The MBTA Pipeline for Detecting Compact Binary Coalescences in the Third LIGO-Virgo Observing Run

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On behalf of the MBTA team

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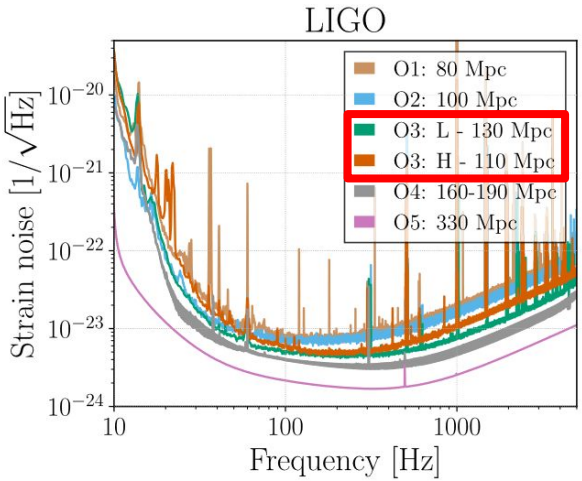
The LIGO-Virgo-KAGRA collaboration

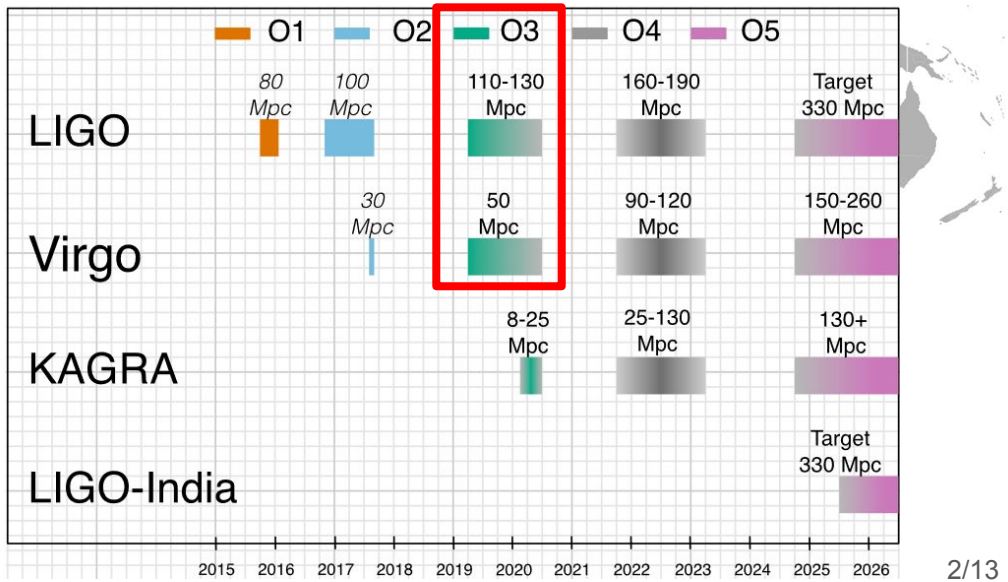
A network of **Gravitational Waves** (GW) detectors

- **Heterogeneous sensitivities**
- Different duty cycles

Observing runs

- **O3**: 2019-2020
  - LIGO + Virgo
- O4: 2022-2023
  - LIGO + Virgo + KAGRA





The O3 Multi-Band Template Analysis in a Nutshell

- **Compact Binary Coalescences** (CBC)
  - **Online**
    - Low latency **automatic and public alerts**
  - **Offline**

- **Match filtering** analysis
  - Two frequency bands
  - 3 regions parameter space
  - ~ 750k templates

Region	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\lvert\chi_{1,z}\rvert_{\max}$	$\lvert\chi_{2,z}\rvert_{\max}$
1	[1;2]	[1;2]	0.05	0.05
2	[1;2]	[2:100]	0.05	0.997
3	[2;195]	[2:195]	0.997	0.997
	$(m_1 + m_2) < 200\,\mathrm{M}_\odot$			

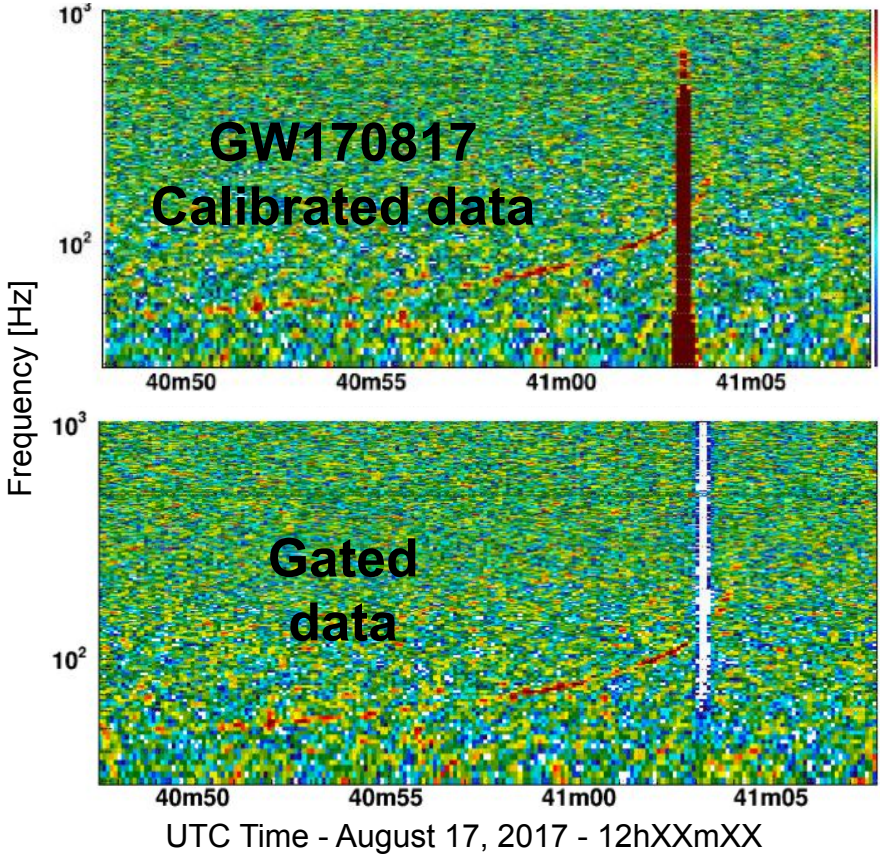
- **Noise rejection**
  - Preprocessing
  - Signal consistency tests

Data preprocessing

Receiving data from detectors
- **Calibrated** and conditioned data
- Resampling at 4 kHz

Applying a **gating** procedure
- Searching for **rapid variation in PSD**
- Monitoring of the “instantaneous” **BNS range**

Data quality flags provided by detectors
- External triggers for the gating procedure



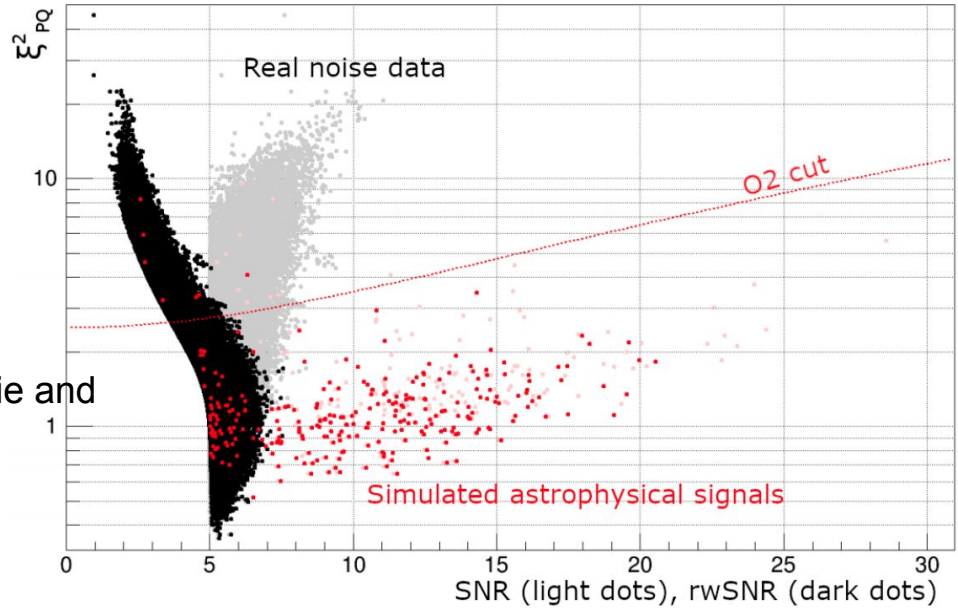
Single detector searches

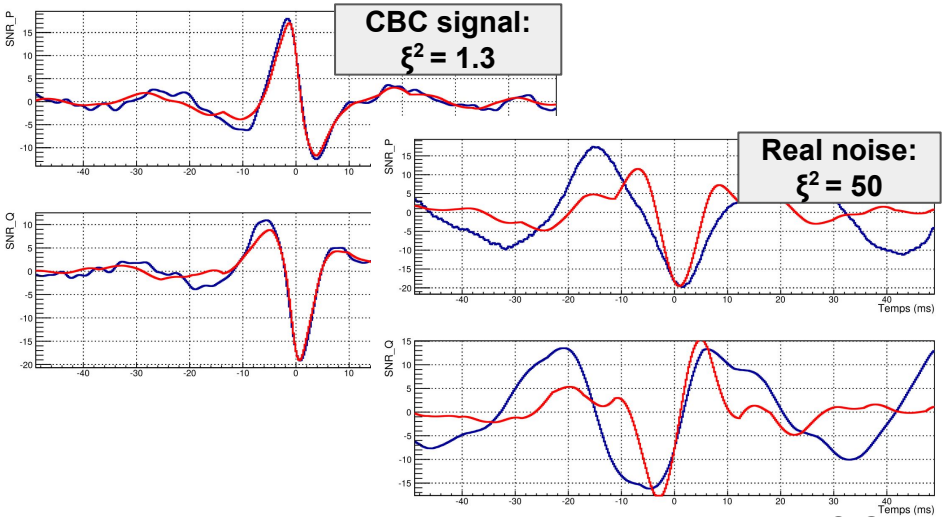
Matched filtering

- **Signal to Noise Ratio** (SNR ≡ ρ) time series
- In-phase (P) and in-quadrature (Q)
- **Ranking Statistic** (RS) **threshold**

Signal consistency tests

- **ξ^2**: χ^2-test between the measured SNR time serie and **template autocorrelation**
- Modified RS: **reweighted** SNR (ρ_{rw})



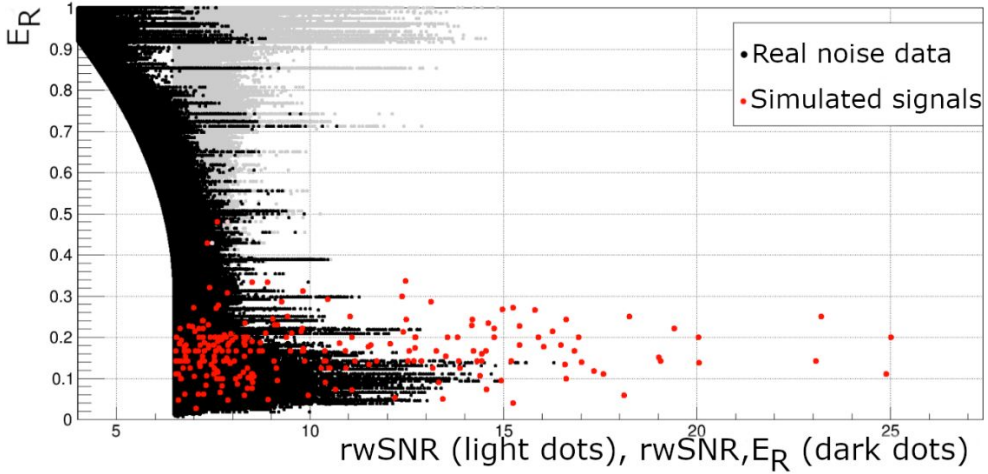


$$\rho_{rw} = \begin{cases} \rho & \text{if } \xi^2_{PQ} \leq 1 \\ \rho \left(\frac{A + \xi^2_{PQ}{}^{\alpha}}{A+1} \right)^{-1/\beta} & \text{if } \xi^2_{PQ} > 1 \end{cases}$$

Penalize noisy periods

Noise rejection tools are efficient

- Some bad candidates survive in **noisy periods**
- **Identify** these periods
  - **ExcessRate** (E_R): comparing the rates before and after ξ^2
  - Using a **median** value over 10 sec



Modified RS

$$\rho_{rw,E_R} = \begin{cases} \rho_{rw} & \text{if } E_R \leq 0.3 \\ \rho_{rw}\,[1 - A(E_R - 0.3)^{\alpha}] & \text{if } E_R > 0.3 \end{cases}$$

Coincidence search

Time coincidences between single detector triggers

- **Same template**
- **Double** coincidences: HL, HV, LV
  - Time windows: ω_{HL} = ± 15 ms ; $\omega_{HV} = \omega_{LV}$ = ± 35 ms
- **Triple** coincidences: HLV
  - **Pair of HL and HV** sharing the same H trigger

Combined ranking statistic (cRS)

Doubles

$$\rho^2_{RS,ij} = \underbrace{\rho^2_{rw,E_R,i} + \rho^2_{rw,E_R,j}}_{\text{Single trigger RS}} + 2\ln(\underbrace{P_{\Delta t_{ij}} P_{\Delta \phi_{ij}} P_{RA_{ij}}}_{\text{Probabilities}})$$

Probabilities for astrophysical signals

- time delay
- phase shift
- relative amplitude

Assessing a False Alarm Rate

Rate of noise triggers produced by the analysis with a cRS equal or larger than the candidate

- Based on **all possible pairs of noise triggers**
- Over **past 24h** (online)

Doubles

$$FAR_{ij}(\rho_{RS,ij}) = N_{ij}(\rho_{RS,ij}) w_{ij} / (T_i T_j)$$

Coincidence time window

FAR of a ij coincidence with cRS = $\varrho_{RS,ij}$

Number of pair of noise triggers with a cRS ≥ $\varrho_{RS,ij}$

Effective analyzed time

IFAR (≡ 1/FAR) for the overall search

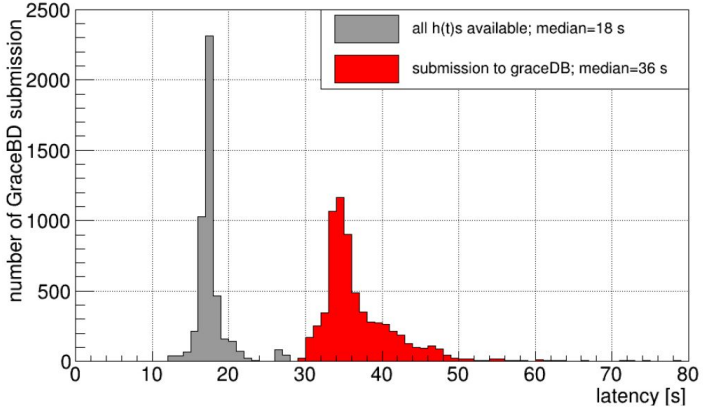
- **Multiple searches**
  - 3 regions
    - Same weights 1/3
  - 4 types of coincidences
    - Weights estimated with an **astrophysical simulation**
- **Clustering**

$$\mathrm{IFAR} = \frac{\kappa_{\mathrm{region}}\ \kappa_{\mathrm{coinc}}}{\kappa_{\mathrm{cluster}}\ \mathrm{FAR}(\rho_{RS})}$$

The behaviour of the MBTA online pipeline during O3

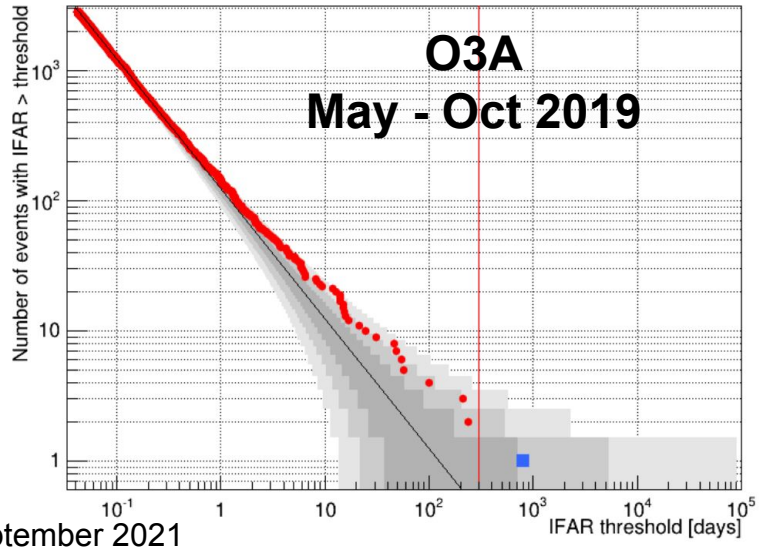
Technical behaviour

- ~ 18 sec addition to global latency
- ~ 0.2% gated data
- ~ 3% ExcessRate > 0.3 (noisy periods)



Results of the analysis

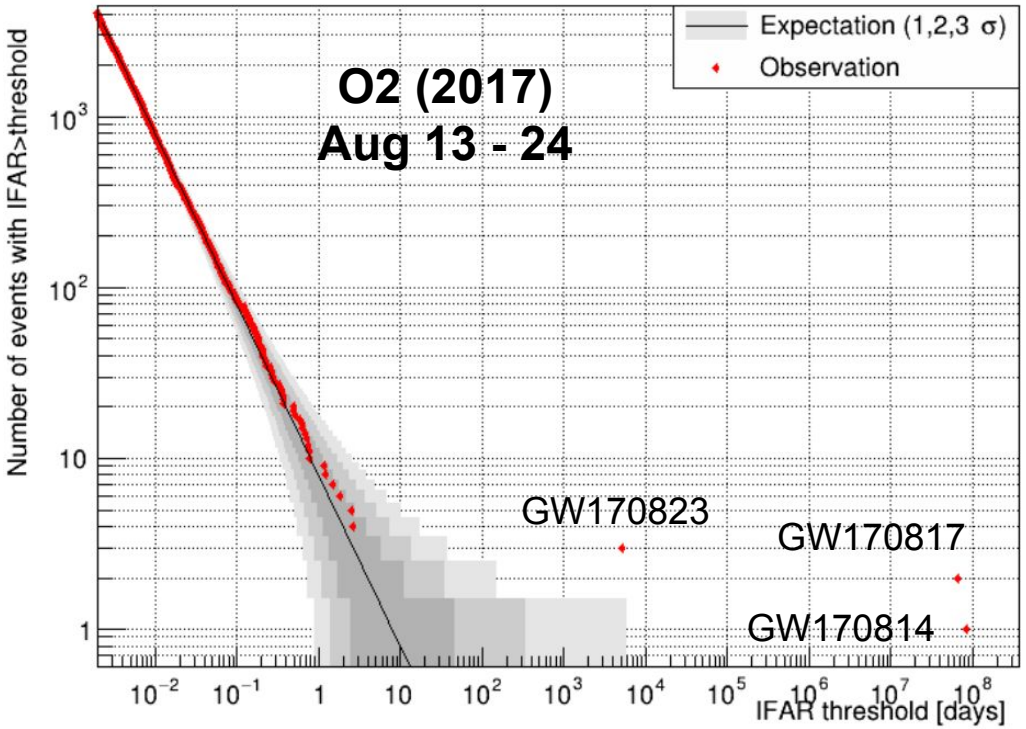
- **Similar** to the other pipelines
- Contribution to **42 low-latency public alerts**
- Noise produced consistent with **stationary noise**
  - 5 retractions



The new MBTA offline analysis

Searching CBC on chunks of ~ **1 week**

- **Same version** than online with **slight modifications**
  - ExcessRate computed with a +7 sec offset
  - **FAR estimated on full chunk**
    - Past and future



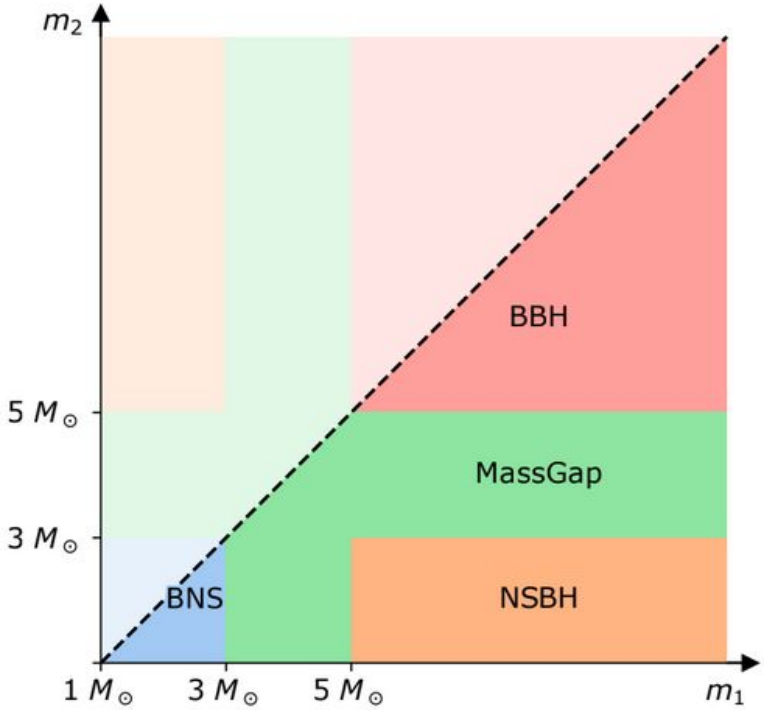
Assessing astrophysical probabilities

Events are given with a set of **origin probabilities P_{Astro}**

- O3 online
  - 5 categories
    - Terrestrial, BNS, NSBH, BBH, MassGap
  - Computed with an other pipeline approach

O3 offline MBTA P_{Astro} estimation

- 4 categories
- **Background rate**
  - Estimated with **FAR**
- **Astrophysical rates**
  - Based on astrophysical **priors**
  - Normalized by **simulation**

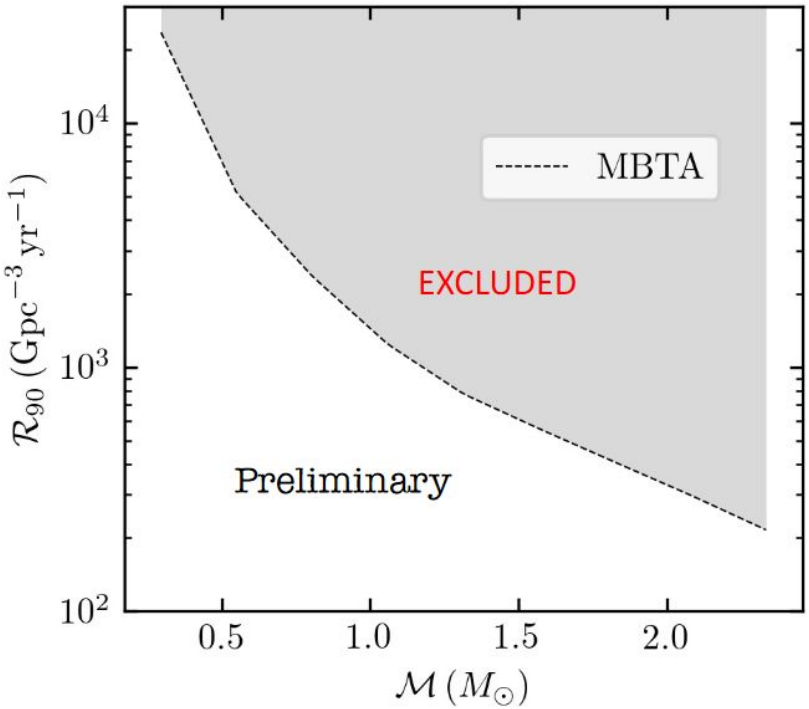


$$pAstro(cRS) = \frac{rateBNS(cRS) + rateBBH(cRS) + rateNSBH(cRS)}{rateBNS(cRS) + rateBBH(cRS) + rateNSBH(cRS) + rateBackground(cRS)}$$

MBTA in the O3 catalogues

O3A: May 2019 - Oct 2019 [arXiv:2108.01045]

- CBC search
  - **44** high-significance ($P_{Astro} \geq 0.5$) **candidates**
    - 30 identified by MBTA
  - **Exciting scientific results**
- **Sub-Solar Masses** search
  - Publication coming very soon
  - MBTA
    - **No significant candidate**
    - Upper limit on **merger rate**



O3B: Nov 2019 - March 2020

- Some exceptional events already public
  - NSBH, IMBH...
- Full catalogue coming soon

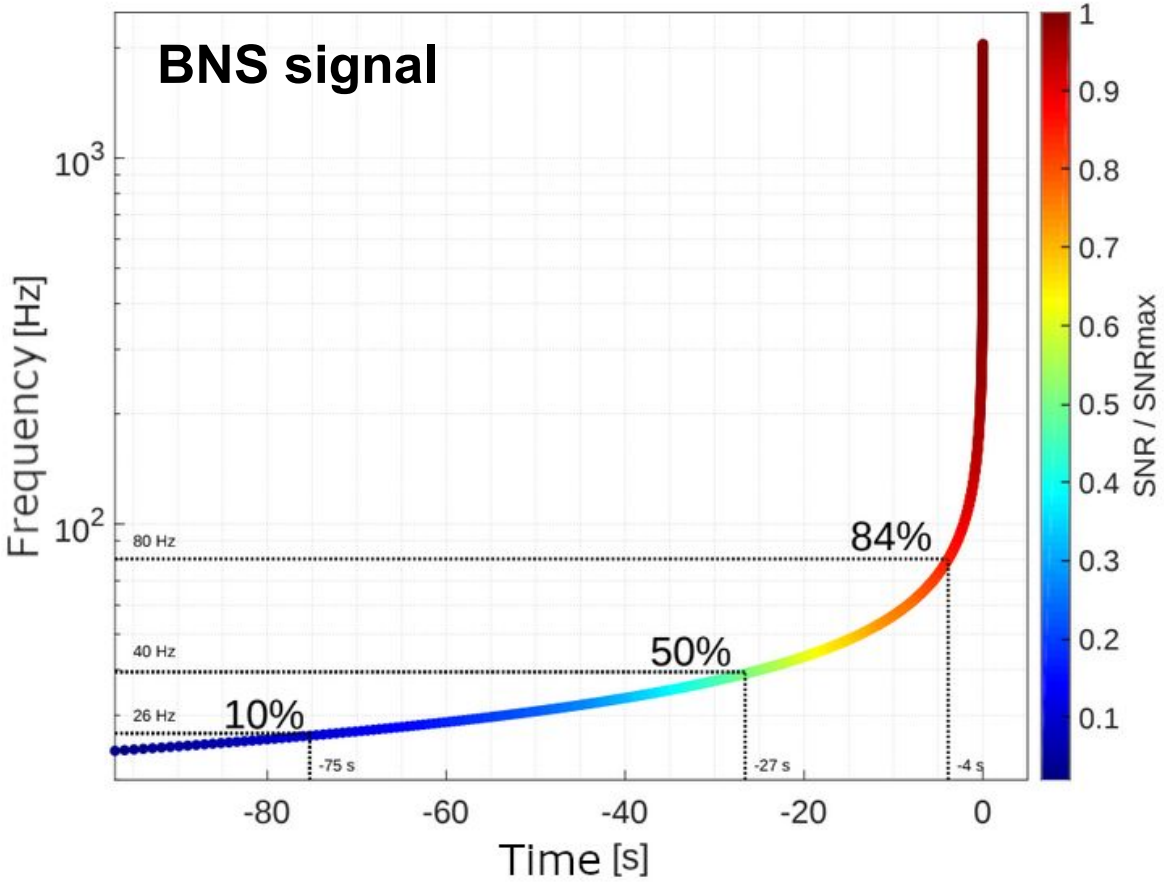
Towards O4 and beyond

Include **KAGRA**

Parameter space
- Up to **500 solar masses**
- **Higher Order Modes**
- **Precession**

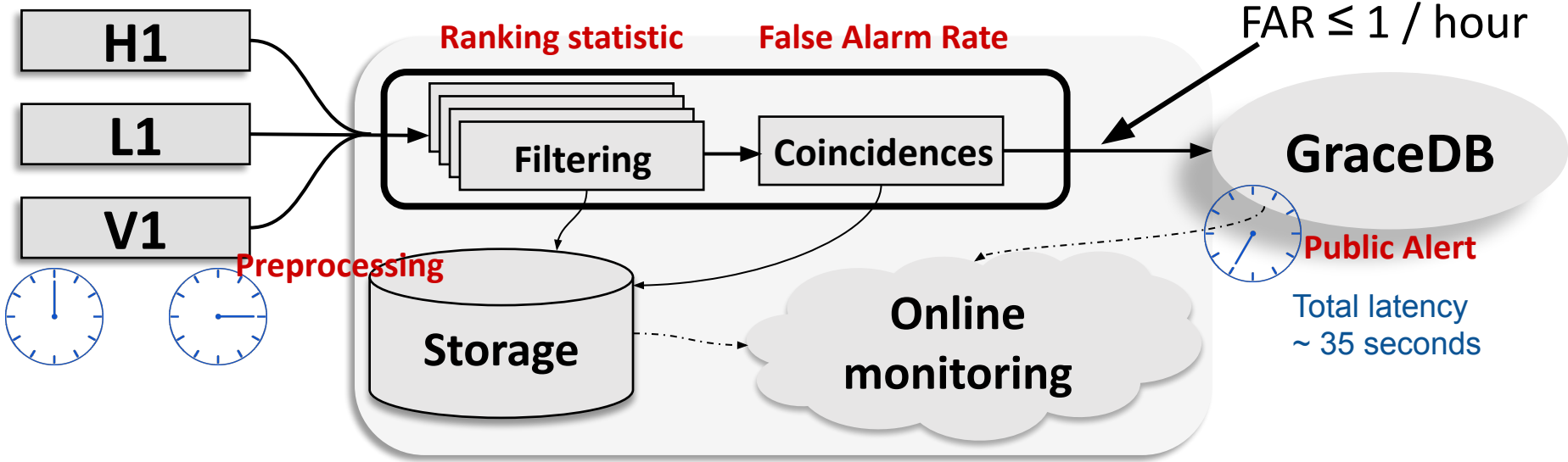
Noise rejection
- Fine tuning and new tools
- **Finer division** of the bank

New features
- Online $\mathbf{P_{Astro}}$
- **Single** detector candidates
- **Early warning** alerts



Backups

The low latency MBTA pipeline



The public alert chain