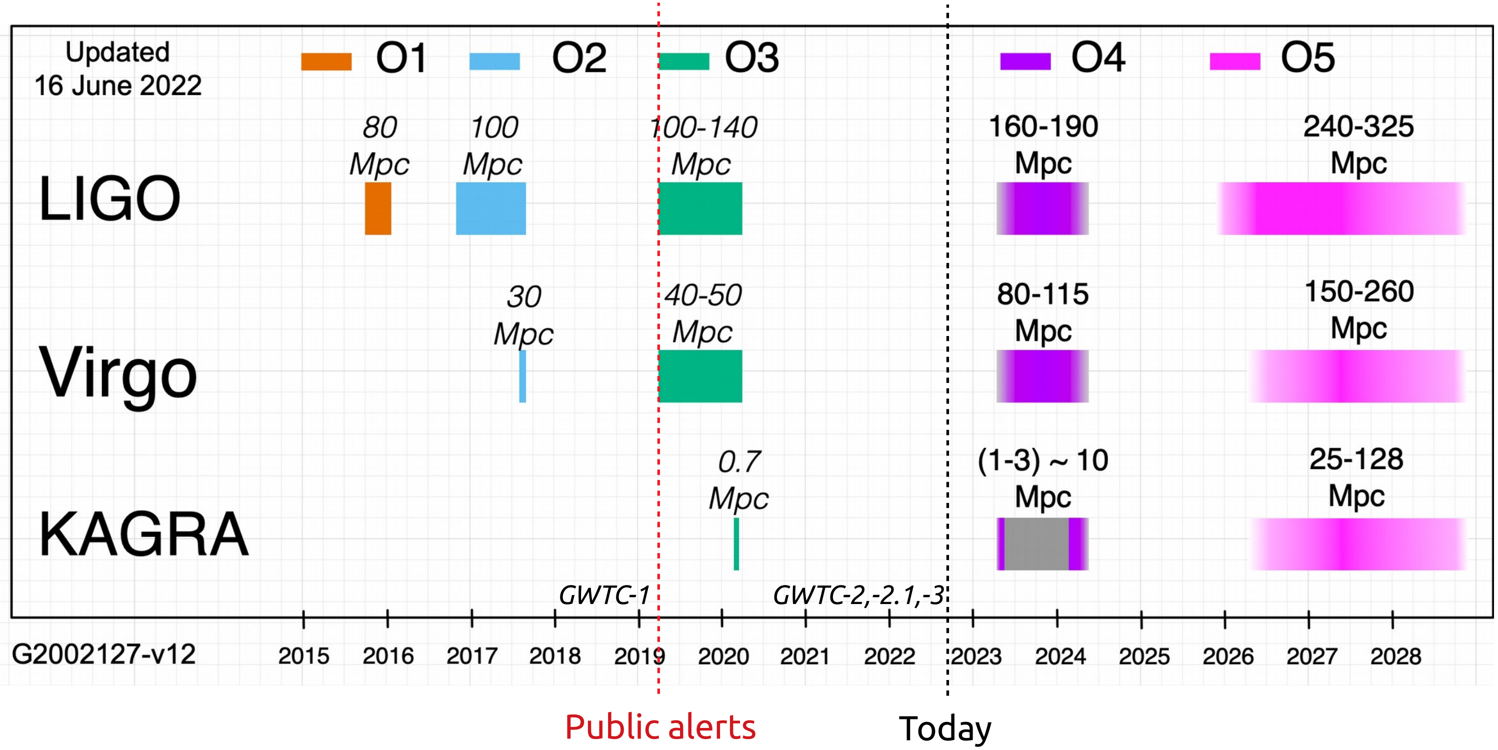
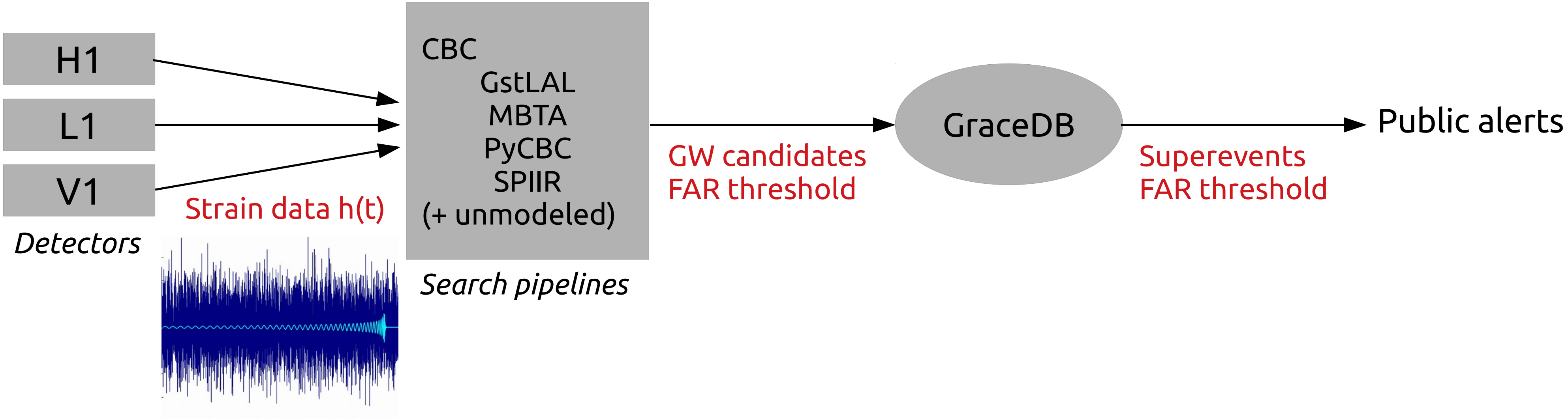
Gravitational wave observations timeline



- Number of detections keeps increasing
  - → During O4 we expect ~O($3*N_{O3}$) GW candidates
  - → Provide information to help astronomers to decide to follow-up or not (EM, neutrinos, …)
    - ➢ Benefit from developments made for the catalogs

Multi-Band Template Analysis (MBTA) in the low-latency chain

Low-latency chain:



MBTA search pipeline: *Adams et al. 2016, Aubin et al. 2021*

- Matched filtering based search
- Require banks of waveform templates
- Candidates are searched in coincidence between at least two detectors
  - Will also provide single-detector candidates in O4
- Assess the significance of triggers (false alarm rate, probability of astrophysical origin…)

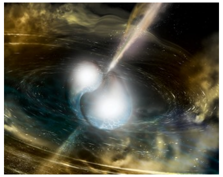
GCN/LVC NOTICE content during O3 (similar in O4)

Example for the Binary Neutron Star GW190425

https://gcn.nasa.gov/notices_l/S190425z.lvc

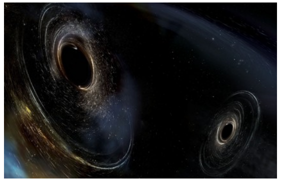
```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/LVC NOTICE
NOTICE_DATE:      Thu 25 Apr 19 09:00:55 UT
NOTICE_TYPE:      LVC Initial Skymap
TRIGGER_NUM:      S190425z
TRIGGER_DATE:     18598 TJD;   115 DOY;   2019/04/25 (yyyy/mm/dd)
TRIGGER_TIME:     29885.017147 SOD {08:18:05.017147} UT
SEQUENCE_NUM:     1
GROUP_TYPE:       1 = CBC
SEARCH_TYPE:      1 = AllSky
PIPELINE_TYPE:    4 = GSTLAL
FAR:              4.538e-13 [Hz]  (one per 25502705.6 days)  (one per 69870.43 years)
PROB_NS:          1.00 [range is 0.0-1.0]
PROB_REMNANT:     1.00 [range is 0.0-1.0]
PROB_BNS:         0.99 [range is 0.0-1.0]
PROB_NSBH:        0.00 [range is 0.0-1.0]
PROB_BBH:         0.00 [range is 0.0-1.0]
PROB_MassGap:     0.00 [range is 0.0-1.0]
PROB_TERRES:      0.00 [range is 0.0-1.0]
TRIGGER_ID:       0x10
MISC:             0x189E806
SKYMAP_FITS_URL:  https://gracedb.ligo.org/api/superevents/S190425z/files/bayestar.fits.gz
EVENTPAGE_URL:    https://gracedb.ligo.org/superevents/S190425z/view/
COMMENTS:         LVC Super Initial Skymap -- a location probability map.
COMMENTS:         This event is an OpenAlert.
```

Binary Neutron Star (BNS)



Neutron Star - Black Hole (NSBH)

Binary Black Hole (BBH)



For MBTA triggers:
- What do those numbers mean?
- Which assumptions/limitations?

Assessing the nature of a GW candidate with MBTA: $p_{astro} = p_{BNS} + p_{NSBH} + p_{BBH}$

Probability of astrophysical origin:

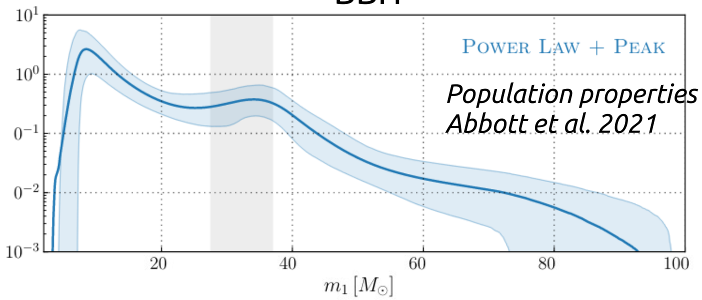
- Jointly estimated with source membership probabilities { p_{BNS} ; p_{NSBH} ; p_{BBH} }
- $p_{astro} = p_{BNS} + p_{NSBH} + p_{BBH} = 1 - p_{noise}$

$$p_{\mathrm{astro}} = \frac{\text{astro. signal rate}}{\text{background rate} + \text{astro. signal rate}}$$

Need to assume some population models (MBTA example from O3)

	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

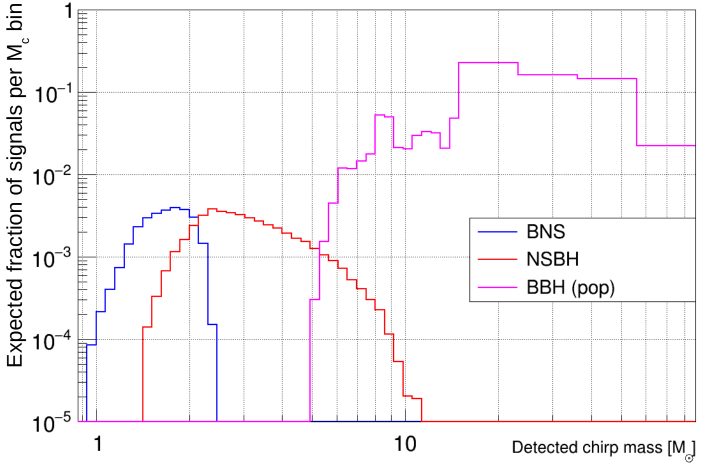
BBH



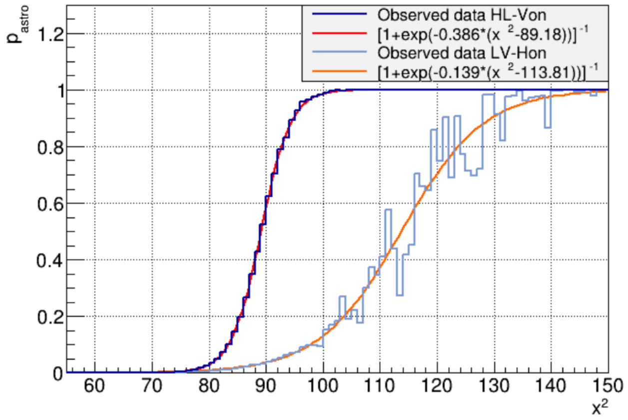
Population properties LIGO-Virgo Abbott et al. 2021

Search pipelines accurately estimate chirp mass but not individual masses!

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



Parameterize p_{astro} as a function of ranking statistic



MBTA pastro Andres et al. 2021

Source properties of GW candidates with MBTA: p_{NS}, $p_{REMNANT}$

- In MBTA for O4, plan to construct p_{NS} and $p_{REMNANT}$ as:

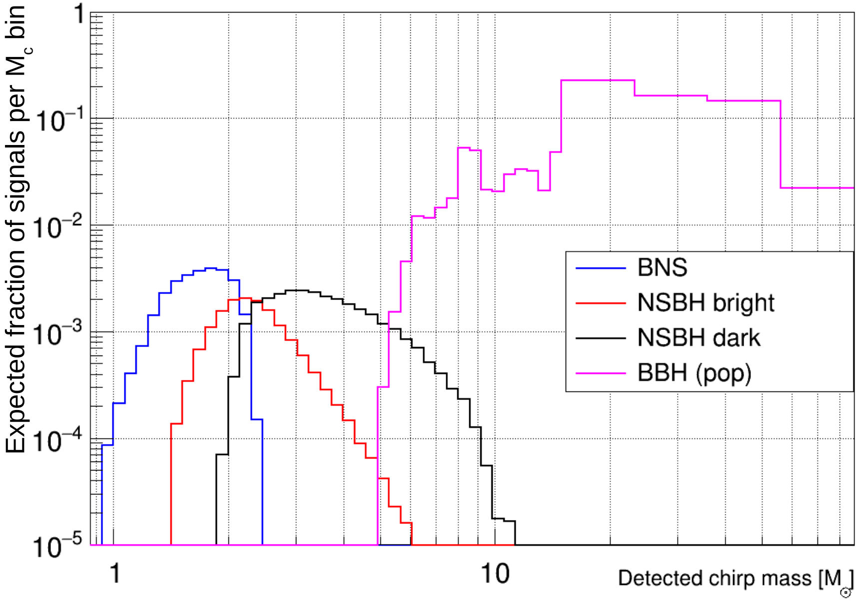
  $p_{NS} = (p_{BNS} + p_{NSBH}) / p_{astro}$

  $p_{REMNANT} = (p_{BNS} + p_{NSBH,bright}) / p_{astro}$

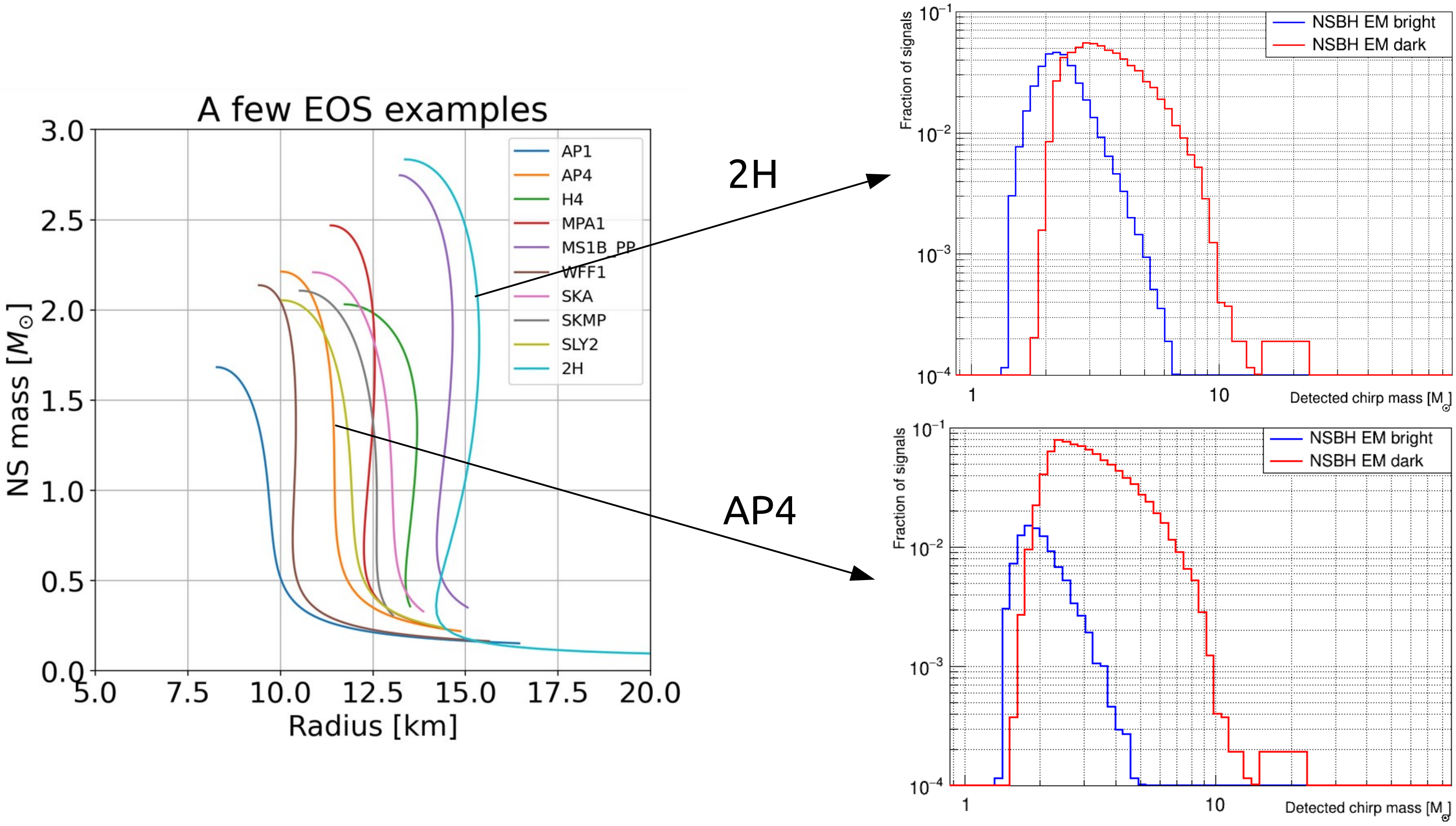
- NSBH can be EM bright or dark
  - Depends on compactness (from EOS), mass ratio and BH spin
  - *Foucart 2012, Stone at al. 2013, Pannarale et al. 2014, Foucart et al. 2018*
  - During O3, $p_{REMNANT}$ common to all pipelines: *Chatterjee et al. 2020*
    - Conservative stiff EOS (2H with $m_{NS,max}$=2.83 $M_\odot$)

      → less compact → easier to disrupt
  - For O4, new pipeline-specific method for MBTA

Example: splitting NSBH population on remnant mass with 2H EOS



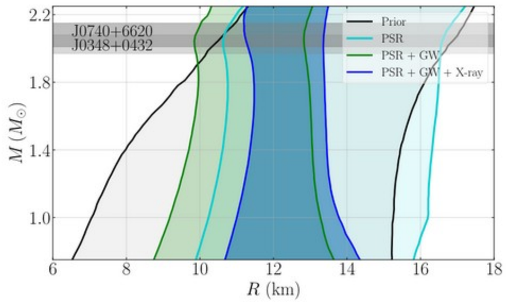
Effect of EOS choice on NSBH brightness



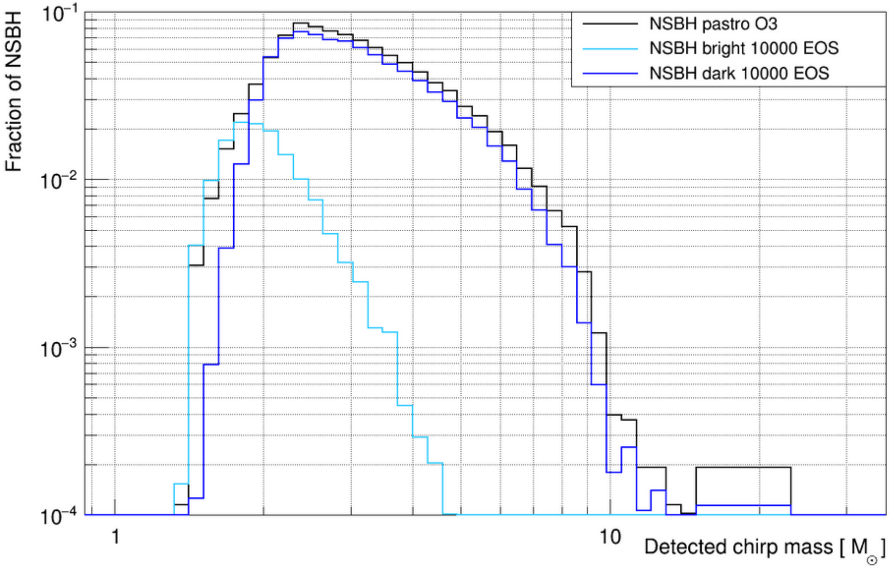
Marginalization over EOS posterior from observations

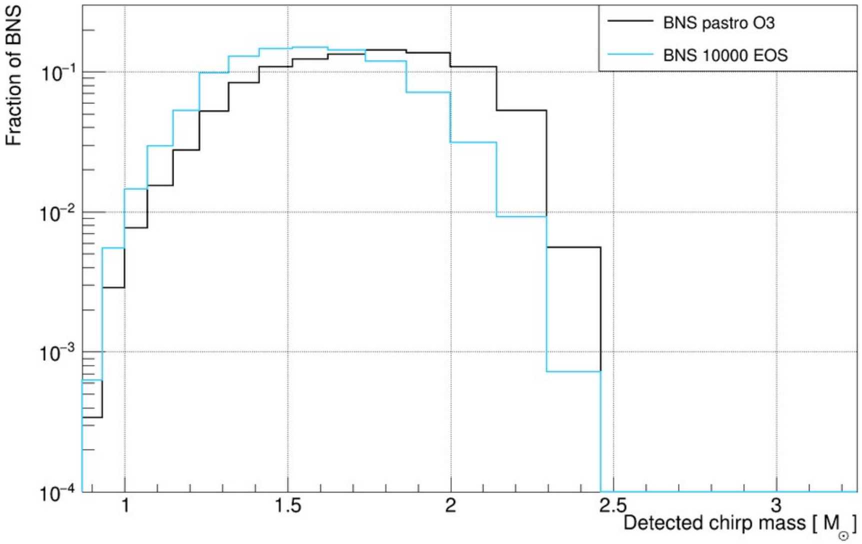
Add information on NS population using EOS from combined measurements of PSR + GW + X-ray:

- 10 000 EOS posterior samples
- Consider NSBH if component masses allowed by EOS
- Compute NSBH remnant mass: *Foucart et al. 2018*
- Consider EM-bright-NSBH if $M_{rem} > 0.01\ M_{\odot}$
- Consider BNS if component masses allowed by EOS

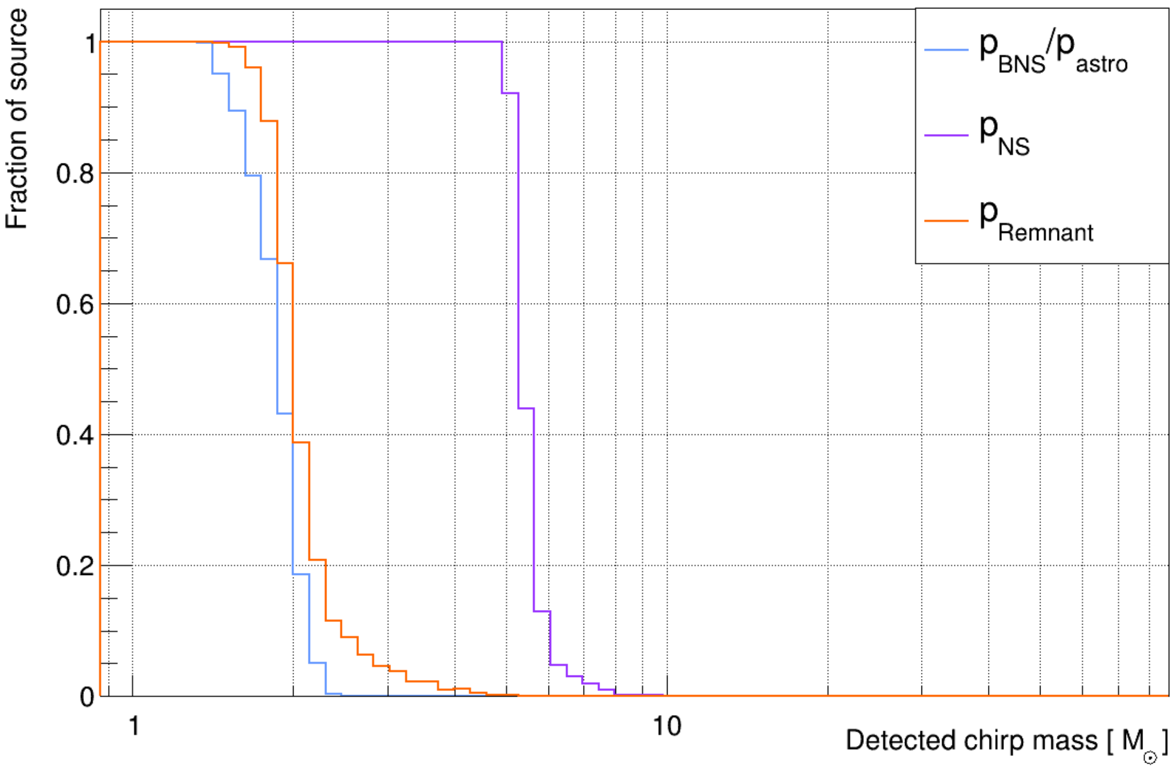


Legred et al. 2021





Source properties as a function of detected chirp mass



$$p_{NS} = (p_{BNS} + p_{NSBH}) / p_{astro}$$

$$p_{REMNANT} = (p_{BNS} + p_{NSBH,bright}) / p_{astro}$$

Conclusion

- MBTA will compute p_{astro} , source classification and properties for O4 with:
  - ➔ Detailed population models:
    - ➢ NS population using a large set of EOS inferred from GW+PSR+X-Ray results
    - ➢ Foucart fitting formula for NSBH “bright” / “dark” classification with EOS marginalization
    - ➢ Latest BBH population model from LVK
  - ➔ Population recovery and background estimation specific to MBTA
  - ➔ Parameterization of those quantities
    - ➢ Allows for a ~0s latency production