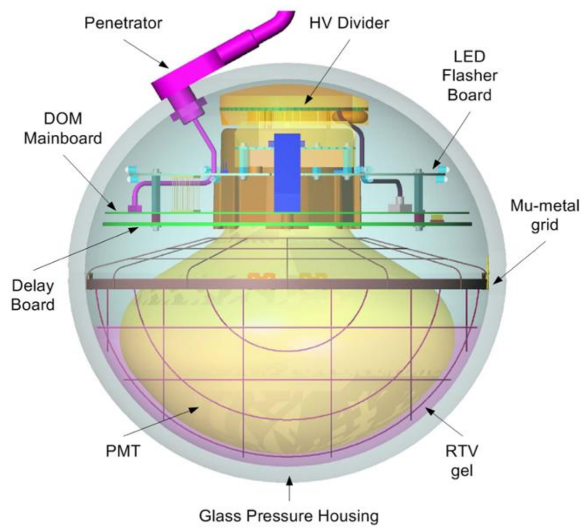
IceCube searches for neutrinos from gravitational wave sources

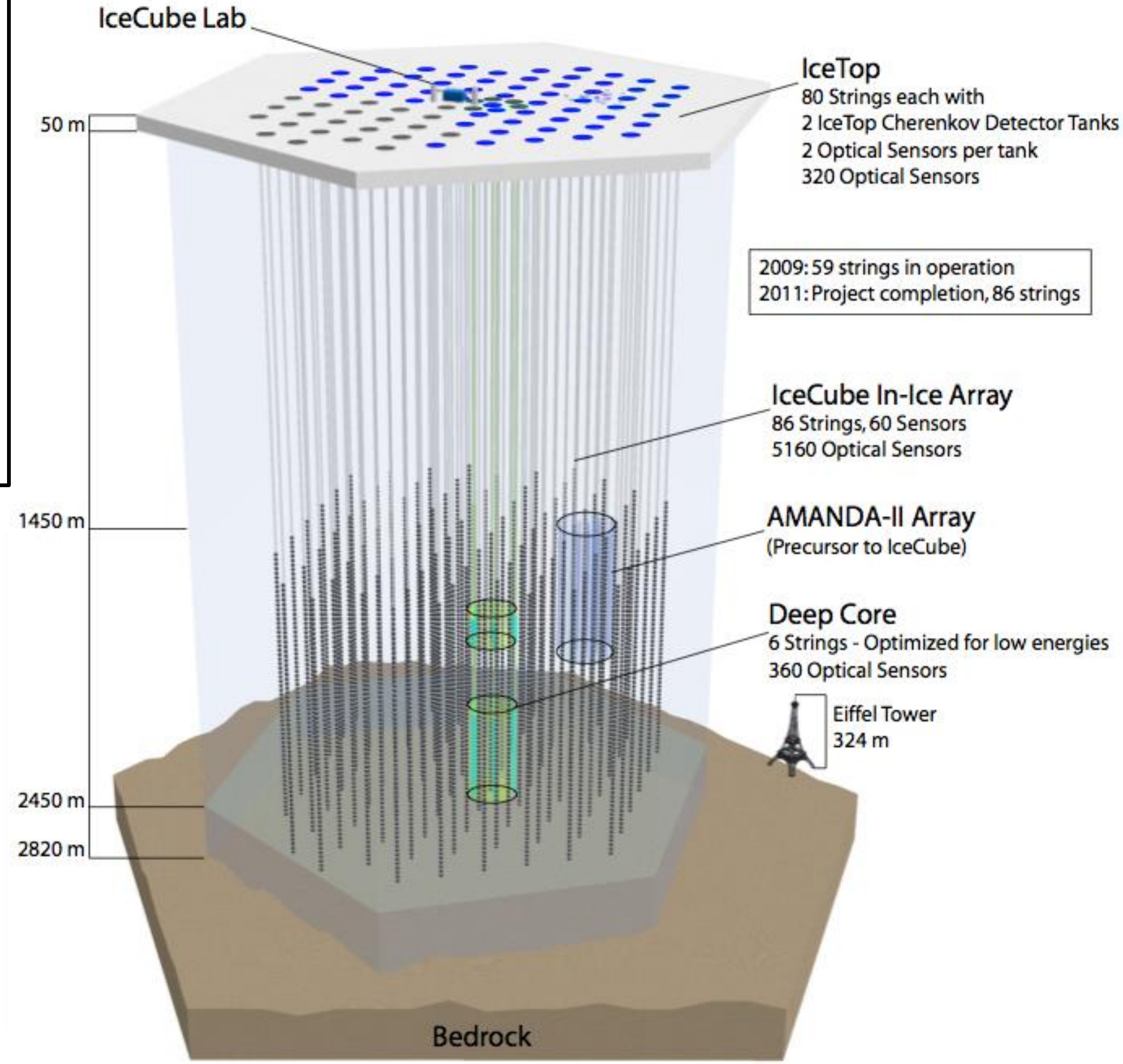
Justin Vandenbroucke (UW – Madison)
for the IceCube Collaboration

TeVPA, August 27, 2024

The IceCube Neutrino Observatory

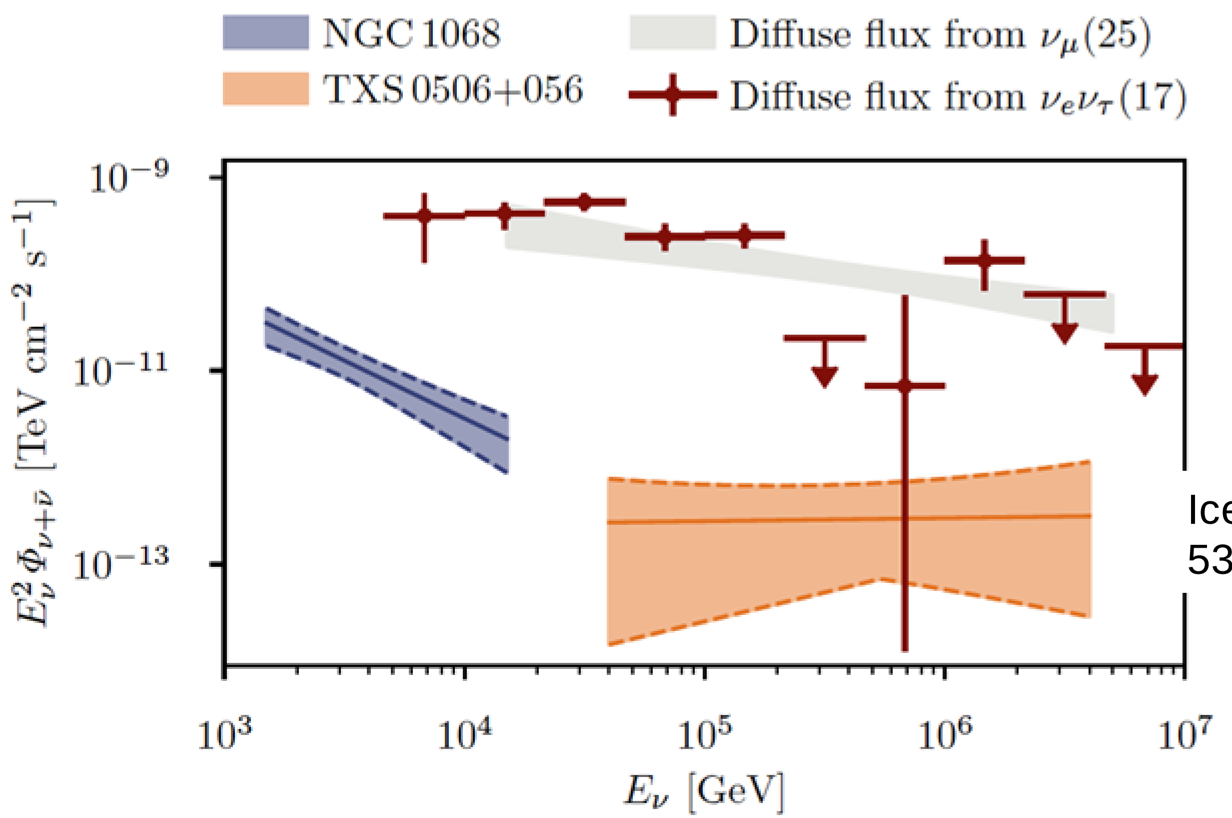
- Sensitive to neutrinos at MeV, GeV, TeV, PeV, EeV scales
- >99% up time
- Full sky (both hemispheres) capability
- Better sensitivity in North than South (at TeV scale)
- Tracks and cascades





Extragalactic neutrinos in a nutshell

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

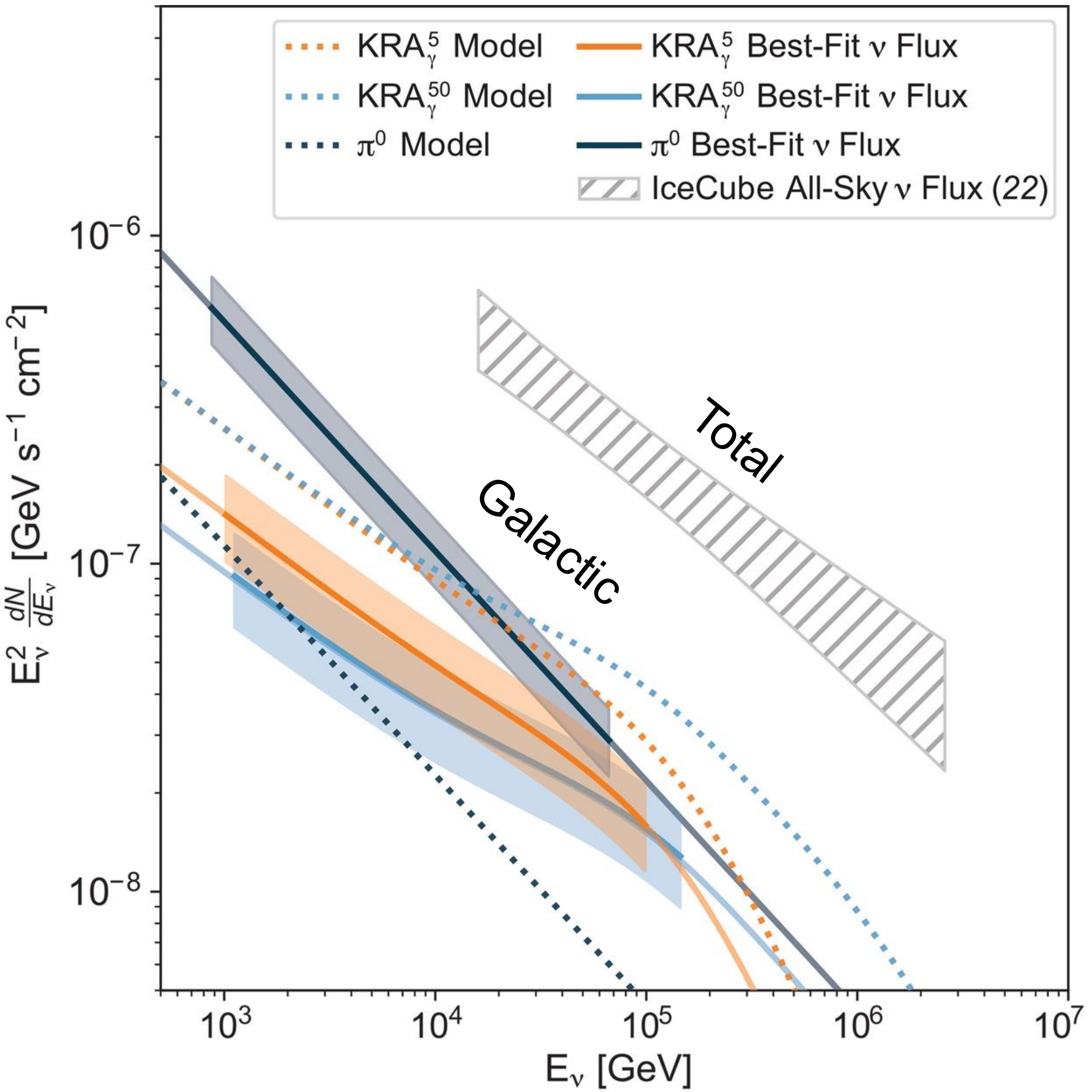


IceCube, Science 378, 538-543 (2022)

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

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

About 10% of astrophysical neutrinos are Galactic

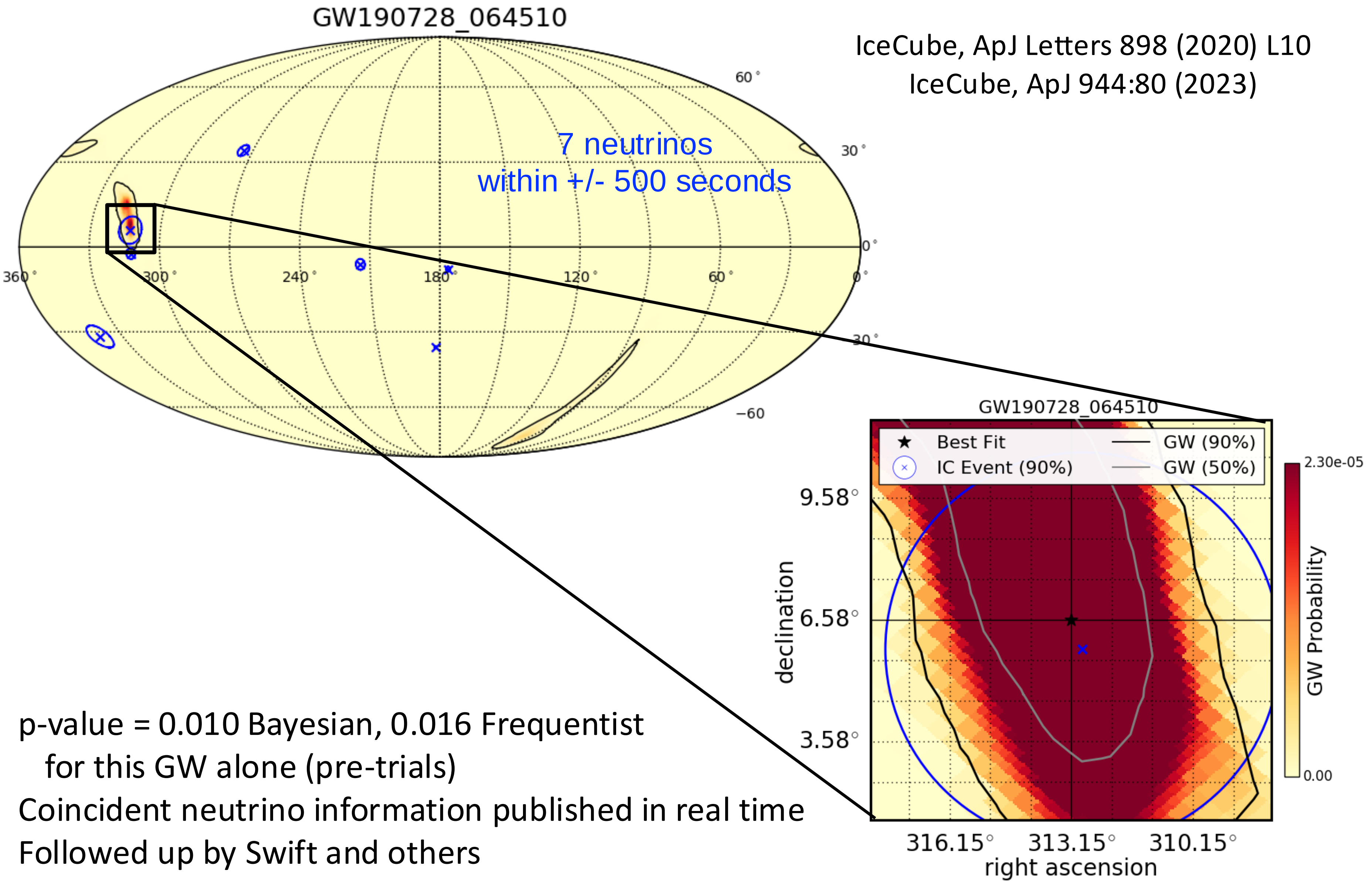


IceCube, Science 380, 1338-1343 (2023)

Why search for neutrino counterparts of gravitational wave sources, especially in real time?

- Models predict particle acceleration (with 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. if BBH occur preferentially within accretion disks of SMBH
- Neutrino localization area is 10^3 times smaller than GW sky localization
- Publishing candidate neutrino coincidences in real time enables observers to search the small neutrino localization area

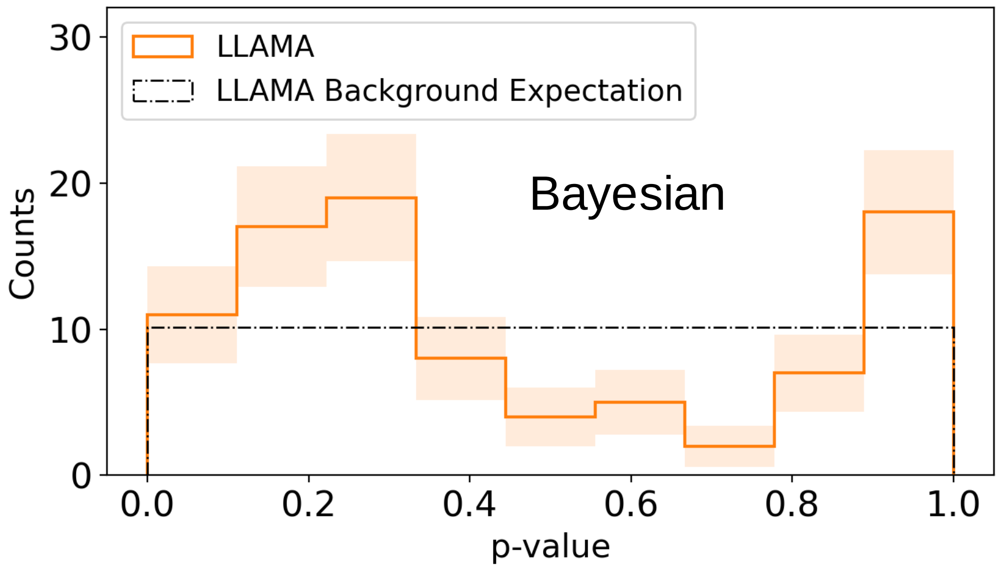
An example GW analyzed in real time during O3



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

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

Through end of observing run O3: no significant neutrino association with 91 GW events



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

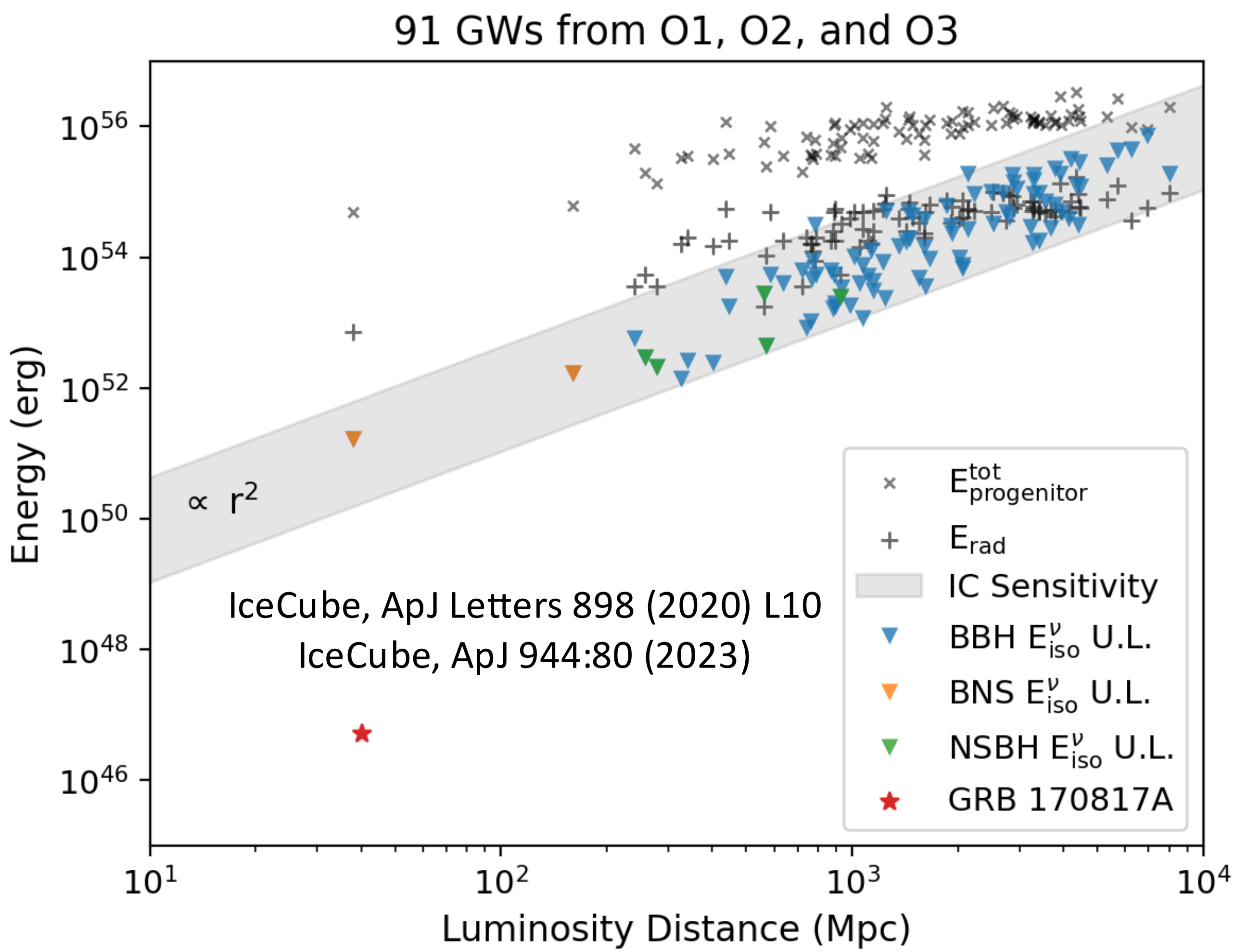
1) Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA): Bayesian

2) Un-binned Maximum Likelihood (UML): frequentist

p-value distributions consistent with background expectations

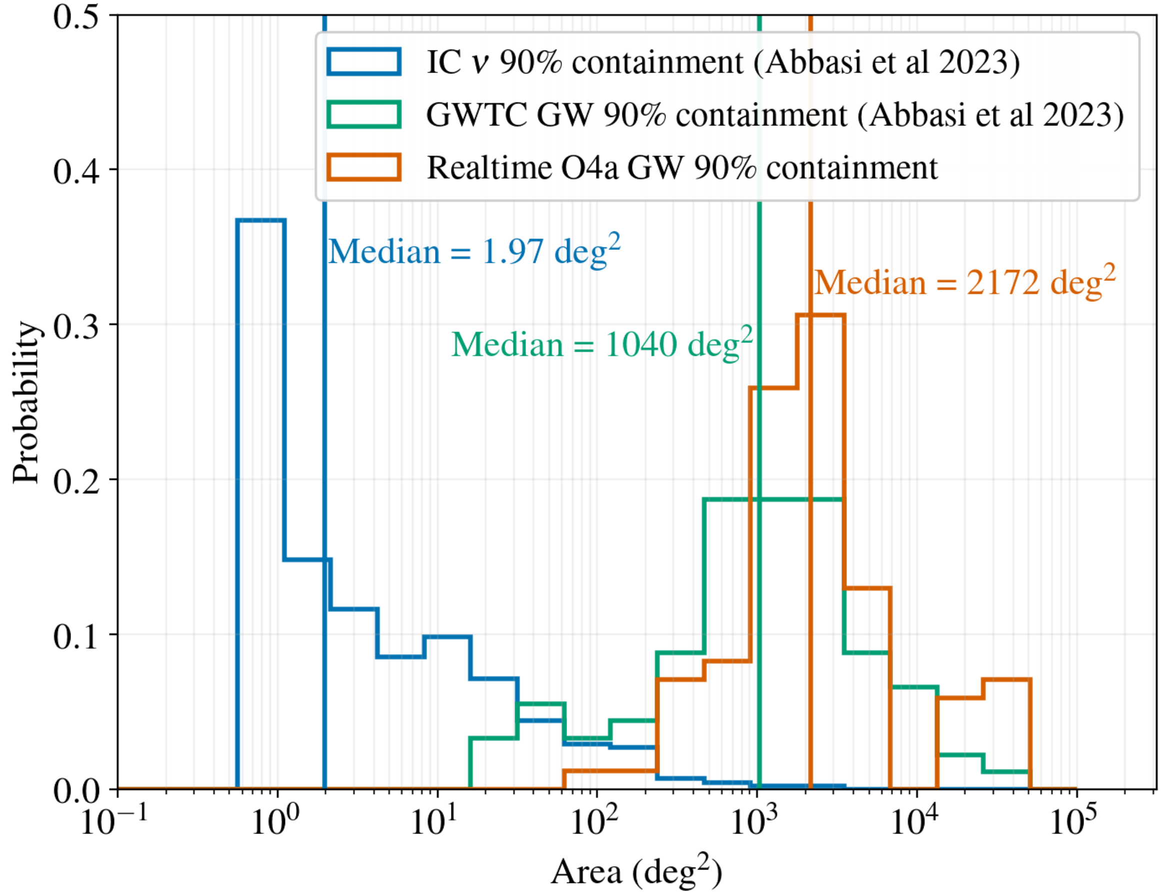
IceCube, ApJ Letters 898 (2020) L10
IceCube, ApJ 944:80 (2023)

Upper limits on neutrino emission: the first 91 GWs



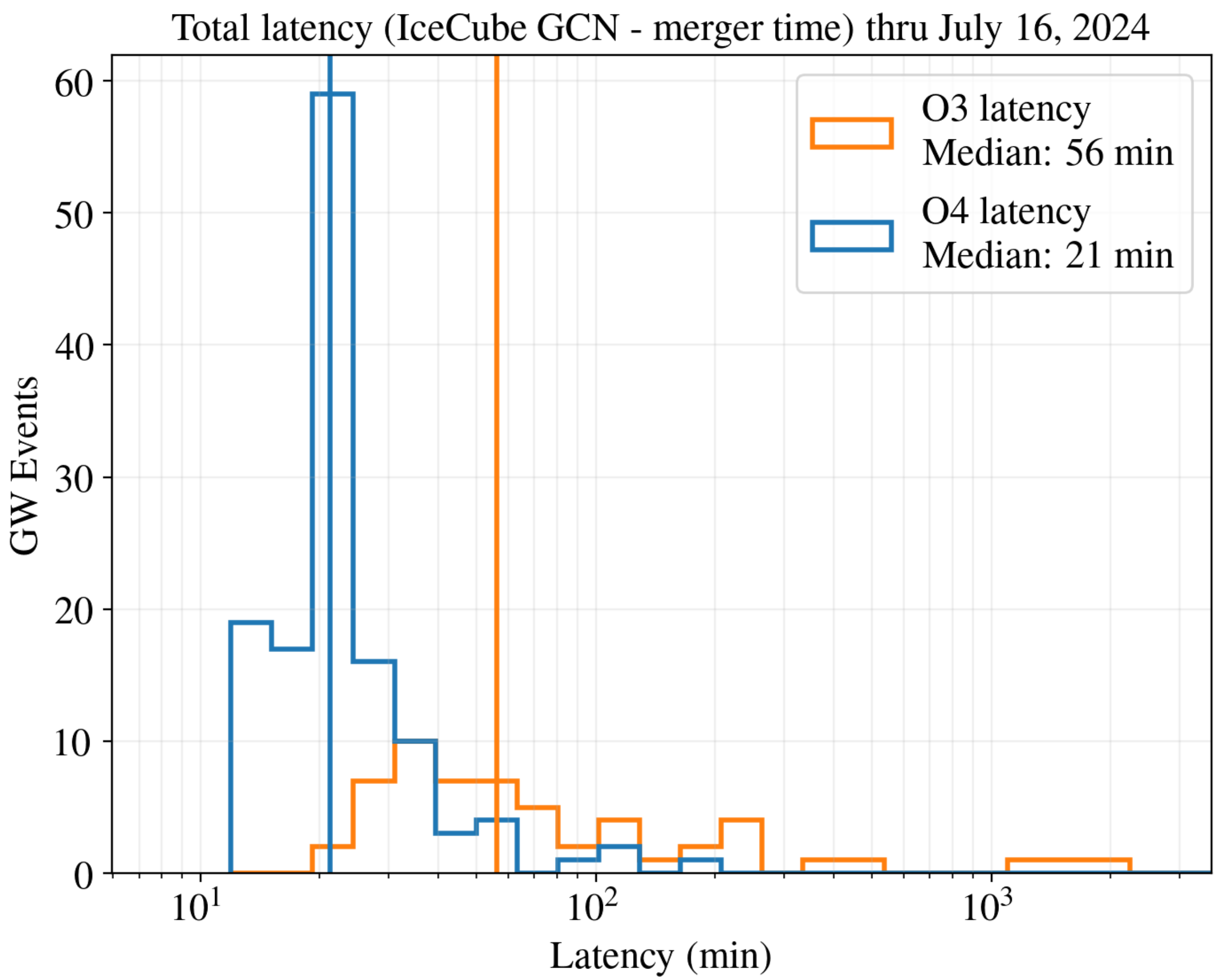
Comparison of bolometric isotropic-equivalent energy in gravitational waves, gamma rays, and neutrino upper limits

Neutrinos are localized to areas 10^3 times smaller than gravitational waves



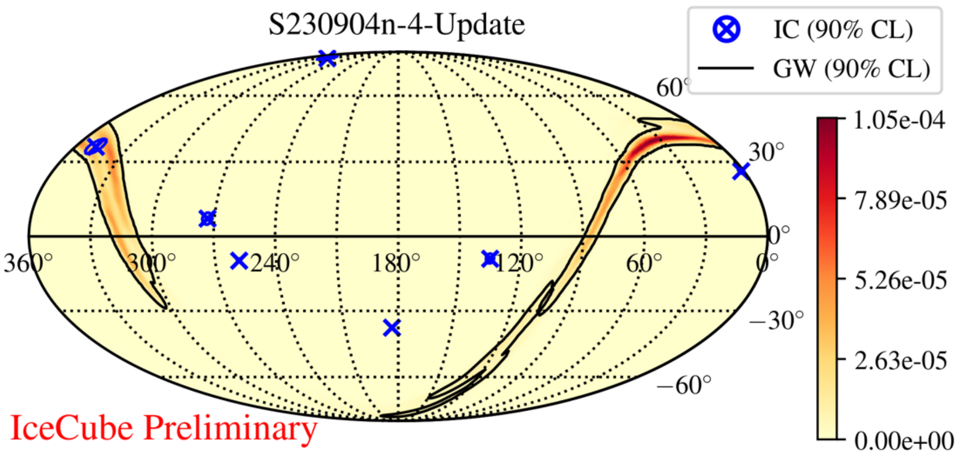
Rapid publication of neutrino directions spatially and temporally compatible with GW directions enables rapid search of a small area by other telescopes

Real-time follow-up of O3 and O4 gravitational waves

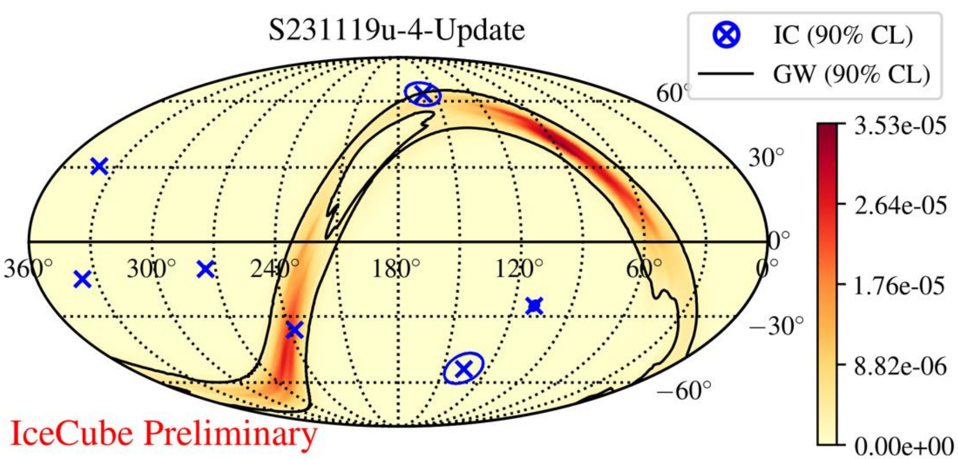


- O3 total (LVK + IceCube) latency median 56 minutes, with human in the loop
- O4 total latency median 21 minutes, thanks to automation

Example sky maps: most significant GW-neutrino associations so far



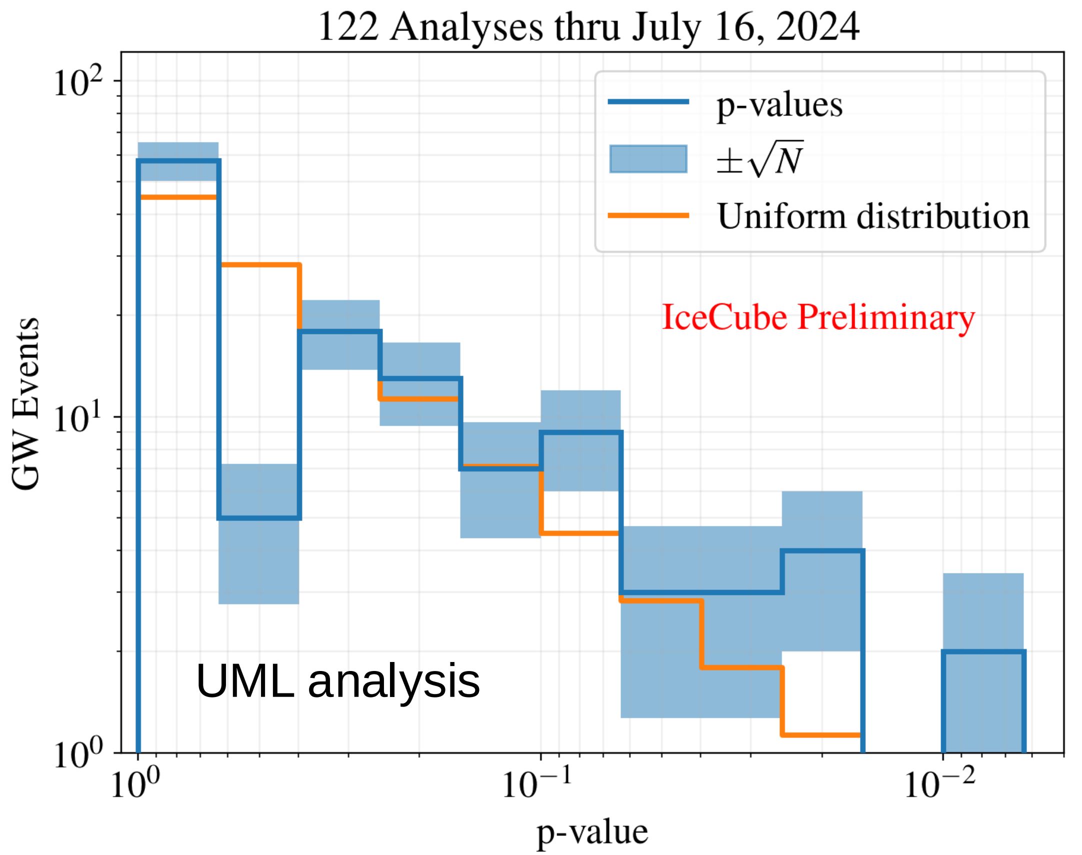
LLAMA (Bayesian)
p value 0.8%



UML (frequentist)
p value 0.8%

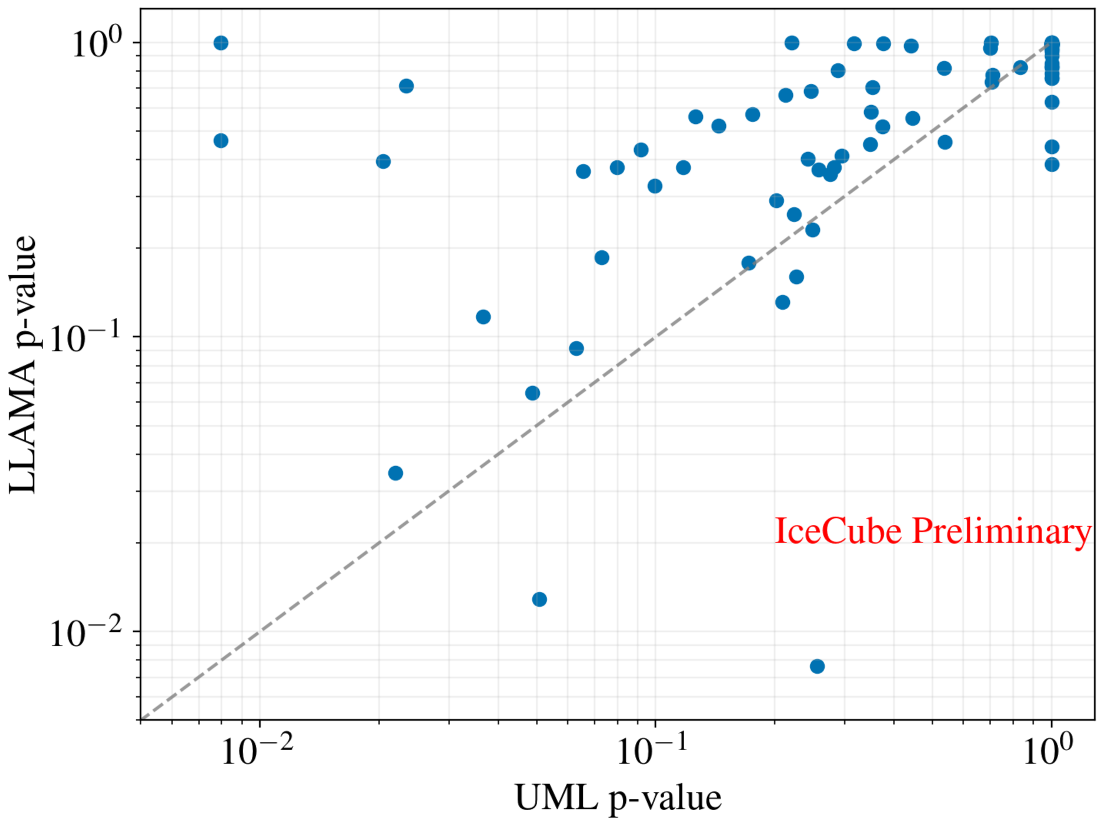
These p values are per-GW
(pre-trials; 91+122 GW)

All 122 GW neutrino searches to date during O4



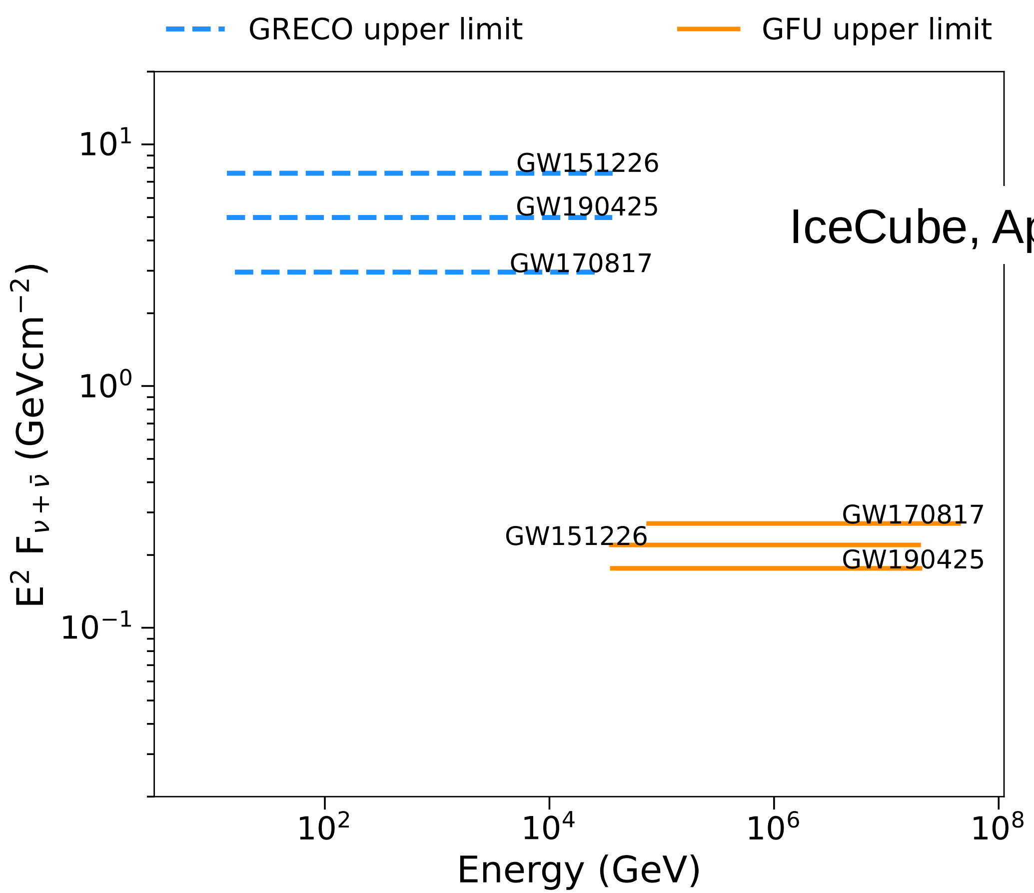
- 91 gravitational waves through O3 + 122 so far in O4 = 213 total
- Background expectation is not uniform due to neutrino background event counting statistics

Complementary results from two analysis methods



- Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA): Bayesian (including distance prior)
- Un-binned Maximum Likelihood (UML): frequentist
- Results shown for all 122 O4 GW through July 16, 2024

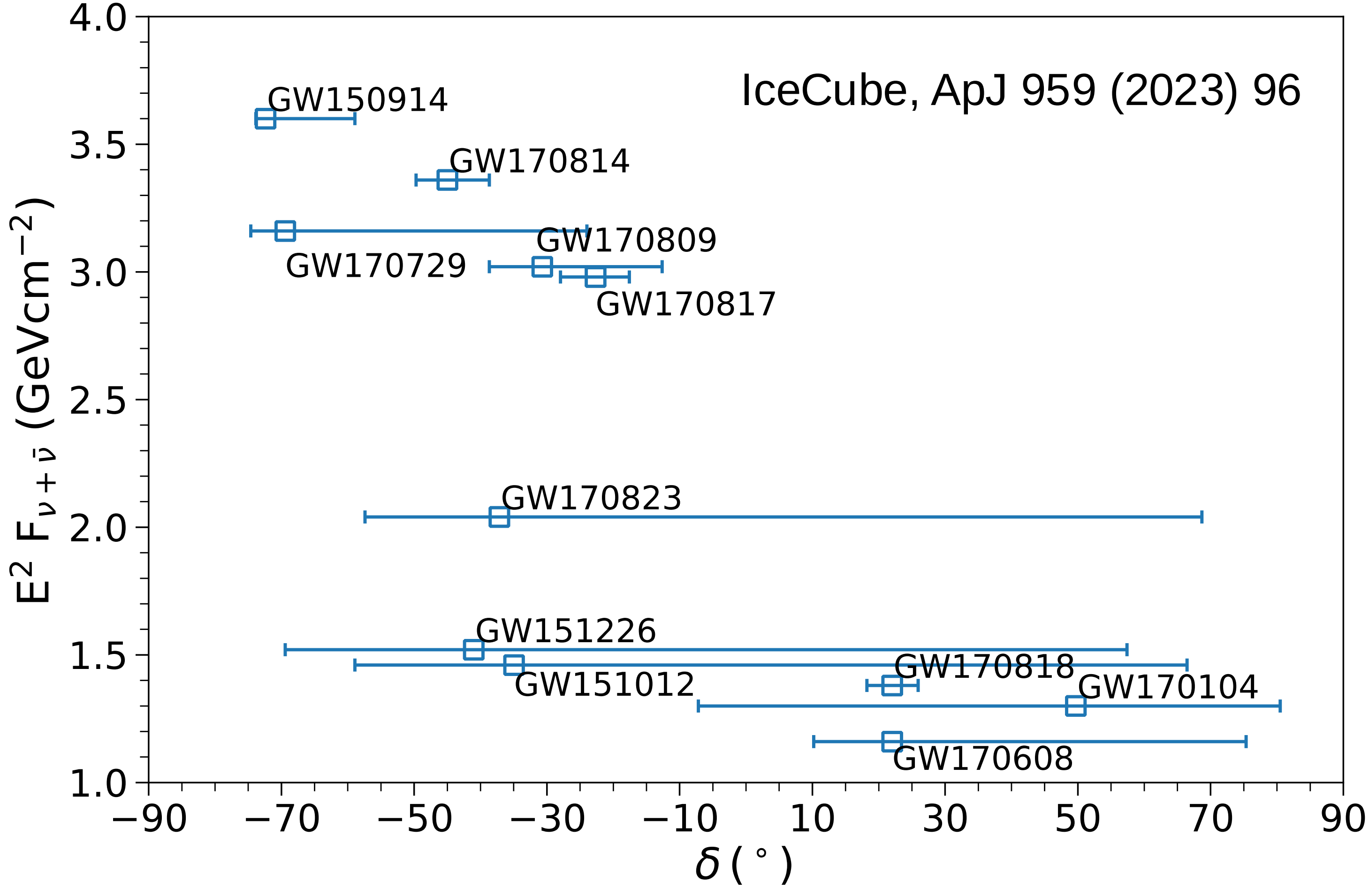
Searching for "low energy" GW-associated neutrinos using IceCube DeepCore



IceCube, ApJ 959 (2023) 96

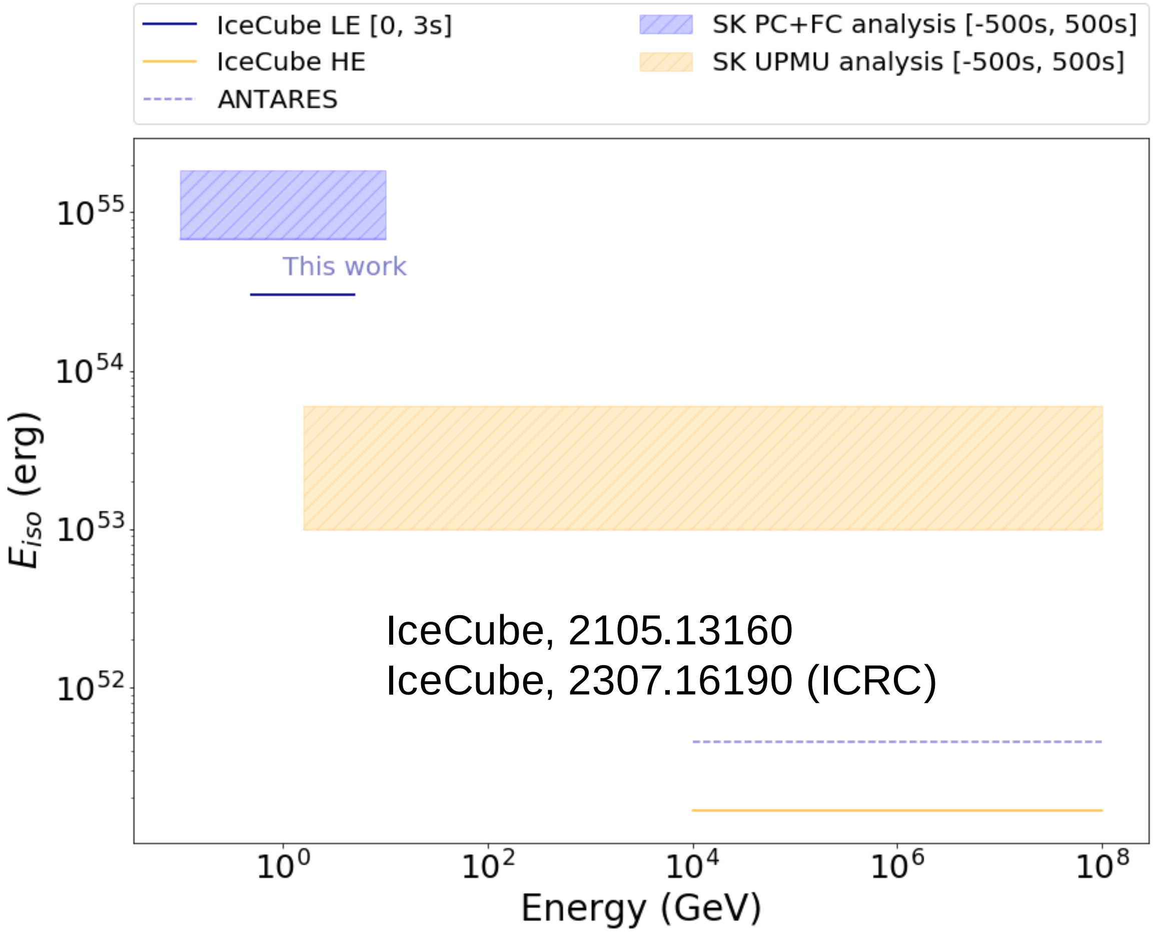
- Previous searches focused on 1 TeV-10 PeV neutrinos using the main IceCube array
- This search uses IceCube DeepCore (dense inner array) for 10 GeV – 10 TeV neutrinos

Searching for "low energy" GW-associated neutrinos using IceCube DeepCore



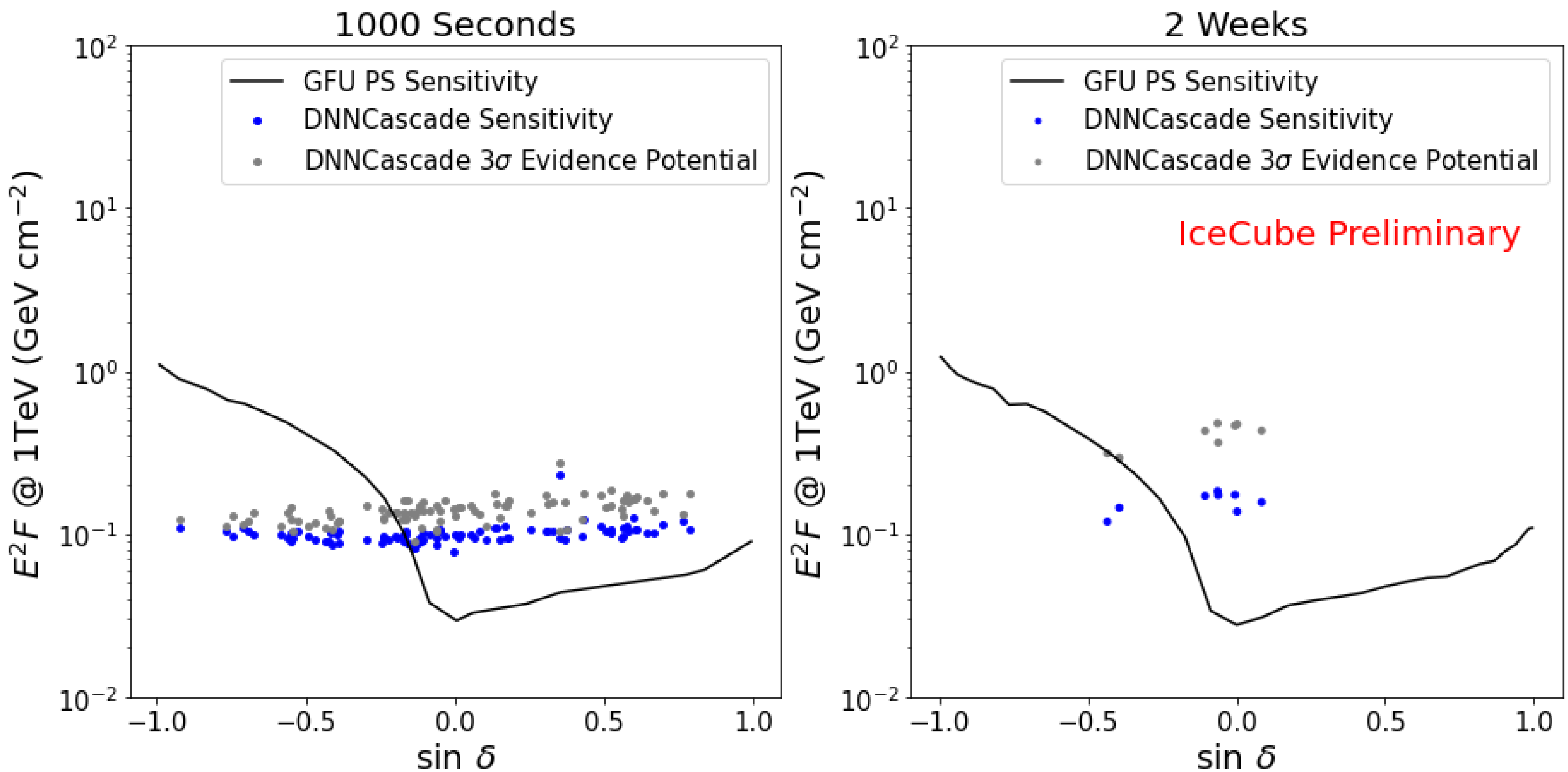
- No evidence of signal found in 10 GeV – 1 TeV neutrino search
- Upper limits now span 10 GeV – 10 PeV (and 4π sky)

Even lower energies: 0.5–5 GeV



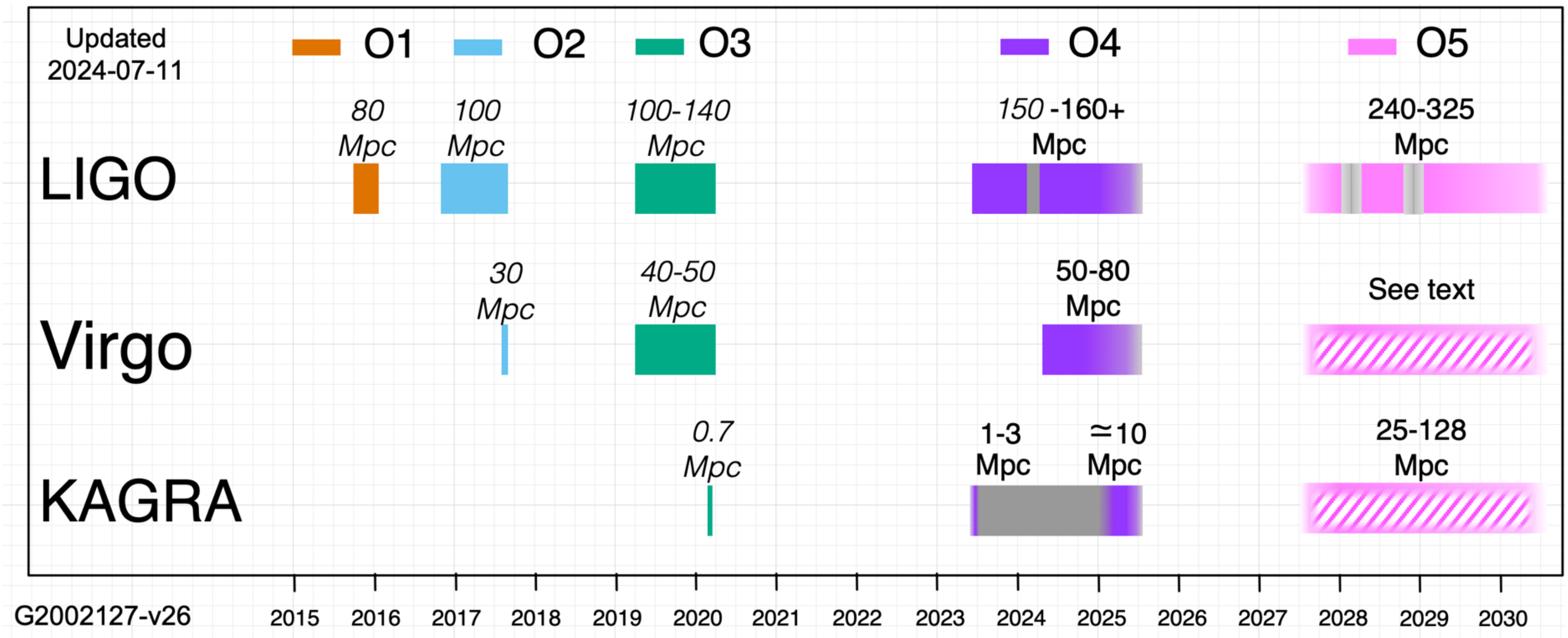
- Using coincident hit method instead of full event reconstruction
- Upper limits now span 0.5 GeV – 10 PeV (and 4π sky)
- Searching even lower, to MeV scale (same method as supernova neutrinos)

Opening the Southern sky with cascades



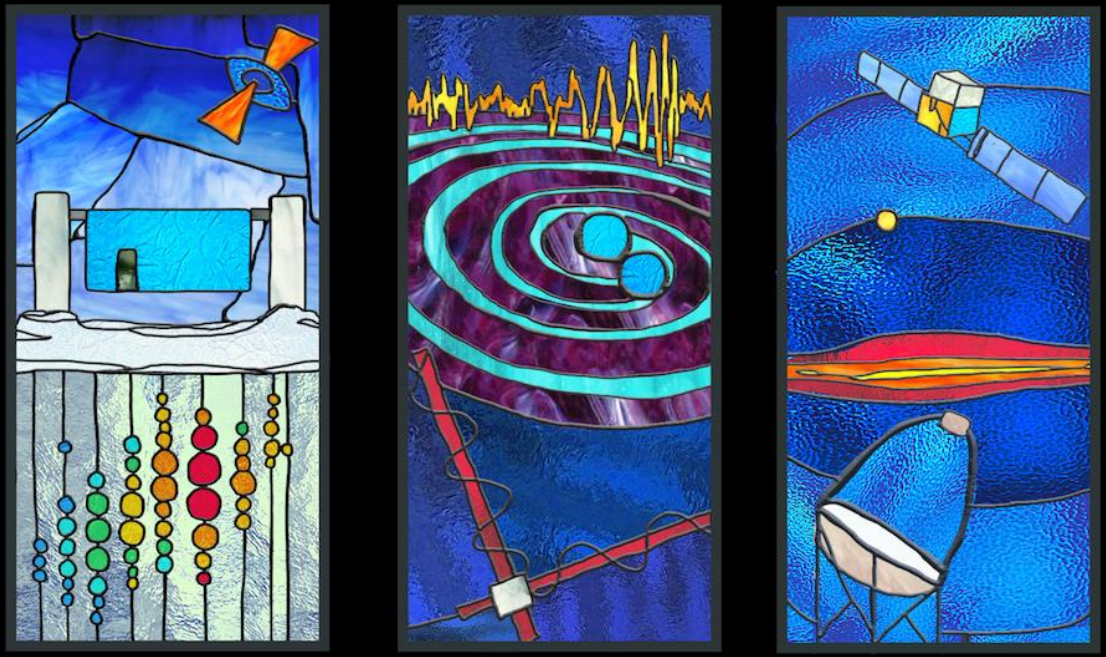
- Same event selection ("DNN Cascades") used to detect Galactic neutrinos
- Better sensitivity than muon tracks in Southern sky (shown for E^{-2})

Continuing real-time LIGO/Virgo/KAGRA follow up throughout O4 (and beyond)



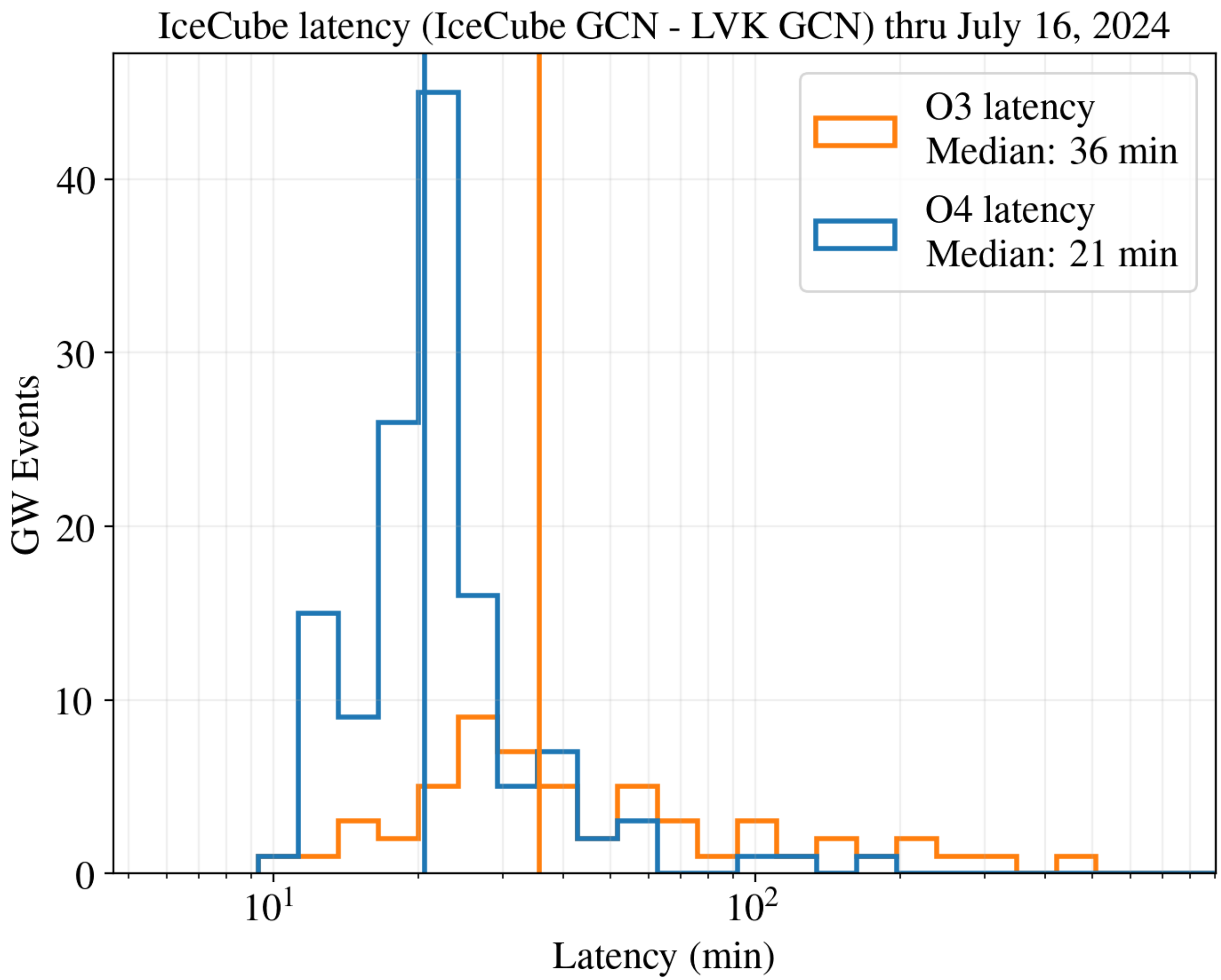
- O4 planned to conclude June 9, 2025
- Will continue to follow up each LVK open public alert (including BBH) and report results from both pipelines with low (~21 minute) latency
- Analyzing low-significance (sub-threshold) as well as high-significance GW
- We encourage other observers to follow up our coincident neutrino alerts!

Conclusion and outlook



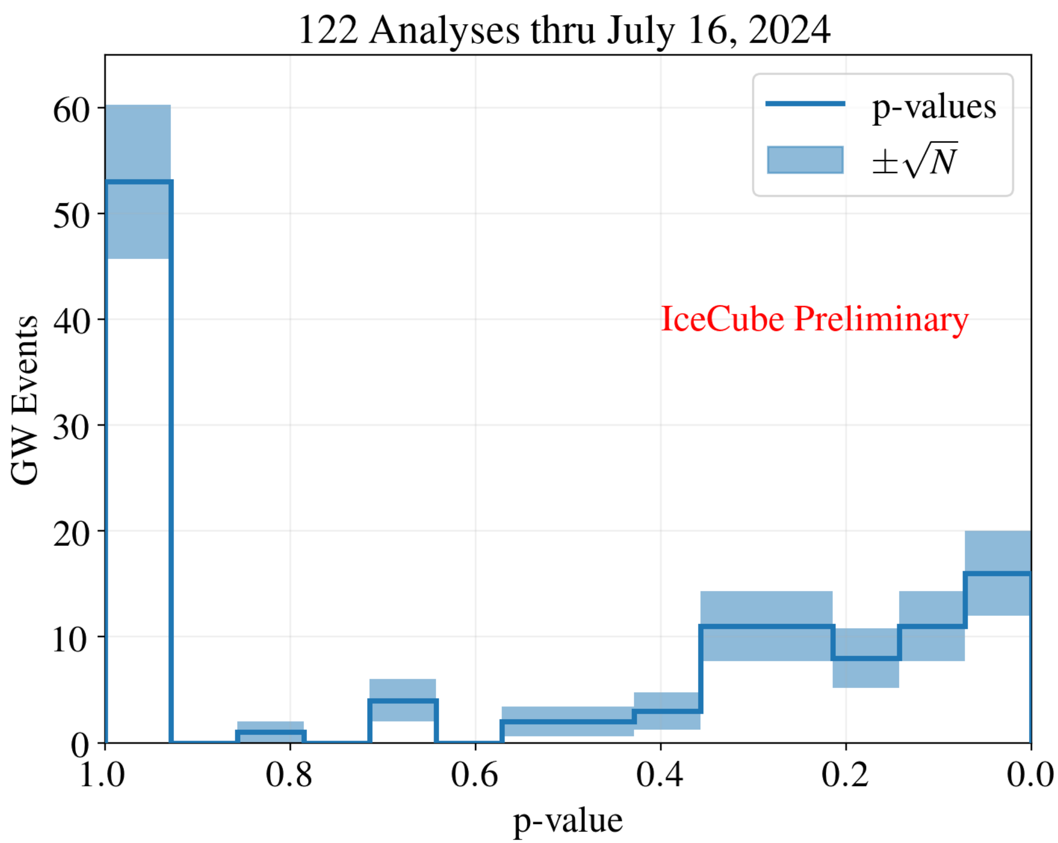
- IceCube is searching for neutrinos from GW sources from MeV to EeV scale
- Searches for neutrinos associated with BBH, BNS, NSBH, and unclassified bursts
- Low (~21 minute) latency follow-up in O4: automated posting of results via GCN
- Neutrinos localized to area 10^3 times smaller than GW, supporting EM follow-up
- Multi-messenger GW-photon and neutrino-photon sources have been detected: ready for GW-neutrino!

IceCube-only latency

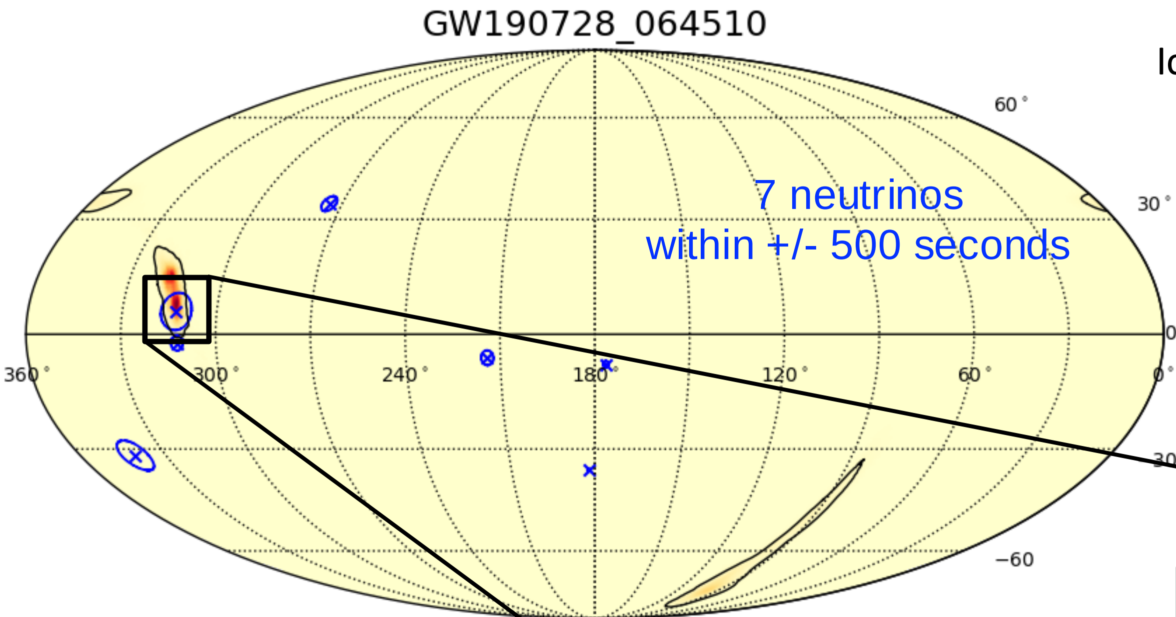


Additional slides

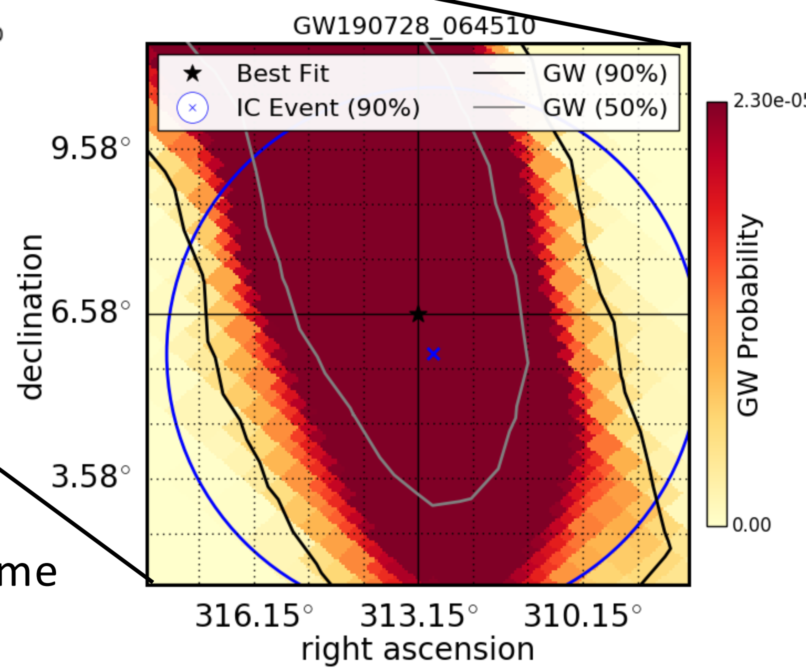
Cumulative p value distribution (linear scale)



An example GW analyzed in real time during O3

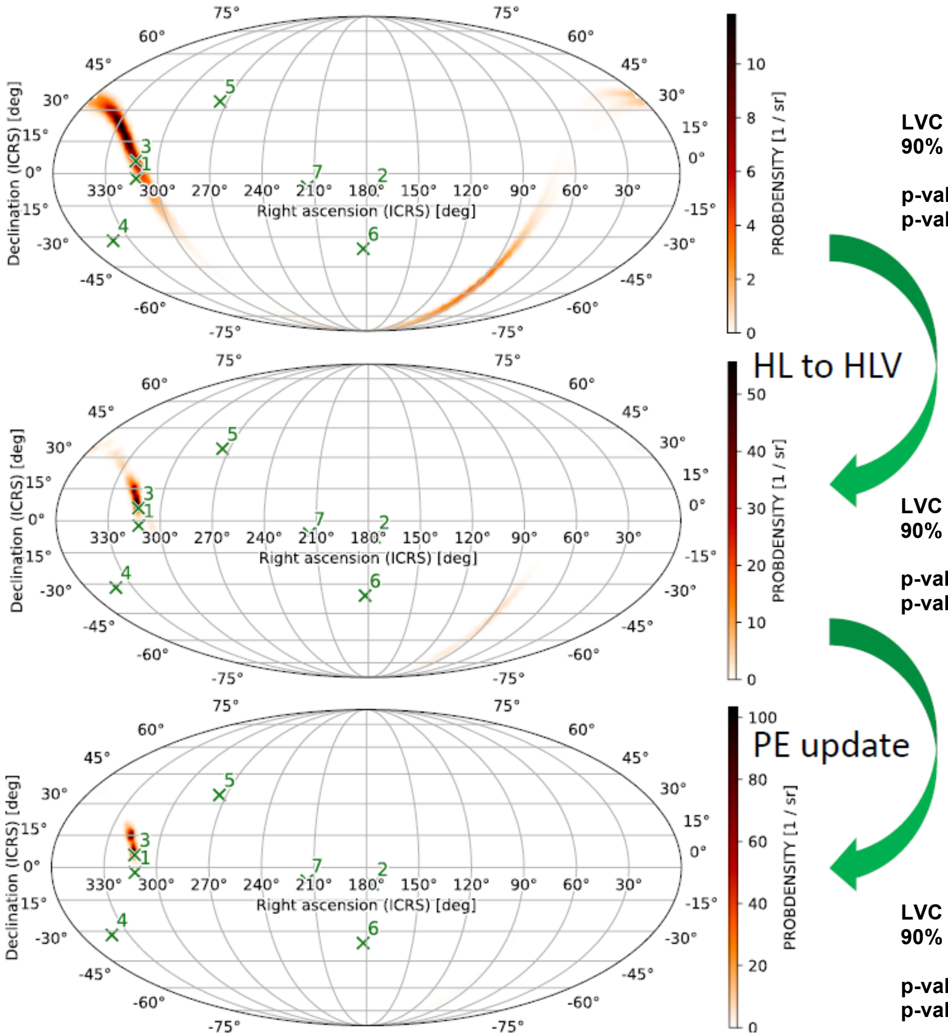


IceCube, ApJ Letters 898 (2020) L10
IceCube, ApJ 944:80 (2023)



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

We follow up each LVK GW 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

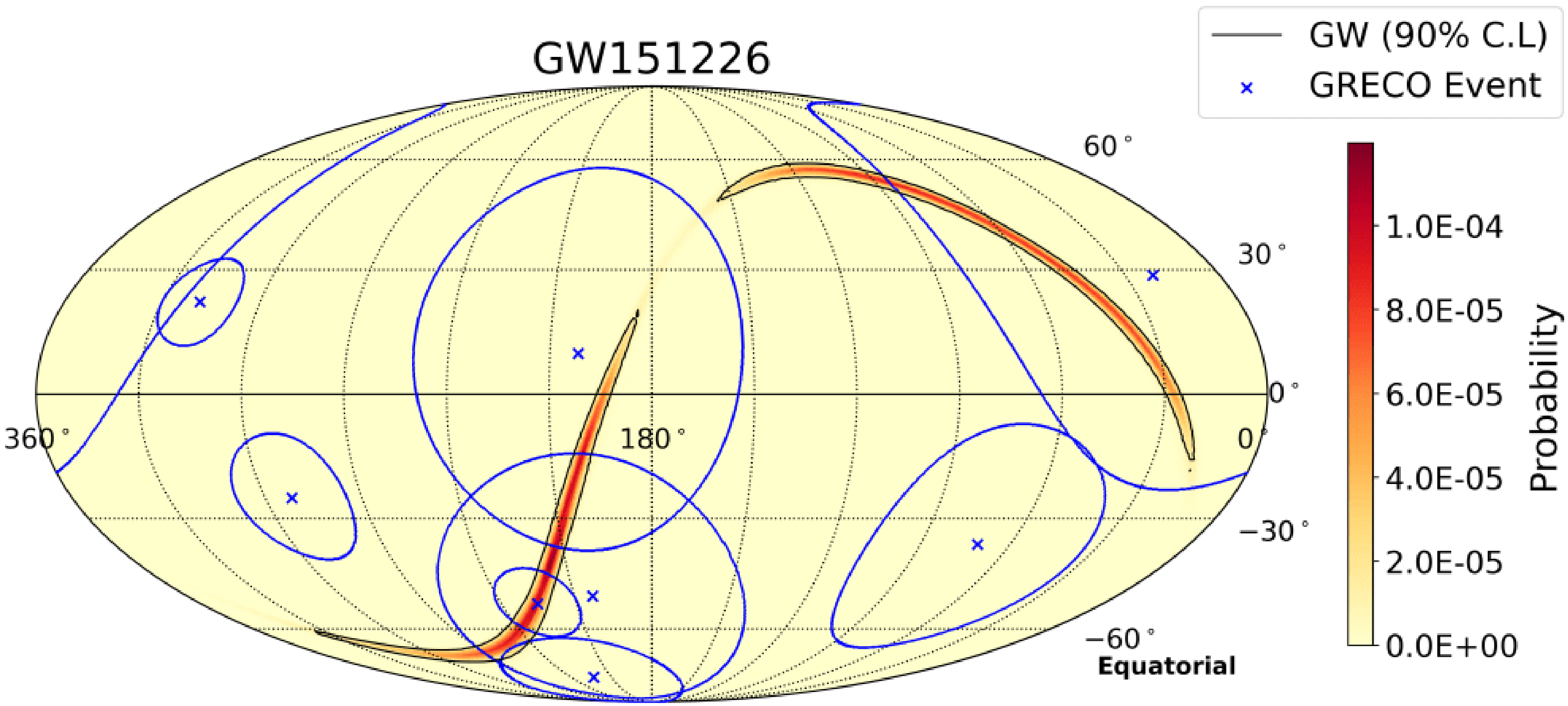
p-value (Maximum Likelihood): 0.039
p-value (LLAMA): 0.013

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)

Searching for 10 GeV-1 TeV neutrinos



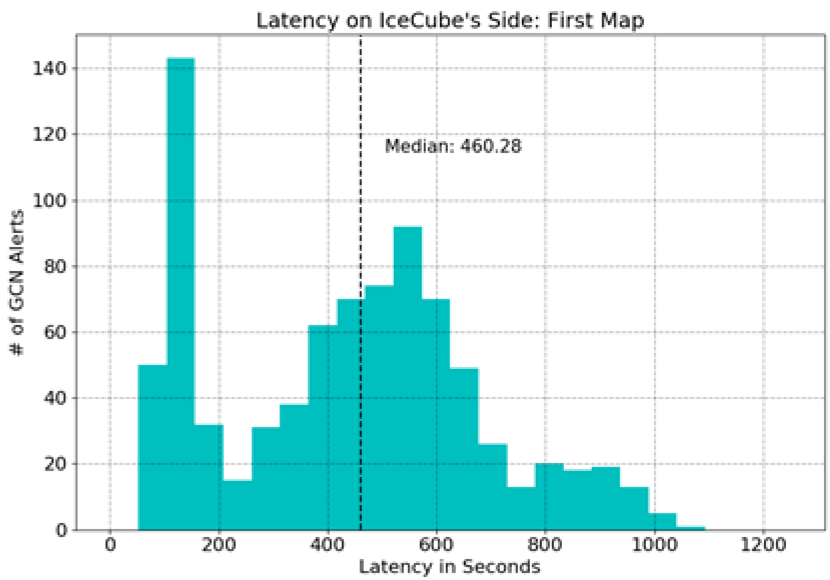
IceCube, ApJ 959 (2023) 96

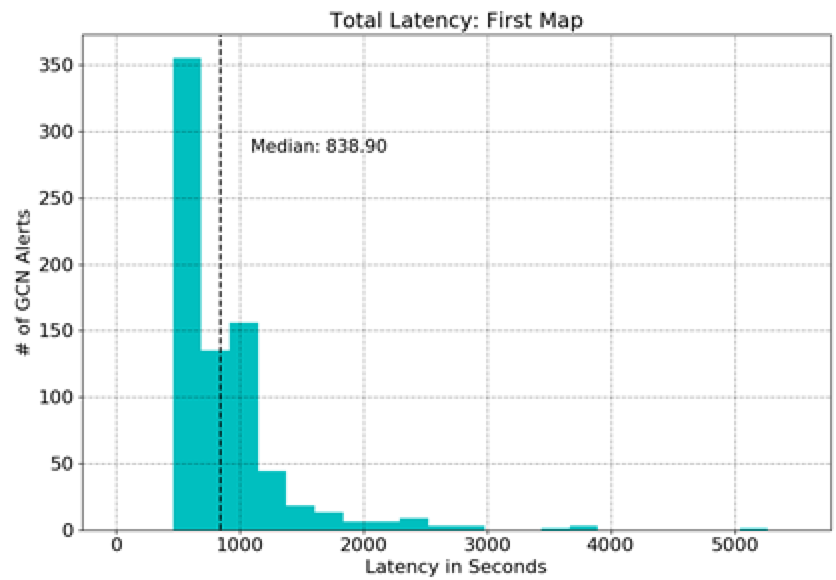
- Previous searches focused on 1 TeV-10 PeV neutrinos using the main IceCube array
- New search uses IceCube DeepCore (denser inner array) for 10 GeV – 10 TeV neutrinos

Preliminary IceCube-GW GCN Notice format

Shaded: included if p<0.1

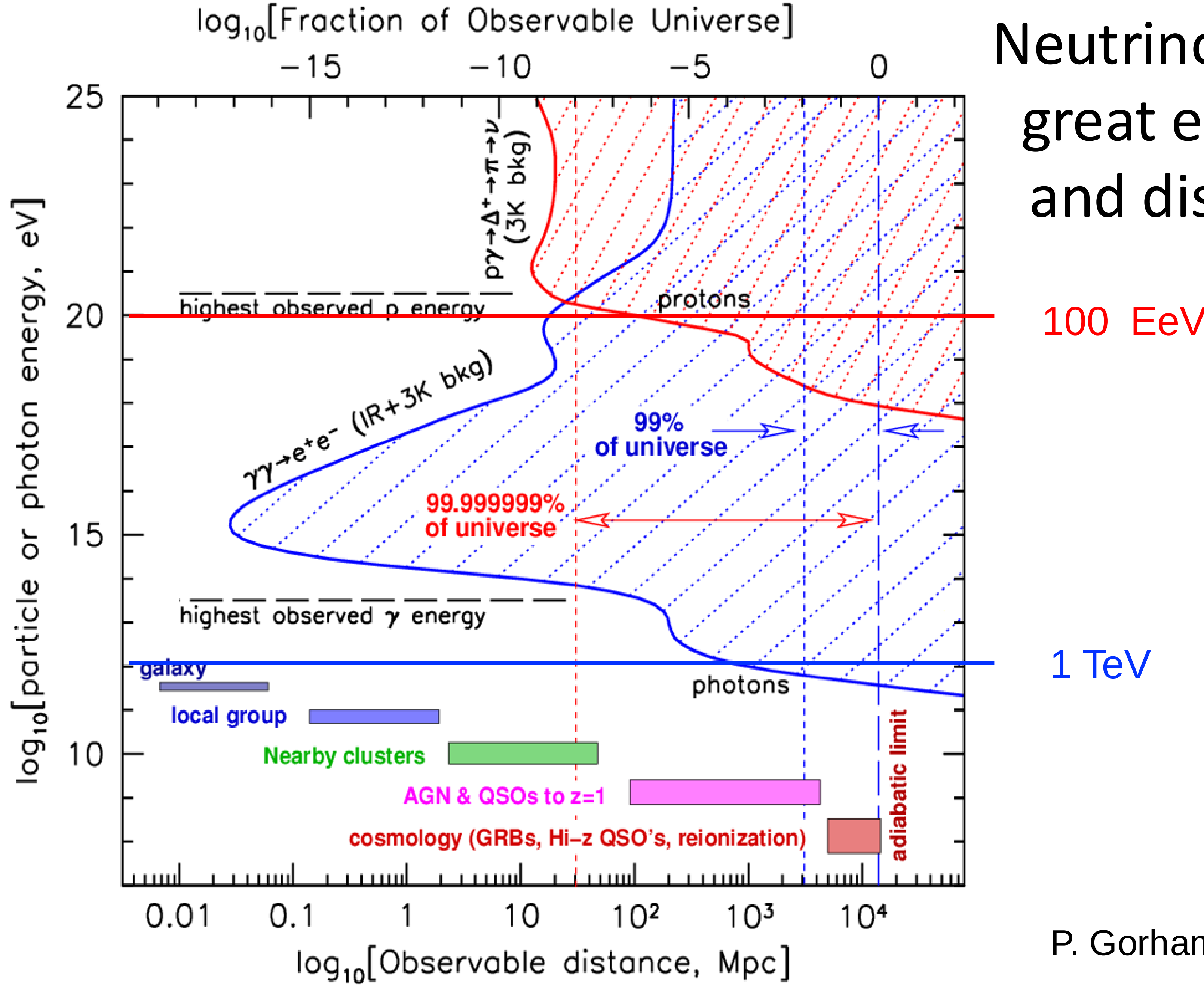
Parameter	Description	Comment
TITLE	GCN NOTICE	
NOTICE_DATE	[date]	UTC
NOTICE_TYPE	IceCube_GW_Coinc	notice type name
STREAM	##	standard
GW_EVENT_NAME	[lvk_name]	From LVK, GW event followed up
GW_GCN_NOTICE_NUM	[notice_id]	notice id from GW detectors
T_MERGER	[trigger_time]	UTC
T_START	[tstart]	UTC; start 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

Neutrinos see to great energies and distances



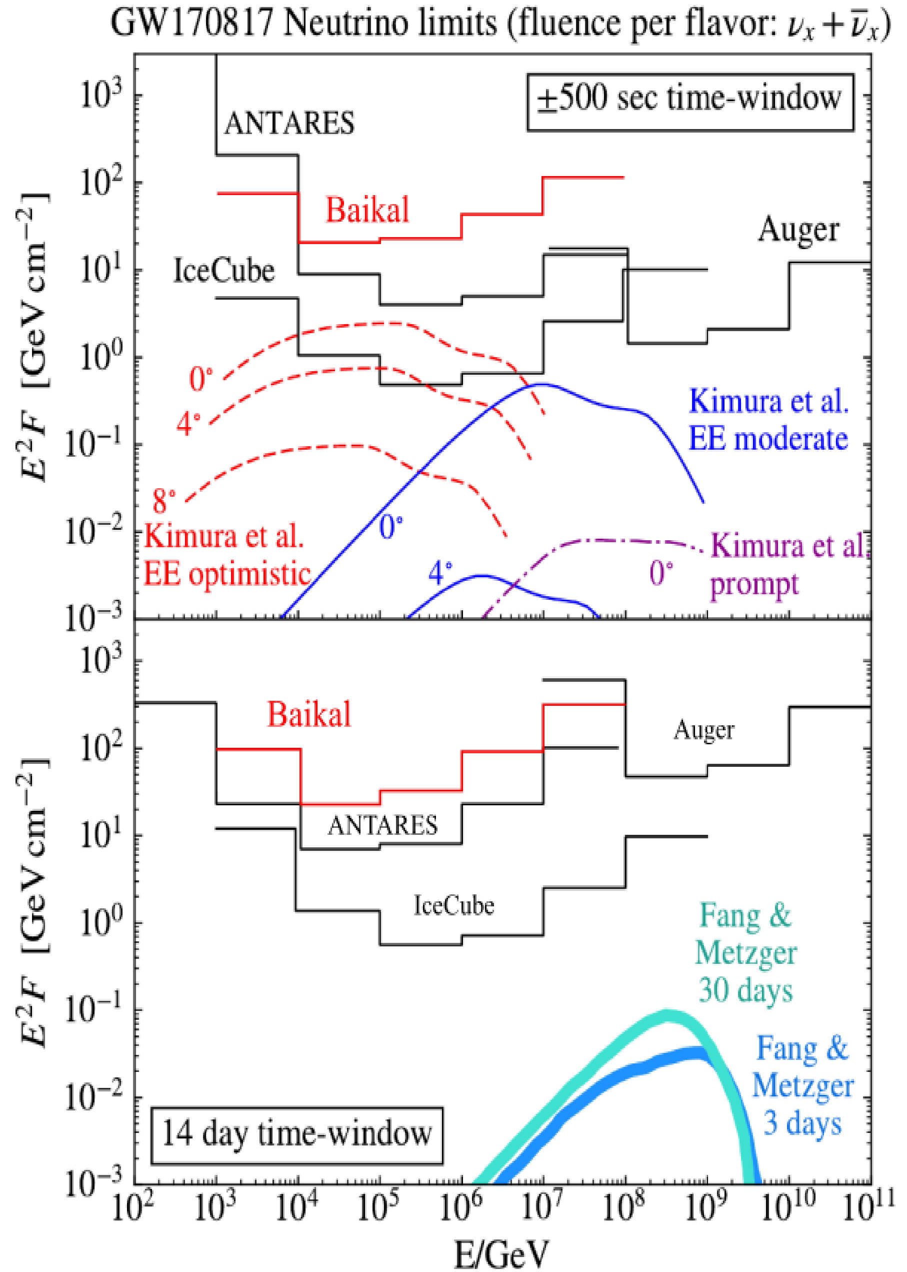
P. Gorham

ANTARES, Auger, GVD, IceCube analysis of BNS merger GW 170817

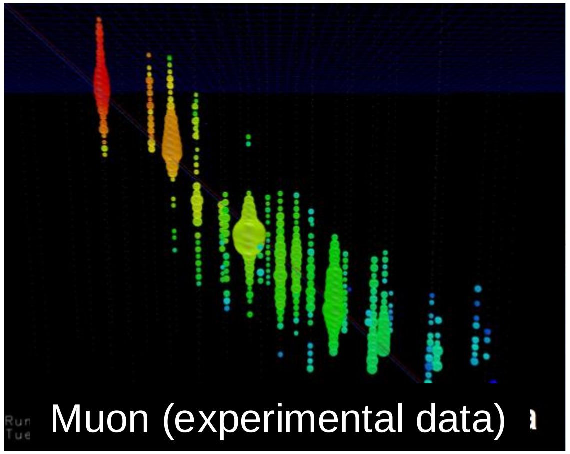
No neutrino events associated with GW170817A found in cascade search within ± 500 seconds or +14 days

Assuming E^{-2} and equal fluence in all flavors, upper limits at 90% have been derived on the neutrino fluence from GW170817 for each energy decade.

GVD, JETP Lett. 108 (2018) no.12, 787-790

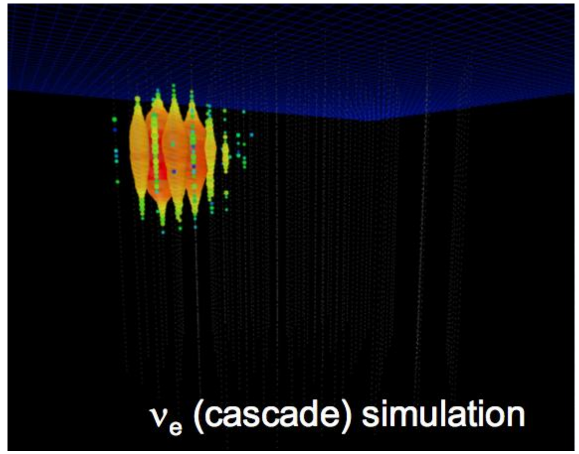


Interaction channels and flavor identification



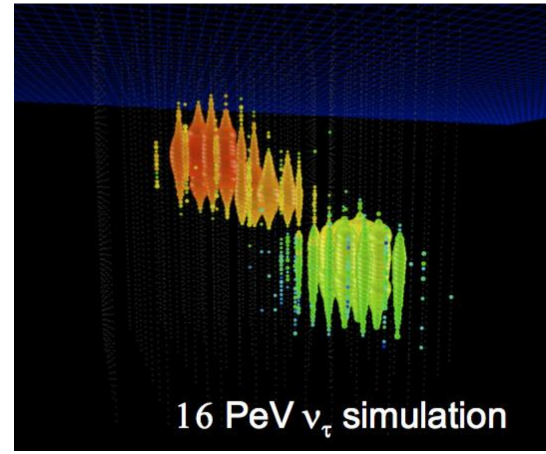
Muon neutrino

+ Straight track, points to neutrino source, angular resolution ~1°
- Cosmic-ray muon background



Electron neutrino

+ Good energy resolution
- Cascade, ideally in detector
- Poor angular resolution

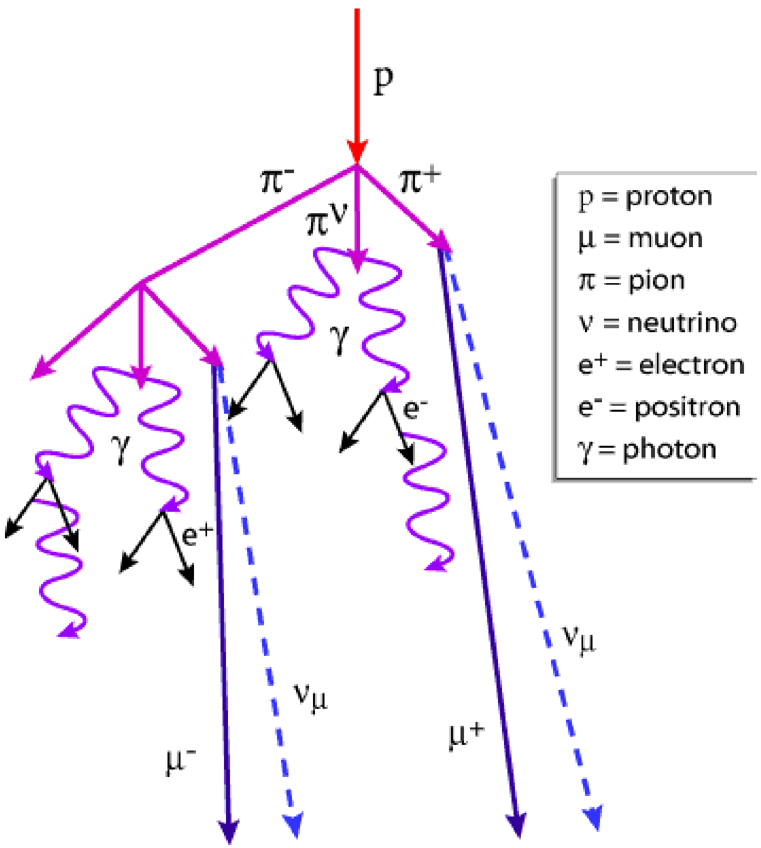


Tau neutrino

+ Double bang signature, low background
+ Pointing capability
- Low rate

- Tracks: ~0.5° (ice) ~0.1° (water)
- Cascades/showers: ~5-10° (ice) ~1° (water)

Signals and backgrounds in neutrino telescopes



Rates for a km^3 telescope

- Atmospheric muons: 70 billion per year
- Atmospheric neutrinos: one in ~10^6
- Astrophysical neutrinos: one in ~10^9

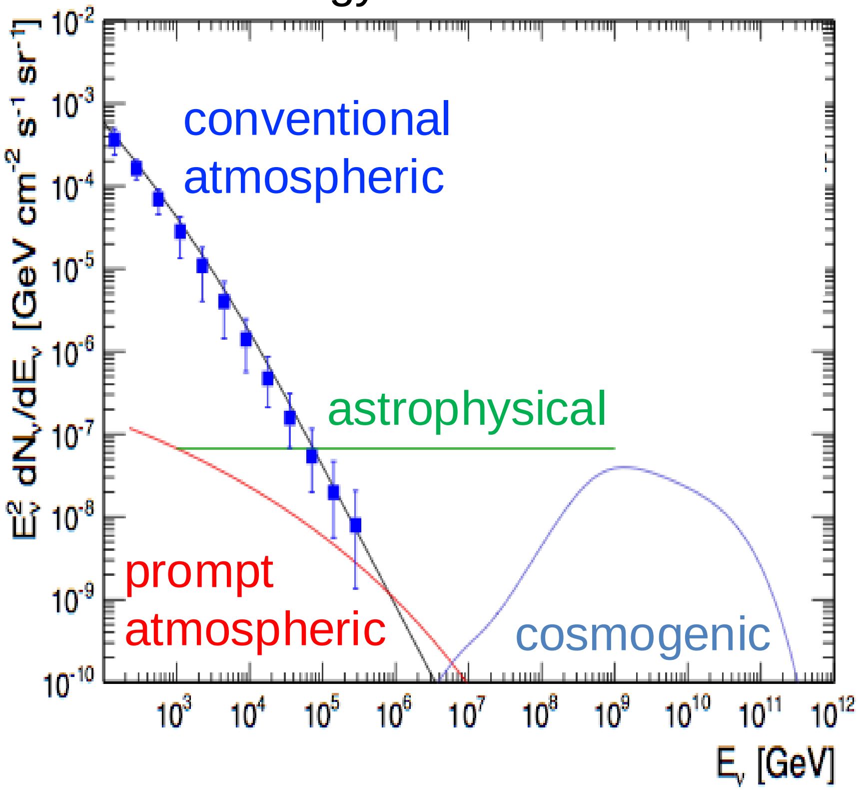
Signals and backgrounds in neutrino telescopes

Most events detected by neutrino telescopes are not astrophysical neutrinos

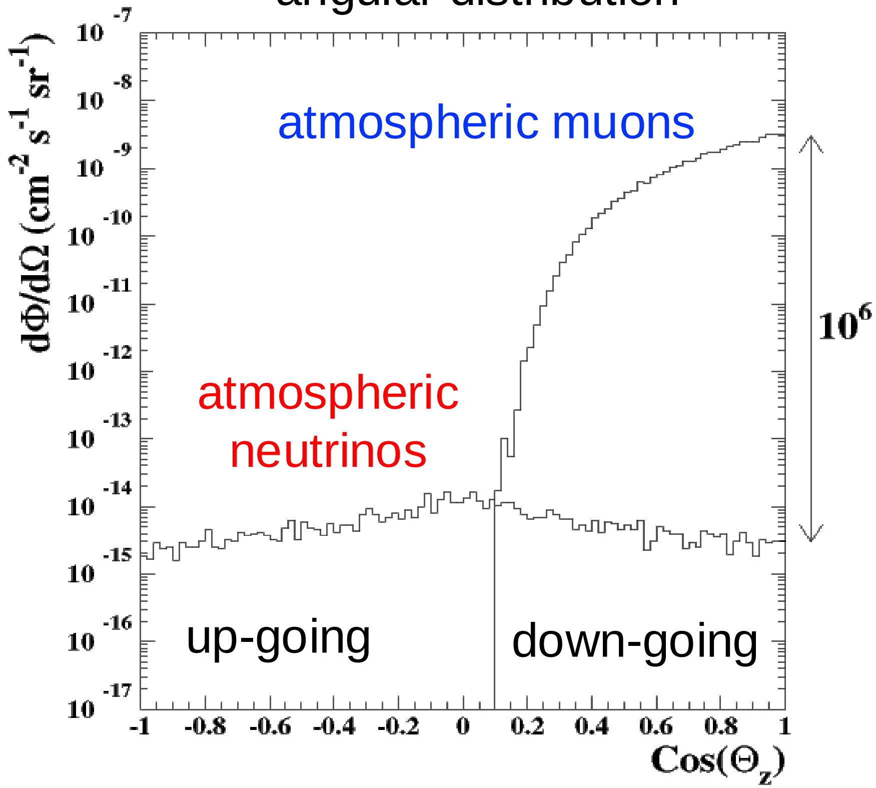
- atmospheric μ ~70 billion / year / km³
- atmospheric $\nu_\mu \rightarrow \mu$ ~80 thousand / year / km³
- astrophysical $\nu_\mu \rightarrow \mu$ ~10 / year / km³ (above 200 TeV)

Background and signal differ in spectrum and angular distribution

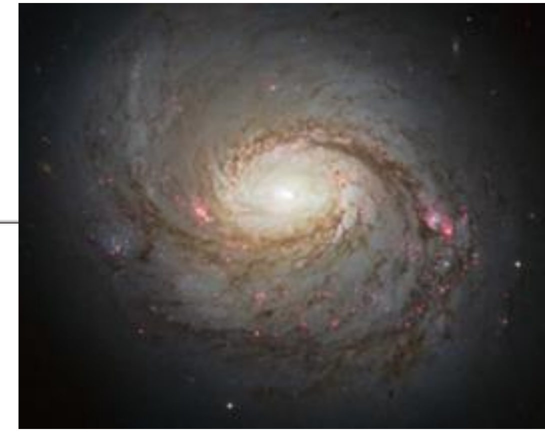
energy distribution



angular distribution



New paper published today



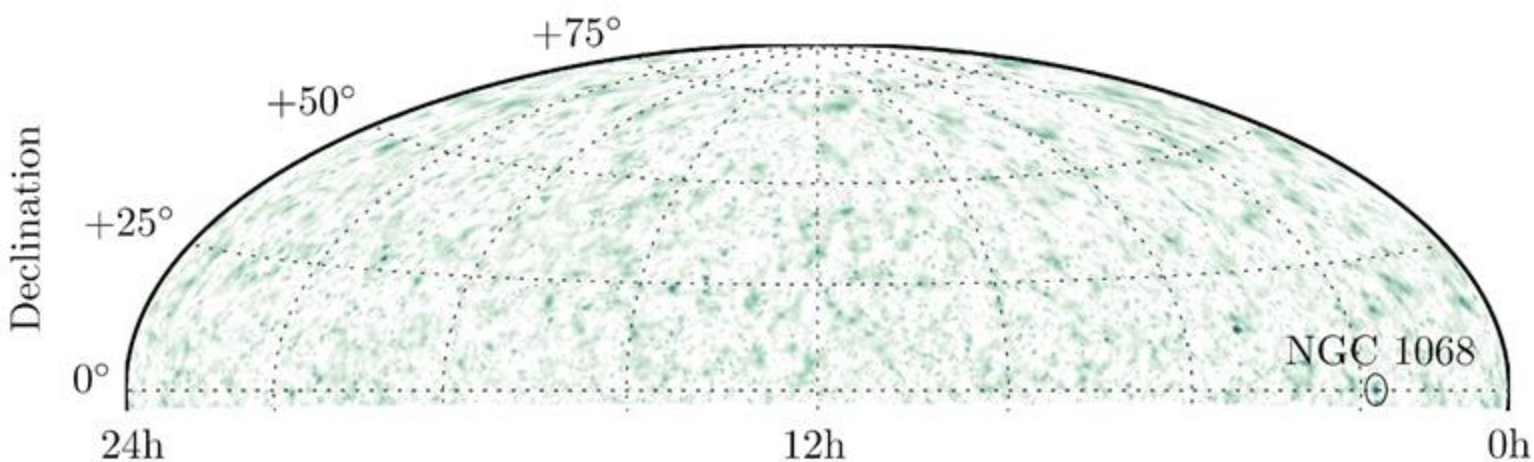
RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

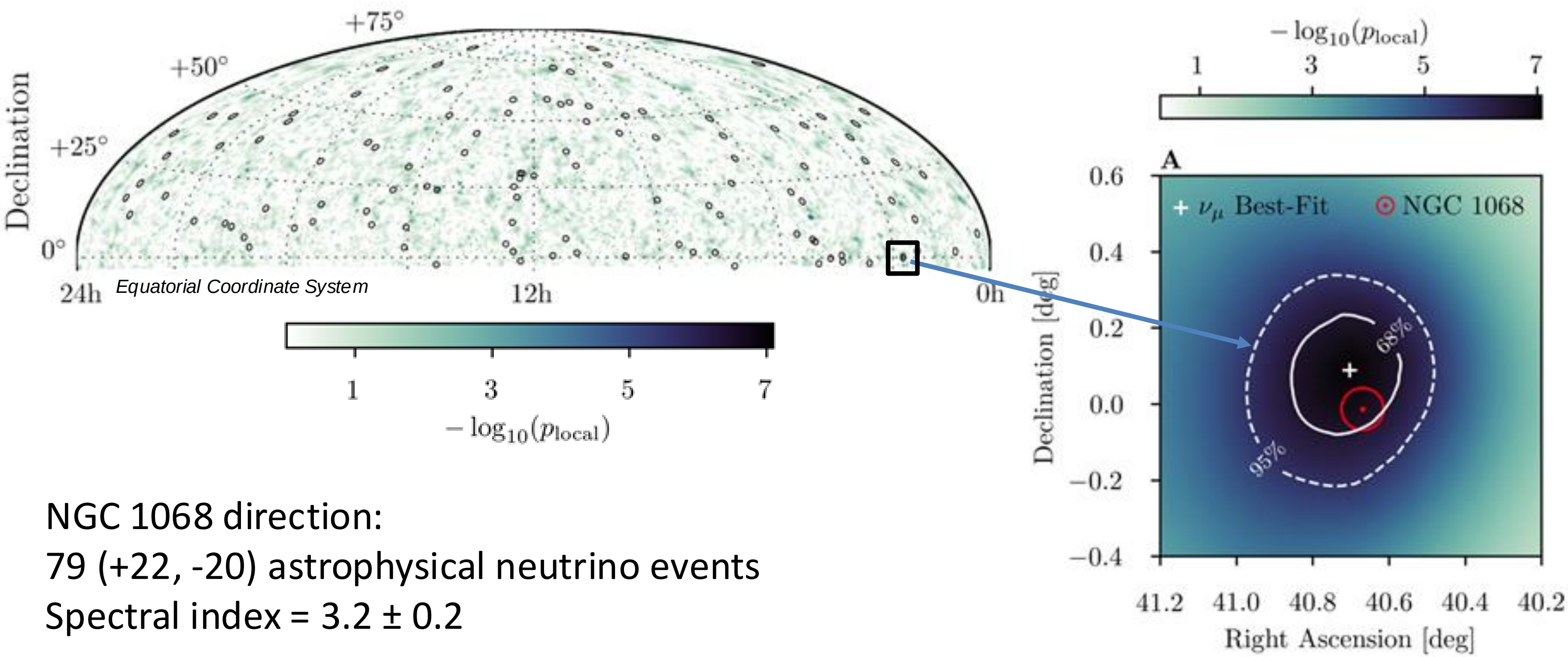
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†



Right Ascension

Evidence for neutrino emission from NGC 1068



NGC 1068 direction:

79 (+22, -20) astrophysical neutrino events

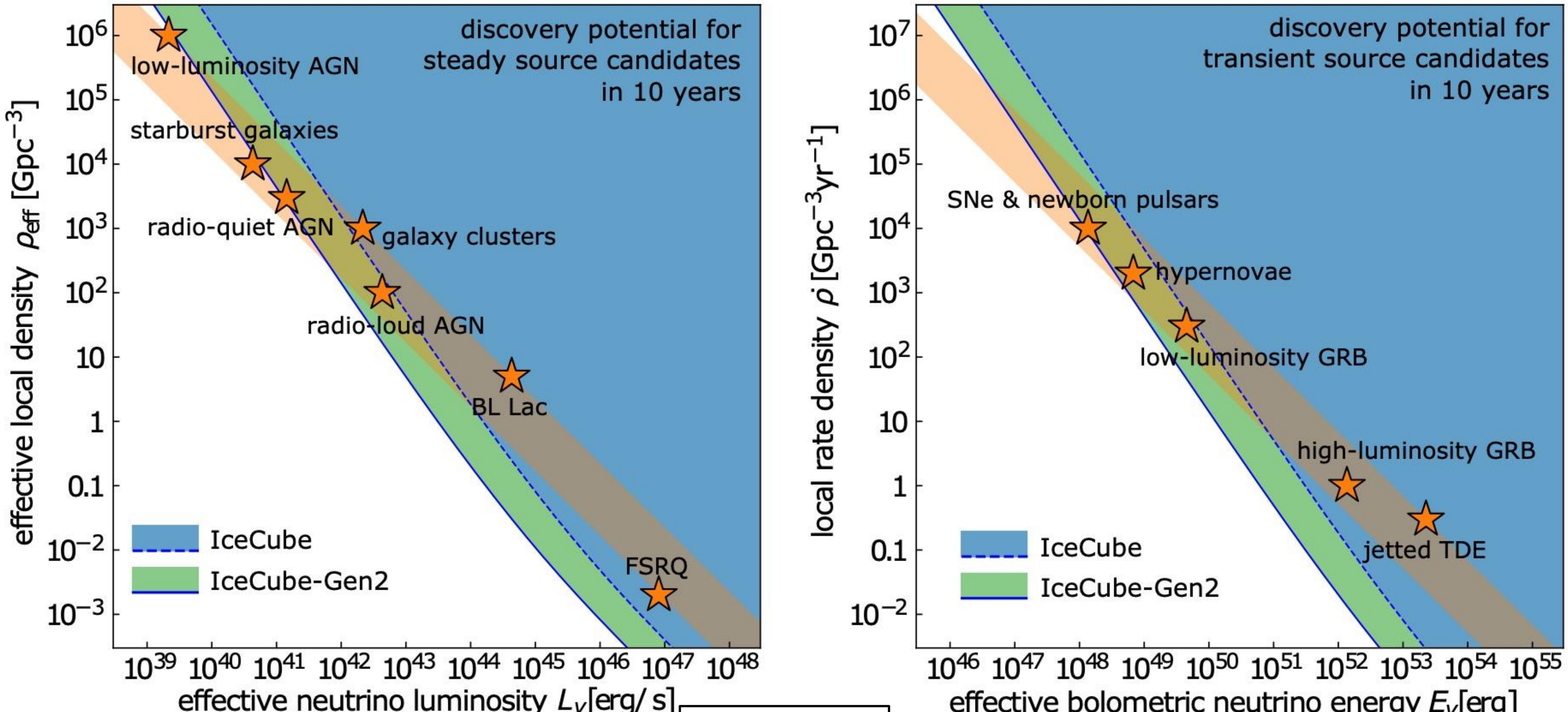
Spectral index = 3.2 ± 0.2

Significance **4.2 σ**

Many dim sources, or few bright sources?

If they are steady | or transient

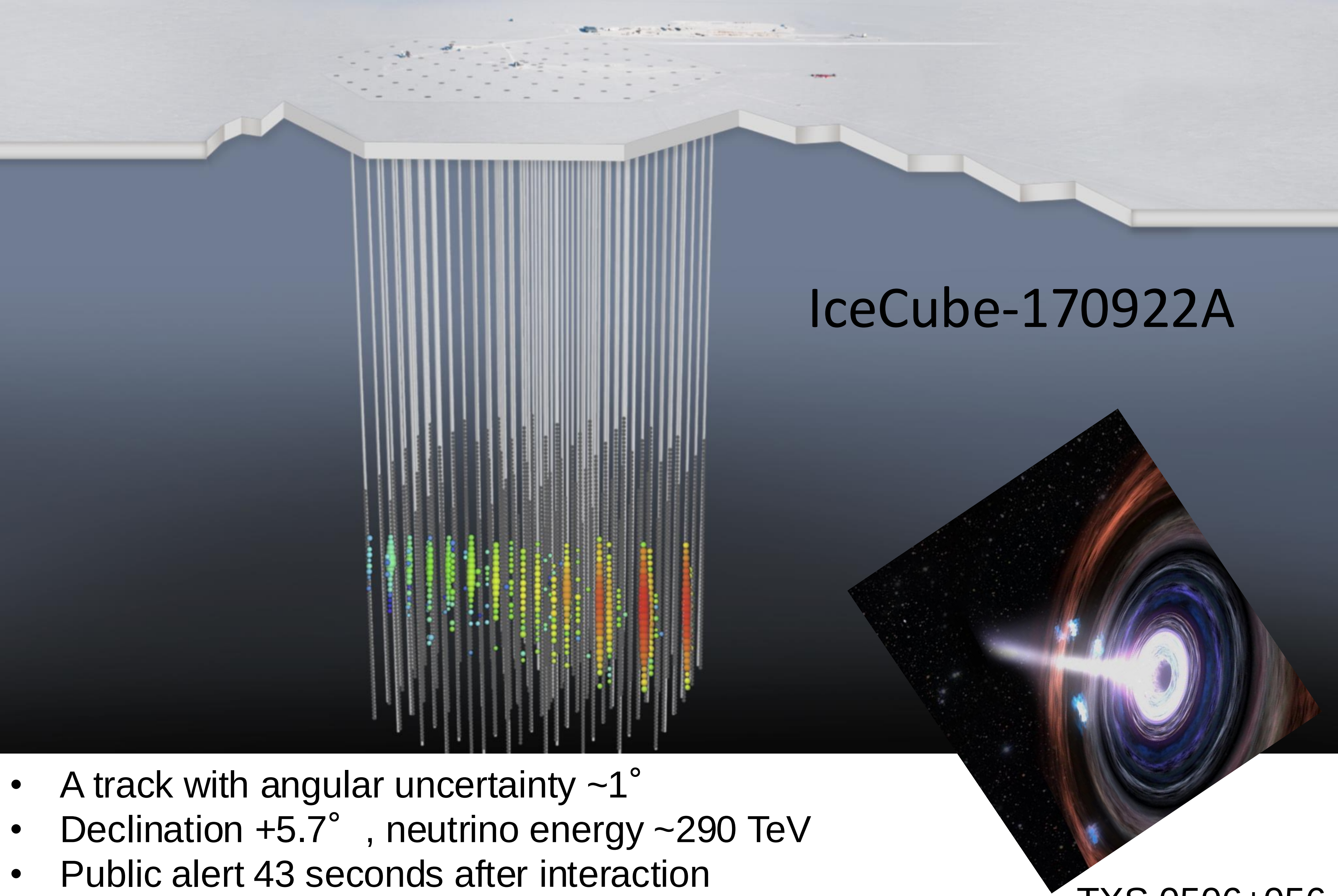
many dim



few bright

“IceCube-Gen2: The Window to the Extreme Universe”
J. Phys. G: Nucl. Part. Phys. 48 060501 (2021)

IceCube-170922A



- A track with angular uncertainty ~1˚
- Declination +5.7˚ , neutrino energy ~290 TeV
- Public alert 43 seconds after interaction

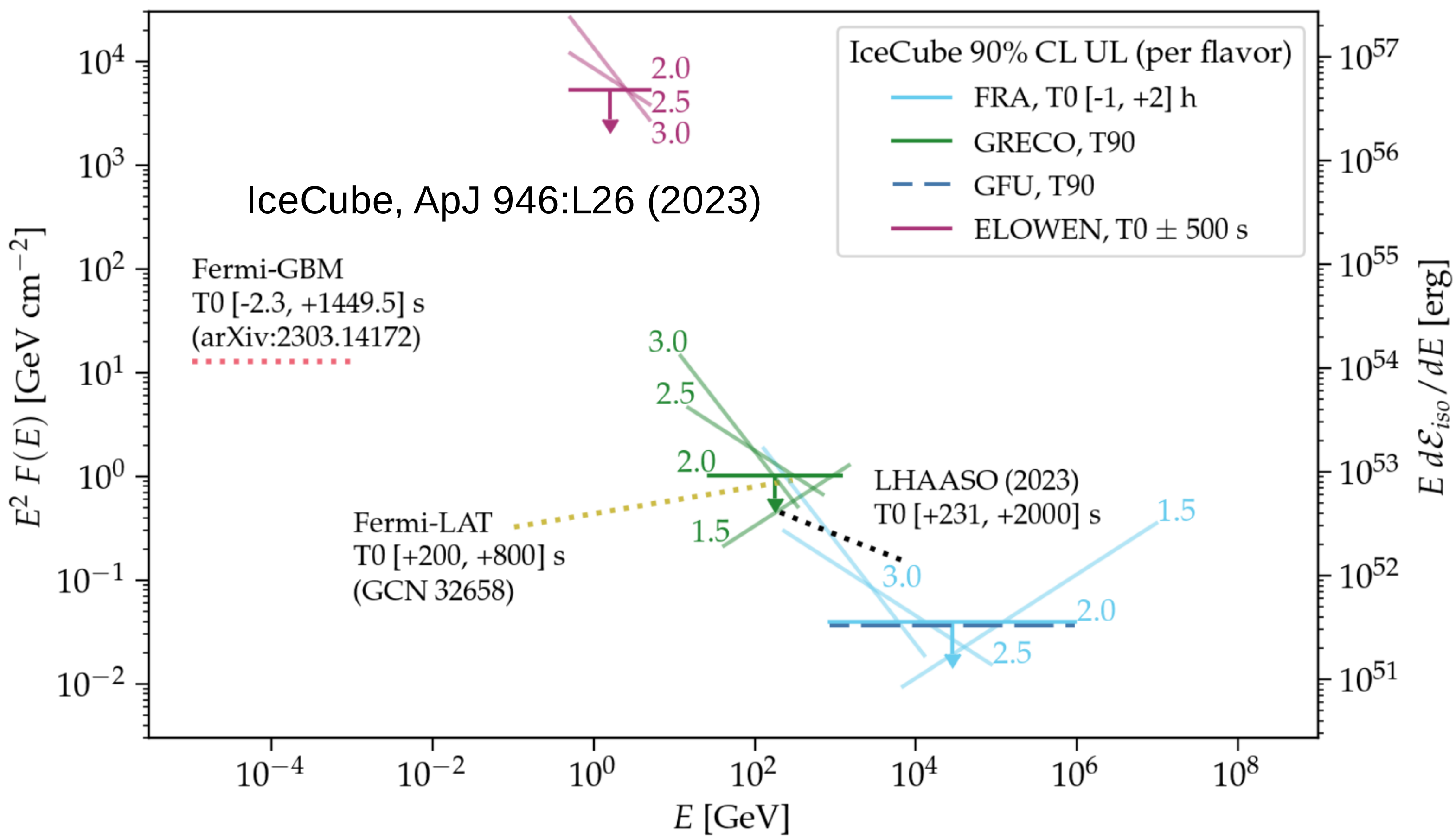
TXS 0506+056
(the galaxy from 4 billion years ago)

The galaxy that emitted gammas and neutrinos, 4 billion years ago: TXS 0506+056

- "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A"
  - 3 σ neutrino-gamma coincidence
- "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert"
  - Neutrino flare in late 2014 – early 2015: 3.5 σ

IceCube, Science 361, 147-151 (2018)
IceCube et al., Science 361, eaat1378 (2018)

Gamma-ray burst 221009A: the brightest of all time



- Highest ever measured gamma-ray peak flux and bolometric energy
- IceCube neutrino search published within hours via GCN
- Neutrino limits from MeV to PeV
- Strong constraints on baryons in GRBs