Low Latency gravitational wave alerts of the advanced LIGO and Virgo collaboration

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The New Era of Multi-Messenger Astrophysics
SCIOPS, Nov, 2019
Sources can be transient or of continuous nature, and can be modeled or unmodeled

**LIGO-Virgo analyses for sources of gravitational waves**

- **Coalescence of Compact Sources** (e.g. black holes, neutron stars)
  - EM: Short GRBs, Kilonova

- **Burst**
  - Asymmetric core collapse supernovae
  - EM: supernovae emission, long GRBs

- **Continuous Waves**
  - Rapidly rotating neutron stars (with lumps on them)

- **Stochastic**
  - A stochastic, unresolvable background (from the Big Bang, or all of the above)
Multi-messenger astronomy with LIGO/Virgo: since 10 years!

**Triggered Analysis**

Search that uses EM or neutrino observations to drive the detection of GWs

- GRB prompt emission, SN explosion in local galaxies, flares SGR, pulsar glitches, low and high energy neutrino
- Known event time and sky position
- Reduction in search parameter space for GW searches
- Gain in search sensitivity

**Coincidence Search**

Compare sets of candidates events

**EM Follow-up**

Search EM/neutrino counterpart candidates after GW identification
GW170817 multi-messenger discovery

Multimessenger Bayesian parameter inference of a binary neutron star merger, Coughlin et al., 2019

A gravitational wave standard siren measurement of the hubble constant, LVC et al., 2017
14 alerts sent during O2, 6 confirmed!
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it.

Virgo allowed source location via triangulation.

Low latency gravitational wave alerts for multi-messenger astronomy during the second advances LIGO and Virgo observing runs APJ, 2019.
O3 observational campaign, starting April 2019

O3a summary status
V1: 50 Mpc - H1: 100 Mpc - L1: 140 Mpc

O3a summary status
Triple duty cycle (45%) compared to 60% during the August 2017
O3 observational campaign: Rate and Prospects

Anticipated GW sky localization for CBC signals during O3 and O4. Up: Cumulative fractions of events with sky-localization area, luminosity distance smaller than the abscissa value.

Around 10% of the event having a 90% credible region smaller than 20 deg².
The 90% median credible region is 250-340 deg².

O3 aLIGO 110 – 130 Mpc, AdV 50 Mpc, KAGRA 8 – 25 Mpc
The BNS search volume V is $2.5 \times 10^6$ Mpc³ yr
2 (+8 −2) expected BNS detections
O3 LIGO-Virgo PUBLIC alerts

GCN Notice times after a gravitational-wave signal

- Original Detection
- Set Preferred Event
- Automated Vetting
- Classification
- Rapid Localization

- Parameter Estimation
- Human Vetting
- Classification

Initial Alert or Retraction Sent

- Parameter Estimation
- Classification

Update Alert Sent

10 second  1 minute  1 hour  1 day  1 week
Low latency R&D infrastructure team

- Erik Katsavounidis
- Shaon Ghosh
- Stuart Anderson
- Deep Chatterjee
- Giuseppe Greco
- Shasvath Kapadia
- Soichiro Morisaki
- Alex Pace
- Roberto de Pietri
- Brandon Piotrzkowski
- Leo Singer

With the support of many others including Data analysis groups and Detchar groups
Alert Generation

- Several pipelines, each can make several detections with **1-min latency**
  - Modeled searches: GstLAL, PyCBC, MBTA, SPIIR
  - Unmodeled searches: OLIB, cWB
- Detection FAR:
  - CBC: 1 event / 2 months
  - Burst: 1 event / year
- Based on a given criteria, one is chosen as being the **Preferred Event** starting with **BIG S** for **Superevent** for the public alert (criteria depends on the type of search but also number of interferometers involved)
Automatic alert vetting

Before sending the GCN notice

- Check if the basic status of the IFO are ok
- If there is no injection

Medium latency tools
Omega and Omicron scans

Human vetting to estimate if a glitch
- may mimic a GW candidate
  → alert retraction
- may bias the candidate properties
  → alert update
Human Vetting

Classes in the Gravity Spy dataset

Machine learning for Gravity Spy: Glitch classification and dataset
# GCN Notices content

Alert notices send within 5-10 minutes with:
- delivery of a first skymap
- False Alarm Rate
- Classifiers of the nature of the source

Initial notices sent after validation
Updates notices sent couple of hours later

Visible as well on gracedb public page

<table>
<thead>
<tr>
<th>Root</th>
<th>1vo://nasa.gsfc.gcn/LVC#{{T,M}}SYMONDrbc-(-1,2,3)-{Preliminary,Initial,Update,Preliminary-Retrac}</th>
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<td>IVORN</td>
<td>{observation,test}</td>
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<tr>
<td>Who</td>
<td></td>
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<tr>
<td>Date</td>
<td>Time sent (UTC, ISO-8601), e.g. 2018-11-01T12:34:49</td>
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<tr>
<td>Author</td>
<td>LIGO Scientific Collaboration and Virgo Collaboration</td>
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<tr>
<td>WhereWhen</td>
<td>Time of signal (UTC, ISO-8601), e.g. 2018-11-01T12:22:22:45.654437</td>
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<td>Notice Type</td>
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<td>Sky Map</td>
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<tr>
<td>Duration</td>
<td></td>
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<tr>
<td>Fluence</td>
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<tr>
<td>BNS, NSBH, BBH, Noise</td>
<td>Probability that the source is a BNS, NSBH, BBH merger, or terrestrial (i.e., noise) respectively</td>
</tr>
<tr>
<td>HasNS, HasRemnant</td>
<td>Probability, under the assumption that the source is not noise, that at least one of the compact objects was a neutron star, and that the system ejected a nonzero amount of neutron star matter, respectively.</td>
</tr>
</tbody>
</table>
Machine Learning Base: A self-consistent method to estimate the rate of compact binary coalescences with a Poisson mixture model, Kapadia et al, 2019
“EM bright” the binary is expected to have at least one neutron star (NS) component

Predictions of the trained binary classifier upon performing a parameter sweep on the \((m_1, m_2)\) values.
Parameters estimations

Bayesian parameter estimation Markov Chain Monte Carlo (MCMC) or Nested sampling

15 parameters (2 Masses, Lum Distance, Inclination angle, …)
Frequency Domain vs Time Domain with different post-newtonian waveforms and EOS for BNS or NSBH
O3a-b alerts summary

48 public GW alerts

- 6 BNS
- 4 NS-BH
- 25 BBH mergers candidates
- 13 retractions

FINAL CONTENT MAY DIFFER!
Low latency parameters estimations

NS-BH and BNS merger candidates (DL < 350 Mpc)

- S190425z
- S190510g
- S190814bv
- S190901ap
- S190910h
- S190930t

BBH merger candidates (DL < 1000 Mpc)

- S190930s
- S190924h
- S190728q
- S190720a
- S190707q
- S190503bf
- S190412m

Sky localization area (50 and 90 c.r init and upd) deg. sq.
GCN traffic during O3a

LIGO-Virgo candidates currently generate ~50% of GCN circular traffic
Traffic is getting lower ...

- S190425z (BNS) and S190814bv (NSBH) generated ~120 circulars
- S190728q (MassGap then BBH) generated ~40 circulars
- Fermi GBM-190816 generated ~20 circulars
Who is following the alerts?

30% of the GCN traffic is due to gamma-ray observations.

14% by GRANDMA, GROWTH, MASTER and GTC follow-up.

8% from neutrino and high energy observations.

40% by other groups as radio or optical teams.
What is new in O3b?

Two preliminary alerts (for most of the events) sent via GCN to observing partners.

- The first will be sent out as soon as we have a publishable event with all relevant data products that we share.
- Upon receipt of first preliminary, the second preliminary alert generation process will be launched after a timeout.
- Accumulating and revising the preferred event.
- A second preliminary GCN will then be sent, even if the preferred event did not change.

If the event is retracted before second preliminary, no further second preliminary notice will be sent. Only a retraction GCN will be sent.

Unexpected/Exceptional situation: A manual preliminary alert triggered by human before Initial Notice. Help potential time-sensitive case
What is new in O3b?

RAVEN alert system online

- Automated alerts for coincident GW candidates associated with a GRB or SNEWS event (RAVEN pipeline).
  - GW candidates that may not be significant on their own
  - Have an associated GRB or supernova
  - Resulting increases in joint significance to meet the current established threshold.
- RAVEN-specific preliminary GCN Notice under work; expected development by November.
  - Until then a preliminary LIGO-Virgo GCN notice would be sent.
- Containing usual data products: GW sky-maps; classification & properties.
- The association will be clarified in the following GCN circular.
Perspectives

Toward real time gravitational wave astronomy
● Alerts produced during the inspiral sequence?
● Robustness of the low-latency classifiers for low masses objects
● Easing digestion of the multiple pipelines search “Super-event”

Toward sub-threshold event alert distribution
● Single of Multiple IFOs in coincidence with EM signal?

Toward a 4-detector network

Toward a multi-messenger searches
Extension of RAVEN to other Gamma-ray surveys and neutrinos
Targeted searches case by case
Question of X-ray/Optical surveys under debate (estimation of GW T0 emission)

Infrastructure linked to alerts in O4 and beyond connected to a new/update alert broker?