Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA) with Gravitational-Wave and High-Energy Neutrino Candidates

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Abstract

We summarize the online data analysis pipeline that was used in the multi-messenger search for common sources of gravitational waves (GWs) and high-energy neutrinos (HENs) during the second observing period (O2) of Advanced LIGO and Advanced Virgo. **Beyond providing added scientific insight into source events, low-latency coincident HENs can offer better localization than GWs alone**, allowing for faster electromagnetic follow-up. Transitioning GW+HEN analyses to low-latency, automated pipelines is therefore mission-critical for future multi-messenger efforts. The O2 Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA) also served as a proof-of- concept for future online GW+HEN searches and led to a codebase that can handle other messengers as well. **During O2, the pipeline was used to take LIGO/Virgo GW candidates as triggers and search in realtime for temporally coincident HEN candidates provided by the IceCube Collaboration** that fell within the 90% confidence region of the reconstructed GW skymaps. The algorithm used NASA's Gamma-ray Coordinates Network to report coincident alerts to LIGO/Virgo's electromagnetic follow-up partners. See papers in the select bibliography [1, 2] for a full list of relevant references.

Introduction

Recent multi-messenger discoveries of GWs in coincidence with electromagnetic (EM) observations have opened up new windows to the Universe:

1. The detection of a short gamma-ray burst (sGRB) 1.7 seconds after the GW detection from a binary neutron star (BNS) merger on August 17, 2017 (**GW170817**) was the first multi-messenger/multi-wavelength observation of GWs. The LIGO/Virgo detectors recorded the GW170817 signal, which was followed by the detection of spatially-and-temporally coincident GRB 170817A by Fermi-GBM and INTEGRAL. This event was subsequently followed up by several different observatories in a broad range of wavelengths and cosmic messengers.
2. The detection of a high-energy neutrino (HEN; IceCube-170922A) by the IceCube Neutrino Observatory, which is the first 3σ correlation with EM emissions from a flaring blazar, **TXS 0506+056**. This confirms that HENs are produced by cosmic accelerators such as blazars.

These two recent multi-messenger discoveries enable us to better understand and explore the origin of cosmic particles, the astrophysical mechanisms that produce them, and the physical implications of their sources.

Advantages of a GW+HEN Online Search

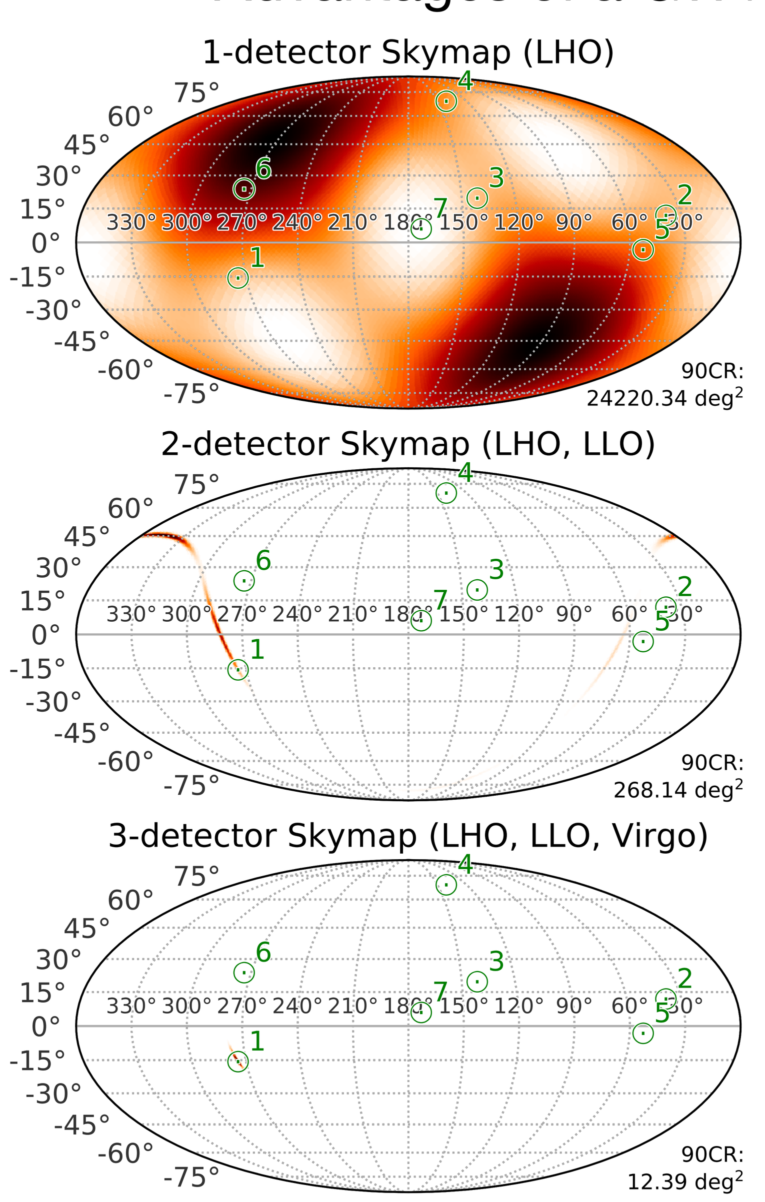

Fig. 1. Simulated joint detection skymaps for 1, 2, and 3 GW detectors from a BNS merger. The darkest regions are the likeliest GW source directions; sizes of the 90% credible regions are noted at bottom right. The neutrinos are located at the green dots (surrounding circles added for emphasis). The localization of neutrino 1 is vastly superior to the GW alone, particularly with fewer GW detectors.

LLAMA's low-latency joint GW+HEN event search, a first of its kind, was enabled to respond to new event candidates during O2. Its rapid analysis and alert distribution offer advantages over previous offline GW+HEN searches:

1. Improved localization with neutrinos. The GW search area size is a limiting and costly factor in the speed of EM follow-up efforts for all but the highest energy photons. Coincident neutrinos can provide far superior localization, shortening searches and allowing EM observations to start immediately:
   - GW skymaps: 10s-1000s of [deg²]
   - GW+HEN: 0.5 [deg²]
   - Typical optical telescope viewing area: <10 [deg²]

   Providing rapid joint localization was a primary goal of the GW+HEN pipeline during O2 (Fig. 1).
2. **Low-latency sub-threshold search.** In principle, sub-threshold GW and neutrino triggers can be run through a joint analysis with the intention of finding events whose significances are high enough that the resulting multi-messenger event candidates exceed the detection threshold. Doing a sub-threshold search in low-latency enables EM follow-up on such triggers, an opportunity missed by offline sub-threshold searches. *LLAMA did not run an online sub-threshold search during O2, but its sub-threshold triggering features were successfully tested during that run.*
3. **Automation needed for higher event rate.** Event rates for both GW and neutrino searches are expected to climb in the coming years. Automation will be necessary to avoid analysis backlogs.

Analysis Method

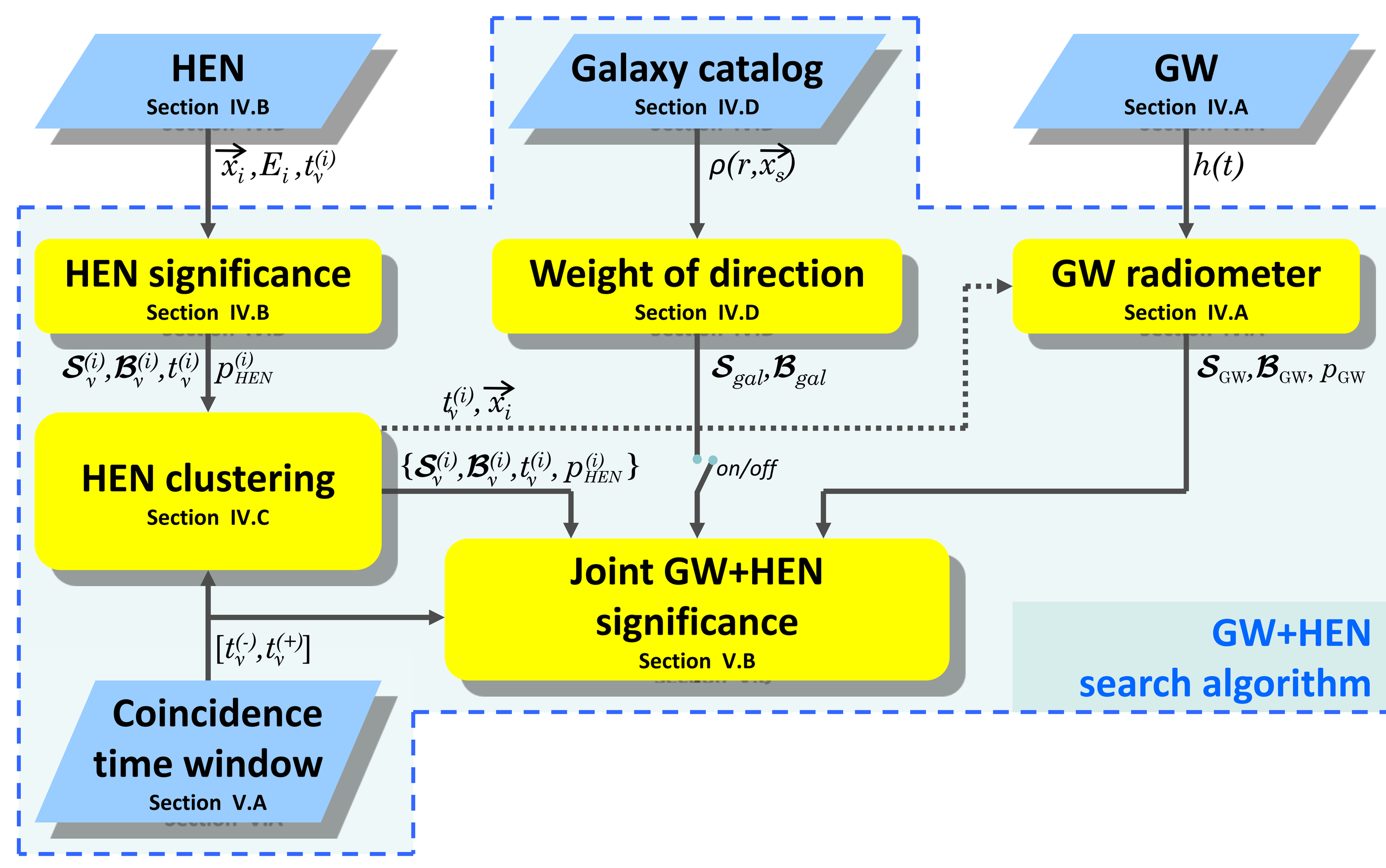

Fig. 2. During O2, LLAMA used a modified version of the Baret et. al [1] analysis method, a minimally-modeled search accounting for spatial and temporal overlap of GW and HEN triggers. The galaxy catalog capabilities were turned off due to the lack of reliable catalog data out to LIGO/Virgo's maximum observing distances.

The analysis method used in this paper was an up- graded version of Baret et al. [1] (Fig. 2). A HEN event, provided by the IceCube Collaboration, was automatically internally marked as coincident with a GW if it was detected within the t_{GW} ± 500s time window (where tGW is the time of the GW event) and if any region of the GW's 90% confidence region had a neutrino signal likelihood density greater than 10−4 deg−2. The likelihood was calculated as ratio of the GW+HEN signal and background skymap products (see [1, 2] for details):

$$\mathcal{L}(\vec{x_s}) = \frac{\mathcal{S}_{\mathrm{GW}}(\vec{x}_{\mathrm{s}})\mathcal{S}_{\nu}(\vec{x}_{\mathrm{s}})}{\mathcal{B}_{\mathrm{GW}}\mathcal{B}_{\nu}}$$

Data Flow to and from LLAMA

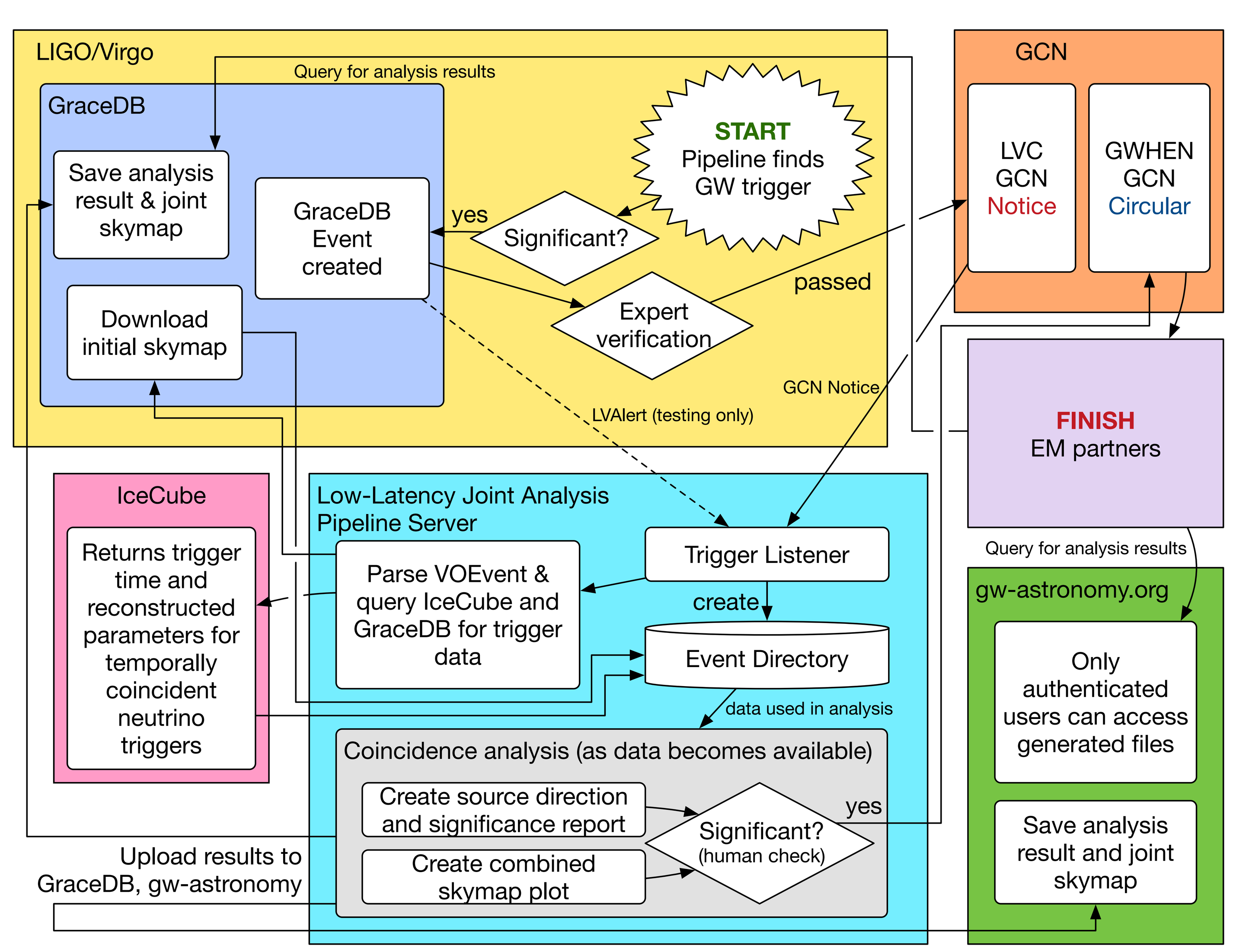

Fig. 3. Information flow in the pipeline. This diagram shows trigger and data sources and destinations used during O2, though the pipeline itself can readily accomodate new sources and destinations for both.

LLAMA relied on LIGO/Virgo and IceCube data for input; GCN (as an intermediary) for GW triggers; LIGO/Virgo and gw-astronomy.org for result storage; and GCN for dissemination of results (via GCN Circular) to EM followup partners (Fig. 3). LLAMA received and parsed VOEvents from promising LIGO/Virgo GW candidates (received through GCN Notices), used the metadata they contained to fetch GW and neutrino localizations from LIGO/Virgo and IceCube, and then used those localizations to run the joint analysis. Data products from the joint analysis (in the form of a joint skymap and neutrino candidate data) were uploaded to GraceDB and gw-astronomy.org to facilitate data archiving and access by EM followup partners [3].

Target Timeline for an Online Search

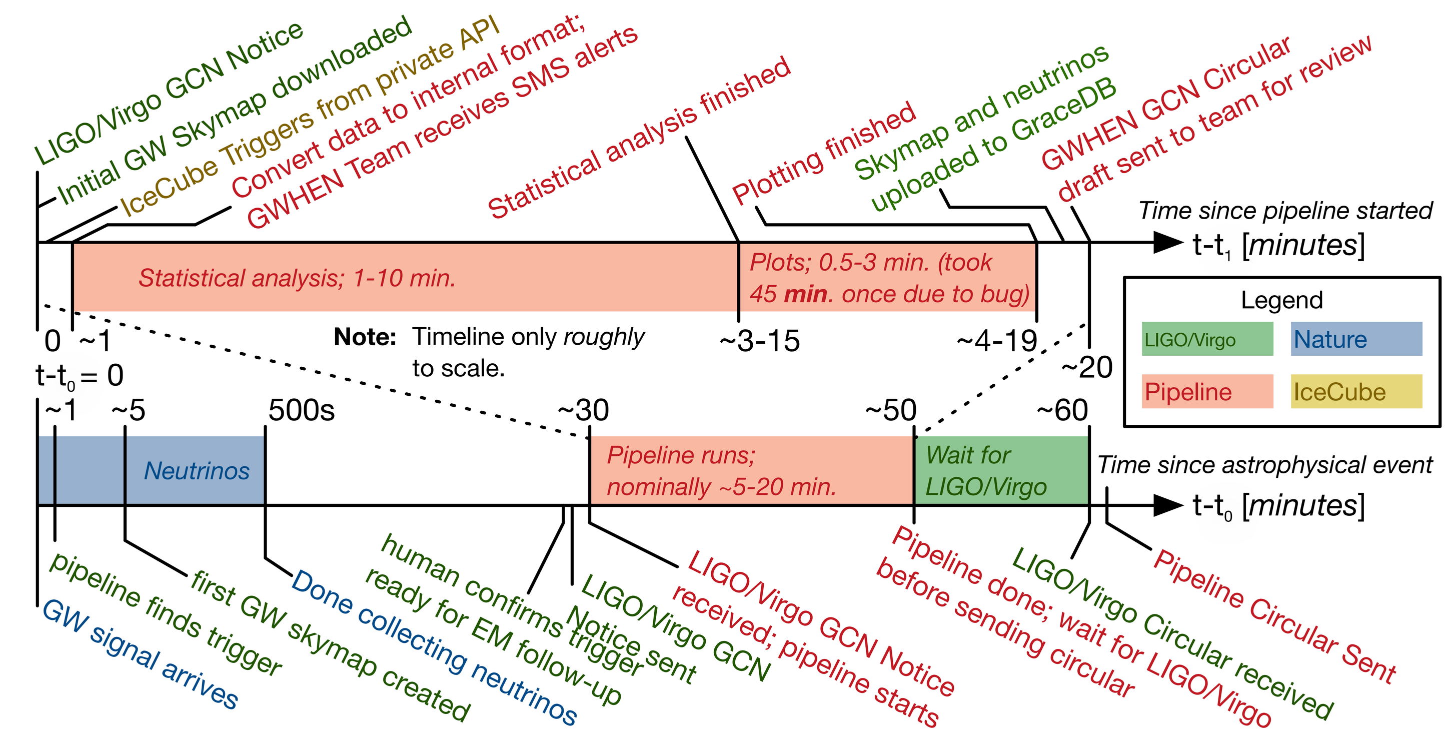

Fig. 4. A typical timeline for LLAMA's GW+HEN follow-up of a LIGO/Virgo trigger.

During O1 and O2, there was typically a latency of 30+ minutes between LIGO/Virgo GW trigger identification and alert dissemination via a GCN *Notice* describing the GW event in VOEvent format (Fig. 4), mostly due to human-in-the-loop data quality checks. After each VOEvent GCN Alert, a human-readable GCN *Circular* would follow after a time period of half an hour or greater. The O2 multi-messenger pipeline would typically run to completion during the window between LIGO/Virgo GCN Notice and Circular. It then disseminated results in the form of a separate human-readable GCN Circular sent out after the LIGO/Virgo GCN Circular.

Pipeline Architecture

The O2 pipeline was mostly implemented as a Python library [2], with steps in the pipeline (and their dependencies on one another) explicitly described in software by a Directed Acyclic Graph (DAG) (Fig. 5). Two Python scripts (`gcnd`, which acquired triggers, and `gwhend`, which executed DAG steps) continuously processed incoming events. See [2] for a full description.

This approach accomplished LLAMA's design goals and provided many valuable features:

- High reliability
- Trivial extensibility
- Full reproducibility
- Clear design (thanks to limited, explicit relationships between analysis steps)
- Ability to stop and restart at any time
- Ability to start processing external data in whatever order they became available
- Dual online/offline analysis capabilities

The LLAMA library's powerful features (including features not listed here; see [3] for up-to-date post-O2 developments) and proven reliability make it a promising foundation for future low-latency multi-messenger studies. The authors hope to use it again for GW+HEN (and other) follow-up campaigns in O3 and beyond.

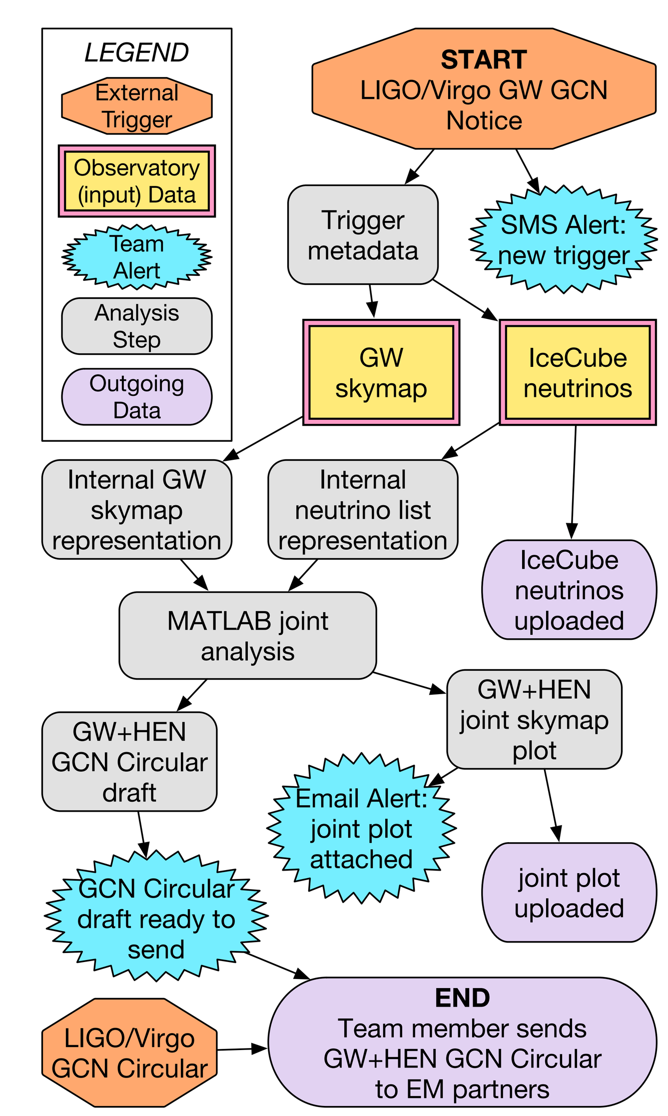

Fig. 5. Analysis steps as a DAG. Each node corresponds to an output file. External triggers are created outside the pipeline but stored and used internally. LLAMA will repeatedly try to fetch observatory data if not available. Team alerts are used internally. Outgoing data are uploaded to GraceDB and gw-astronomy.org.

1. B. Baret *et al.*, Phys. Rev. D 85, 103004 (2012) <http://dx.doi.org/10.1103/PhysRevD.85.103004>.
2. S. Countryman *et al.*, arXiv, 1901.05486 (2019) <https://arxiv.org/abs/1901.05486>.
3. S. Countryman and K.R. Corley, LLAMA Documentation (2019) <http://multimessenger.science>