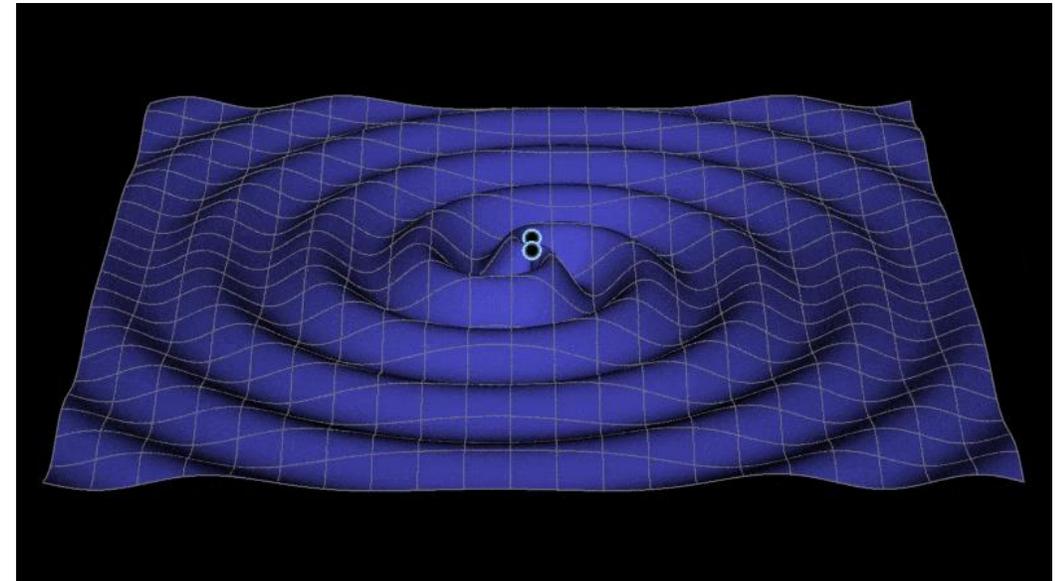
A black hole with a glowing accretion disk and a blue jet of light. The background is a dark, starry space with a galaxy visible in the upper left.

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

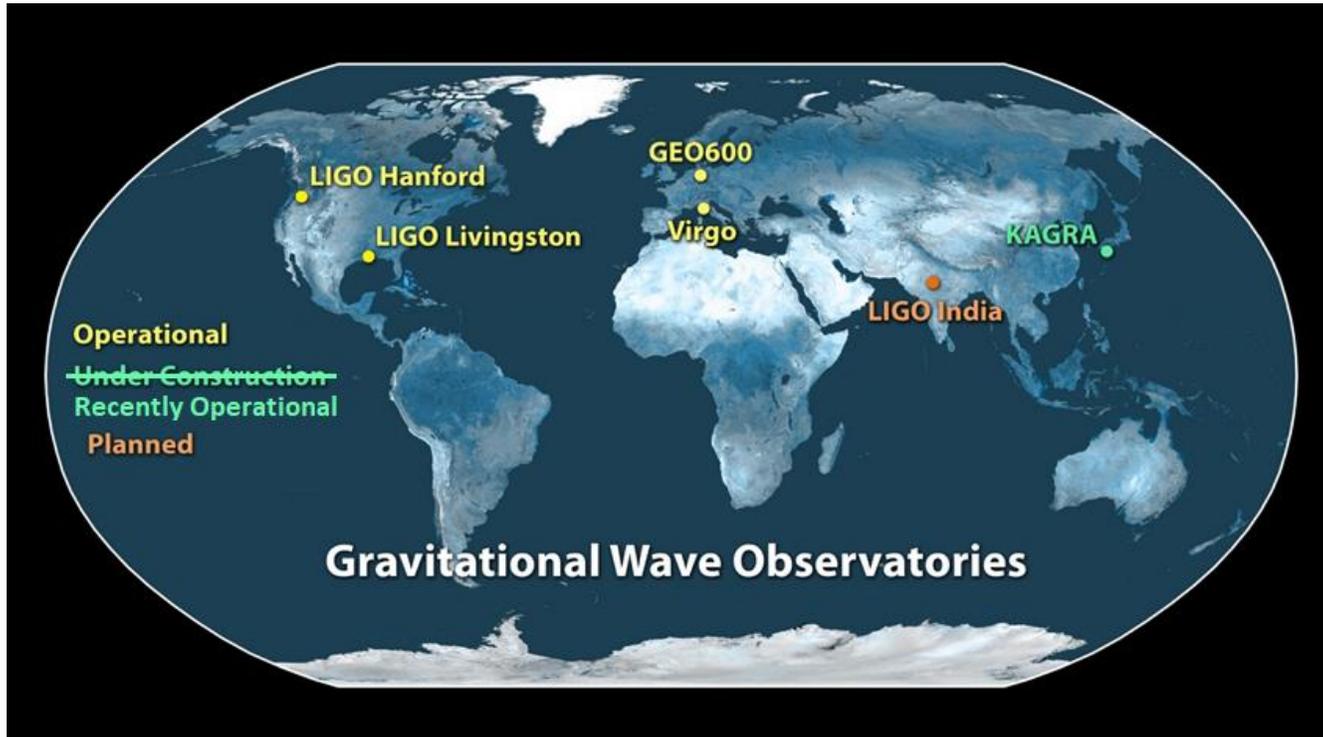
Dođa Veske for the IceCube Collaboration

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
 - ...



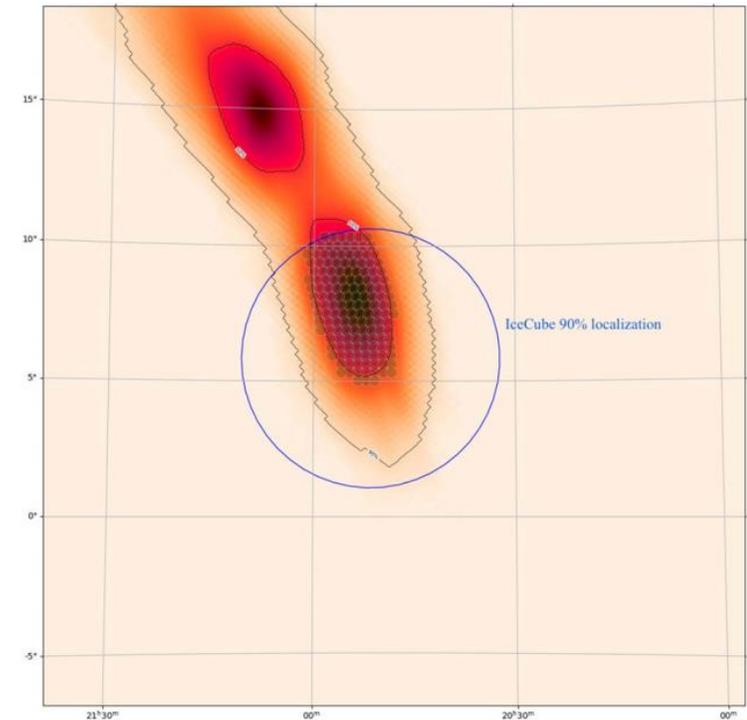
Gravitational-wave detector network



- 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 $\sim 10 - 10^4 \text{ deg}^2$
 - High energy neutrino localization $\sim 0.1 - 10 \text{ deg}^2$
 - 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 ± 500 s 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

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)
- Released neutrinos 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>
```

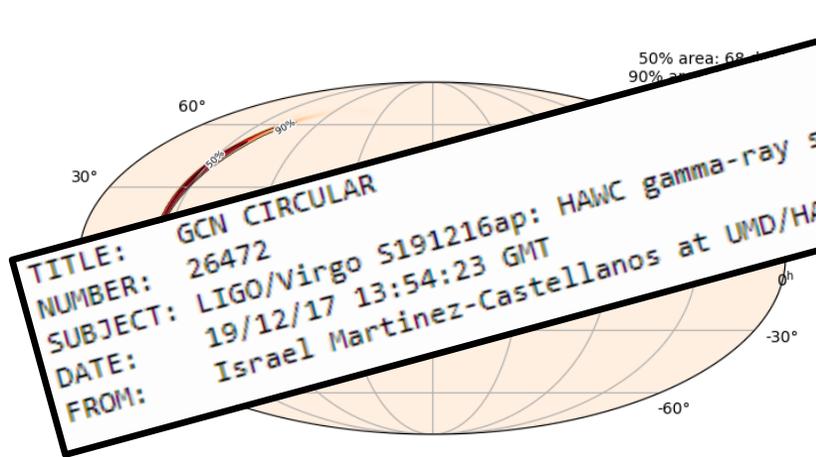
IceCube Collaboration (<http://icecube.wisc.edu/>) reports:

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

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

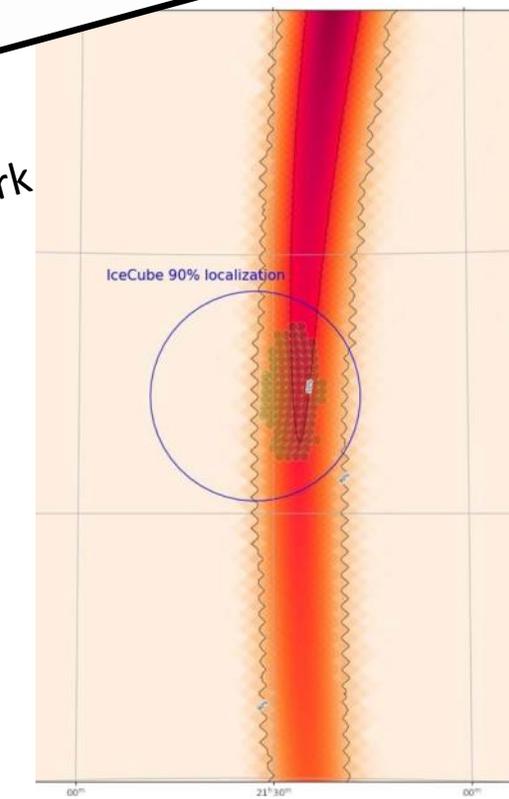
Case study: S191216ap



Localization from
gracedb.ligo.org

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

- A “close” BBH merger ~ 376 Mpc
- One significant neutrino
- p-value $\sim 0.6\%$ in LLAMA search
- p-value $\sim 10\%$ in the generic transient search



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

Offline searches

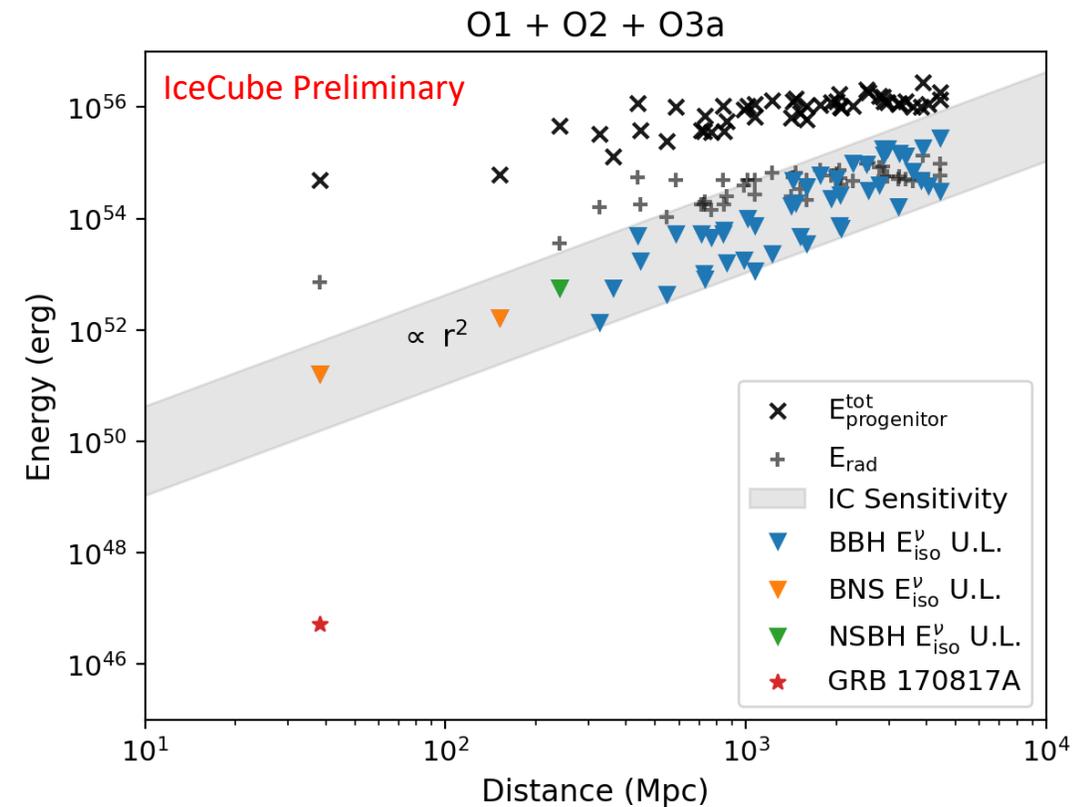
• O1-O2

- 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

- 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 decisive discovery yet
- Guiding astronomers with real-time follow-ups

