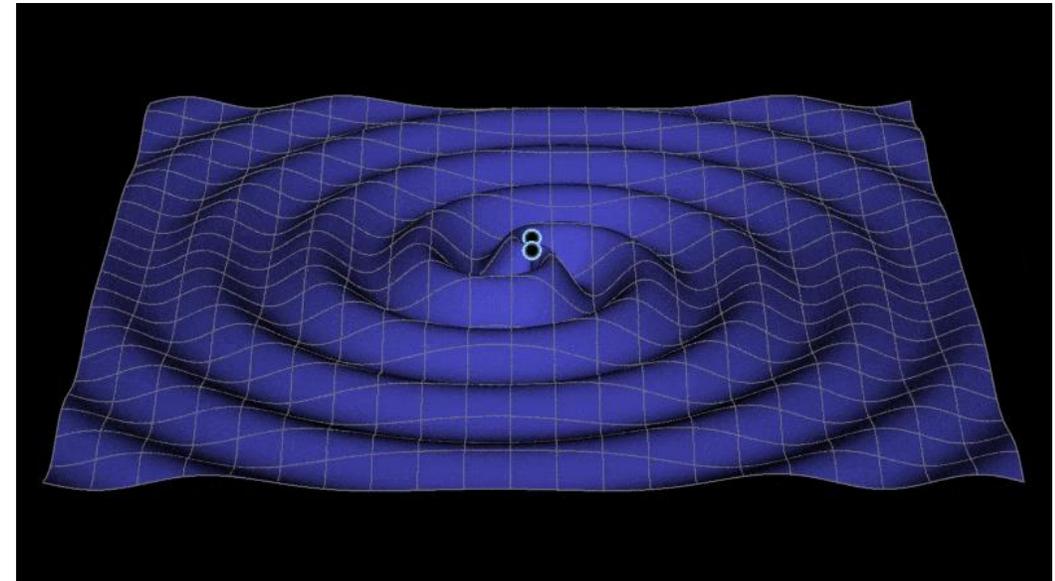


Searching for the missing duo: coincident gravitational-waves and high-energy neutrinos

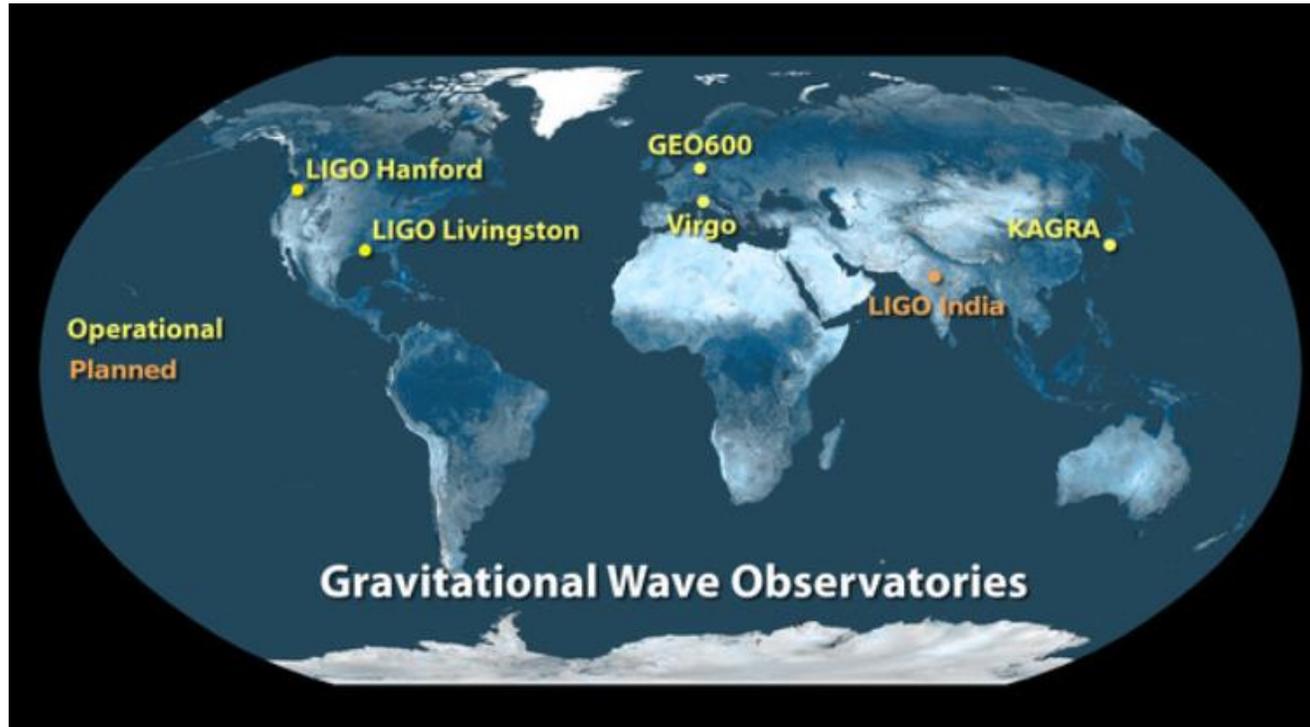
Dođa Veske

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

IceCube

- High energy neutrino detector located at the geographical South Pole
- Consists of “digital optical modules” which see the Cherenkov radiation from the muons created by neutrinos/from scattered particles
- We use muon tracks which have better localization compared to cascade events
- All sky but higher sensitivity for upgoing muons (coming from North Hemisphere)

$$\nu_{\mu}(\bar{\nu}_{\mu}) + N \rightarrow \mu^{-}(\mu^{+}) + X$$

$$\nu_{\mu} + e^{-} \rightarrow \mu^{-} + \nu_e$$

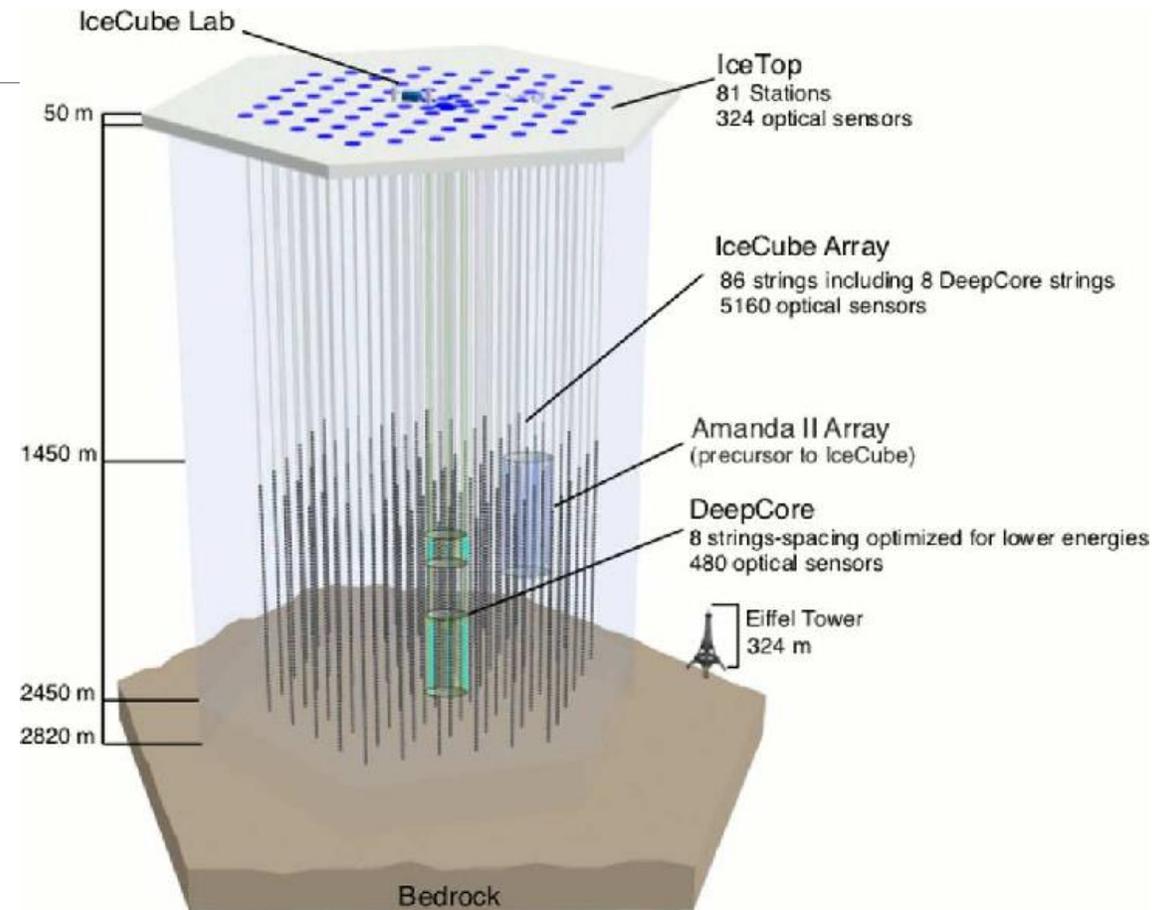
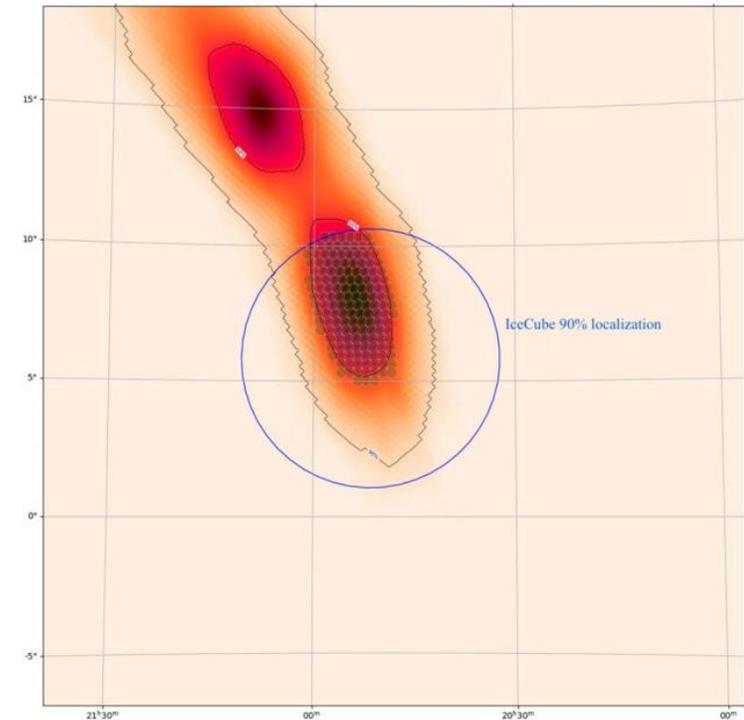


Image from [Measurement of South Pole ice transparency with the IceCube LED calibration system](#) - IceCube Collaboration (Aartsen, M.G. et al.) Nucl.Instrum.Meth. A711 (2013) 73-89

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

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>
```

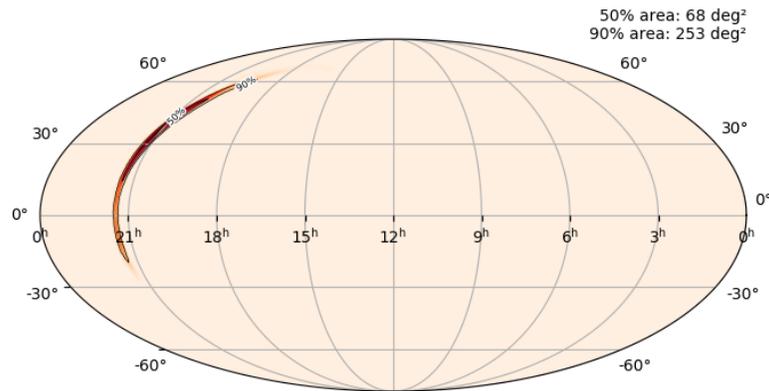
IceCube Collaboration (<http://icecube.wisc.edu/>) reports:

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.

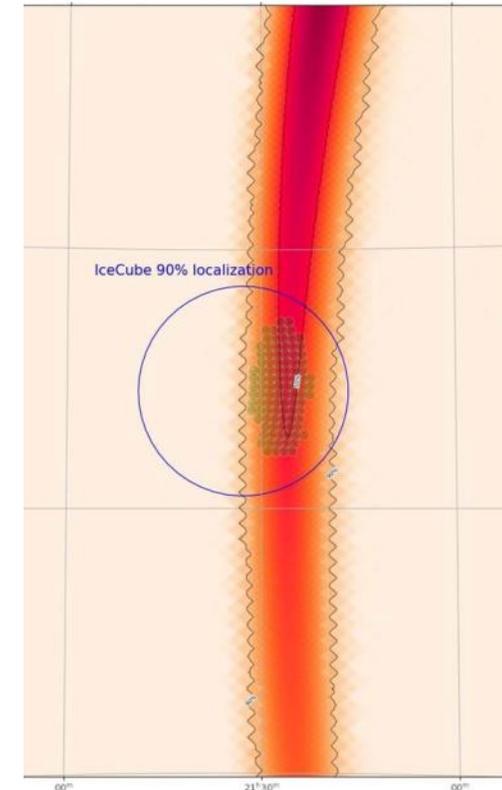
dt	ra (deg)	dec (deg)	Angular Uncertainty(deg)	p-value (bayesian)	p-value(generic transient)
-360	312.87	5.85	4.81	0.010	0.016

Case study: S191216ap



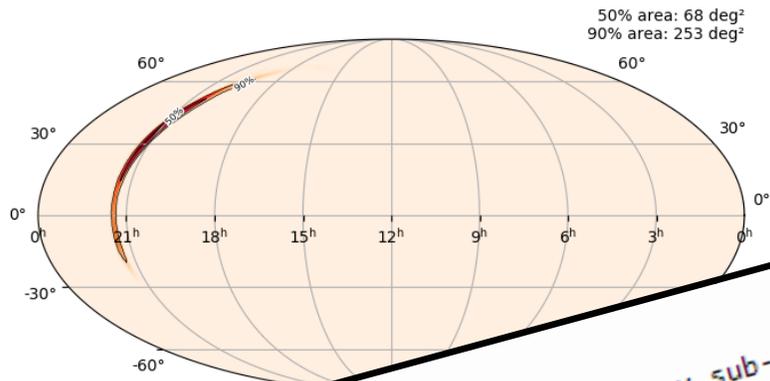
Localization from
gracedb.ligo.org

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



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

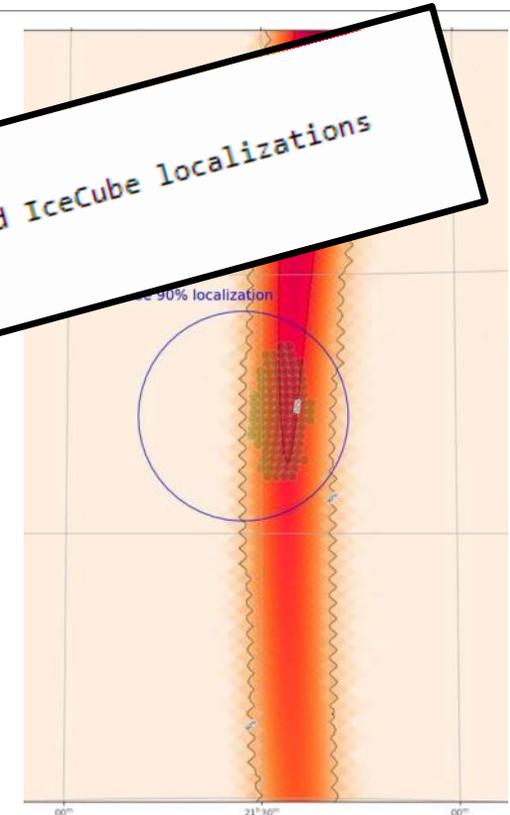
Case study: S191216ap



Localization from
gracedb.ligo.org

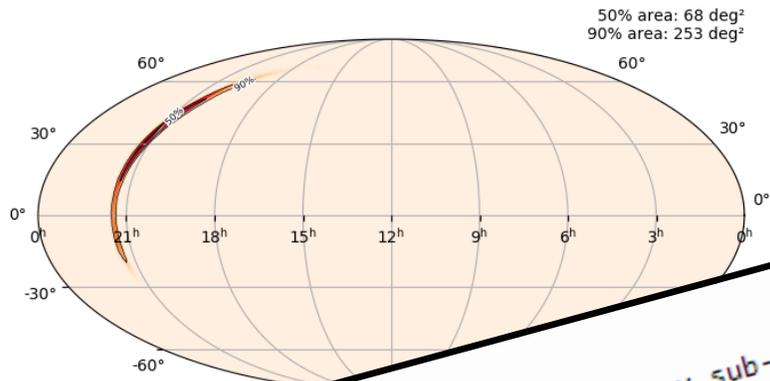
TITLE: GCN CIRCULAR
NUMBER: 26472
SUBJECT: LIGO/Virgo S191216ap: HAWC gamma-ray sub-threshold event coincident with LIGO/Virgo and IceCube localizations
DATE: 19/12/17 13:54:23 GMT
FROM: Israel Martinez-Castellanos at UMD/HAWC <imc@umd.edu>

- p-value $\sim 0.6\%$ in LLAMA search
- p-value $\sim 10\%$ in the UML search



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

Case study: S191216ap

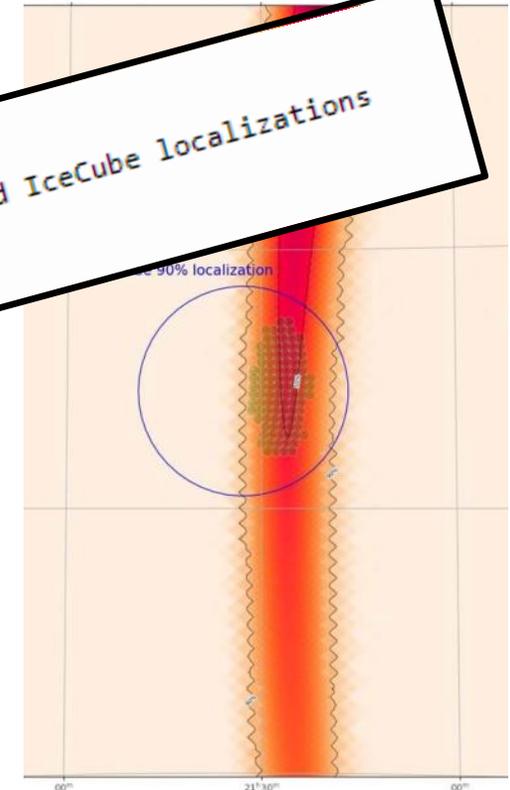


Localization from
gracedb.ligo.org

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>

- 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

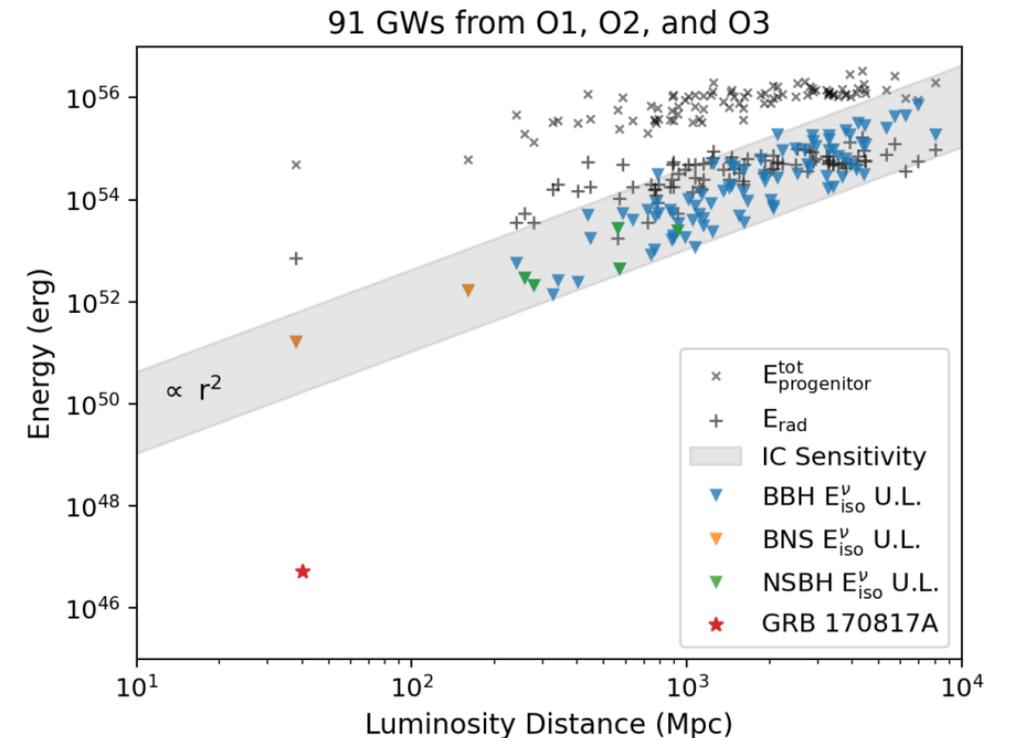
• O1-O2

- 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%.

• O3

- GWTC 2.1, GWTC 3 -> +80 events
- [Abbasi et al., ApJ **944** 80 \(2023\)](#)
- Lowest p-value is 0.48%, 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



Latest: O4 real-time run

- Since end of May 2023
- Only 2 LIGO detectors so far
- LLAMA search runs on “low-significance” triggers as well

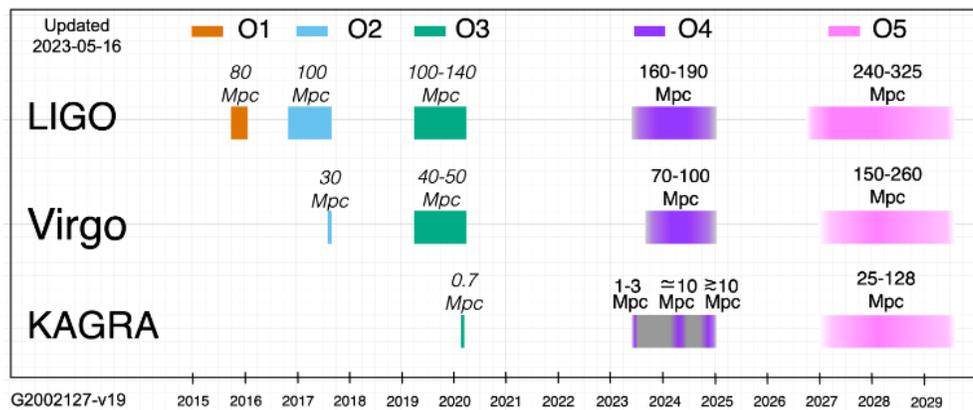
GCN Circular 34646

Subject LIGO/Virgo/KAGRA S230908b: one counterpart neutrino candidate from IceCube neutrino searches
Date 2023-09-09T20:18:10Z (3 days ago)
From acz2122@columbia.edu
Submitted By Web form

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

Properties of the coincident event(s) are shown below.

dt(s)	RA(deg)	Dec(deg)	Angular uncertainty(deg)	p-value(generic transient)	p-value(Bayesian)
+144.76	186.17	+29.37	1.082	not applicable	0.0056



Concluding remarks

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

