
THE LVK O4 LOW LATENCY ALERT PLANS

Roberto De Pietri

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Discussion of the timeline of the 80 Alerts of O3

Expectation for O4

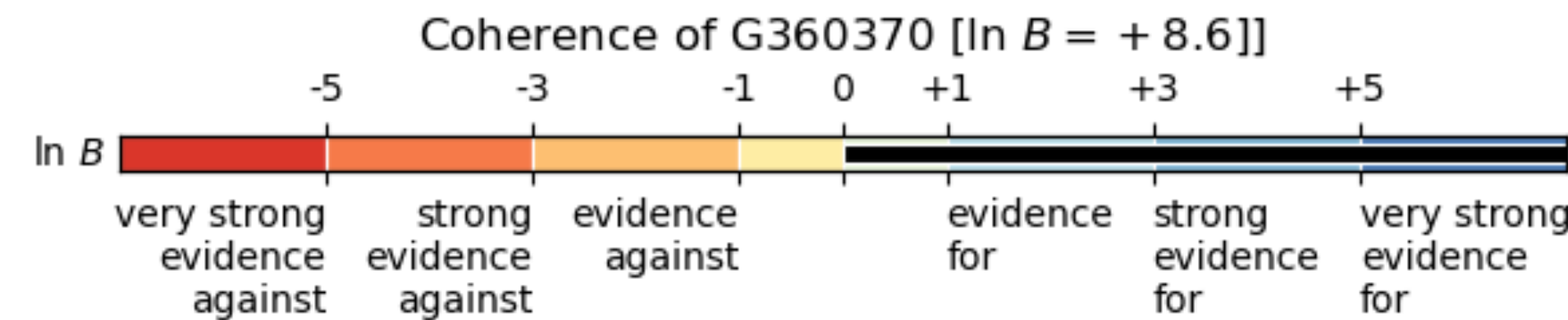
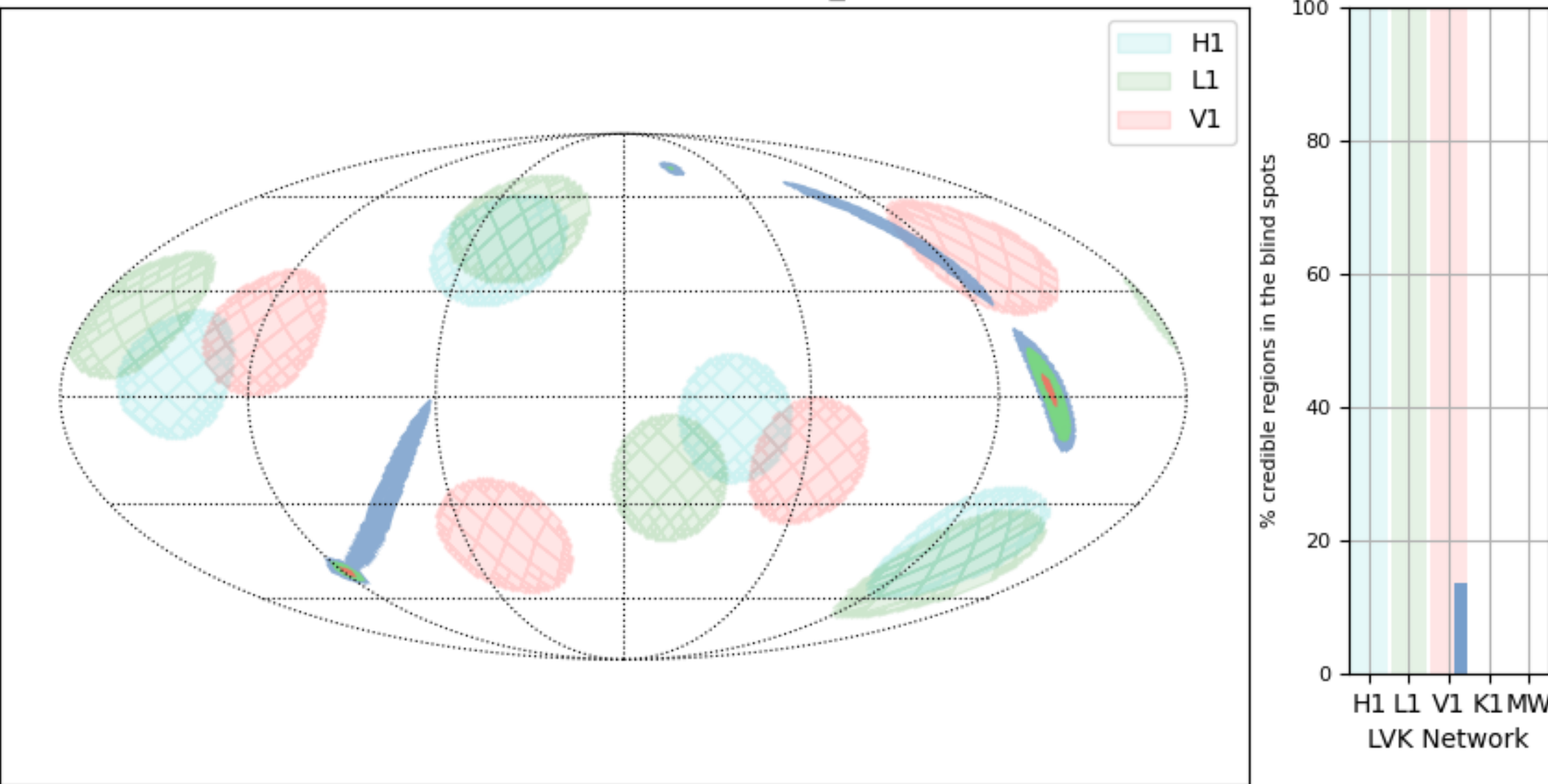
The LVK (igwn) alert system

New functionality with respect to O3

The planned main Open Public Alert (OPA) timeline

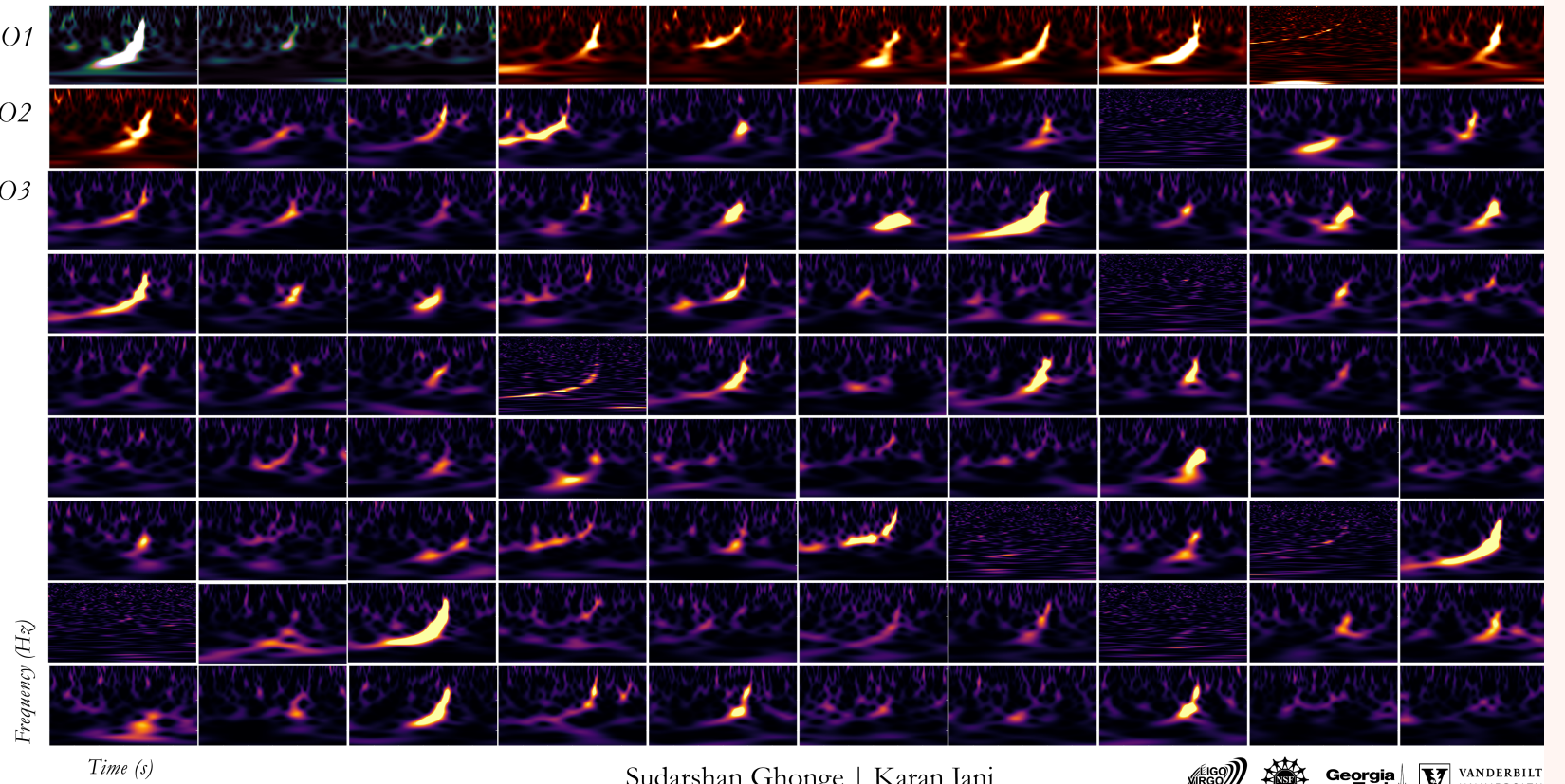
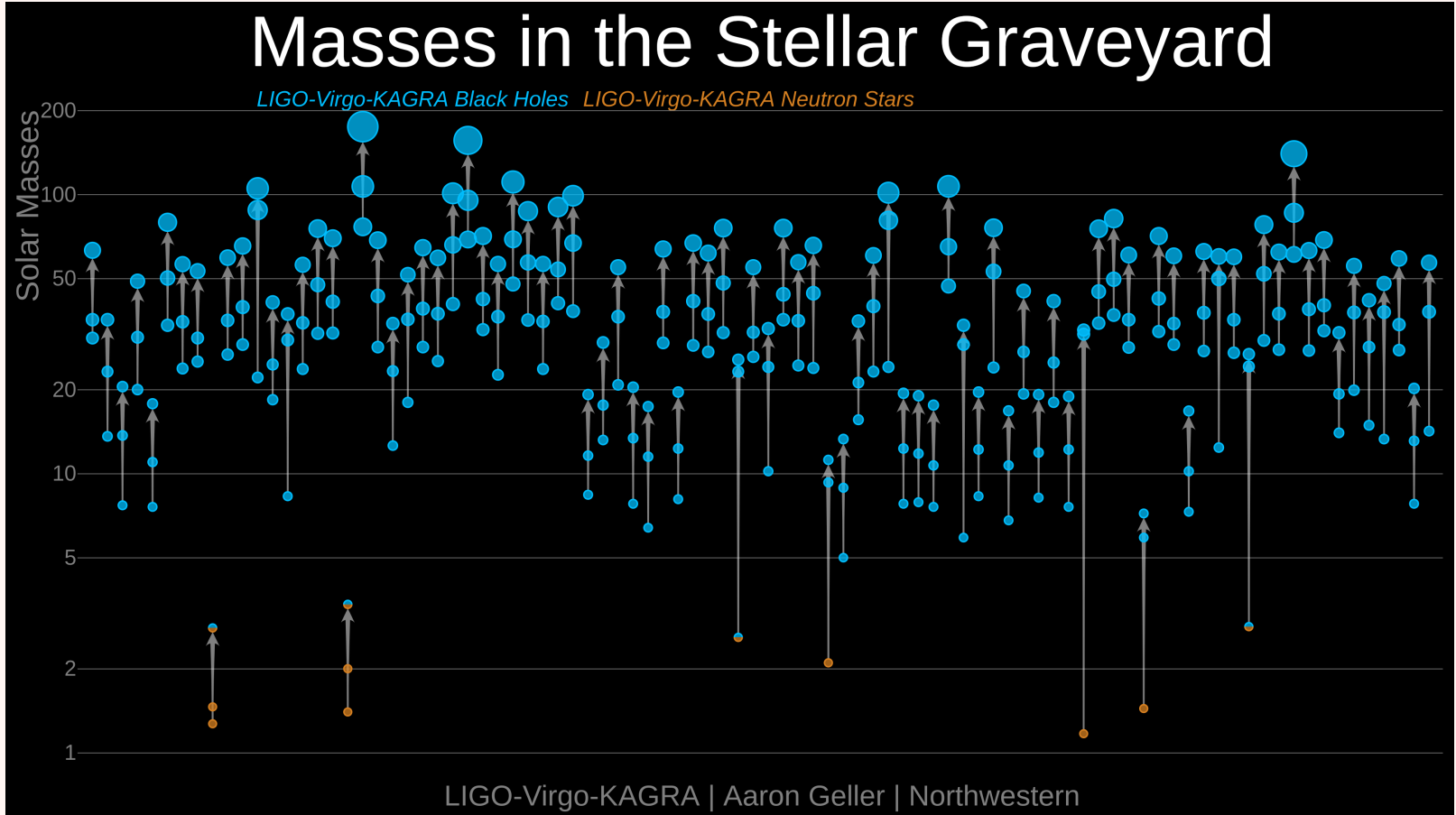
GW200115_042309 (NSBH)

S200115j-1-Preliminary [GW200115_042309]



INFO:
 Area cr90 = +919.4 deg²
 Area cr50 = +163.7 deg²
 Area cr10 = +17.0 deg²
 SevName = S200115j
 GevName = G360370

Distributed 6.3 minutes after merger time



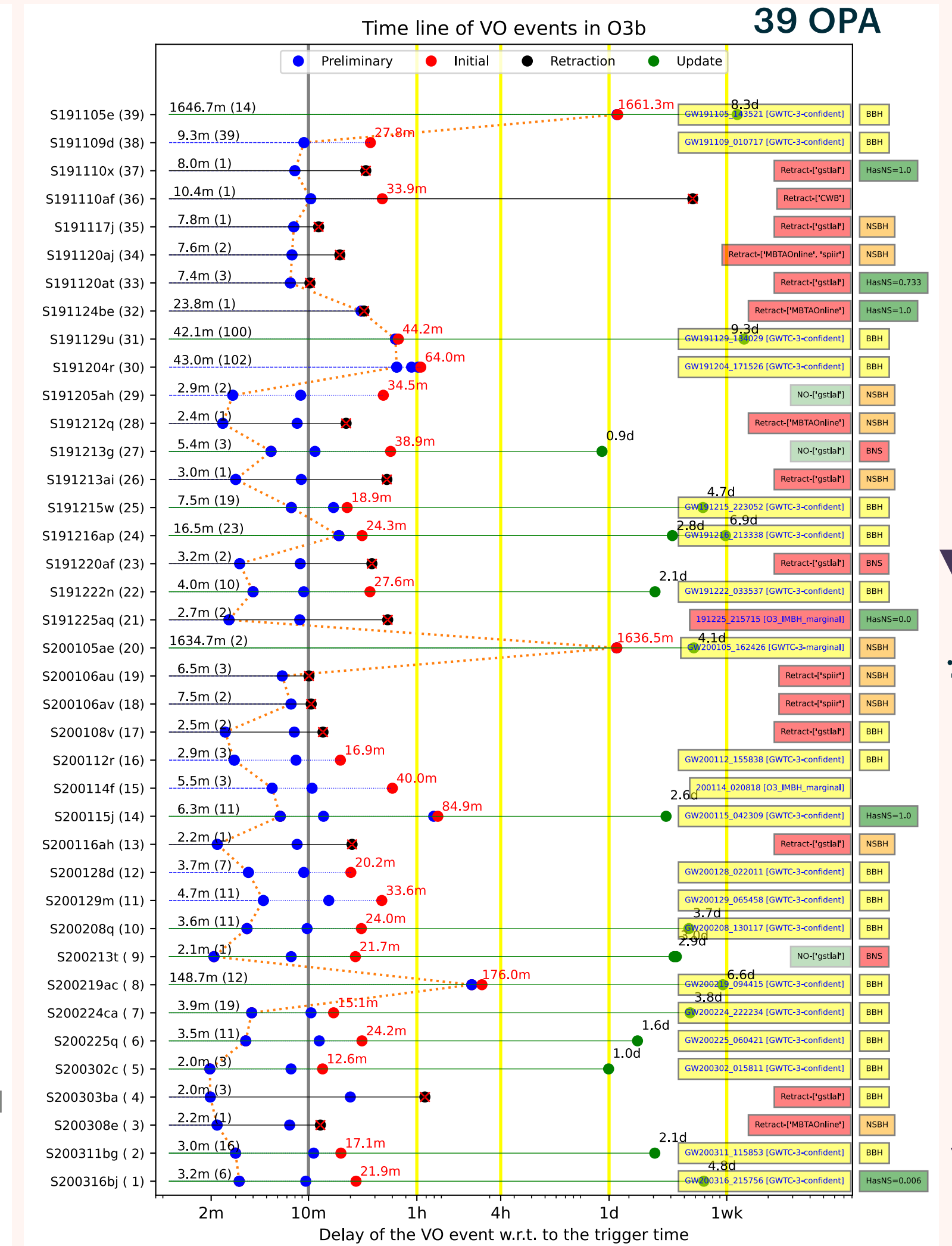
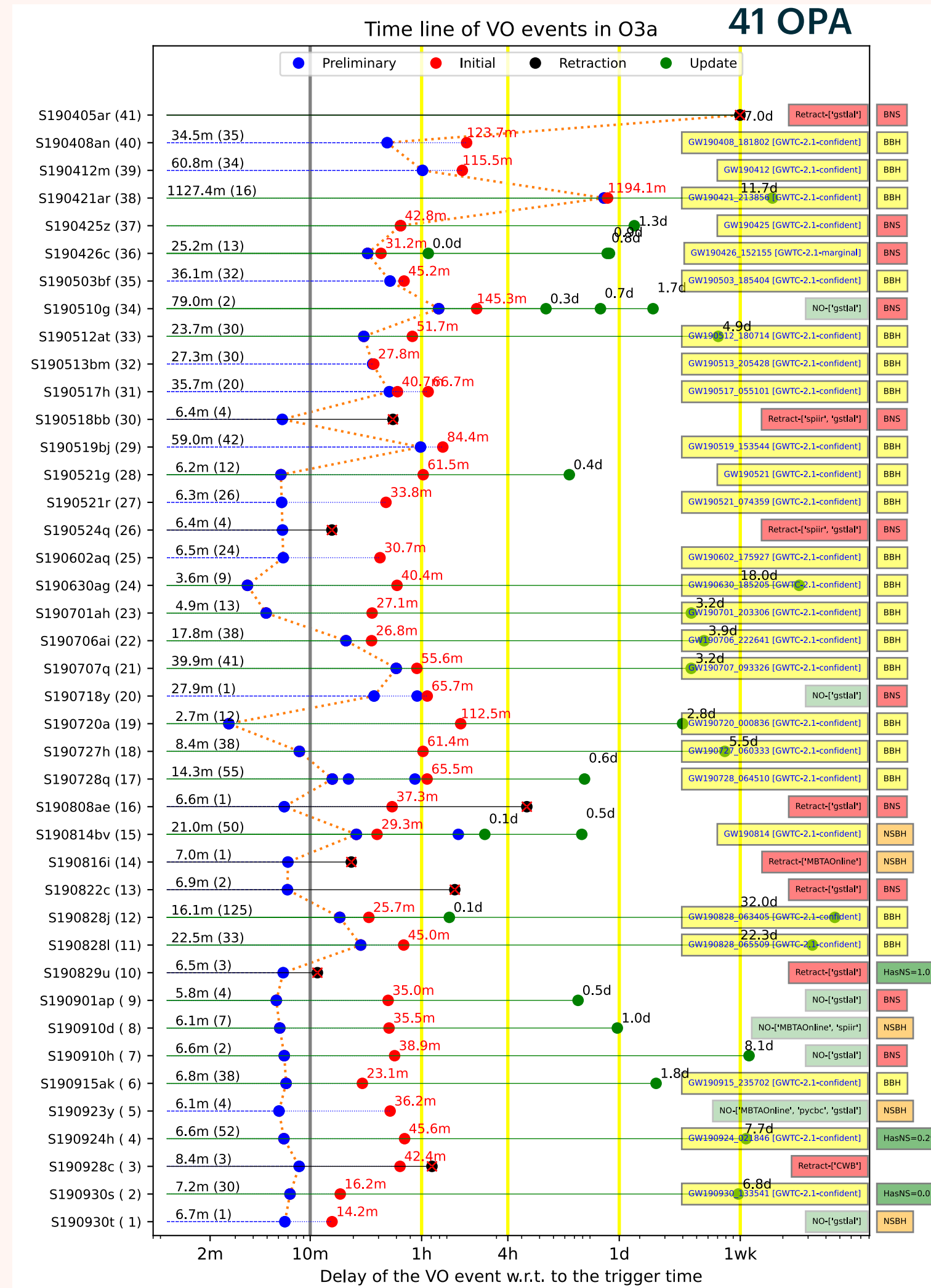
https://www.gw-openscience.org/eventapi/html/GWTC-3-confident/GW200115_042309/v2

<https://gracedb.ligo.org/superevents/S200115j/view/>

<https://iopscience.iop.org/article/10.3847/2041-8213/ac082e>

➤ **Three of O3b open OPAs are not confirmed GW and one retracted OPA is GW:**

- **S190510g, S190718y, S190901ap, S190910d, S190910h, S190923y, S190930t.**
- Three of O3b open OPAs are not confirmed GW and one retracted OPA is GW:**
- **S191205ah:** It is classified in the **O3b catalog** as a low-SNR ($\rho < 10$) single-detector candidate
 - **S191225q:** It was **retracted**, but it is now classified as an **O3 marginal IMBH**
 - **S191213g:** It is discussed in the **O3b catalog**. It was found in low latency by GstLAL in both LIGO Hanford and LIGO Livingston, with low network SNR and a modest FAR of 1.1/yr
 - **S200213t:** It is discussed in the **O3b catalog**. It was found in low latency by GstLAL as a low-SNR single-detector candidate in LIGO ford with a modest FAR of 0.56/yr



Some GW event in catalog do not have a corresponding OPA

- Seven of **O3a open OPAs** are discussed in **GWTC2** but not confirmed GW, namely:
 - **S190510g**, **S190718y**, **S190901ap**, **S190910d**, **S190910h**, **S190923y**, **S190930t**.
- Three of **O3b open OPAs** are not confirmed GW and one retracted OPA is GW:
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- 12 marginal event
 - 9 without an OPA
 - 3 with an OPA
 1. **S200105ae** **RETRACT** (**GW200105_162426** [GWTC-3-marginal])
 2. **S191225aq** (191225_215715 [O3_IMBH_marginal])
 3. **S200114f** (200114_020818 [O3_IMBH_marginal])
- 82 events (3 of them has been reclassified)
 - 36+2 without an OPA
 - 43+1 with an OPA
- 80 OPA during O3
 - 23 Retraction
 - 1 Retraction is now Marginal
 - 43 Confirmed confident GW
 - 4 Confirmed as marginal GW
 - 9 not in GW catalogs and not **RETRACT**

1.	GW	GW190403_051519	sev=S190403cj	OFFLINE
2.	GW	GW190413_134308	sev=S190413ac	
3.	GW	GW190413_052954	sev=S190413i	
4.	GW	GW190424_180648	sev=S190424ao	RECLASSIFIED OFFLINE
5.	GW	GW190426_190642	sev=S190426l	
6.	GW	GW190514_065416	sev=S190514n	
7.	GW	GW190527_092055	sev=S190527w	
•	(1)	GW190531_023648	sev=S190531n	MARGINAL
8.	GW	GW190620_030421	sev=S190620e	
9.	GW	GW190708_232457	sev=S190708ap	
10.	GW	GW190719_215514	sev=S190719an	
11.	GW	GW190725_174728	sev=S190725t	
12.	GW	GW190731_140936	sev=S190731aa	
13.	GW	GW190803_022701	sev=S190803e	
14.	GW	GW190805_211137	sev=S190805bq	OFFLINE
15.	GW	GW190909_114149	sev=S190909w	RECLASSIFIED
16.	GW	GW190910_112807	sev=S190910s	OFFLINE
17.	GW	GW190916_200658	sev=S190916al	
18.	GW	GW190917_114630	sev=S190917u	
•	(2)	190924_232654	sev=S190924am	MARGINAL OFFLINE
19.	GW	GW190925_232845	sev=S190925ad	OFFLINE
20.	GW	GW190926_050336	sev=S190926d	
21.	GW	GW190929_012149	sev=S190929d	
22.	GW	GW191103_012549	sev=S191103a	
23.	GW	GW191113_071753	sev=S191113q	
•	(3)	GW191118_212859	sev=S191118ae	MARGINAL
24.	GW	GW191126_115259	sev=S191126l	
25.	GW	GW191127_050227	sev=S191127p	
26.	GW	GW191204_110529	sev=S191204h	
27.	GW	GW191219_163120	sev=S191219ax	OFFLINE
•	(4)	GW 191223_014159	sev=S191223an	OFFLINE
28.	GW	GW191230_180458	sev=S191230an	
•	(5)	200121_031748	sev=S200121aa	MARGINAL
•	(6)	GW200201_203549	sev=S200201bh	MARGINAL
29.	GW	GW200202_154313	sev=S200202ac	
30.	GW	GW200208_222617	sev=S200208am	
31.	GW	GW200209_085452	sev=S200209ab	
32.	GW	GW200210_092254	sev=S200210ba	OFFLINE
•	(7)	200214_224526	sev=S200214br	MARGINAL
33.	GW	GW200216_220804	sev=S200216br	
•	(8)	200219_201407	sev=S200219bj	MARGINAL
34.	GW	GW200220_061928	sev=S200220ad	
35.	GW	GW200220_124850	sev=S200220aw	
36.	GW	GW200306_093714	sev=S200306ak	
37.	GW	GW200308_173609	sev=S200308bl	
•	(9)	GW200311_103121	sev=S200311ba	MARGINAL
38.	GW	GW200322_091133	sev=S200322ab	

O4 EXPECTATIONS

- **LIGO, VIRGO, AND KAGRA OBSERVING RUN PLANS** as of 15 November 2021 update; next update by 15 March 2022
- **Start of the run in mid-December 2022. Target sensitivity:**
 - **LIGO: 160-190 Mpc**
 - **Virgo: 80-115 Mpc**
 - **Kagra: 1 Mpc with a plan to improve to 3-25 Mpc during O4**
- **Ligo O3 sensitivity ~115 Mpc Hanford and ~133 Mpc Livingston => $(160/115)^{**3} \sim 2.7$ in Volume**
- **Virgo O3 sensitivity ~50 Mpc => ~4 in Volume**
- **We do expect a factor 3 in the number of events: We should reasonably expect (arXiv:2111.03606 [gr-qc] reported 79 GW events) to have: ~ 240 OPA , ~ 240 GW events. That is almost 1 detection per day.**

LOCALIZATION: O3 SKY-AREA

		BNS	NS-BH	BBH
		Area (deg ²) 90% c.r.	Area (deg ²) 90% c.r.	Area (deg ²) 90% c.r.
O3	HLV	270 ⁺³⁴ ₋₂₀	330 ⁺²⁴ ₋₃₁	280 ⁺³⁰ ₋₂₃
O4	HLVK	33 ⁺⁵ ₋₅	50 ⁺⁸ ₋₈	41 ⁺⁷ ₋₆

Abbott et al. 2020, LRR

Since Kagra not reaching the sensibility of that simulation the number for O4 will be the same of O3 not having the Advantage of a proper 4-detector improvement.

O3a low-latency → median 90% c.r area for BBH detected in O3a = 600 deg² (BAYESTAR)

Larger with reported respected to the O3 predictions, but:

- simulation more conservative SNR threshold ($\text{SNR}_{\text{net}}=12$) vs online (SNR_{net} of about 8.5)
→ sky area scale inversely with SNR^2
- released single interferometer candidate (while simulation requires a detection of $\text{SNR} > 4$ in at least two instruments)

O4 area ~ 300 deg²

We are performing injection studies to give more accurate number before the start of O4



$$R_{\text{BNS}} = 110 - 3840$$

$$R_{\text{BBH}} = 25 - 109$$

O1, O2 Astrophysical rate

$$R_{\text{BNS}} = 13 - 1900 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

$$R_{\text{BBH}} = 16 - 130 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

$$R_{\text{NSBH}} = 7.4 - 320 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

O1, O2, O3

EXPECTED NUMBER OF DETECTIONS FOR O4

Observation Run	Network	Expected BNS Detections	Expected BBH Detections
O4	HLVK	10^{+52}_{-10}	79^{+89}_{-44}

Detection: SNR > 4 in at least two detectors and network SNR > 12

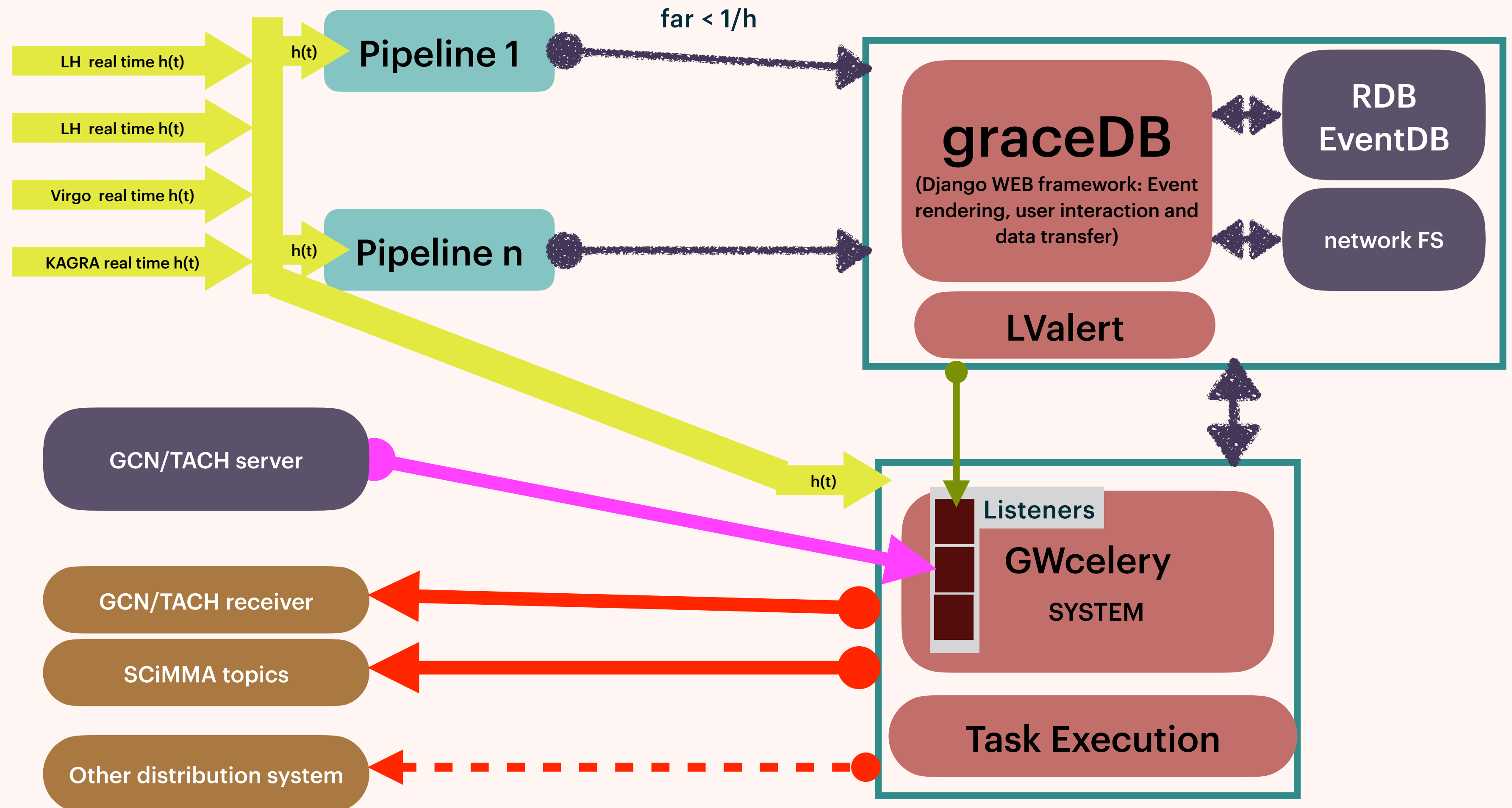
Abbott et al. 2020, LRR

BACK OF THE ENVELOPE COUNTS (EXTREMELY ROUGH)

- SCENARIOS for online triggers (SNR>8)**
- OPTIMISTIC (highest L sensitivity) **6 BNS in O4**
 - PESSIMISTIC (lowest L sensitivity) **4 BNS in O4**
- ~ 1 BNS Early Warning in O4**

ALERT INFRASTRUCTURE

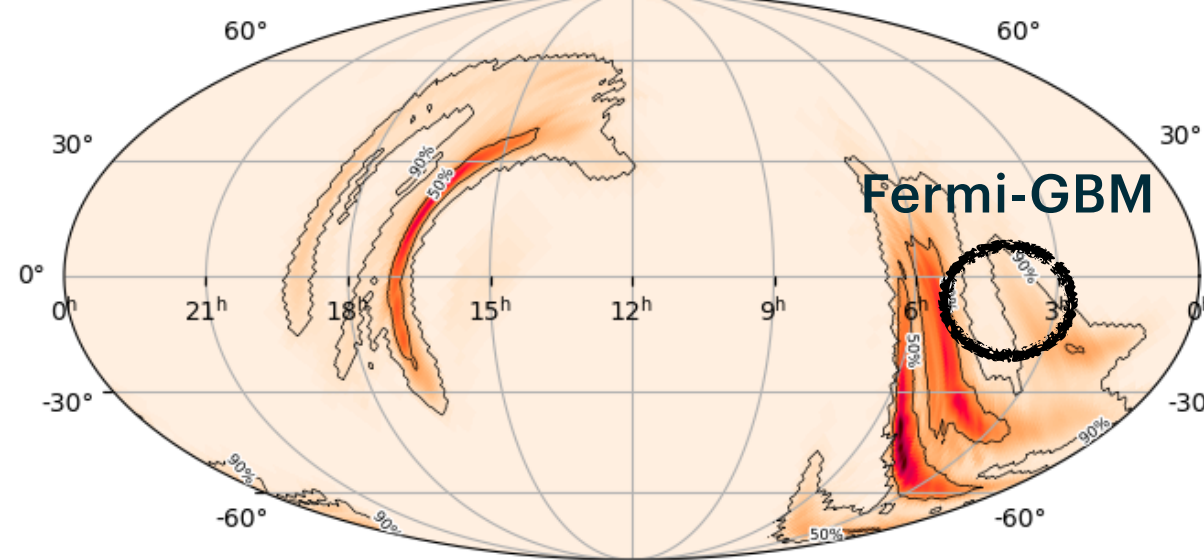
- We operate multiple on-line detection pipelines that upload candidate events (G-event) to a database (GraceDB) if they have a false alarm rate (far) of less than 1/hours.
- An events database (GraceDB)
- The GWcelery system that:
 - **Ingest GCN/TAC alerts** to ingest external events (E-events)
 - **Aggregate coincident-in-time events** into super-events (S-events).
 - **Generate external alerts** if the combined far of the S-events meet publication criteria.
 - $\text{far} < 1/(2 \text{ months})$ for CBC events
 - $\text{far} < 1/(\text{years})$ for Burst events
 - combined spatial-temporal far with external events.



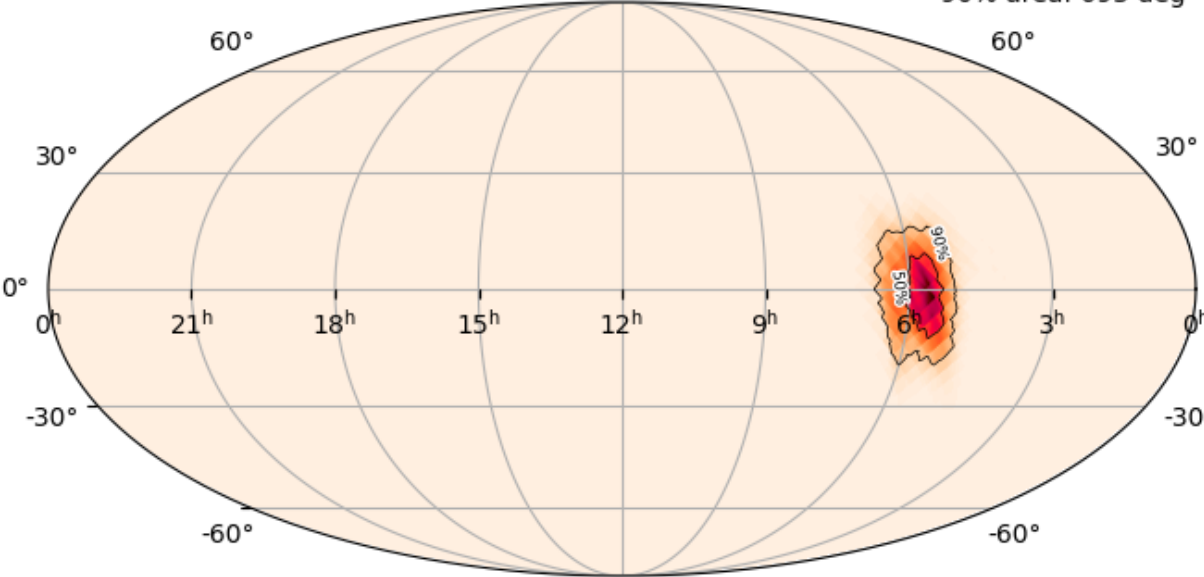
RAVEN (AND LLAMA) PIPELINE

- **LLAMA:** online search pipeline combining LIGO/Virgo GW triggers with High Energy Neutrino (HEN) triggers from IceCube. Looks to temporally-coincident sub-threshold IceCube neutrinos.
- **RAVEN:** Rapid On-Source VOEvent Coincidence Monitor (RAVEN). It searches confidences between GW events with alerts for gamma-ray bursts (GRBs) and galactic supernova alerts from the SNEWS collaboration.
 - Notice Type Considered: FERMI_GBM_ALERT, FERMI_GBM_FIN_POS, FERMI_GBM_FLT_POS, FERMI_GBM_GND_POS, FERMI_GBM_SUBTHRESH, SWIFT_BAT_GRB_ALERT, SWIFT_BAT_GRB_LC.
 - It combines GW+GRB localizations to assist in identifying a counterpart kilonova transient.
 - It attributes new significance by computing additional combined Spatio-temporal significance (far) for sub-threshold GW candidates, allowing the distribution of additional alerts.

Theoretical Example: GW190425 50% area: 1378 deg² 90% area: 7461 deg²



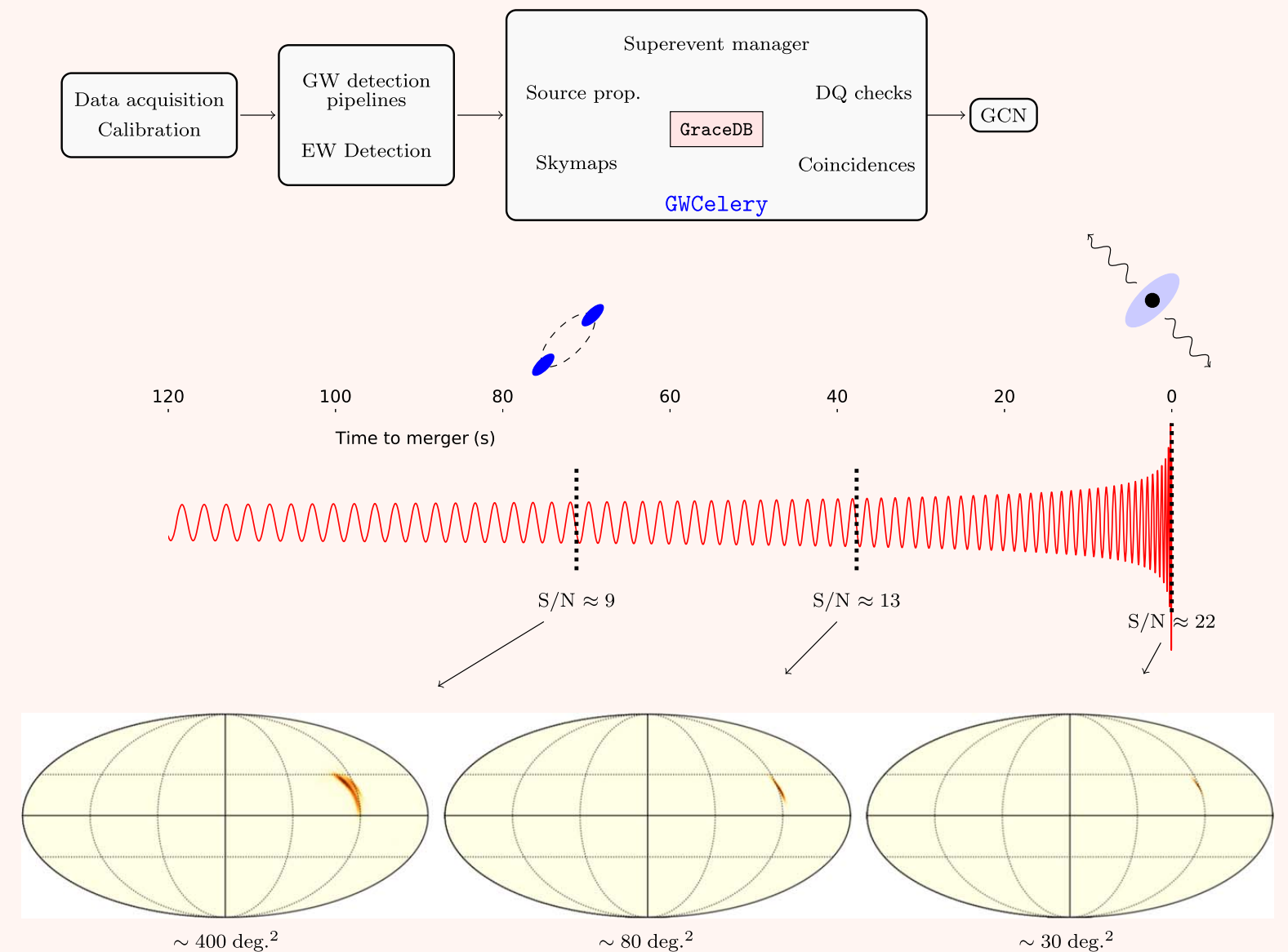
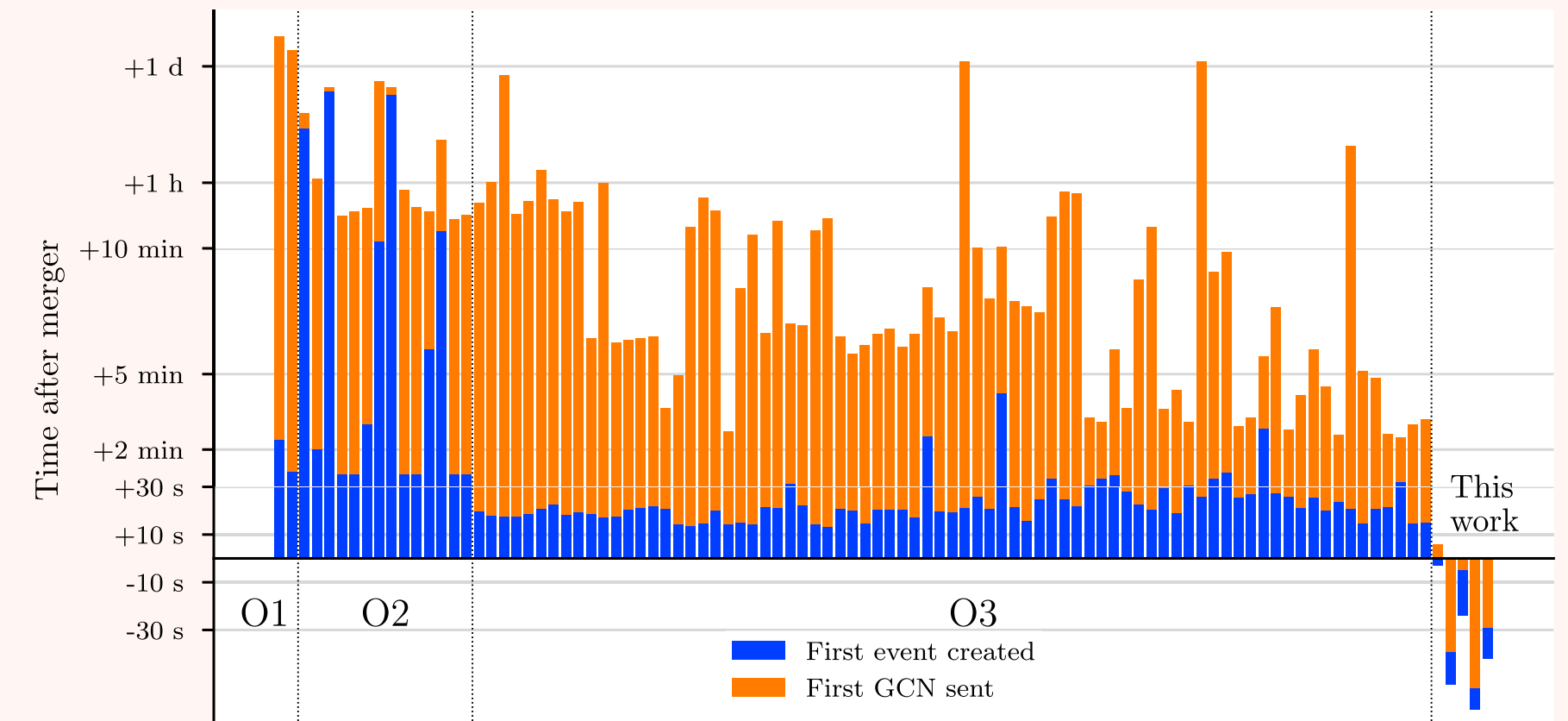
Combined skymap 50% area: 187 deg² 90% area: 693 deg²



Search	Pipeline(s)	Untargeted	Targeted
CBC-GRB	Fermi-GBM	[-1, +5]	[-1, +10]
	<i>Swift</i> -BAT	[-1, +5]	[-10, +20]
	INTEGRAL	[-1, +5]	N/A
	AGILE	[-1, +5]	N/A
Burst-GRB	All GRB	[-60, +600]	N/A
Burst-Neutrino	SNEWS	[-10, +10]	N/A

EARLY WARNING DEMONSTRATION

- **“First demonstration of early warning gravitational wave alerts”, Ryan Magee et al., 2021 ApJL 910 L21 (<https://arxiv.org/abs/2102.04555>)**
- **Test based on results of an early warning matched-filtering pipeline by considering six different discrete frequency cutoffs: 29, 32, 38, 49, 56, and 1024 Hz to analyze signal recovery at (approximately) 58, 44, 28, 14, 10, and 0 s before the merger.**
- **We recovered 5 injections with latency to notice 7.1 s, -35.2 s, -2.9 s, -51.3 s, -27s. To this latency, one should add the latency (from the arrival of the GW) needed to transfer the signal to the pipeline (< 10s)**
- **Early warning will be available during O4 !**



Planned PUBLIC ALERT time-line (GCN)

➤ BNS/NSBH early warning pipeline (This stage may not apply and we should expect that an early-warning event is followed by a general all-sky search (**need to fixed the timing**)).

- (1st) **EarlyWarning** alert (fully automatic) with **no localization information**.
- (2nd) **EarlyWarning** alert (fully automatic) as soon as sensible localization information is available.

➤ After Detection search is completed by All the pipelines (Including RAVEN) or as soon as sensible information is collected. (**Within 1 minutes**).

- **Preliminary** alert (localization information needed)

➤ Fully automatic DET char checks with required latency check that allows for these results to be used as part of a retraction or confirmation that occurs **within 10 minutes**.

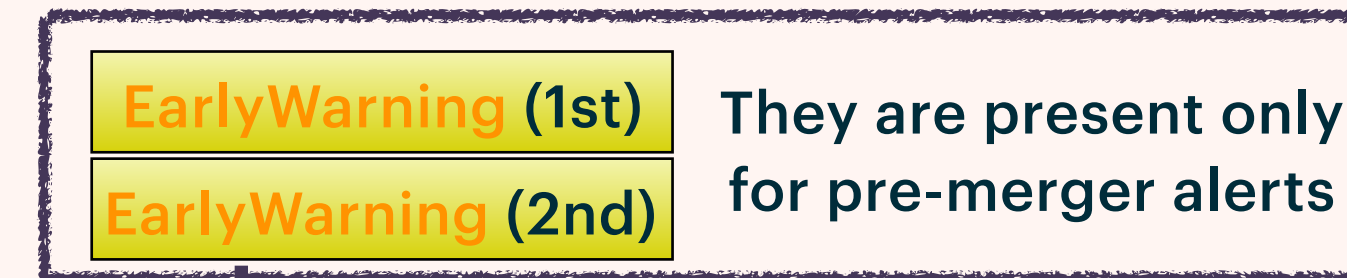
- **Initial (Fully automatic)** alert, automatic Initial **circular** sent
- **Retraction (Fully automatic)** alert, automatic Retraction **circular** sent

➤ RRT meeting and a rapid PE evaluation typically **within 4 hours** for BNS events or **1 day** for vanilla BBH. DQR that have a time scale of 1 hour (**see**)

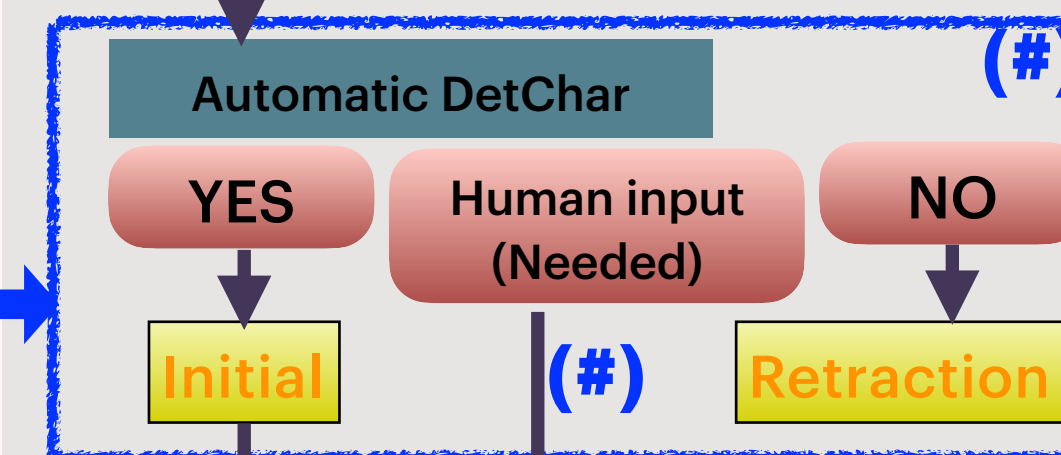
- (1st) **Update** alert (human confirmation and evaluation). Update **circular** sent
- **Retraction** alert (In case the event should be vetted). Retraction **circular** sent

➤ Any time significant new information is collected upon RRT (after PE group, and follow advocate suggestion) approval. In a case-by-case basis. Targeting for BNS candidates.

- (2nd) **Update** notice and circular sent (~ 1 day). Update **circular** sent
- (3rd) **Update** notice and circular sent (~ 2 days). Update **circular** sent
- (4rd) **Update** notice and circular sent (~ 1 week). Update **circular** sent



Preliminary



(#) Roadmap to Autonomous Results

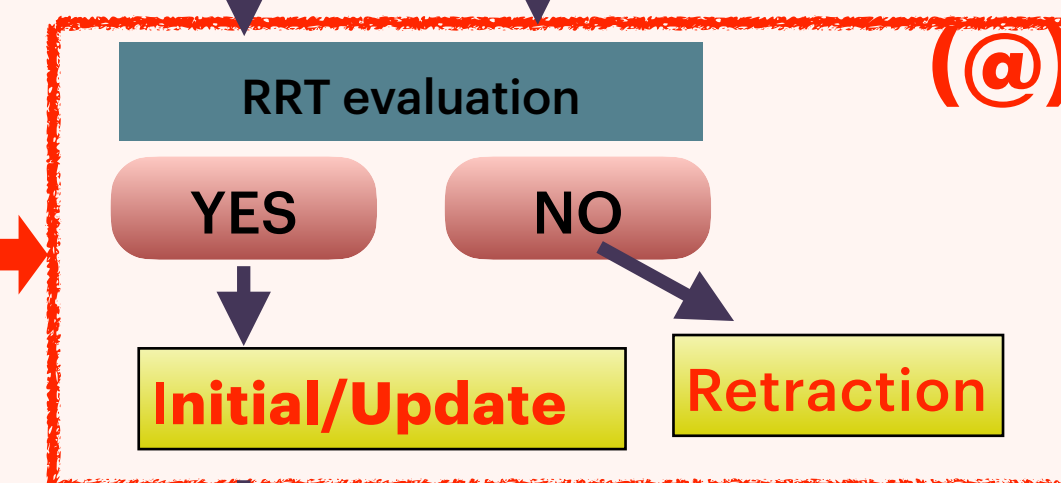
It is still a goal to have the DQR be fully autonomous. One part of this is issuing automatic retractions or data quality warnings in low latency. Due to the untested nature of an automated DQR and the potential for unforeseen data quality conditions at the start of an observing run, we do not plan to enable such a feature at the start of O4.

UNTIL THE GOAL IS REACHED a second Preliminary will be issued if the localization information (within 10 minutes) is significantly improved,

([link](#), section 6):

Astronomer request from Requirement Document

Category	Latency	Information	Products
Opportunity	< - 1 min	Trigger time	point source candidates
AllSky	10 s - few min.	localizations	GRB EM signature, candidates in time coincidence, a GW+EM, GW+neutrino joint localization counterpart candidates
ToO	5 min - 8h - 24h	best rapid skymap, high purity, classification, Full parameter estimation, PE skymap	
Characterization	1 day - 1 week - 1 month	PE skymap, Full parameter estimation, very high purity, very high classification	classification/confirmation of the candidates

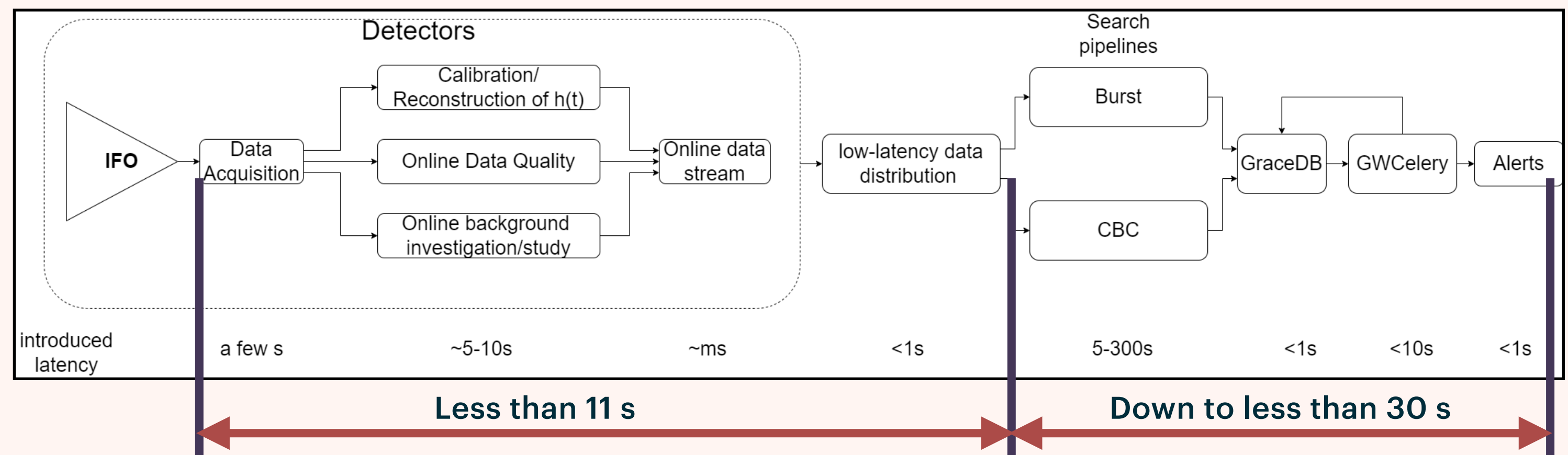


Update (...)

Update (n-th)

LATENCY STUDY (FROM SIGNAL TO ALERT)

- We are running extensive tests (already started - up to engineering runs) from data acquisitions (synthetic) to alert generation, and we are monitoring latency.
- We have the signal ready to be analyzed online in less than 11 seconds from the arrival of the (GW) signal at the detectors.
- That makes pre-merger alerts possible (with negative latency) and to have the first preliminary alerts in less than a minute.
- The study will also allow us to test the effectiveness of the online pipeline to detect and assess the properties of the signal.



CONCLUSIONS

- **We will provide open public alerts (OPA) also for:**
 - **pre-merger (negative time) early warning alerts.**
 - **alerts based on a coincident external public trigger.**
- **We plan to provide alerts not only in the GCN/TACH infrastructure**
- **Alerts for sub-threshold trigger will be provided on MOA-based agreement.**
- **You should expect one OPA per day.**

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