Multi-messenger searches via IceCube's high-energy neutrinos and gravitational wave detections of LIGO/Virgo

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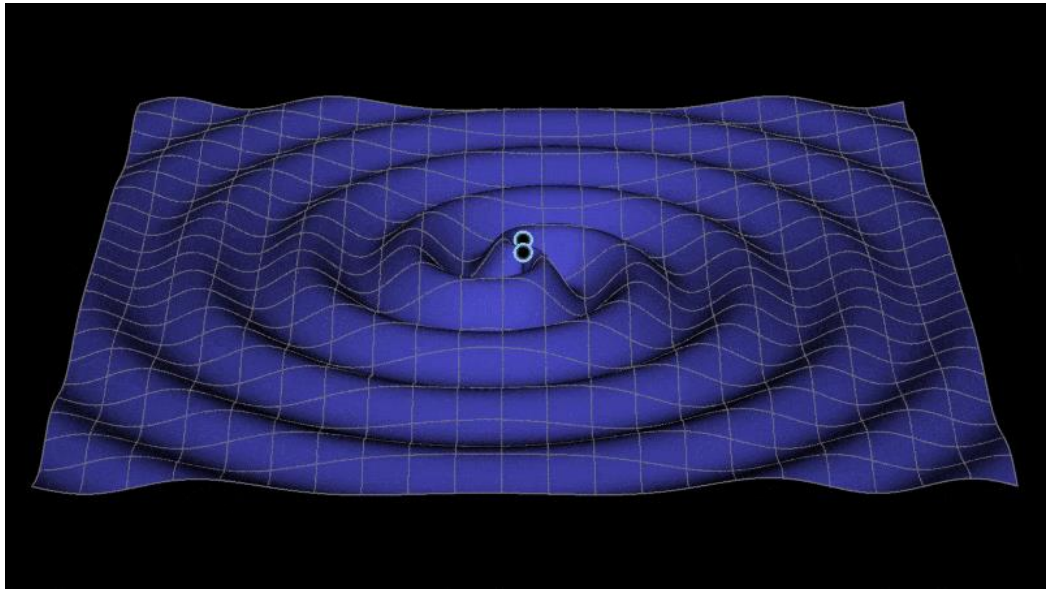
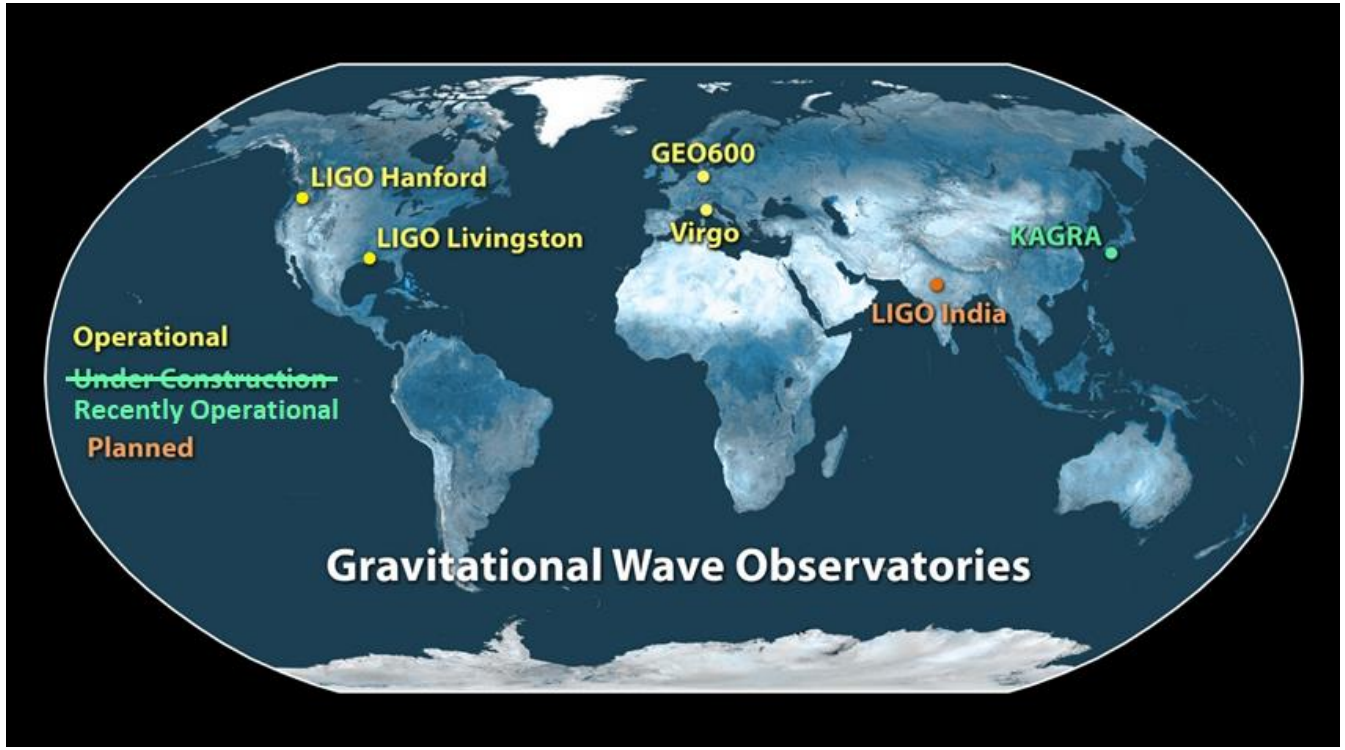
Common sources of gravitational waves (GW) and high-energy neutrinos (HEN)

- Need a changing quadrupole moment for GW emission
  - Binary orbiting systems, non-symmetric ejecta
- Need an energetic flow of matter, for high-energy neutrinos
  - i.e. from decay of photo-mesons created in AGN jets or GRBs
- Most probable (proposed) GW-HEN sources are
  - Binary neutron stars (a potential kilonova)
  - Binary neutron star-black holes
  - Binary black holes with an accretion disc
  - Core collapse supernova
  - …



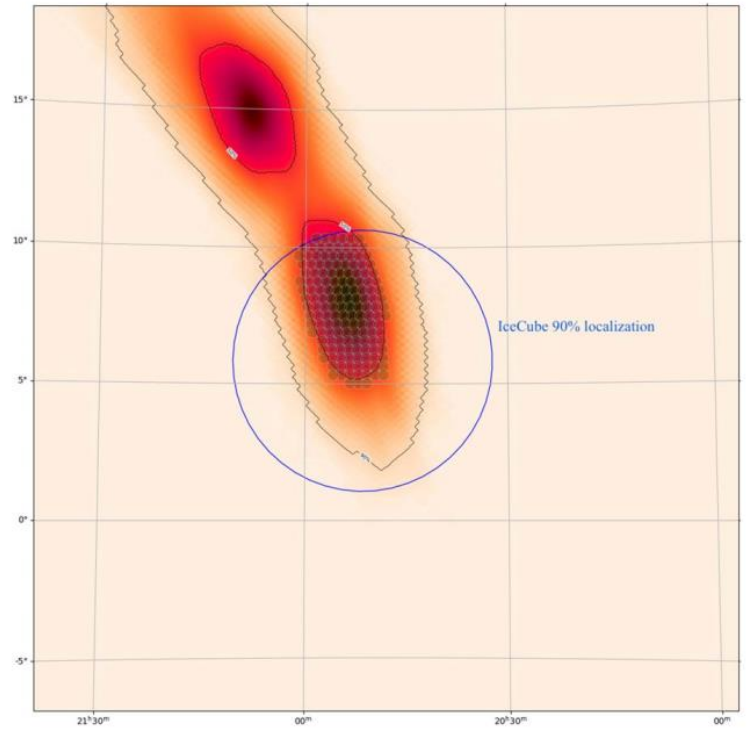
Gravitational wave detector network



- Detectors with different sensitivities
- Detections so far are from LIGO and Virgo detectors
- A network of detectors is important for sensitivity and localization

Search for joint gravitational wave and high-energy neutrino events

- Learn more about the processes before, during and after the event
- Guide astronomers in low latency with better localization
  - GW skymaps can range $\sim 10 - 10^4\ \mathrm{deg}^2$
  - High-energy neutrino localization $\sim 0.1 - 10\ \mathrm{deg}^2$
  - Even smaller overlap with GW and HEN for astronomy follow up



Swift follow-up for the neutrino coincident with S190728q. Keivani et. al. ApJ 2021

Two analyses for the high energy neutrino follow-up

Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA)

- Test statistic calculates odds ratio for a common source by including astrophysical emission priors in order to use the distance information from the GW detection

Unbinned Maximum Likelihood (UML)

- Test statistic uses the best fit for the signal neutrino count and spectral index

- Both analyses look for neutrinos ±500s around the GW event.
- At the end a frequentist p-value is found
  - Background distributions for UML are calculated for each skymap
  - LLAMA uses pre-computed background distributions for different source types for using the distance info considering GW detectors sensitivity to each source type
- Extended search (until 14 days after the merger) for binaries containing neutron stars.

Realtime search during O3 with IceCube

- Combined run of 2 LIGO detectors and Virgo detector
  - 1 year planned run, suspended 1 month before completion
- Performed a low-latency search after each open public alert (OPA) from GraceDB. Alerted the community through GCNs.
  - Total of 56 non-retracted alerts
- 3 events with <1% p-value
  - S190728q (BBH)
  - S191216ap (BBH)
  - S200213t (BNS)
- Coincident neutrino candidates triggered searches from different observatories including HAWC, Swift…

```
TITLE:   GCN CIRCULAR
NUMBER:  25210
SUBJECT: LIGO/Virgo S190728q: Third update on neutrino search with IceCube
DATE:    19/07/28 22:28:20 GMT
FROM:    Raamis Hussain at IceCube  <raamis.hussain@icecube.wisc.edu>

IceCube Collaboration (http://icecube.wisc.edu/) reports:

This is an update of GCN 25197 including updated p-values for the map
circulated in the 5-Update GCN notice.
```

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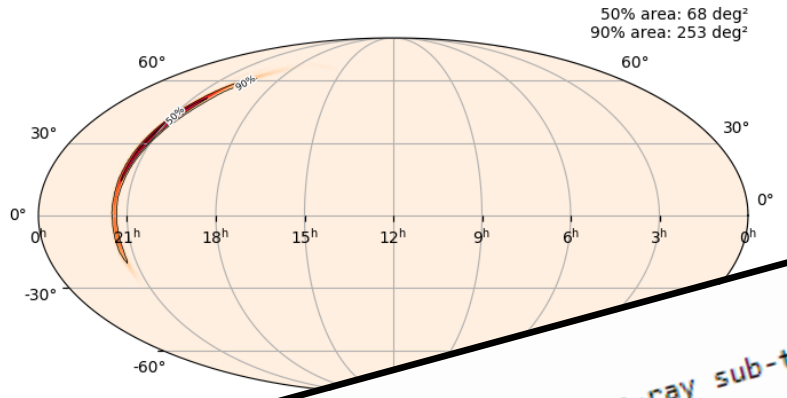
Properties of the coincident events are shown below.

   dt|ra (deg)|dec (deg)|Angular Uncertainty(deg)|p-value
(bayesian)|p-value(generic transient)
-----+--------+---------+-----------------------+-----------------+-----------
 -360|312.87  |5.85     |4.81                   |0.010            |0.016
```

Case study: S191216ap

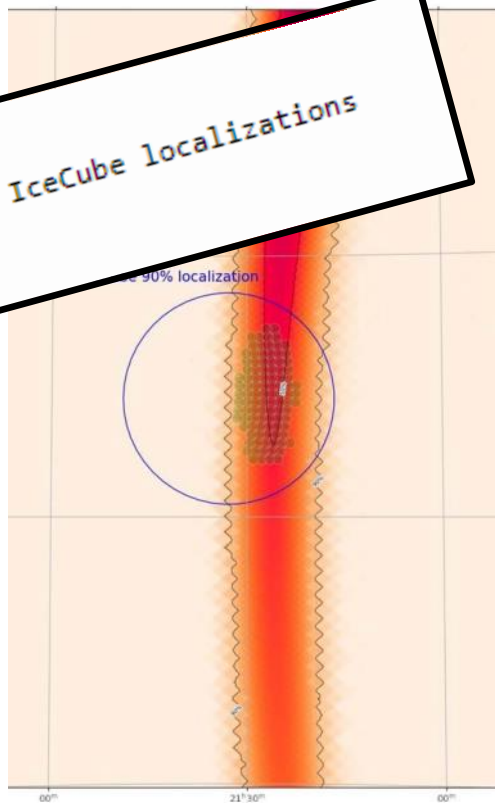


Localization from gracedb.ligo.org

TITLE: GCN CIRCULAR
NUMBER: 26472
SUBJECT: LIGO/Virgo S191216ap: HAWC gamma-ray sub-threshold event coincident with LIGO/Virgo and IceCube localizations
DATE: 19/12/17 13:54:23 GMT
FROM: Israel Martinez-Castellanos at UMD/HAWC <imc@umd.edu>

- eutrino candidate
- p-value ~0.6% in LLAMA search
- p-value ~10% in the UML search

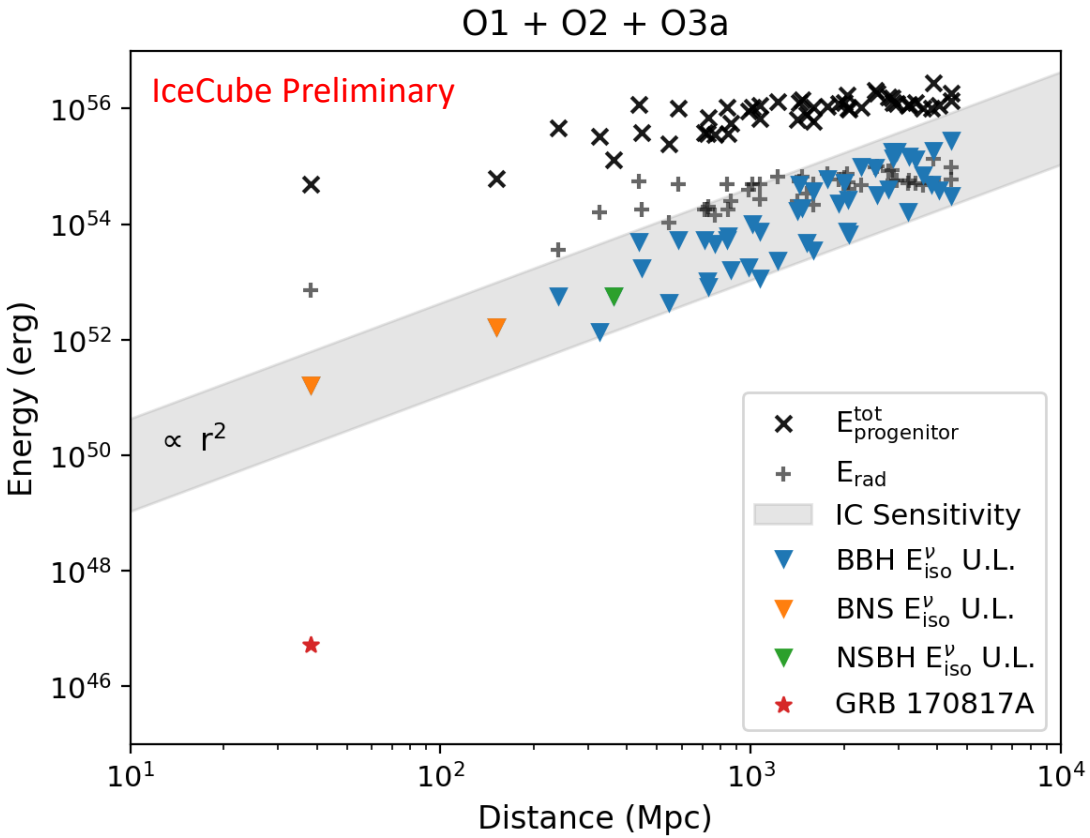
How to Search for Multiple Messengers—A General Framework Beyond Two Messengers
DV et al., ApJ **908** 216 (2021)



Swift follow-up for the neutrino coincident with S191216ap. Keivani et. al. ApJ 2021

Offline searches

- **O1-O2**
  - Analyzed 10 BBH and 1 BNS merger from LIGO-Virgo's first gravitational wave transients catalog GWTC-1
  - Aartsen et al., ApJL **898** L10 (2020)
  - No significant neutrino counterpart is found with the most significant having p-value 16%.
- **O3a**
  - 33 OPA alerts – 7 OPA alert retractions + 13 new offline events = 39 catalog events in GWTC-2
  - Lowest p-value is 1.2%, not significant considering the total number of events
  - 2 week follow-up on GW190425, GW190426_152155 and GW190814 also did not show significant results.



- Lowest E_{iso} 90% U.L belongs to GW170817 as 1.7×10^{51} ergs, due to it being the closest at 40 Mpc

Concluding remarks

- Searching for common sources of gravitational-waves and high energy neutrinos
- No discovery yet
- Guiding astronomers with real-time follow-ups