Hidden Latencies of Real-time Astronomy

HTC26

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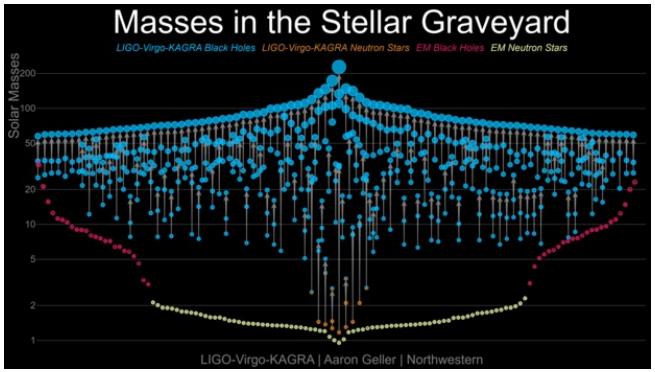
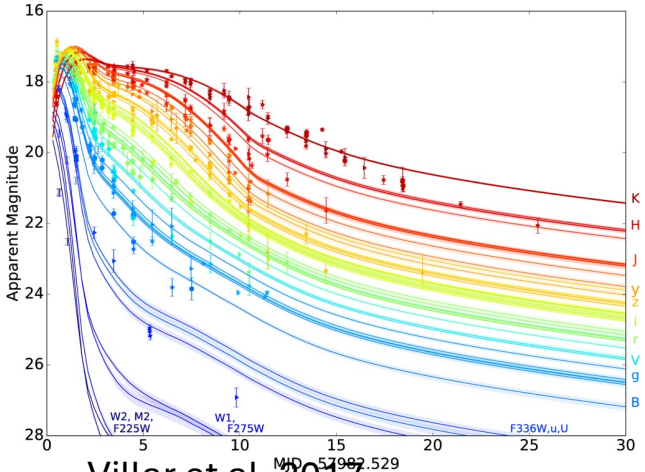
Challenges

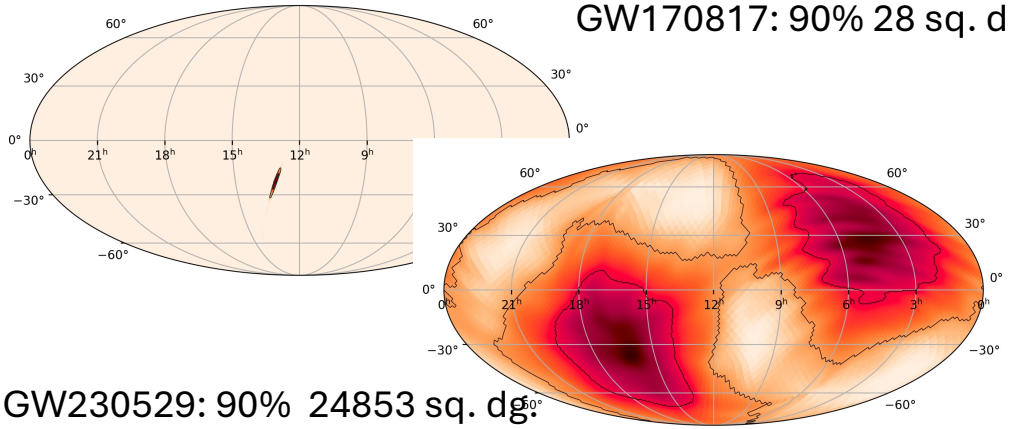


Neutron Star mergers are rarer than Black Holes.



Villar et al. 2017

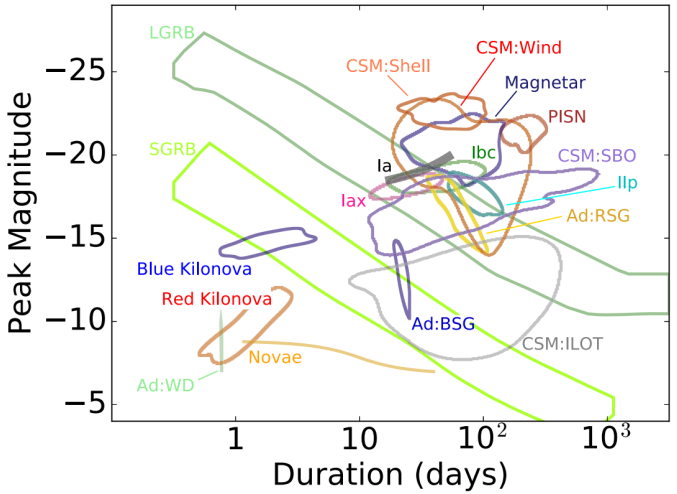
Kilonovae are faint (~<18 mag) and fade quickly (~days)



GW170817: 90% 28 sq. deg.

GW230529: 90% 24853 sq. dg.

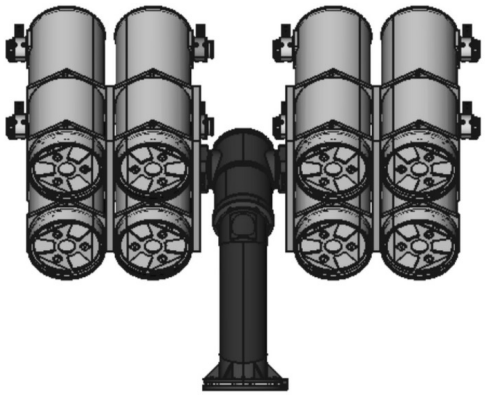
Search localisation areas can be 10s-10,000s of sq deg.

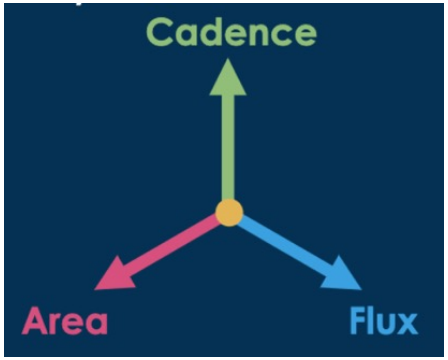


There are many other other transient and variable sources which will contaminate the search.

Design and Philosophy

- Proposed in 2014: build a **dedicated** facility for EM follow-up of GW alerts
- Designed for **rapid, wide-field** searches of exotic transients, especially GW-EM counterparts
- Aims to **catch counterparts early** so larger facilities can perform deeper follow-up
- Built as a **modular network** of multiple unit telescopes and mounts for **staged deployment**, **scaling**, and **adaptability**.
- Uses **off-the-shelf hardware** to allow fast deployment and keep project **cost-effective**
- The entire network should be **autonomous**, with automated control systems & analysis pipelines for rapid detections

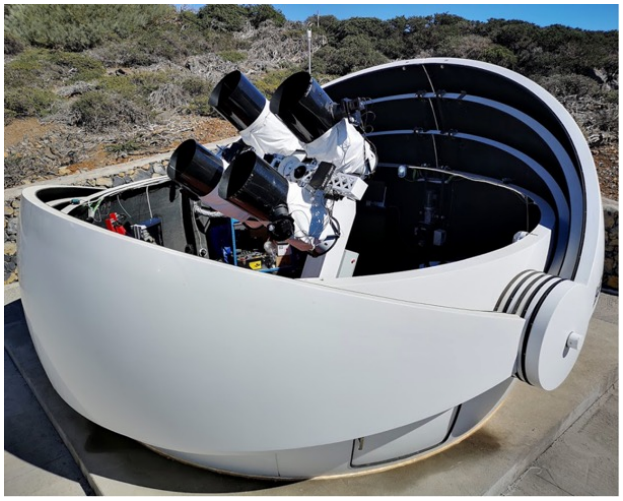




Prototype System (2017-2020)

- The prototype evolved over several distinct phases to inform final design
- Commissioning spanned O1-O3 Observing Runs with stable operations during each run

- D=40 cm, f/2.5 unit telescopes (UT)
- 5-slot filter wheel (Baader LRGBC)
- Survey observations taken in L (400-700nm)
- ~5.5 sq. deg. FoV per UT
- FLI MicroLine cameras with 50 Mpix CCDs



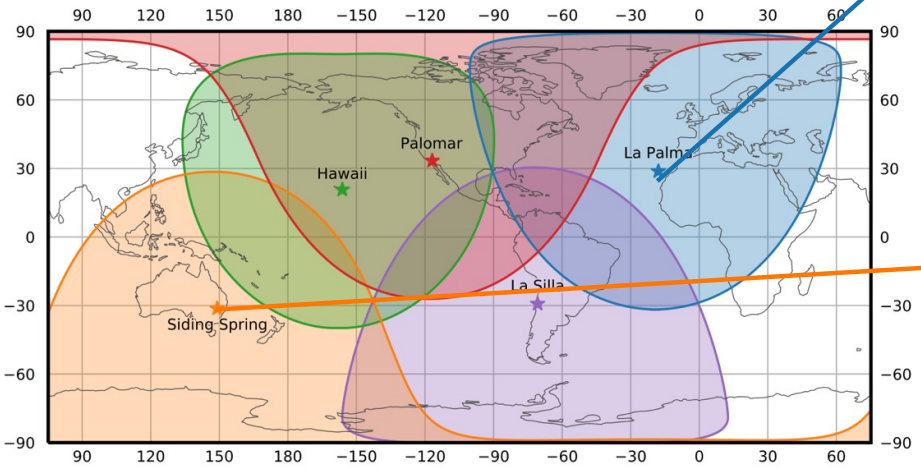
La Palma 4 UT Prototype in 2018

La Palma 8 UT Prototype in 2019

La Palma 8 UT Prototype in 2020

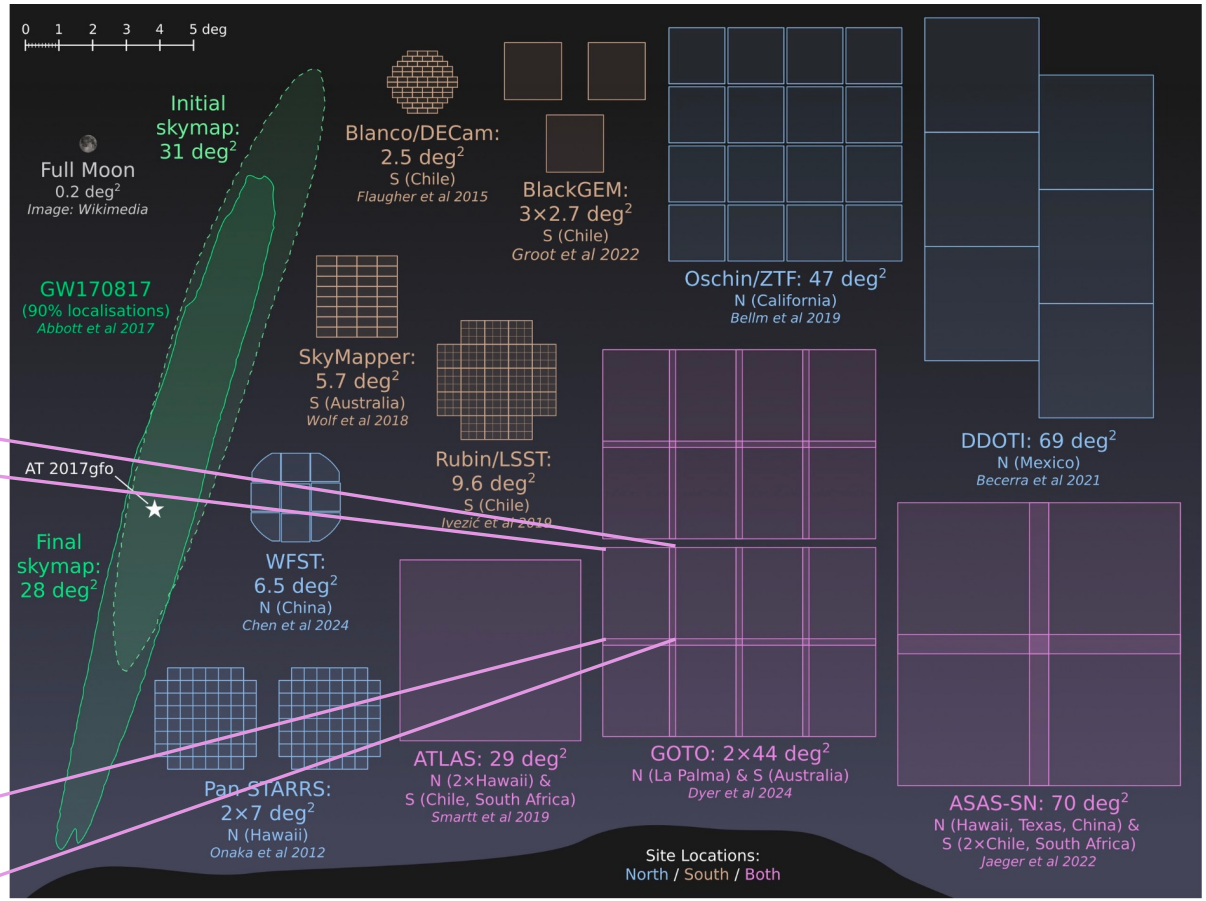
GOTO Network & Operations

- With both sites complete, all four telescopes are **observing autonomously every night** (weather permitting…) as a single network.
- The **two antipodal sites** provide near **24-hour coverage** and the ability to survey the visible sky **every 2-3 days**.
- ~4000 images created per telescope each night → **2-5 TB of data products every 24h**.



Field of View Comparison

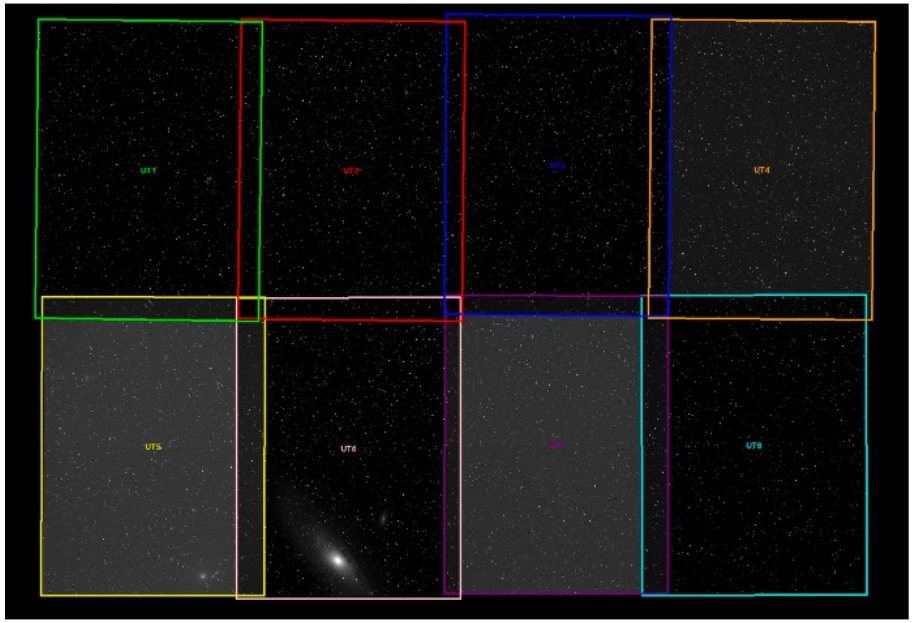
- The array design allows a large FoV by combining UTs → **44 sq. deg**.
- Two mounts per site gives operational flexibility.
- Follow-up strategy can be tailored to the event.
- Options to balance speed vs depth, or use of coloured filters.

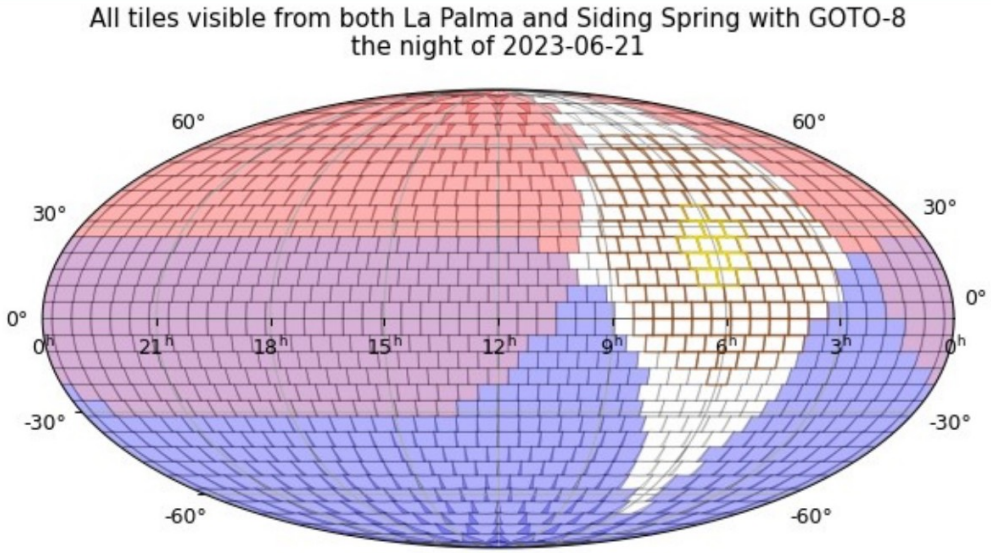


Credit: M. Dyer

Operational Mode

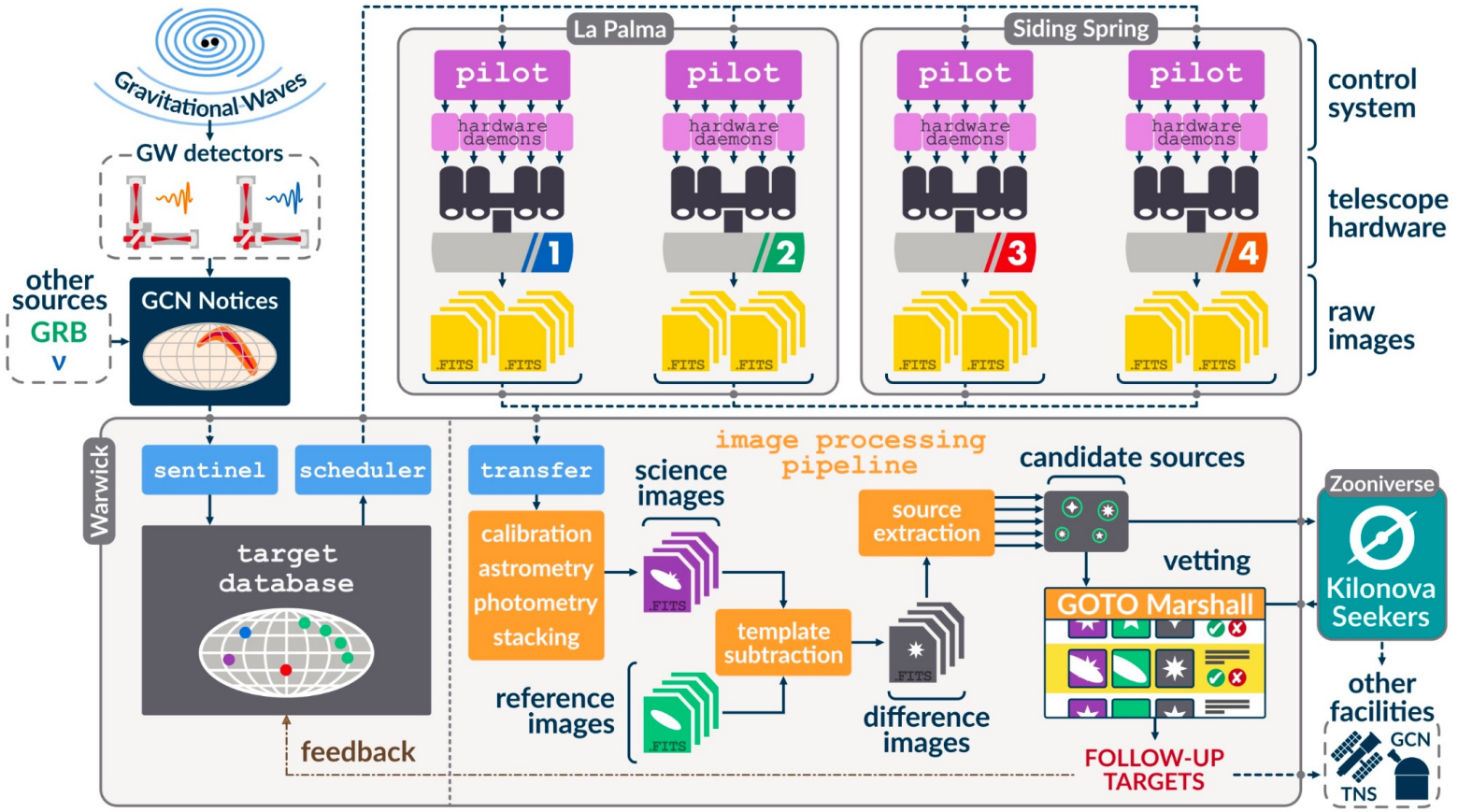
- 4x45s dithered set of exposures - standard tile visit for high-cadence patrol survey (to ~19.6 mag depth)
- 12x60s dithered set for template bank (to ~20.7 mag)
- Image sets can stack for depth
- Responsive mode image sets are flexible





~790 tiles accessible per site
~530 tiles visible from both
~260 visible at any one time
500-600 visible during 8-12hr night

Data flow and control systems



Credit: M. Dyer

Telescope control

G-TeCS (Dyer et al. 2018, 2020, 2024)

- All four telescopes operate autonomously, but receive targets from the central **scheduler**.
- Control system (**G-TeCS**) is Python-based, using multiple daemons with **Pyro** communication.
- Updates are sent to Slack, including routine status messages and important “WAKEUP!” alerts.
- Web dashboards for remote monitoring with webcams, weather, target queue.

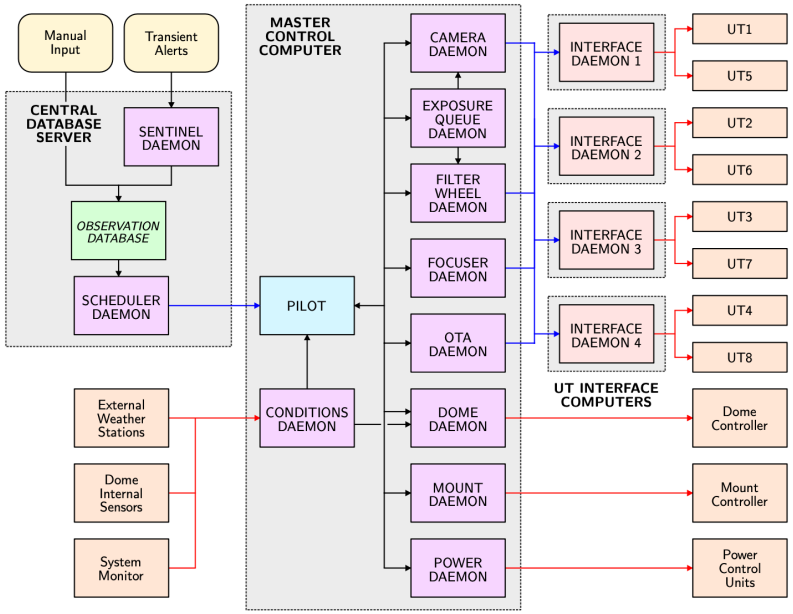
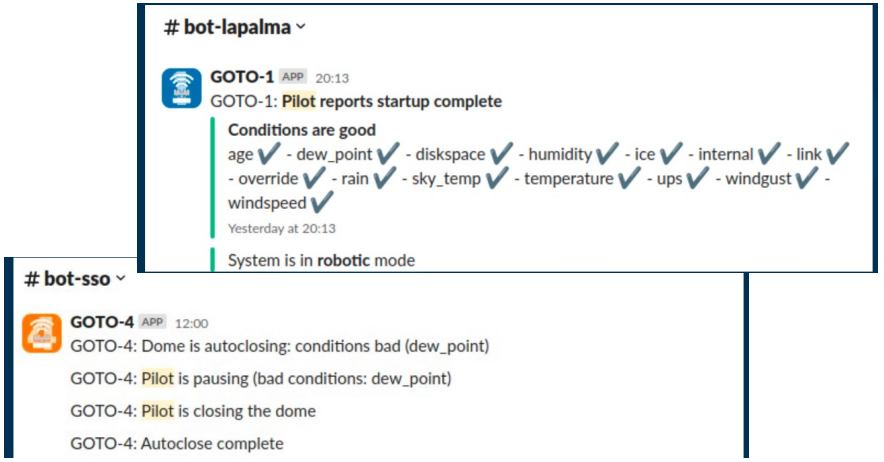


Figure 2. The G-TeCS software architecture.



Scheduling & Strategy

Ackley, Dyer et al. (in prep)

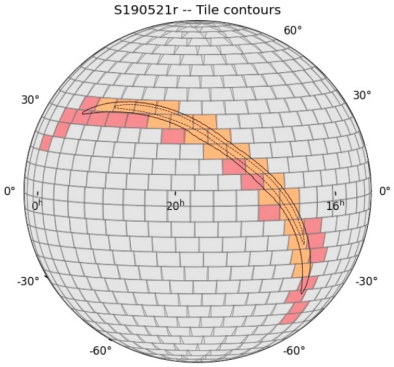
- The **sentinel** alert monitor receives external events (GW/GRB) and determines priority and follow-up strategy (cadence, number of visits, ..)
- Event skymaps are mapped onto all-sky grid
- All GOTO survey and follow-up observations are taken aligned to a fixed grid, to provide consistent references.
- Balanced in time cost against other surveys

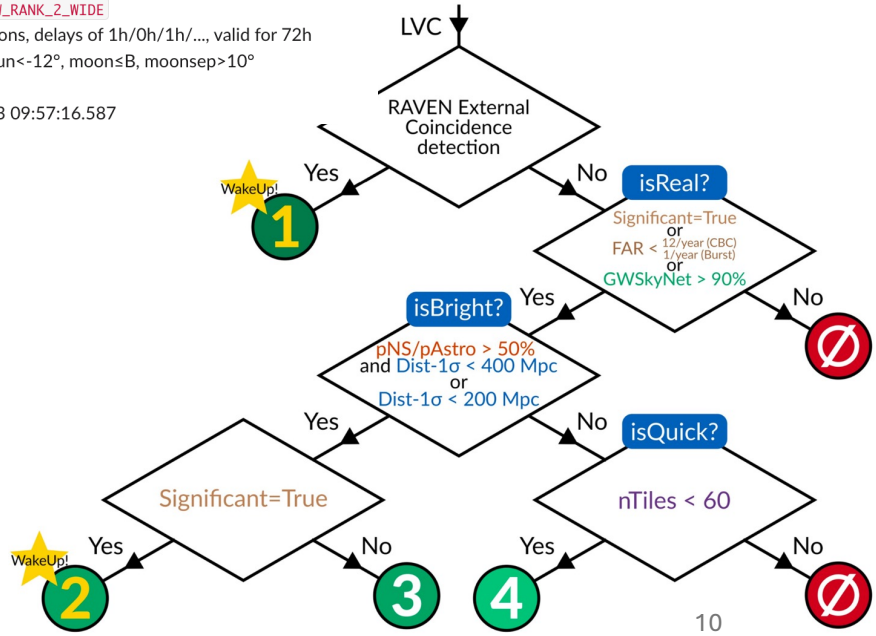
GOTO Status Bot APP 10:57 AM

LVC notice: ivo://gwnet/LVC#S250818k-4-Update
Notice type: UPDATE
Notice time: 2025-08-20 09:57:08.000 *(0.0h ago)*

Event: LVC_S250818k
Detection time: 2025-08-18 01:20:06.030 *(56.6h ago)*
Pipeline: pycbc
Instruments: H1,L1,V1
GraceDB page: https://gracedb.ligo.org/superevents/S250818k/view/
FAR: ~2 per year (significant=True)
Group: CBC
Classification: Terrestrial:70.5%, BNS:29.5%
HasNS: 80%
HasRemnant: 80%
GWSkyNet score: N/A
Distance: 237+/-62 Mpc
90% probability area: 949 sq deg

Observing strategy: `GW_RANK_2_WIDE`
Cadence: 99 observations, delays of 1h/0h/1h/..., valid for 72h
Constraints: alt>30°, sun<-12°, moon≤B, moonsep>10°
Exposure sets: 4x90L
Valid until: 2025-08-23 09:57:16.587

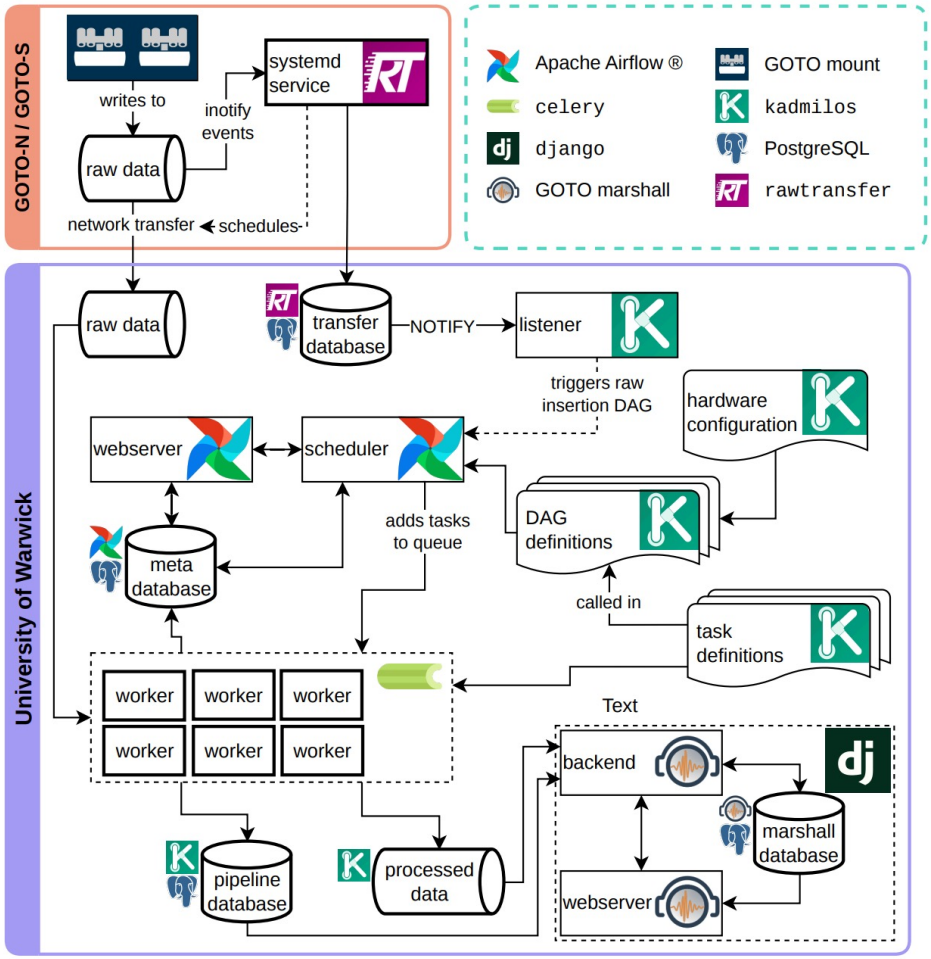




kadmilos Automated Pipeline

Lyman et al. 2026

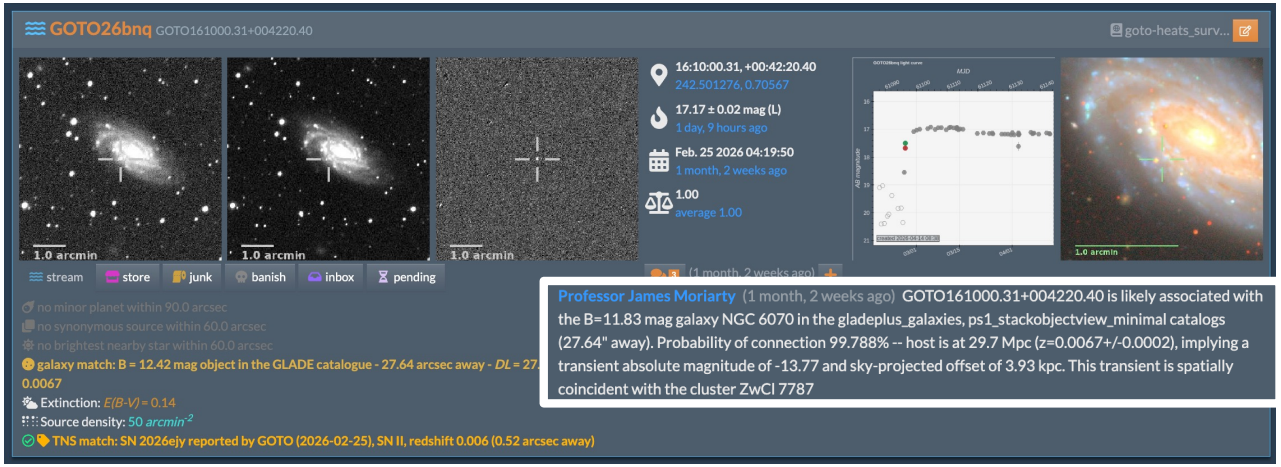
- Raw exposures are transferred to Warwick for processing
  - ~ 0.25 PB raw data/yr
  - ~ 1.0 PB of processed data/yr
  - Rolling storage model for image-level data
  - Key outputs in database
- Processing orchestrated using **Airflow**
- Each image is calibrated individually and stacked into sets
- Archival template images are used as references to detect transient sources, though difference imaging

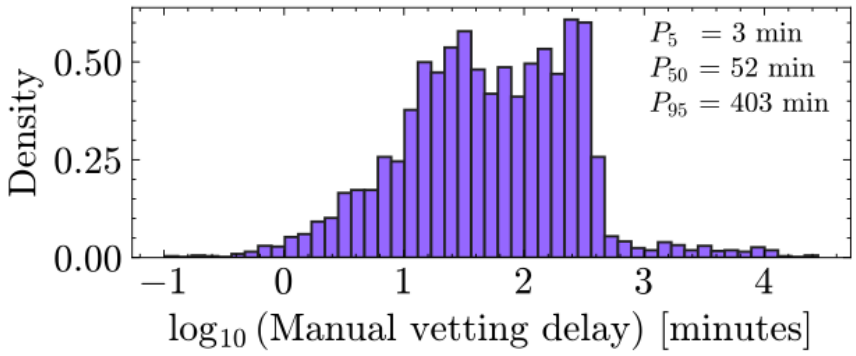


Candidate Vetting through Marshall

Lyman et al. 2026

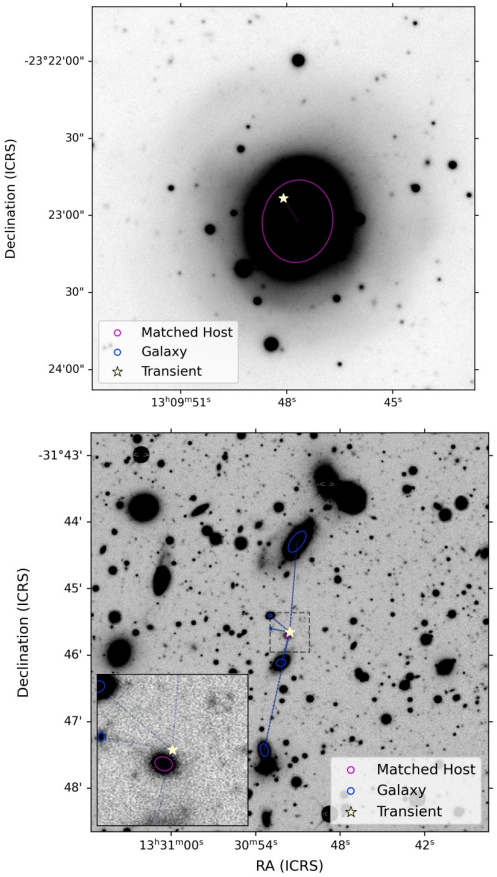
- Candidate sources sent to internal **GOTO marshall** for vetting and classifying
- Crossmatch against catalogs: MPChecker, AAVSO, Gaia, TNS, forced photometry services (ATLAS/ZTF), historic GOTO lightcurves
- Candidates receive contextual classification **(moriarty)**
- Buttons for automated reporting to TNS and trigger follow-up (LT, pt5m).



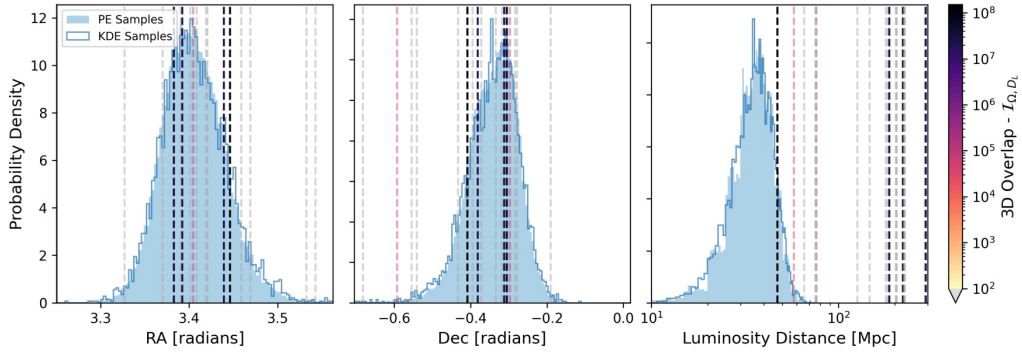


Probabilistic Candidate Vetting for GW follow-up

Ackley 2025 (arxiv:2510.15836)



- Associating **single transients** to GW event via host galaxy association
- Bottleneck:
  - ~tens – hundreds candidates
  - ~tens – hundreds of host galaxy candidates

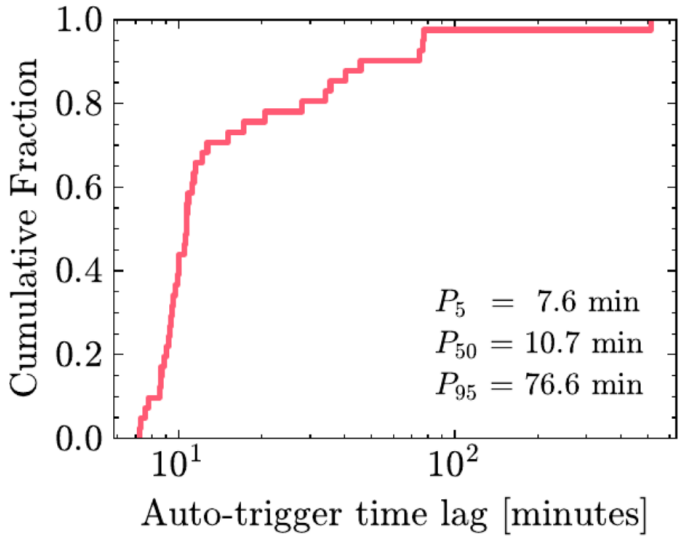


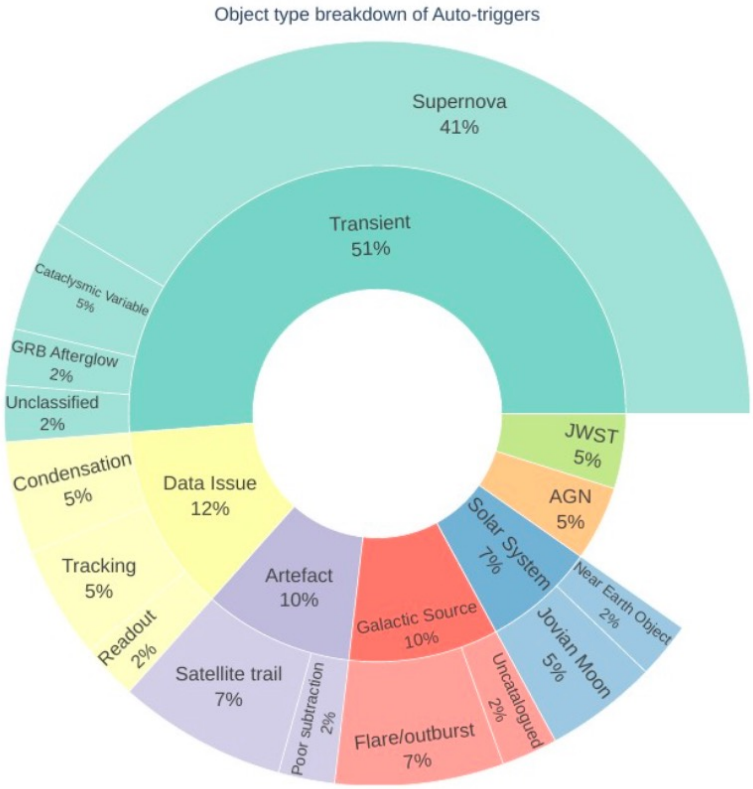
Candidate	z	σ_z	z Type	z Source	D_L (Mpc)	σ_{D_L} (Mpc)	$p_{\rm assoc}$	$\mathcal{I}_\Omega$	$\mathcal{I}_{D_L}$	$\mathcal{I}_{\Omega,D_L}$
AT2017gfo	0.0102	0.0009	spec	GLADE+	44.20	4.00	0.98	1316	242144	312258201
SN2017ddy	0.0497	0.0346	phot	GLADE+	221.06	163.09	1.00	2568	14430	36222954
SN2017djn	0.0651	0.0351	phot	GLADE+	292.75	168.85	1.00	2868	8421	23612693
AT2016frh	0.0424	0.0344	phot	GLADE+	187.59	160.38	0.99	1201	17861	20904408
					...					
AT2017bej	0.1450	0.0378	phot	GLADE+	687.20	199.28	0.85	8	290	1953

GOTO Auto-trigger (GOAT)

Lyman et al. 2026

- Fully autonomous identification of targets
- Direct scheduling of follow-up via API
- Trigger follow-up currently implemented on LT





O4 & Multi-Messenger Prospects

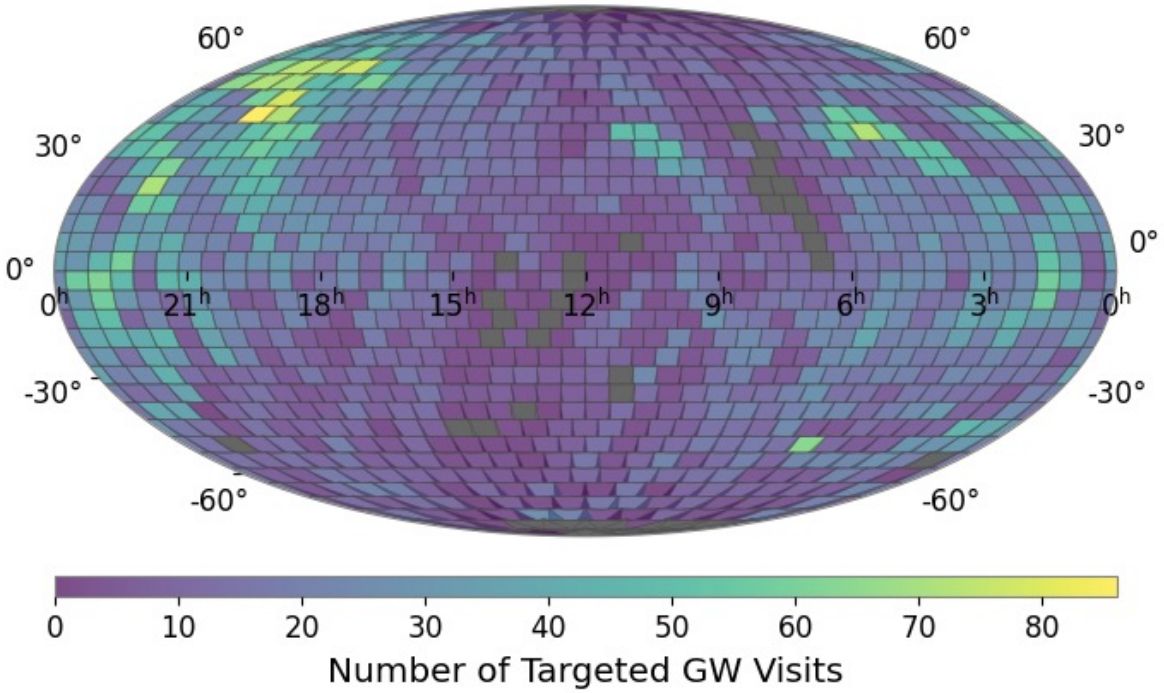
Over the O4 run, we received **5430 superevents** including **29** retractions

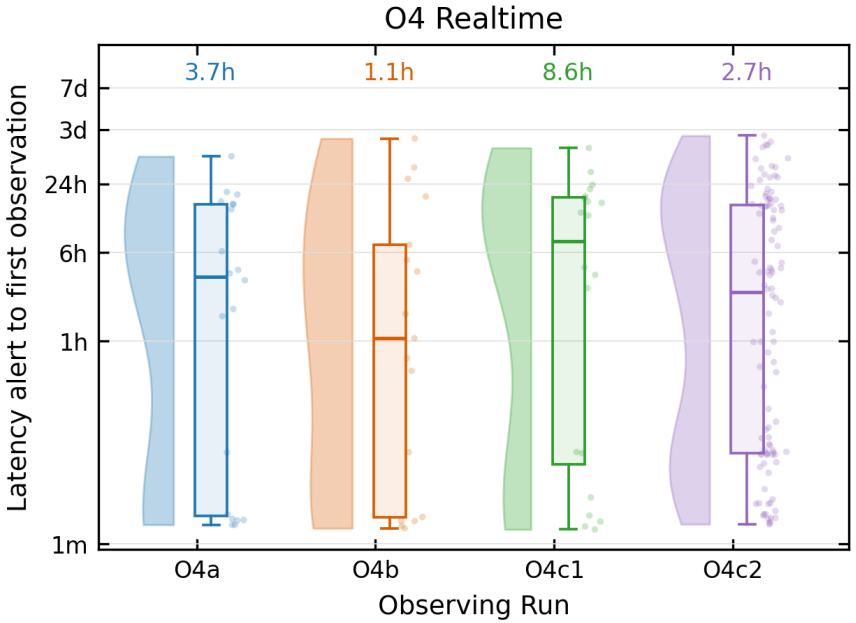
Run	Days	Superevents	Rate (received/day)	Significant	% Significant	Retracted	Low Significance
O4a	237	1702	7.18	81	4.8 %	11	1610
O4b	300	1861	6.20	106	5.7 %	9	1746
O4c < 2025-04	63	487	7.73	17	3.5 %	5	465
O4c > 2025-06	160	1410	8.81	51	3.6 %	4	1355
Total	**760**	**5430**	**7.14**	**255**	**4.7 %**	**29**	**5176**

Of the 255 significant superevents received, GOTO has targeted observations for **163 events**

Ackley et al. in prep

Number of visits for 163 targeted GW alerts

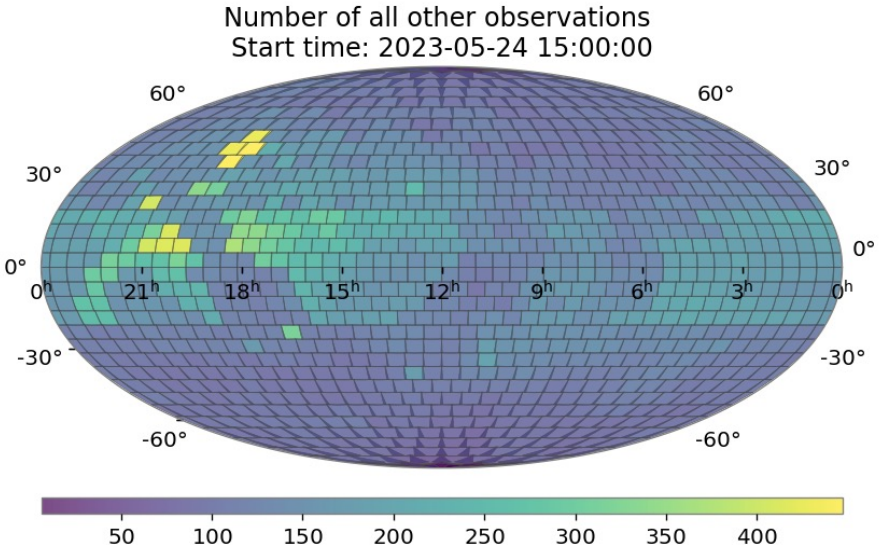


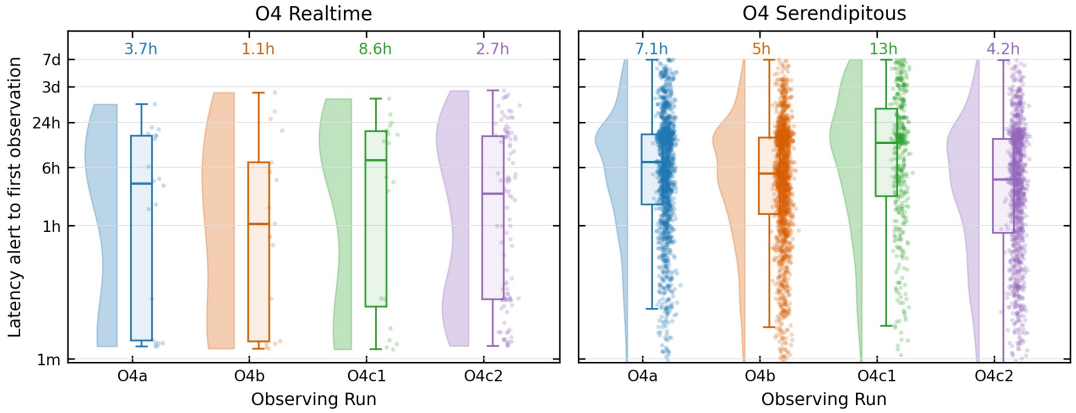


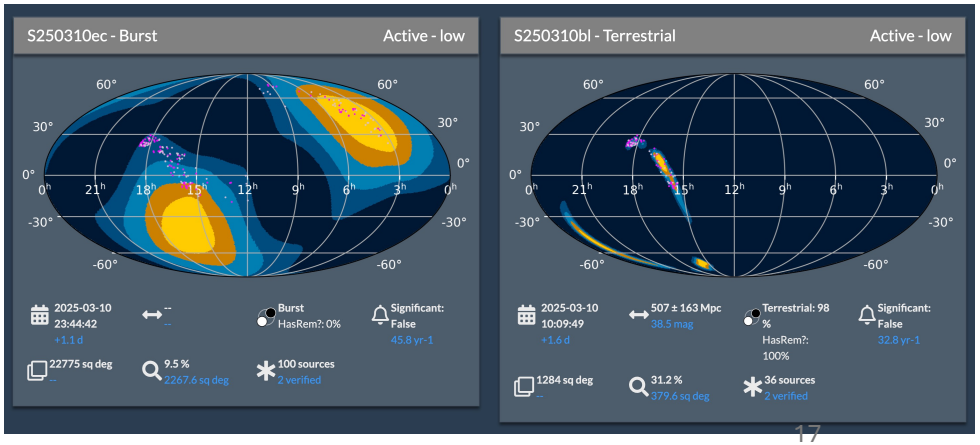
Ackley et al. in prep

Serendipitous Coverage

- Operational challenges from weather, scheduling conflicts, false positives, network downtime.
- Use all-sky strategy to maximize field coverage, even if no current GW events for follow-up
- Given serendipitous coverage – GOTO has observations of **5337 events** (with >= 1 image)







Ackley et al. in prep

Visible Latencies

event → alert	alert → first obs	Raw transfer	Image processing	Observation → marshall
35 s	182 min	10 s	190 s	819 s

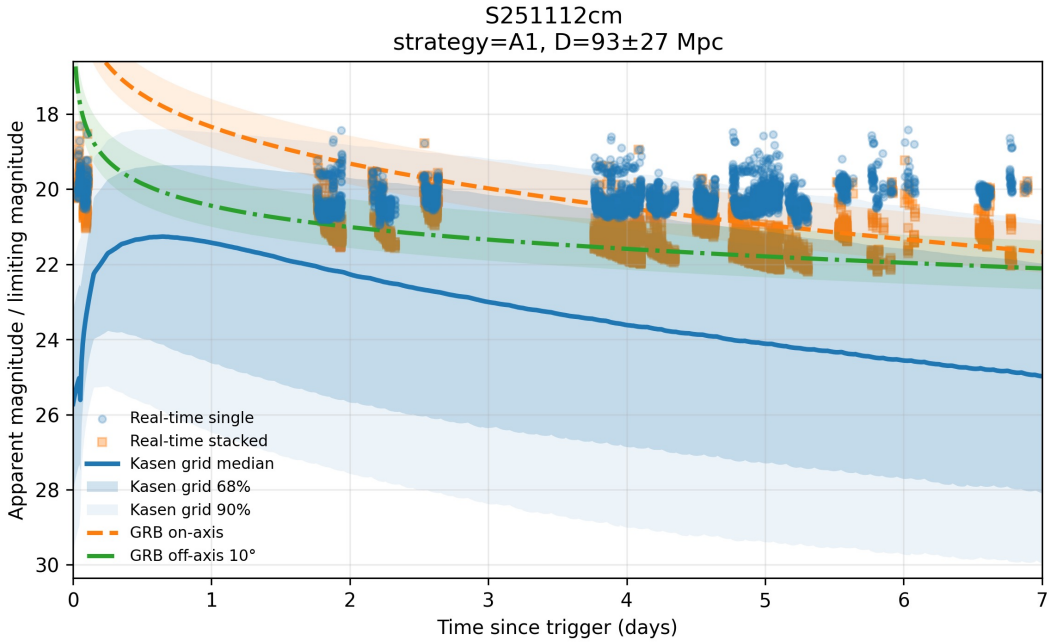
- Receive and process external alert
- Scheduler decides priority and strategy
- Telescope commands
- Exposure/readout
- Raw image transfer
- Airflow orchestrates pipeline processing
- QA + Real-bogus
- Marshall + context
- Automated filtering
- Follow-up

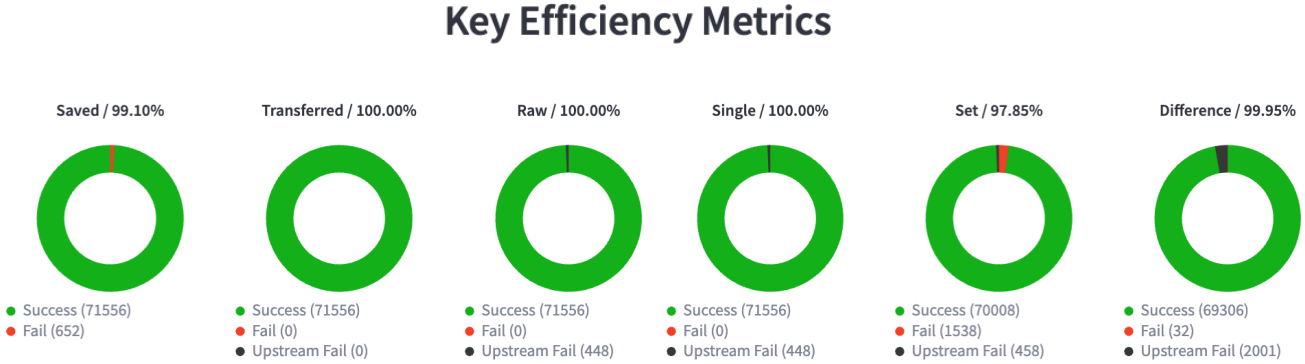
Heaviest processing tasks

Create difference image	106 s
Analyze set image	98 s
Analyze single image	58 s
Create set image	52 s
Analyze difference image	42 s
Create single image	38 s

Hidden Latencies

- Scheduler deliberation
- Stale observing queue
- **Weather/seeing propagation and settle times**
- **Image QA latency (unusable images)**
- **Decision to retake/reschedule/throw-away image**
- Evolving GW event information
- Real-bogus/ML data drift
- Subjective human in the loop
- *All will have physical implications*
- *Difficult to assign with as single decisions at each stage*

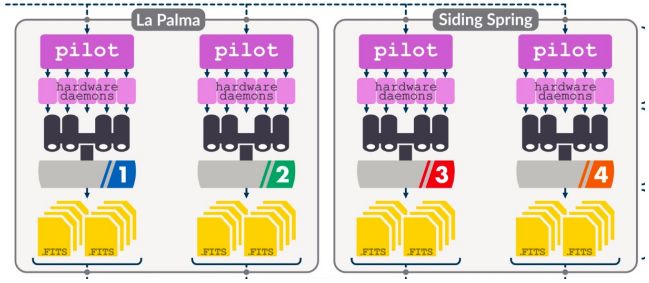




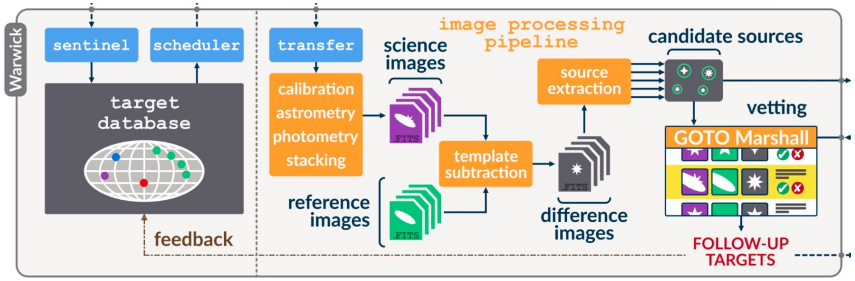
Ackley et al. in prep

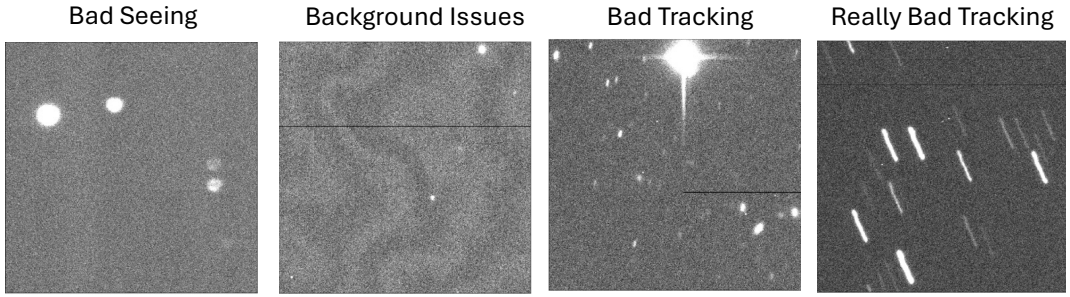
Responsive QA system

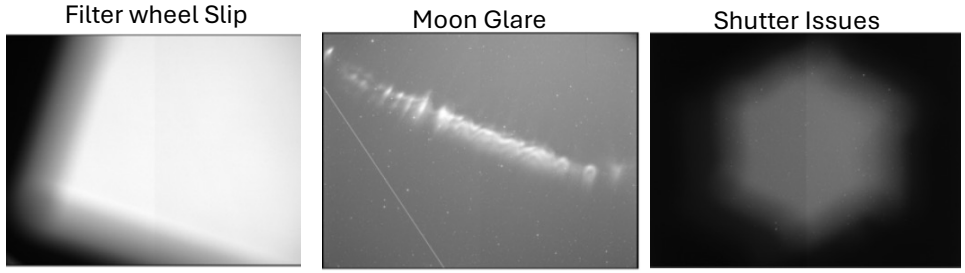
- Data inevitably gets lost: weather, hardware malfunctions, software issues, etc.
- **Data loss is a maximal latency to address**
- Most of the issues are “fixable”
- Control system is closed loop operation
- **Serinus/Canary** is **middle manager** to identify and curtail poor quality observations from full processing loop



Serinus/Canary



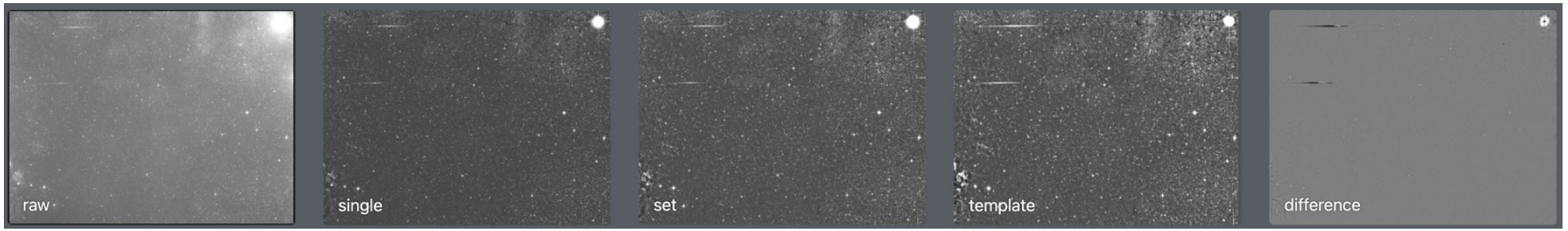




Teimoorinia et al 2021; Mong, Ackley, et al. 2022 MNRAS, *Ackley et al. in prep*

Responsive QA

- Front-end: **GOTO Canary**
  - Dashboard for overview of operational status
  - Live **nightreport** outputs
- Back-end: **Serinus**
- Systems Health Monitoring
  - Key scheduling systems: scheduler, pilot
  - Hardware Health (Camera, Mount, UPS/Power)
  - Network
  - Disk Health
  - Processing Latencies
  - …



Live nightreport output: single raw → difference

Summary

- The era of multi-messenger astrophysics is here
- Not without challenges, but already some
- impressive results, discoveries and constraints
- GOTO has transformed from concept to prototype to full-scale facility in time for O4
- It offers a versatile platform for a variety of time- domain astrophysics, GW being the priority during LVK Science Runs
- Both its responsive and sky patrol mode enables unique discovery space complementary to other facilities
- Science outputs diverse
- Discovery needs follow-up for characterisation
- *Real-time science with robots* is our motto (and volunteers and a great team)

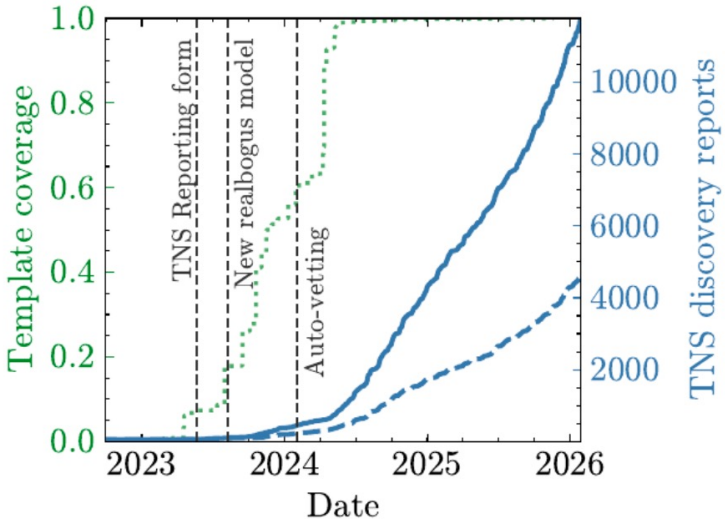
Thank you!

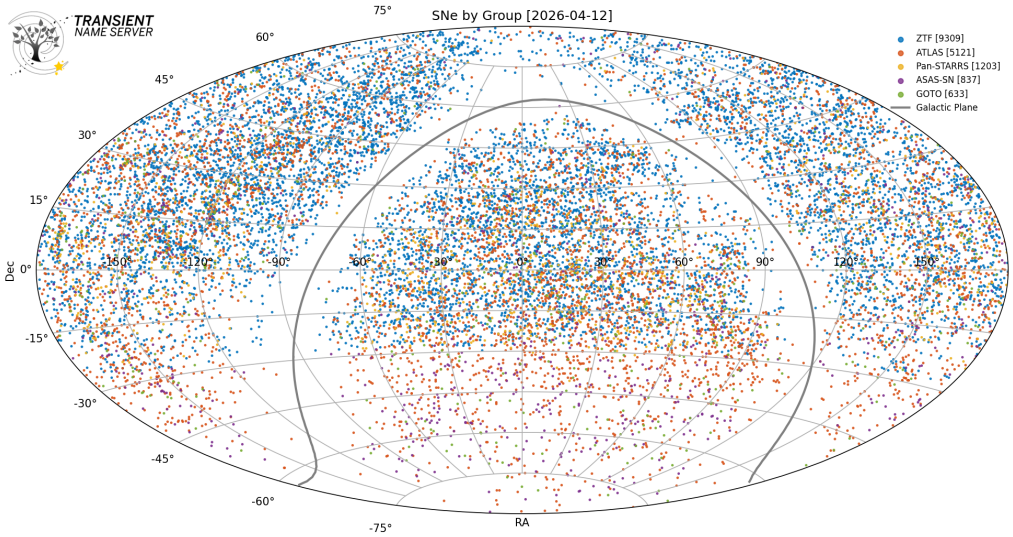
See also:
goto-observatory.org
@GOTOObservatory
http://goto-observatory.warwick.ac.uk/

kendall.ackley@warwick.ac.uk

Transient Discovery

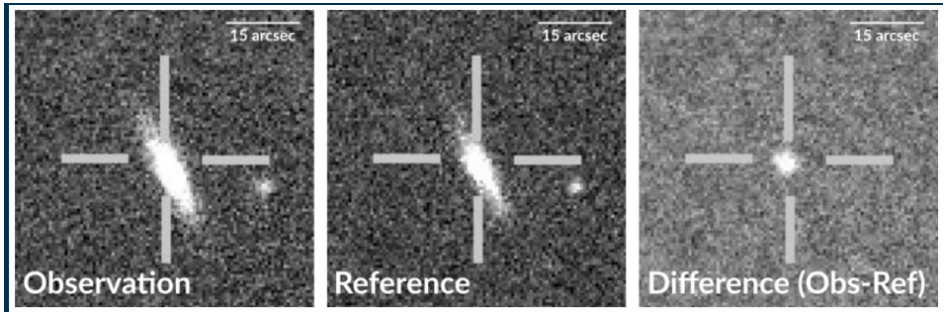
- Sky survey (2–3 day cadence): supernovae, TDEs, blazars, galactic variables, moving objects
- We are now submitting 100-1000s of candidates per month to TNS.

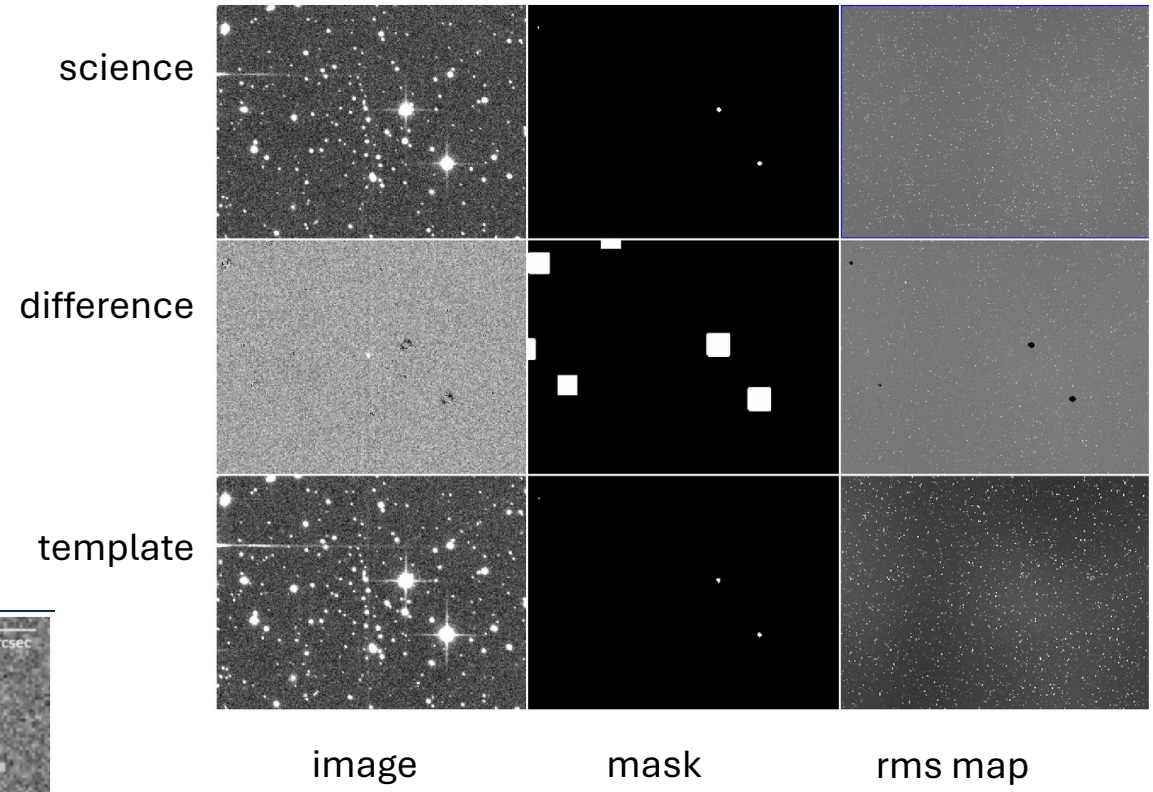




Kadmilos real-time pipeline

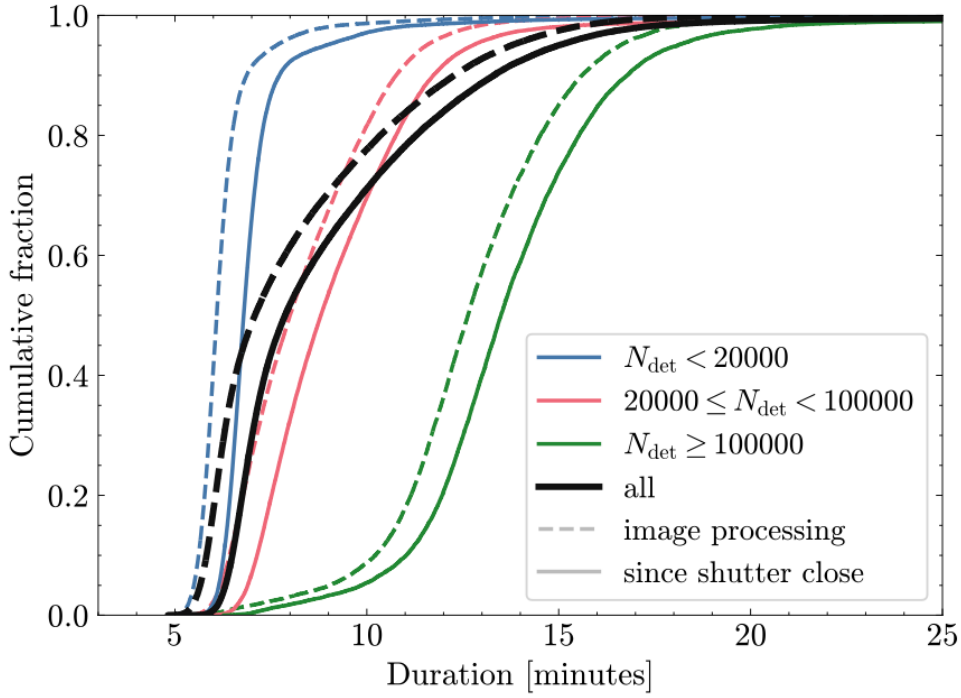
- Sets of exposures from each UT are calibrated individually, then stacked and processed.
- Archival deep-stack images are used as references to detect transient sources, though the method of difference imaging.





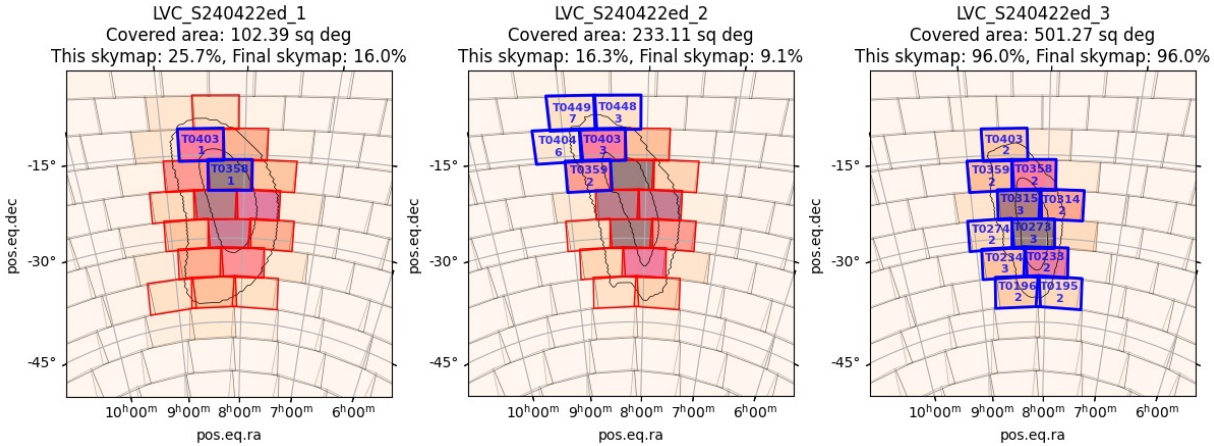
Kadmilos real-time pipeline

- **inotify** detects newly written raw FITS files
- **rawtransfer** database copies them to Warwick
- **PostgreSQL NOTIFY** triggers pipeline
- **Airflow** schedules DAGs and Celery workers
- **Marshall** adds context, associations and vetting
- Images transferred to Warwick data center:
  - ~ 0.25 PB raw data / yr
  - ~ 1.0 PB of processed data /yr
  - Rolling storage model for image-level data



Notable Event – S240422ed

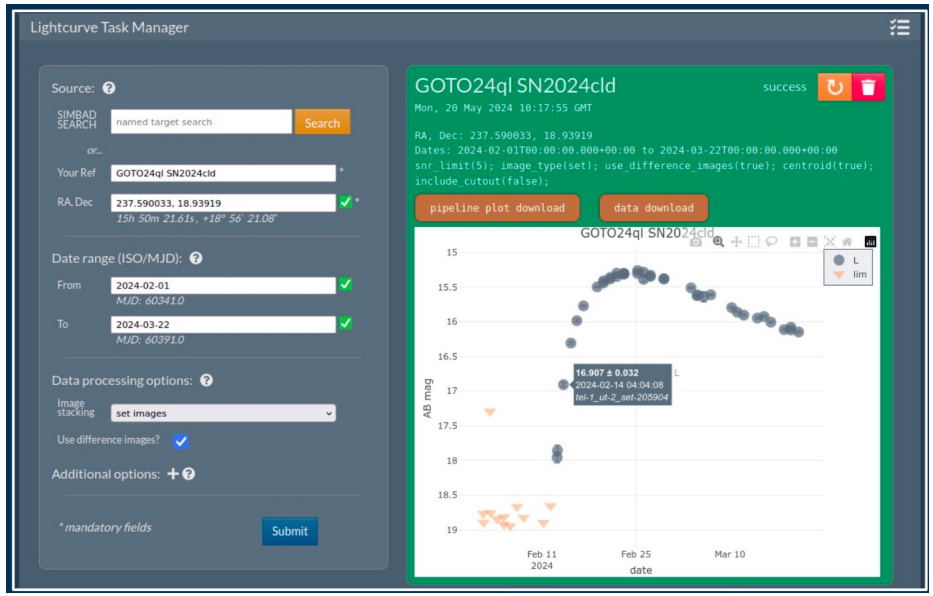
- GOTO observed 96% of the skymap area with both sites contributing.
- Observations started **within 3 minutes** of the GW alert.
- Originally classified as NSBH candidate
- **90 transient candidates** were reported to Transient Name Server



Event	Type	Coverage	First Image	Last Image
		deg^2	$t\text{-}t_0$, hrs	$t\text{-}t_0$, hrs
S240422ed	NSBH?	501.27 (96%)	0.04	85.28

Summary, Improvements & Outlook

- The GOTO network is operational, with 4x8 telescopes (2x8 north, 2x8 south), FoV of 44 sq deg, depth ~20 mag, covering the sky every 2-3 days.
- Archival searches on the **163 observed GW alerts** ongoing.
- Software improvements and hardware improvements will point us toward greater real-time multi-messenger discovery potential
  - **Responsive software** for real-time quality adjustments
  - Currently working on a forced photometry web/API service to make **GOTO data publicly available**
  - **Upgrades** planned for CMOS sensors and additional filters



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