Real-time searches for neutrino counterparts of gravitational waves with IceCube

Justin Vandenbroucke (University of Wisconsin)

for the IceCube Collaboration

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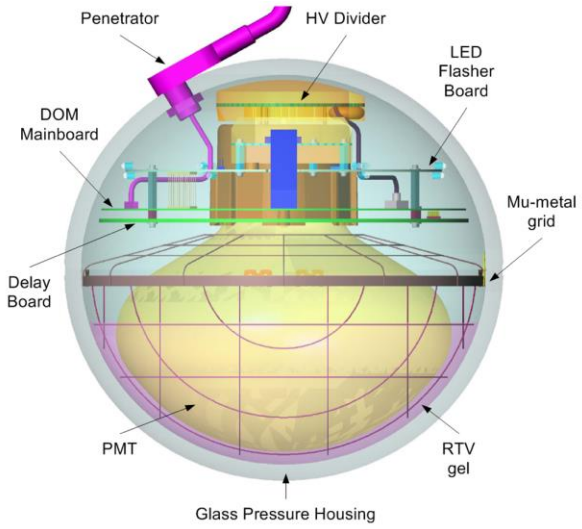
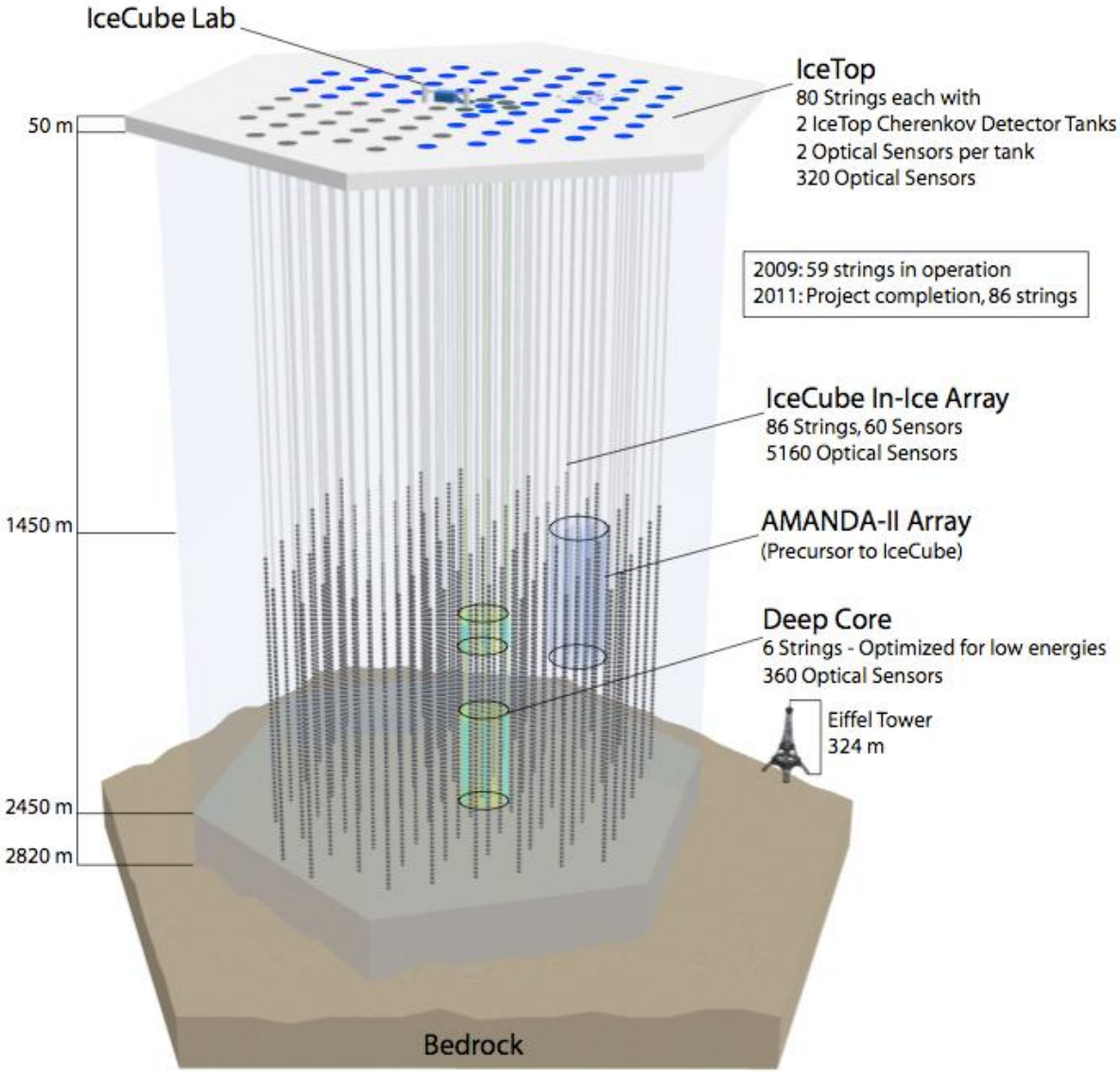
The IceCube Neutrino Observatory

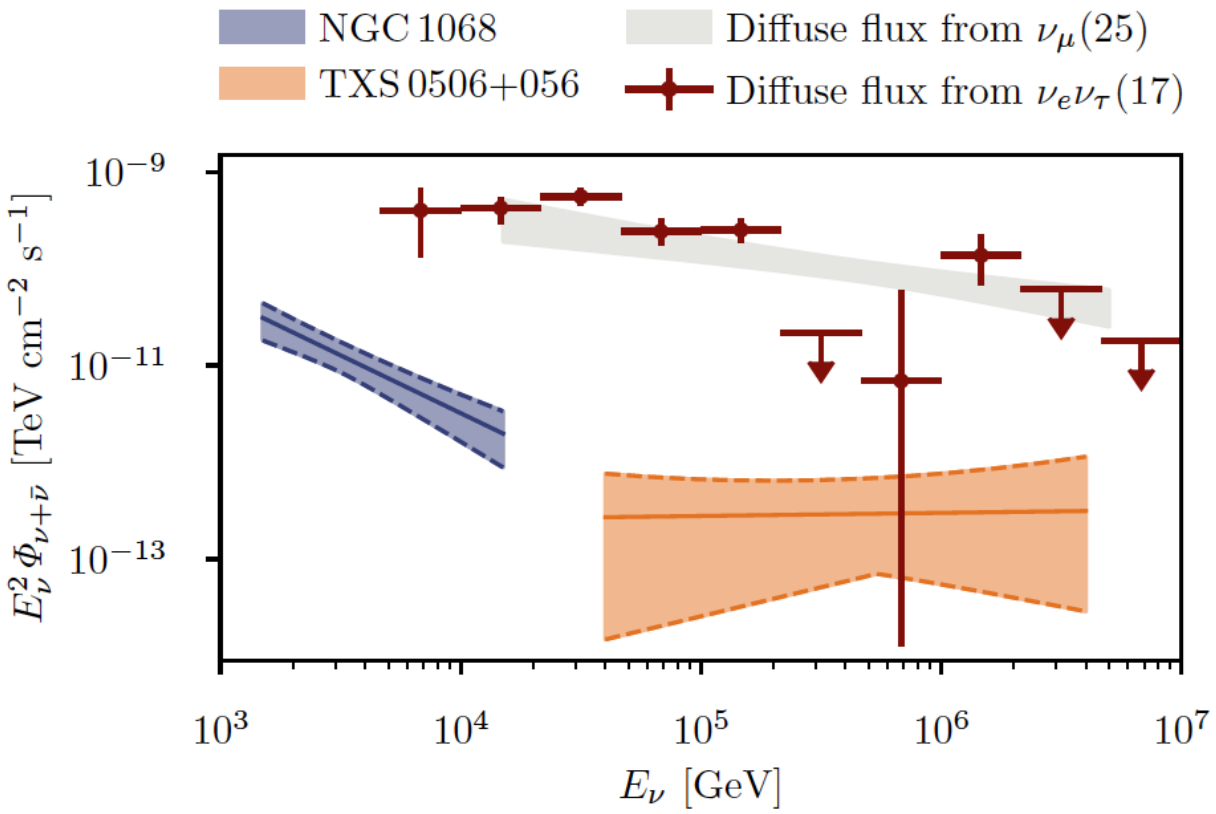
- Sensitive to neutrinos at MeV, GeV, TeV, PeV, EeV scales
- >99% up time
- Full sky (both hemispheres) capability
- Better sensitivity in North than South (at TeV scale)





Astrophysical neutrinos in a nutshell

(1) discovery of a bright extragalactic neutrino signal, mostly unresolved



(3) evidence for neutrinos from Seyfert NGC 1068 (M77)

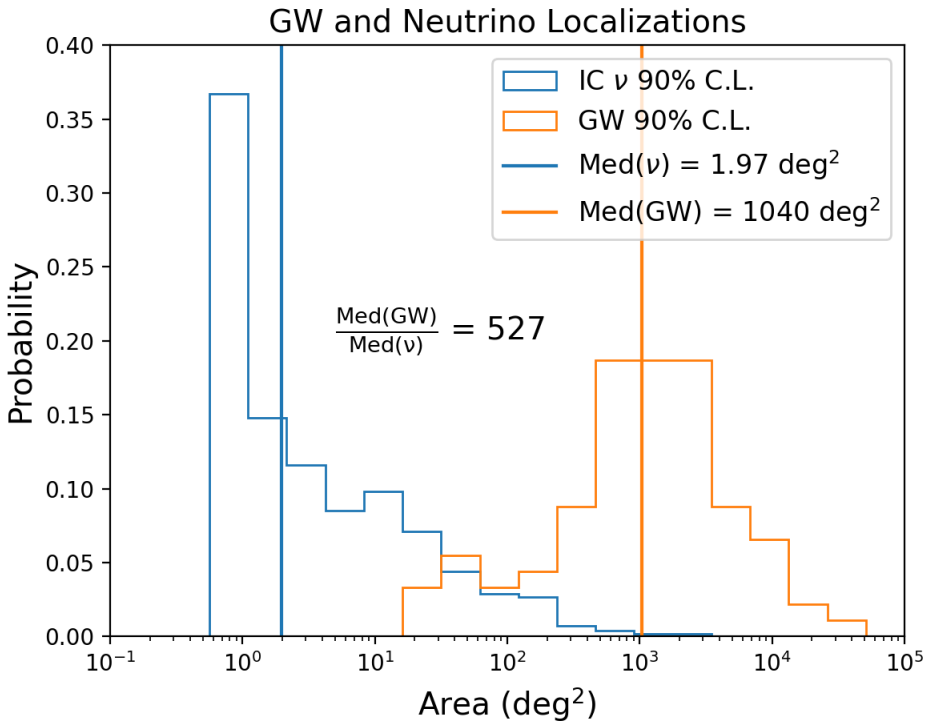
(2) evidence for neutrinos from blazar TXS 0506+056

Why search for neutrino counterparts of GW events in real time?

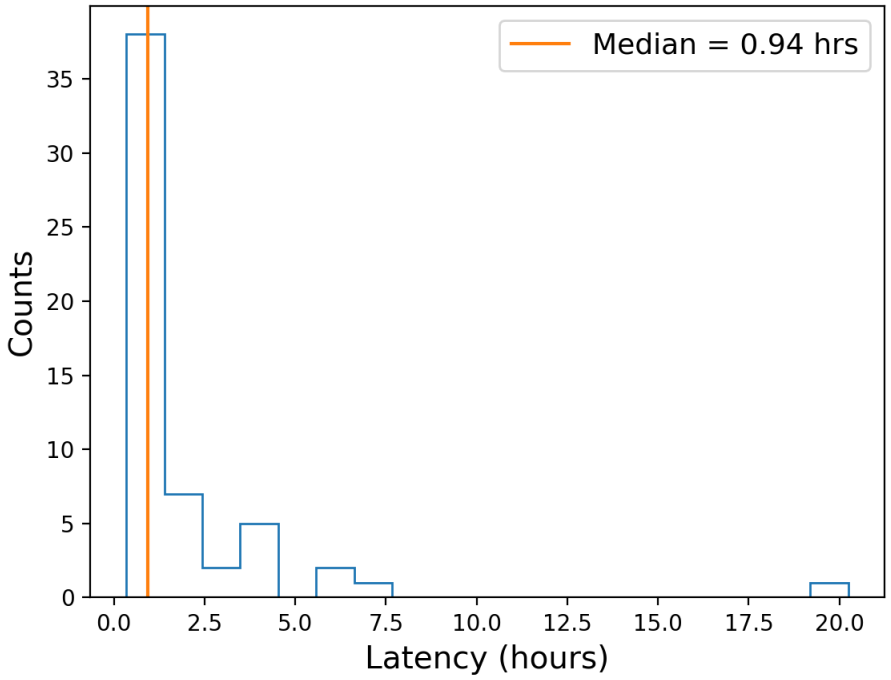
- Models predict particle acceleration (likely involving hadrons at some level) by mergers involving a neutron star (BNS or NSBH)
- Even for BBH, neutrino emission can occur if embedded in sufficient medium, e.g. in models where BBH occur preferentially within accretion disks of SMBH
- Neutrino localization area is ~500 times smaller than GW sky localization
- Publishing candidate neutrino coincidences with low latency enables observers to search the neutrino localization area, to identify a counterpart and confirm the neutrino coincidence is a signal

Real-time follow-up of O3 open public alerts

Neutrinos are hundreds of times better localized than GW



Combined LVK & IceCube latency < 1 hr (!) [faster in O4]

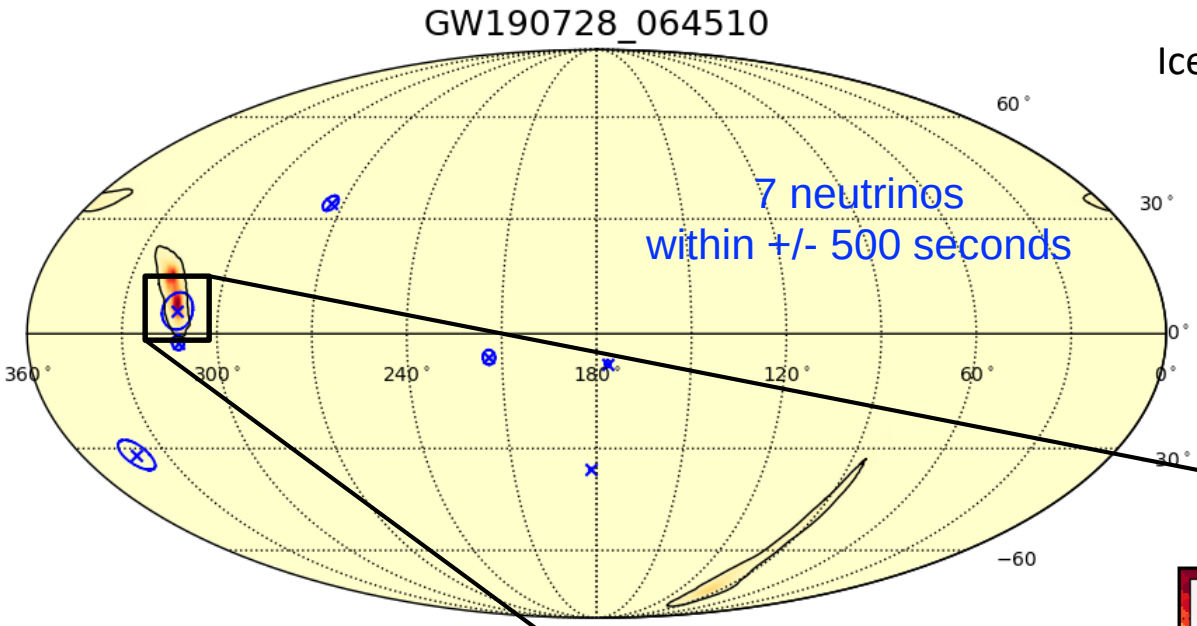


Two analyses each search +/- 500 s around merger time

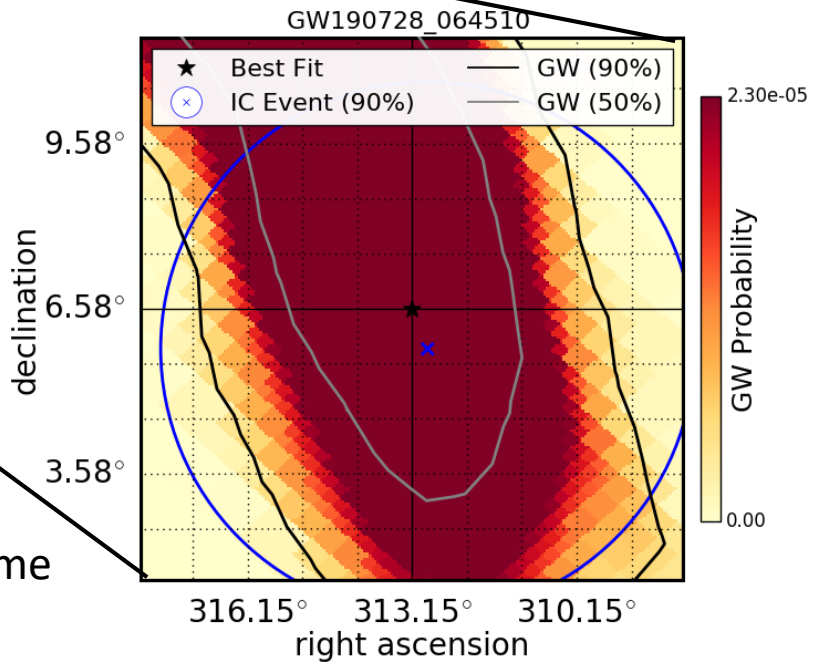
- Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA): Bayesian
- Un-binned Maximum Likelihood (UML): frequentist

IceCube, ApJ Letters 898 (2020) L10
IceCube, ApJ 944:80 (2023)

An example GW analyzed in real time during O3

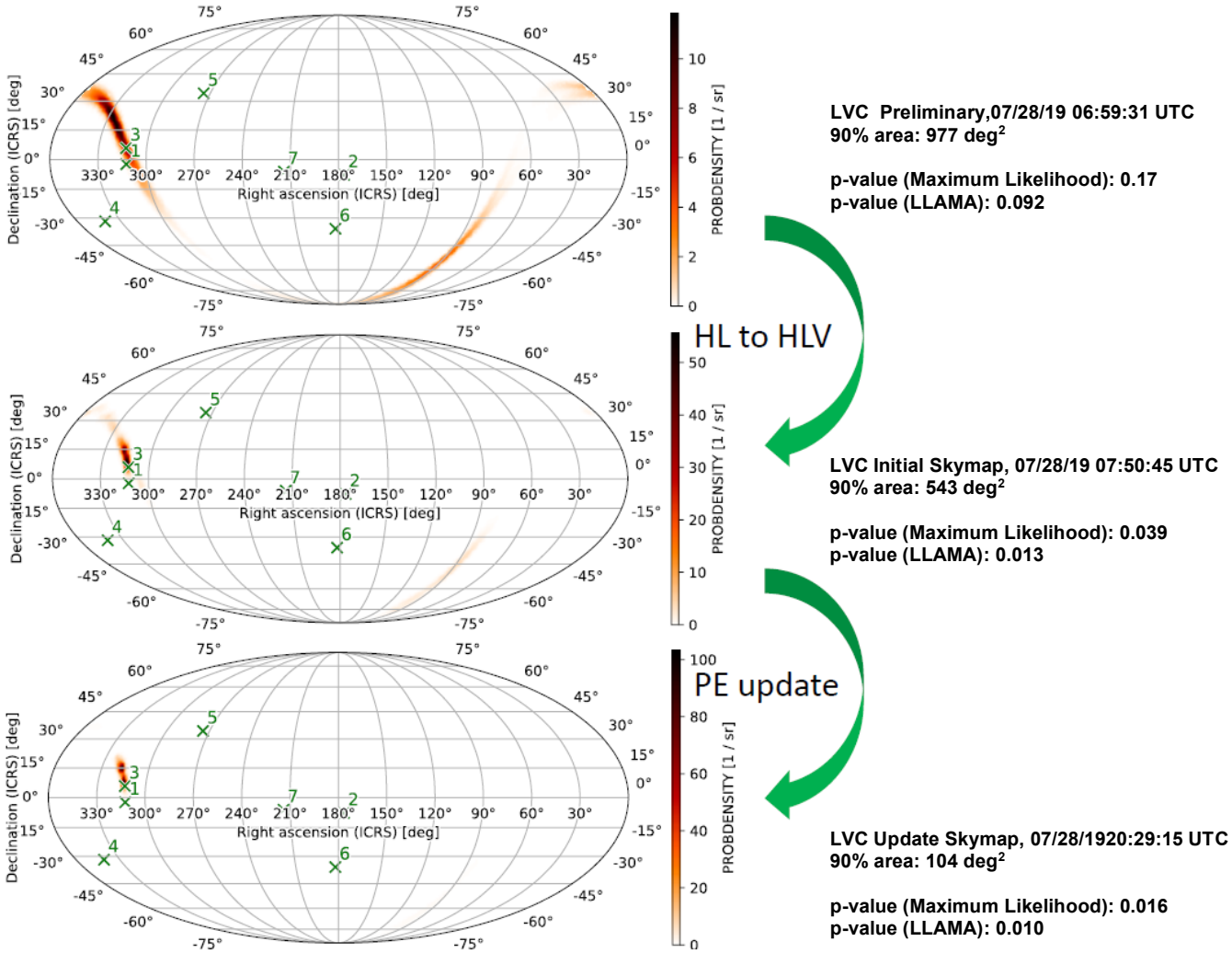


IceCube, ApJ Letters 898 (2020) L10
IceCube, ApJ 944:80 (2023)



- p-value = 0.010 LLAMA, 0.016 UML
  for this GW alone (pre-trials)
- Coincident neutrino information published in real time
- Followed up by Swift and others

We follow up each sky map revision (preliminary, initial, update, …)



LVC Preliminary,07/28/19 06:59:31 UTC
90% area: 977 deg^2

p-value (Maximum Likelihood): 0.17
p-value (LLAMA): 0.092

LVC Initial Skymap, 07/28/19 07:50:45 UTC
90% area: 543 deg^2

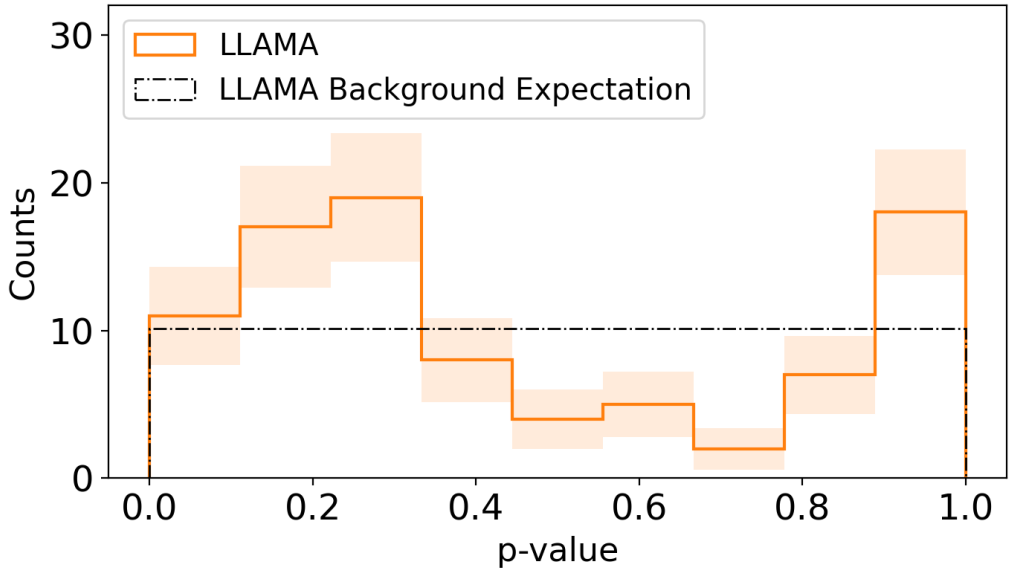
p-value (Maximum Likelihood): 0.039
p-value (LLAMA): 0.013

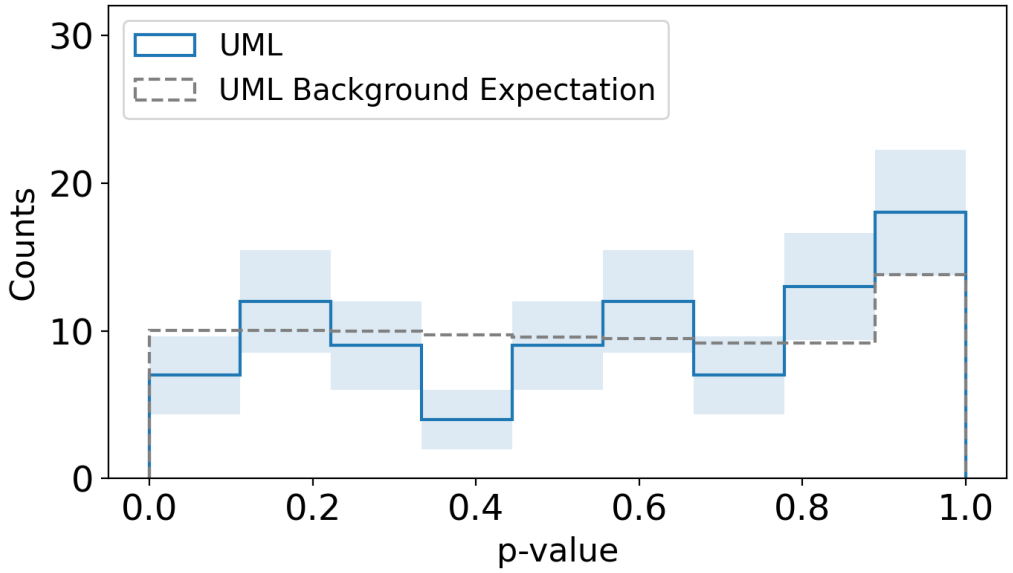
LVC Update Skymap, 07/28/1920:29:15 UTC
90% area: 104 deg^2

p-value (Maximum Likelihood): 0.016
p-value (LLAMA): 0.010

Same example (GW 190728_064510)

Archival analysis through GWTC-3: 91 GWs (O1, O2, O3)

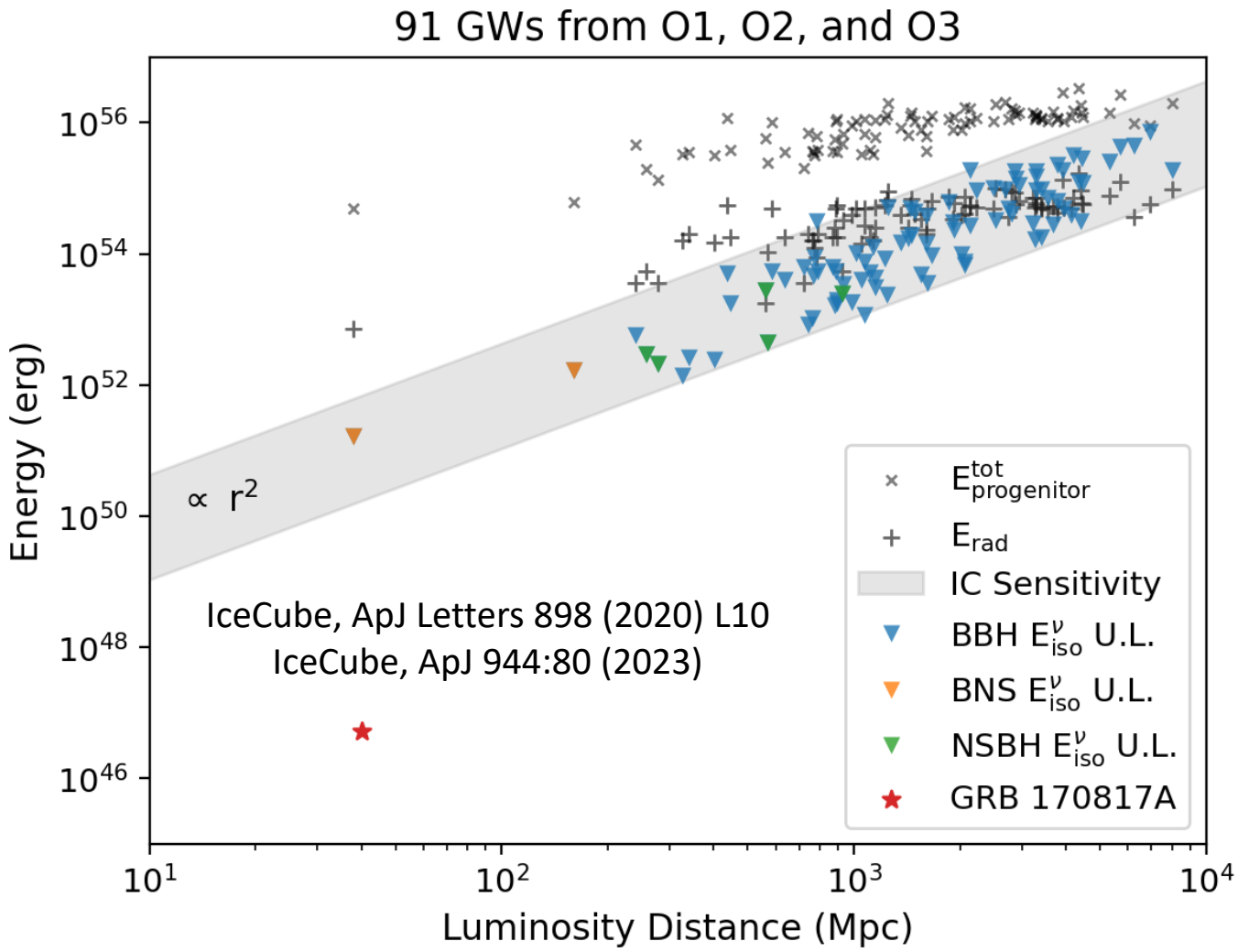




p-value distributions consistent with background expectation

IceCube, ApJ Letters 898 (2020) L10
IceCube, ApJ 944:80 (2023)

Archival analysis through GWTC-3: 91 GWs (O1, O2, O3)



Comparison of bolometric isotropic-equivalent energy in GW, gamma rays, and neutrino upper limits

O4 plans and outlook

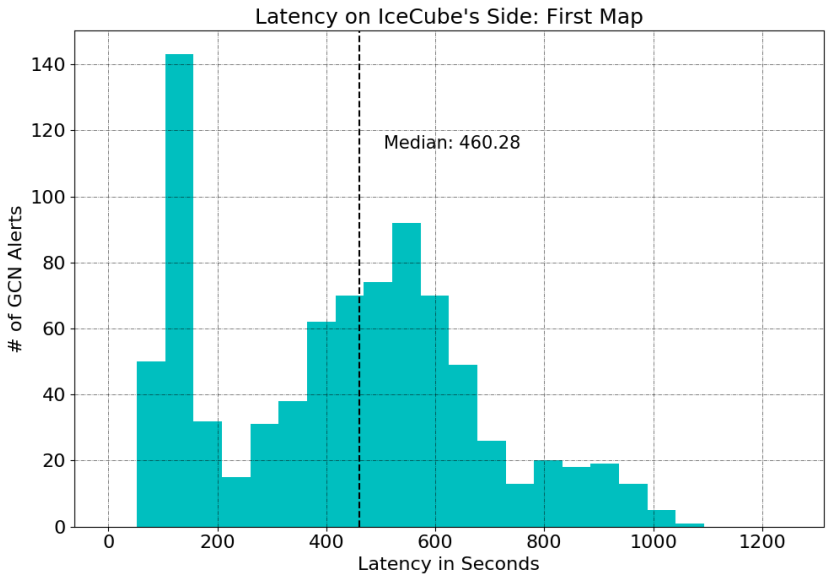
- We plan to follow up each LVK open public alert (including BBH) and report results from both pipelines (LLAMA and UML) with low latency (<1 hour)
- Will analyze low-significance (sub-threshold) as well as high-significance GW
- Automated publication without human in the loop (human cross checks may result in revisions)
  - p-value > 0.1: automated GCN Notice with upper limits
  - 0.01 < p-value < 0.1: automated GCN Notice with coincident neutrino information
  - p-value < 0.01: automated GCN Notice and human GCN Circular with coincident neutrino information
- +/-500 second search window for all GW; two-week search window for GW with neutron star
- Planning to use GCN over Kafka
- Considering also publishing via SCiMMA
- We encourage other observers to follow up our coincident neutrino alerts!
- Any additional or different information other observers would like?

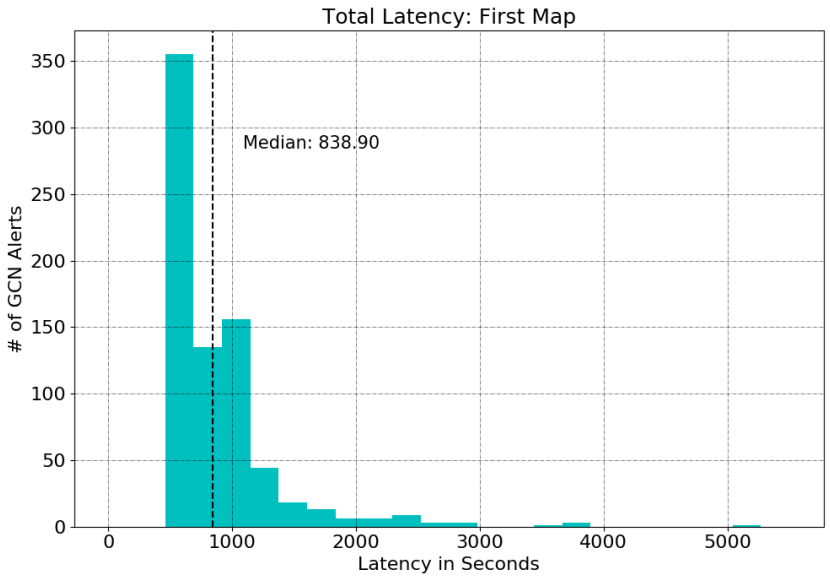
Additional slides

Preliminary IceCube-GW GCN Notice format

Shaded: included if p<0.1

Parameter	Description	Comment
TITLE	GCN NOTICE	
NOTICE_DATE	[date]	UTC
NOTICE_TYPE	IceCube_GW_Coinc	notice type name
STREAM	##	standard
GW_EVENT_NAME	[lvk_name]	From LVK, GW event followed up
GW_GCN_NOTICE_NUM	[notice_id]	notice id from GW detectors
T_MERGER	[trigger_time]	UTC
T_START	[tstart]	UTC; start time of the search (trigger -500s)
T_STOP	[tstop]	UTC; stop time of the search (trigger +500s)
N_EVENTS_COINC	[num_events]	number of IceCube events in spatial and temporal coincidence with the GW map
OVERALL_P_GEN_TRANSIENT	[pval_uml]	overall p-value for UML followup
OVERALL_P_BAYESIAN	[pval_llama]	overall p-value for LLAMA followup
OVERALL_SIG_GEN_TRANSIENT	[sig_uml]	significance for UML followup
OVERALL_SIG_BAYESIAN	[sig_bayesian]	significance for LLAMA followup
COINC_EVENT_DT	[dt]	time offset (sec) of 1st coincident neutrino with respect to GW trigger
COINC_EVENT_RA	[ra]	RA of 1st coincident neutrino (deg)
COINC_EVENT_DEC	[dec]	declination of 1st coincident neutrino (deg)
COINC_EVENT_ANG_UNC	[ang_unc]	angular uncertainty of track event: 90% containment (deg)
COINC_EVENT_P_GEN_TRANSIENT	[pval_uml]	event p-value for 1st coincident neutrino with UML
COINC_EVENT_P_BAYESIAN	[pval_llama]	event p-value for 1st coincident neutrino with LLAMA
SENS_LOW	[lowSens]	Lowest value of point source sensitivity assuming an E^-2 spectrum (E^2 dN/dE) within the GW map localization (GeV cm^-2)
SENS_HIGH	[highSens]	Highest value of point source sensitivity assuming an E^-2 spectrum (E^2 dN/dE) within the GW map localization (GeV cm^-2)
COMMENTS	2 searches for track-like muon neutrino events detected by IceCube consistent with the GW localization in a time window of 1000s	
COMMENTS	(1) generic transient search with unbinned maximum likelihood	
COMMENTS	(2) Bayesian approach assuming a binary merger scenario and accounting for priors such as GW source distance	
COMMENTS	M. G. Aartsen et al 2020 ApJL 898 L10 ; Abbasi et al. arXiv:2208.09532 (2022)	
COMMENTS	The position error is statistical only, there is no systematic added.	


Latency on IceCube's Side: First Map
Median: 460.28
# of GCN Alerts
Latency in Seconds
0
20
40
60
80
100
120
140
0
200
400
600
800
1000
1200


Total Latency: First Map
Median: 838.90
# of GCN Alerts
Latency in Seconds
0
50
100
150
200
250
300
350
0
1000
2000
3000
4000
5000


Merger
LVK Processes
GCN Alert
IceCube Runs Code
Code Finishes