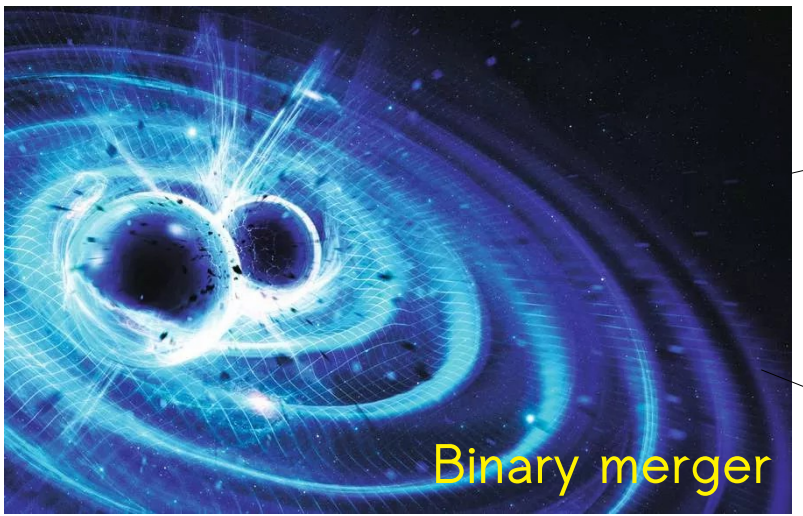
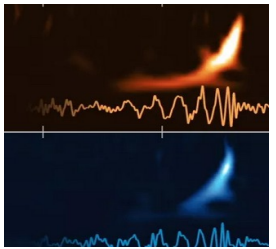
Searches for IceCube-neutrino counterparts to gravitational wave events

Aswathi Balagopal V., Raamis Hussain, Zsuzsa Marka, Justin Vandenbroucke, Doga Veske

for the IceCube collaboration

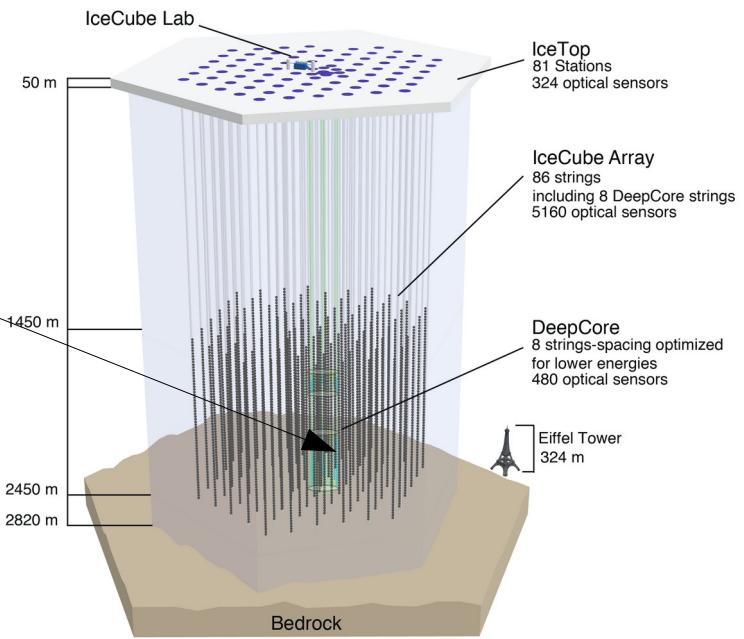
TeVPA 2022





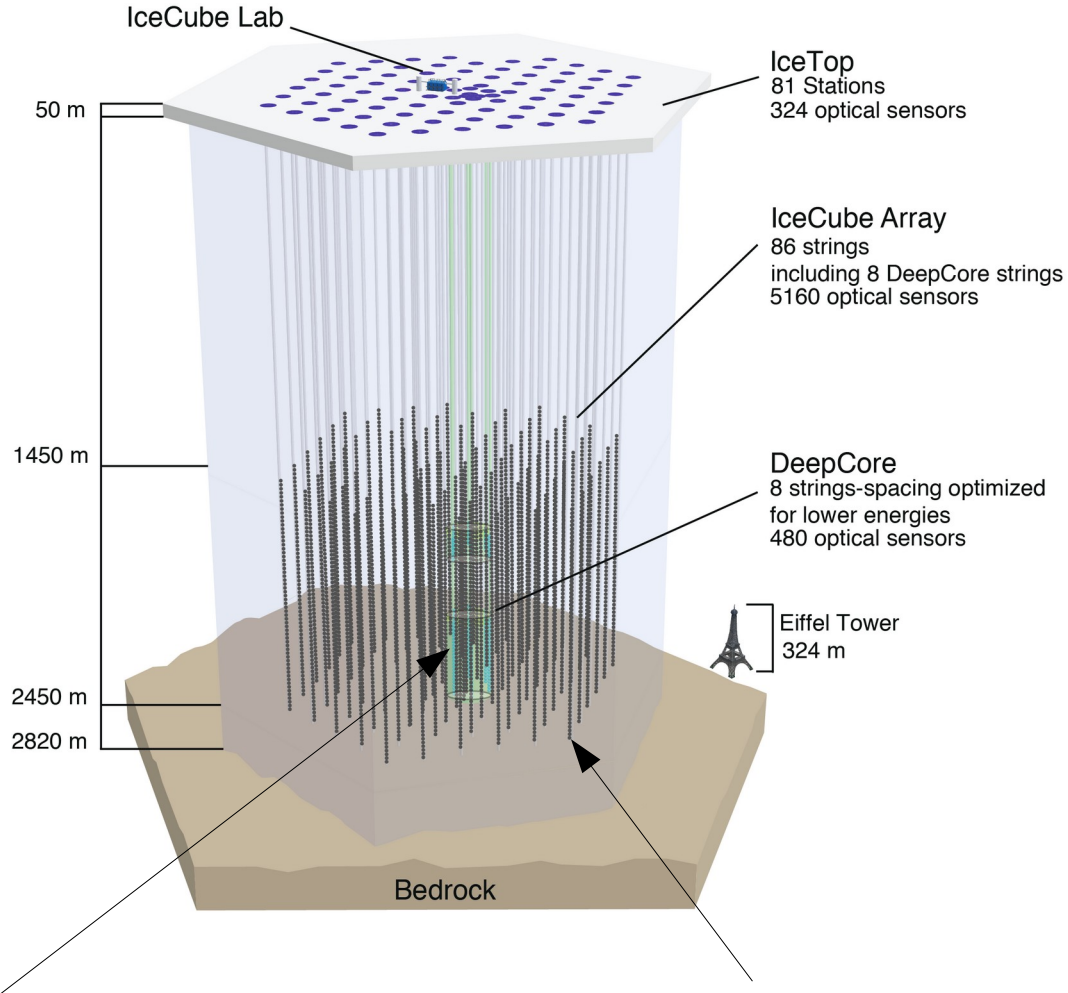
Gravitational waves

Neutrinos?



Motivation

- Several predictions for the production of neutrinos from binary mergers
- Mainly from BNS and BHNS mergers
- Processes may vary for high and low energy neutrinos
- We search for neutrino events from GW events detected by LIGO-Virgo
- Searches done in the **high energy (> 1 TeV), low energy (<1 TeV)** and extremely low energy (< 5 GeV) regime



DeepCore to detect low energy neutrinos

High energy neutrinos from the whole detector

GW searches

Low-latency searches

- Events during the O3 run (56) were followed up in realtime with high energy neutrinos
- 1000 sec time window

Catalog searches

- Follow up GW events in O1, O2 (GWTC-1 catalog) and O3 (GWTC-2.1 and GWTC-3 catalogs) runs of LIGO-Virgo
- GWTC-1 follow-up with high energy neutrinos published
- Newly unblinded: GWTC-2.1 and GWTC-3 events with high energy neutrinos
- Newly unblinded: GWTC-1, GWTC-2.1 and GWTC-3 events with low energy neutrinos
- 1000 sec (low and high energy) and 2-week time windows (high energy)

Astrophys. J. Lett. 898 (2020) L10
Phys. Rev. X 9, 031040 (2019)
arXiv:2108.01045
arXiv:2111.03606

Neutrino datasets

High-energy dataset

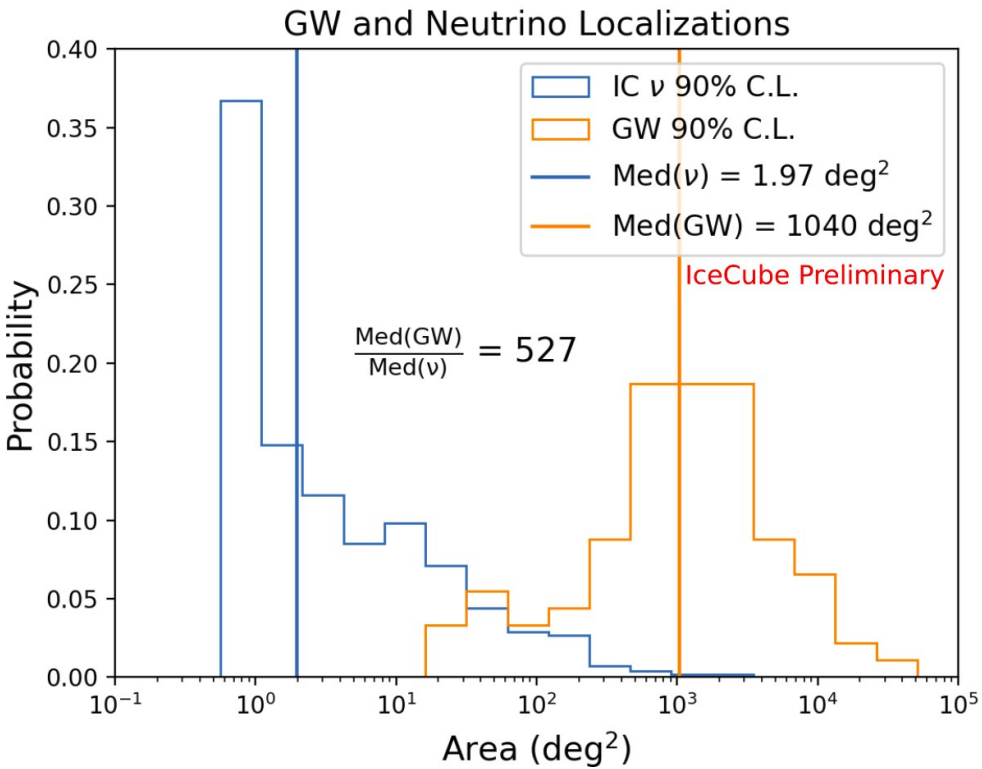
- Energy range: 5×10^5 GeV to 7×10^7 GeV in the southern hemisphere and 5×10^3 GeV-10^5 GeV in the northern hemisphere
- Muon neutrinos only
- Angular resolution ~ 1 degree

Low-energy dataset

- Energy range: ~8 GeV - 3×10^4 GeV in the whole sky
- Neutrinos of all flavour
- Median angular resolution ~ 50 degrees

Localizations

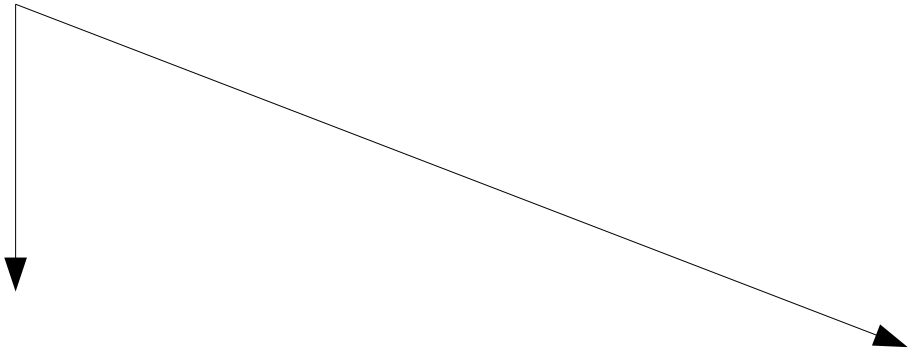
- Area of GW probabilities in sky is large
- High-energy neutrinos (shown here) have much smaller area in sky
- Low-energy neutrinos have similar areas compared to GW areas



Analysis approaches

High energy analysis
(catalog + low-latency)

Low energy analysis
(catalog)



Low Latency Algorithm for Multimesseinger Astrophysics (LLAMA)

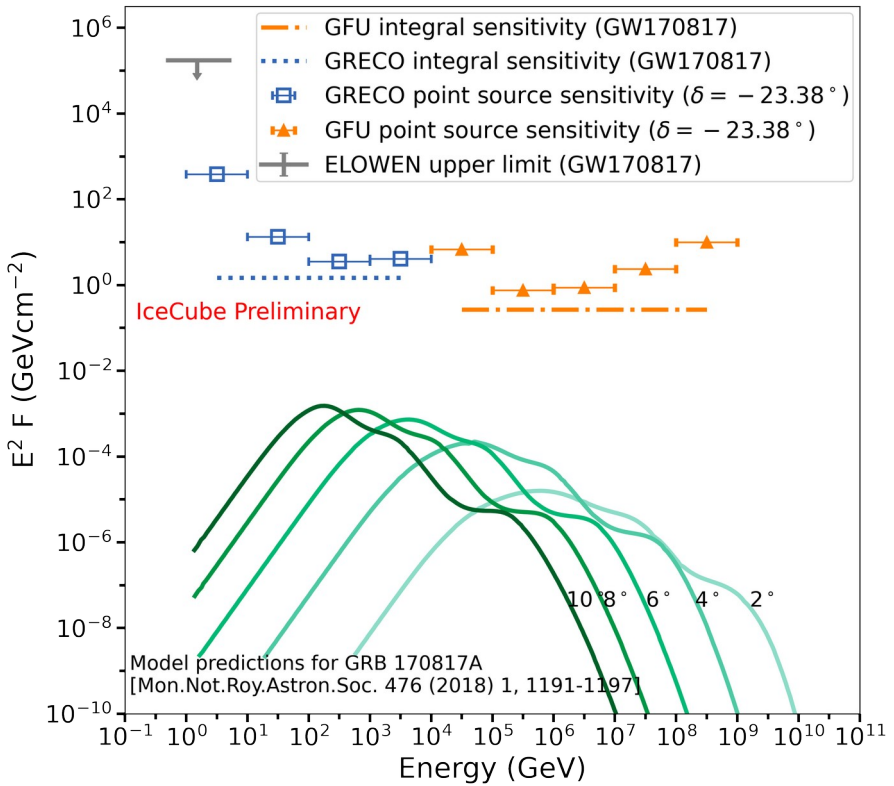
Test statistic = odds ratio for a common source; includes astrophysical emission priors which uses distance information from the GW

Unbinned Maximum Likelihood Method (UML)

Test statistic = likelihood ratio of signal+background hypothesis vs background only hypothesis

Astrophys. J. Lett. 898 (2020) L10

Sensitivity comparison

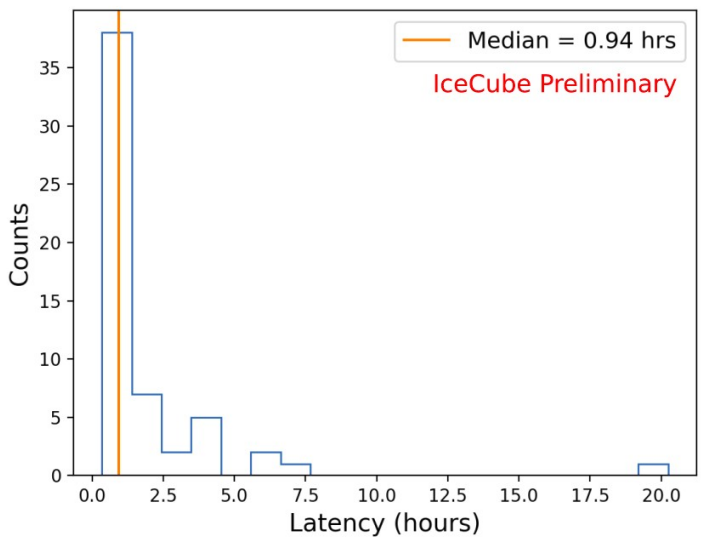


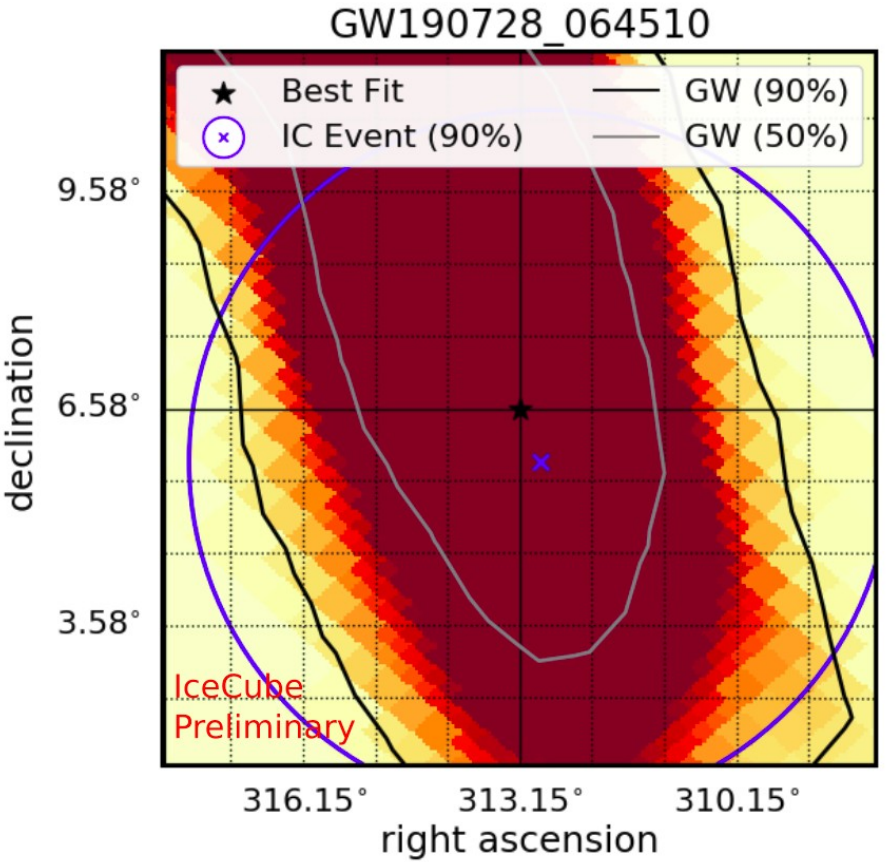
Comparison of differential (and integral) sensitivites of various GW follow-up analyses, with model predictions (selected)

Results

Results: High Energy Analysis (realtime)

- Ran low-latency search on 56 GW events
- Most significant event: GW190728
- Neutrino arrived 360 s before the GW merger
- Had a reconstructed energy of 601 GeV
- No counterparts found from other observatories
- pre-trial p-values for this event are:
  - p = 0.04 (UML) and p = 0.013 (LLAMA)

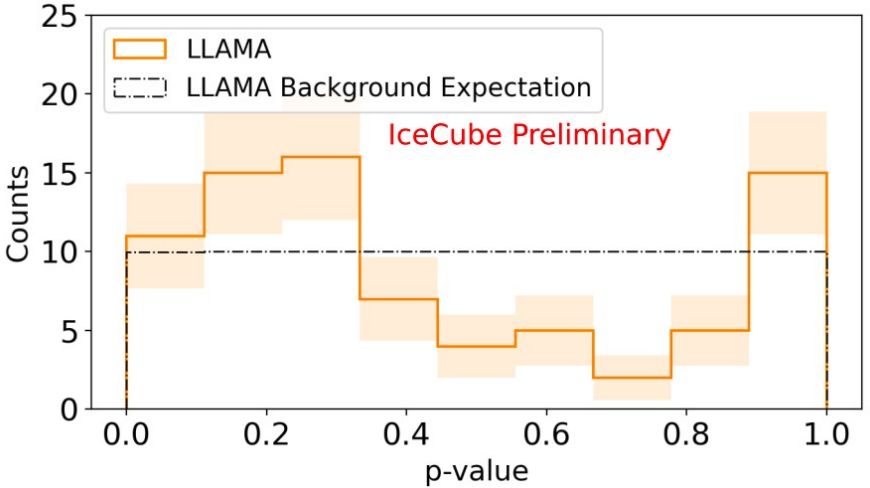


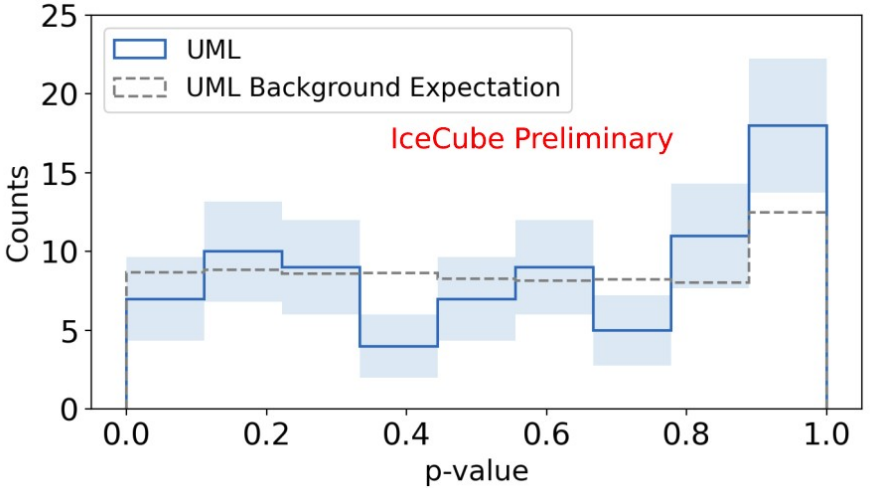


Sky localization of the most significant event

Results: High Energy Analysis (catalog search)

91 GWs from O1,O2,O3



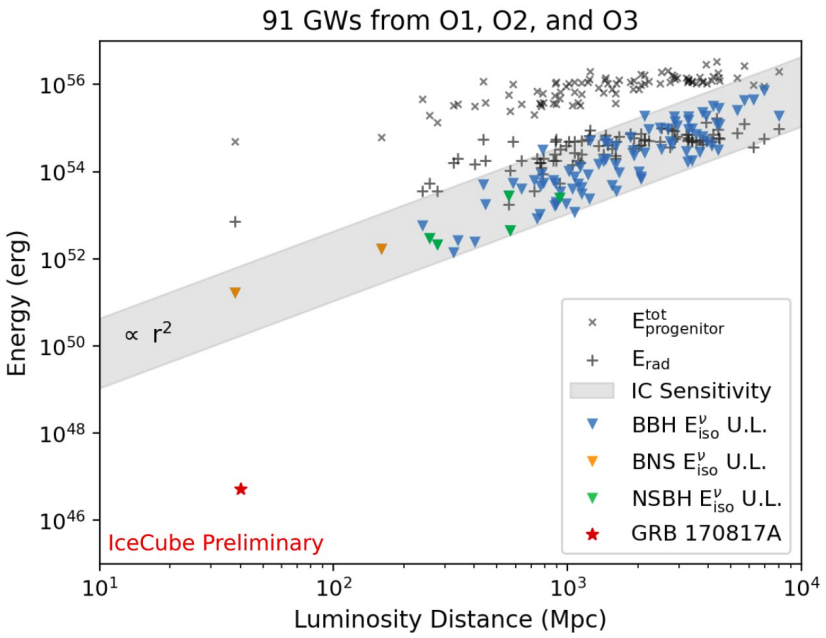


No significant neutrino emission was seen in GWTC-1, GWTC-2.1 and GWTC-3

GWTC-2.1			LLAMA		UML		
Event	Type	Area [deg^2]	p-value	E^2F UL [GeVcm^{-2}]	p-value	E^2F UL [GeVcm^{-2}]	$E_{\rm iso}$ UL [erg]
GW190728_064510	BBH	395.5	0.0084	0.89	0.04	0.315	6.36×10^{53}
GWTC-3			**LLAMA**		**UML**		
Event	Type	Area [deg^2]	p-value	E^2F UL [GeVcm^{-2}]	p-value	E^2F UL [GeVcm^{-2}]	$E_{\rm iso}$ UL [erg]
GW200316_215756	BBH	410.4	0.17	0.066	0.04	0.110	5.19×10^{53}
GW200225_060421	BBH	509.0	0.0048	0.10	0.20	0.055	3.03×10^{53}

Events with lowest pre-trial p-values in UML and LLAMA from GWTC-2.1 and GWTC-3 (out of 80 GW events)

E_{iso} upper limits (high-energy neutrinos)



- 90% UL on the isotropic equivalent energy emitted in high-energy neutrinos
- Total rest mass energy of the progenitors and total radiated energy of the system is also shown
- Grey bands represent the expectation (based on the sensitivities)
- E_{iso} UL on GRB170817A is 4 orders of magnitude lower than that on neutrinos

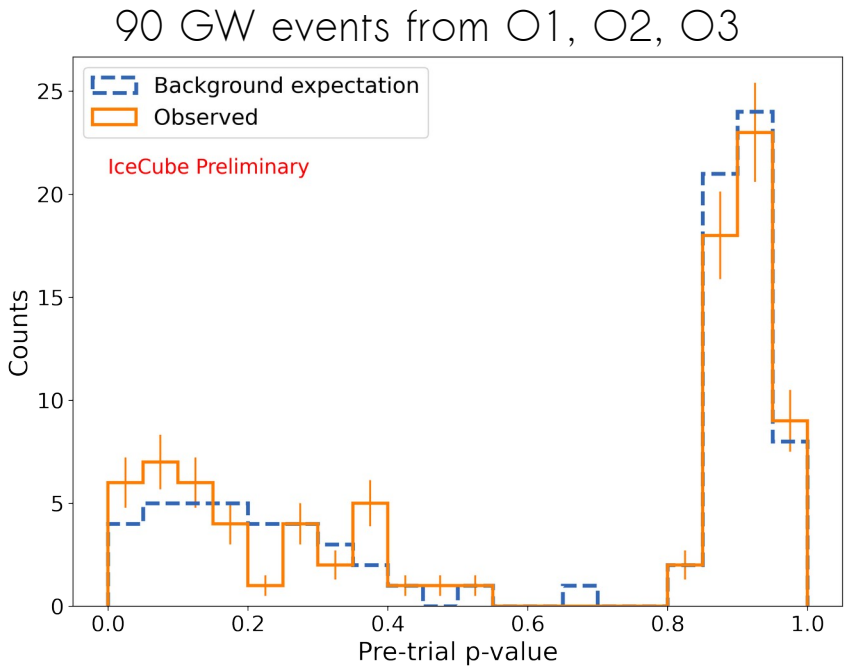
Two week follow-up (high-energy neutrinos)

- Longer time scale: [-0.1,+14] day time window
- Done for all candidate BNS and NSBH events (at least one compact object with mass < 3 $M_{\odot}$
- Motivated by theroretical predictions
- No significant neutrino emission seen

Event	Type	p-value	E^2F UL [GeVcm^{-2}]
GW190425	BNS	0.43	0.661
GW190917_114630	NSBH	0.84	0.442
GW190814	BBH	0.59	0.309
GW191219_163120	NSBH	0.67	0.347
GW200105_162426	NSBH	0.47	0.382
GW200115_042309	NSBH	0.68	0.078
GW200210_092254	NSBH	0.13	0.303

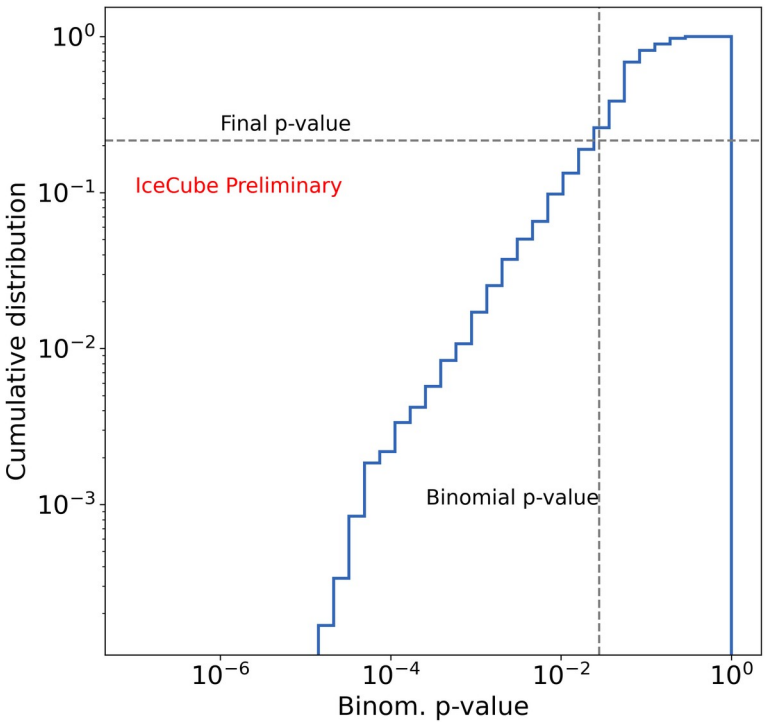
Results: Low Energy Analysis (catalog search)

No significant emission was found



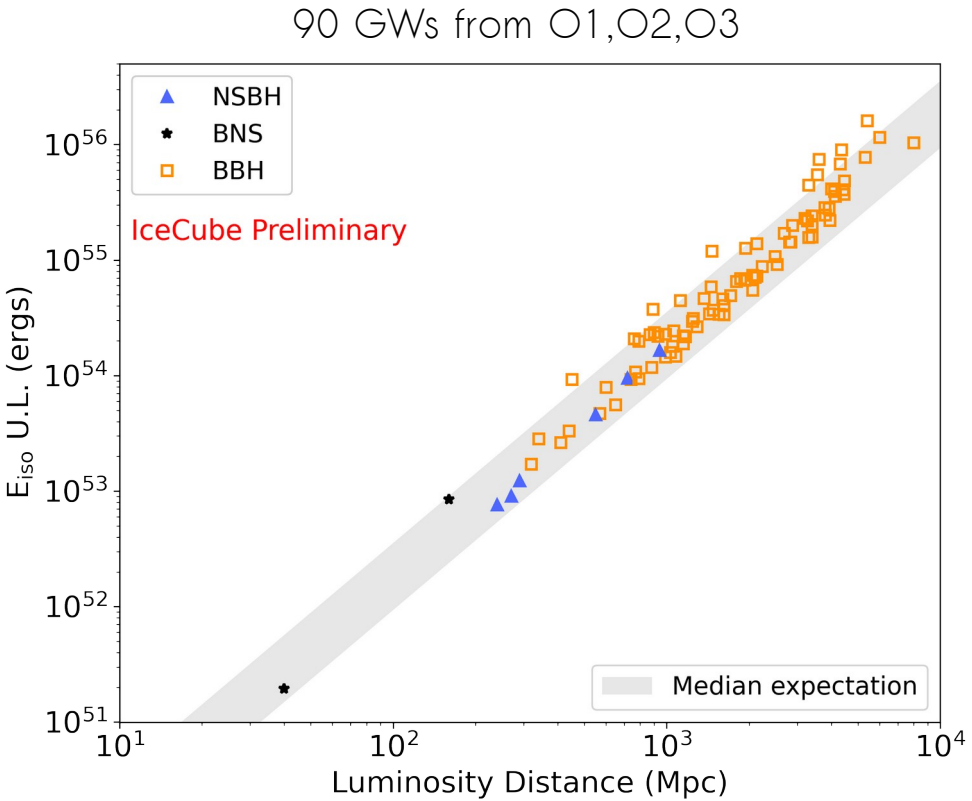
GW	Type	Area	p-value	Upper Limit ($E^2 F$ (GeV cm^{-2}))	E_{iso} U.L. (ergs)	Pre-trial σ
GW151226	BBH	1039.0	7.83×10^{-3}	3.80	3.10×10^{54}	2.42

Event with lowest pre-trial p-value (out of 90 GW events)



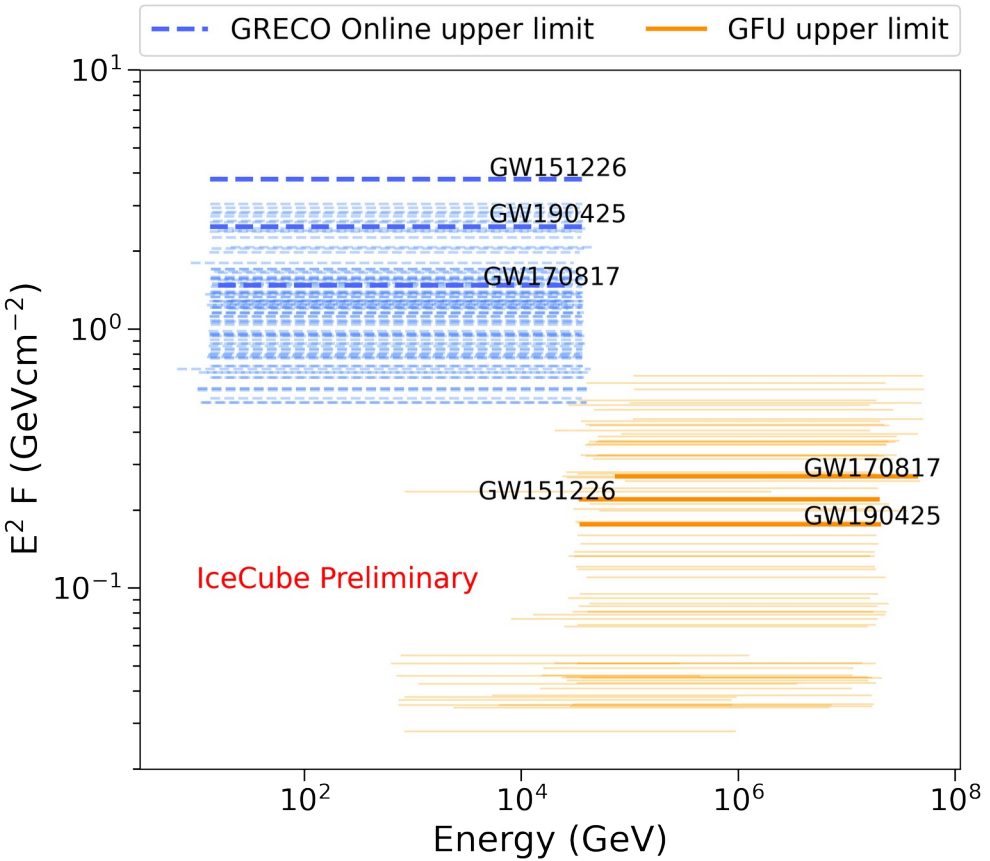
Binomial pre-trial p-value: 0.028
Post-trial binomial p-value: 0.215

E_{iso} upper limits (low-energy neutrinos)



- Upper limits on isotropic equivalent energy emitted in neutrinos of all flavors
- Events that lie above the band are those with p-values < 0.1

Flux upper limits (high+low-energy neutrinos)



- 90 GWs (catalog searches with high and low energy neutrinos)
- Upper limits assuming spectral index=2
- GW151226: event with the lowest pre-trial p-value in low-energy
- GW190425: only BNS event with pre-trial p-value < 0.1
- GW170817: first observed BNS event with associated gamma-ray emission

Summary

- We search for neutrino counterparts to GWs in the < 1TeV and > 1 TeV energy regimes
- Realtime follow-up of GW events (high-energy neutrinos)
- Catalog search events in GWTC-1, GWTC-2 and GWTC-3 detected by LIGO-Virgo (high and low-energy neutrinos)
- No significant emission was found
- We are preparing for O4 run

Backup

The UML method

- Time window: 1000 s (± 500 s)
- Scan over the sky, look for overlap between neutrino and GW events
- Spatial prior *(w)* from healpix skymap of GW events
- Maximum best-fit value (TS) recorded for each trial for each GW event

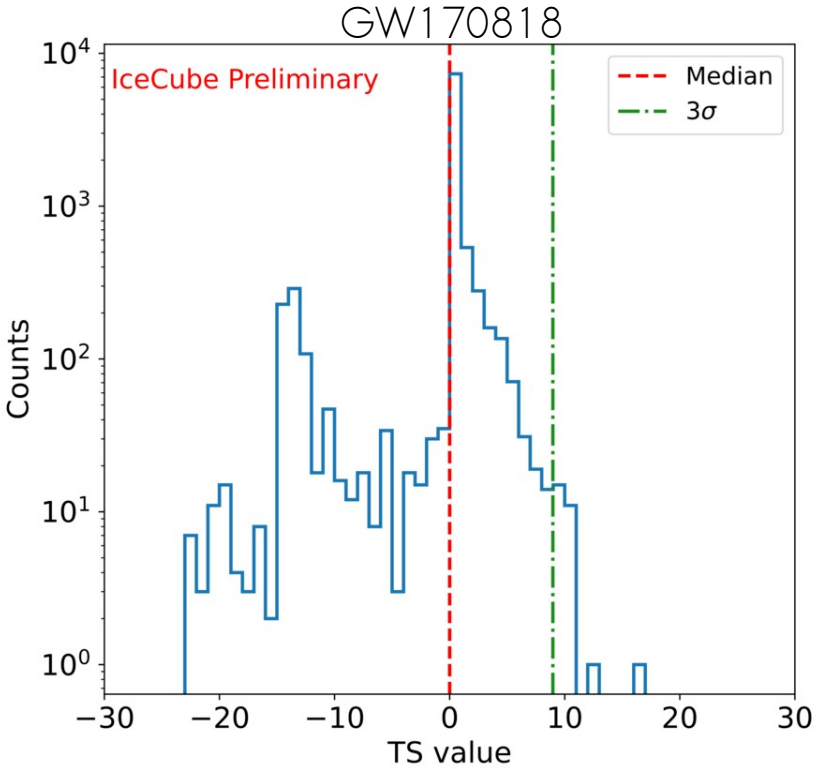
Likelihood $$\mathcal{L} = \frac{(n_s + n_b)^N}{N!} e^{-(n_s+n_b)} \prod_{i=1}^{N} \left(\frac{n_s \mathcal{S}_i}{n_s + n_b} + \frac{n_b \mathcal{B}_i}{n_s + n_b} \right)$$

Spatial prior term

Hypothesis testing $$\text{Test Statistic (TS)} = \max. \left\{ 2 \ln \left(\frac{\mathcal{L}_k(n_s, \gamma) \,.\, w_k}{\mathcal{L}_k(n_s = 0)} \right) \right\}$$

Evaluate at all pixels

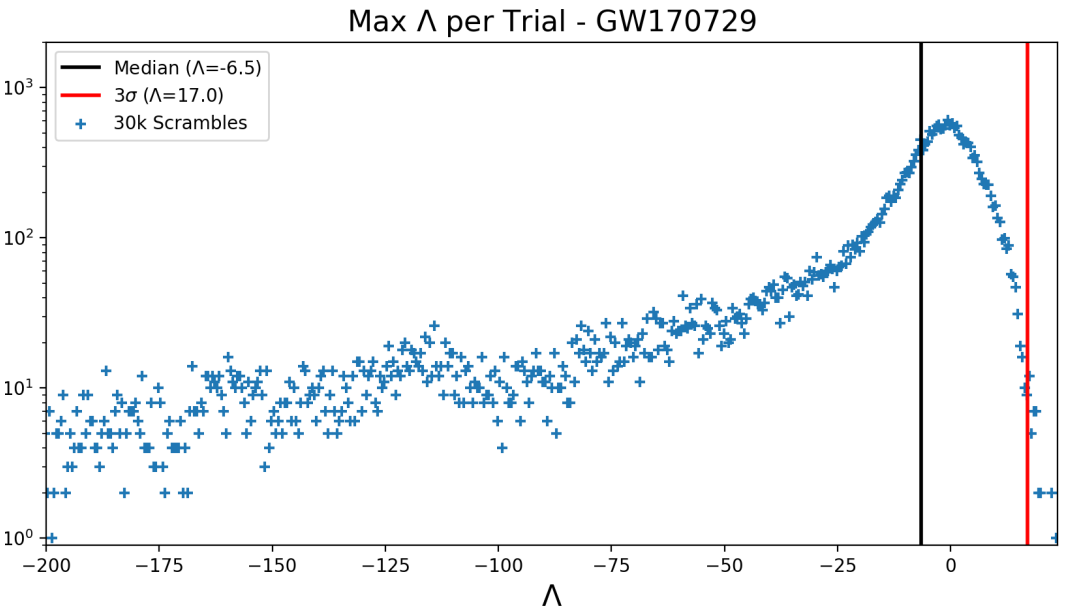
Background distributions



Low energy UML analysis

PoS(ICRC2021)939

A background TS distribution is built for each GW by scrambling data

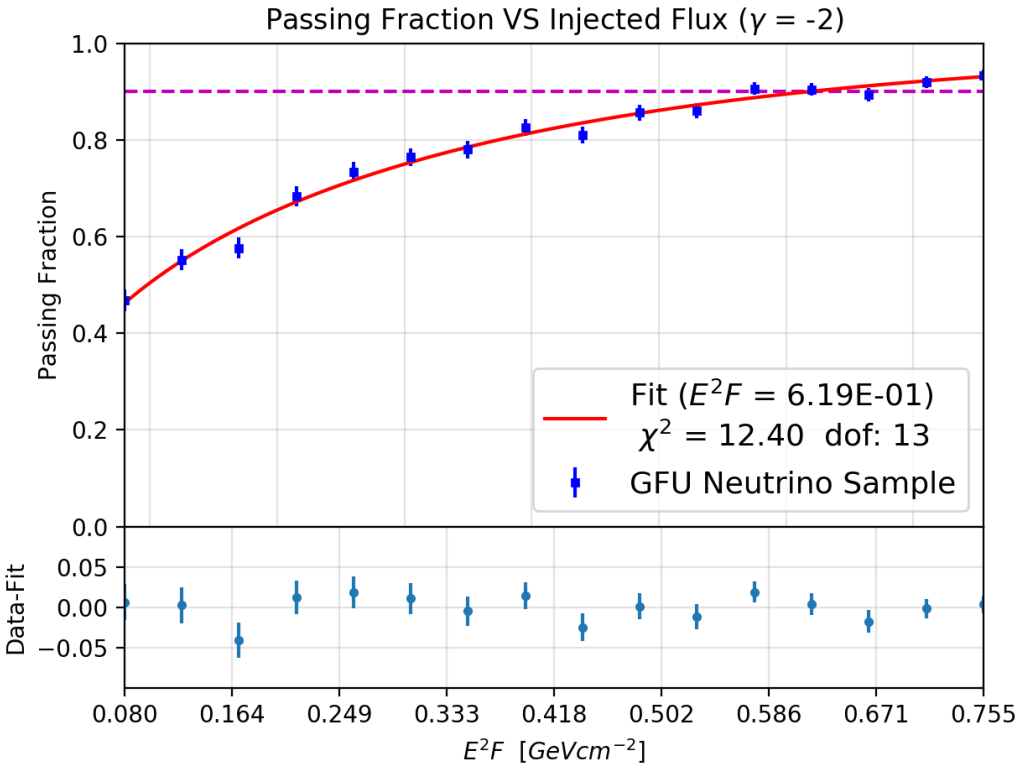


High energy UML analysis

ApJ. Lett. 898 (2020) L10

Sensitivity calculation

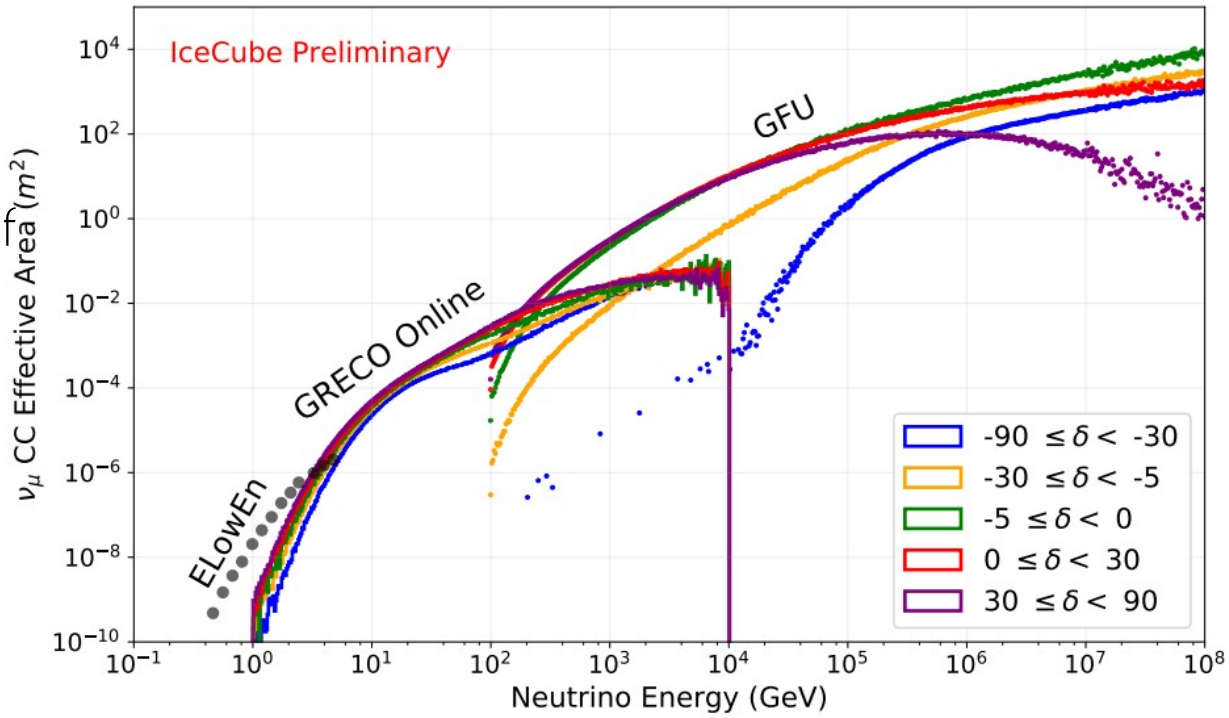
- Inject neutrinos with given flux level
- Fraction of trials (pseudo-expts.) with TS value > median of background TS (passing fraction)
- Fit χ2 cdf; PF = 0.9 gives the 90% sensitivity
- Calculated for all GW events



ApJ. Lett. 898 (2020) L10

Effective areas

- Three datasets with complementary effective areas used for GW follow-up analyses
- High energy dataset: neutrinos of muon flavour; better effective area in the northern hemisphere
- Low energy: neutrinos of all flavours; nearly-uniform effective area in the whole sky
- Low energy dataset is more background dominated
- ~1°angular error for >1 TeV; median ~10-50°angular error for <1 TeV



PoS(ICRC2021)1131

Catalog details

- GWTC-1 for O1, O2 runs: 11 events out of which 1 BNS and 10 BBH
- GWTC-2 for O3a run (with FAR as the threshold parameter): 39 events; 1 NSBH and 38 BBH
- GWTC-2.1 for O3a run (with p_{astro} as the threshold parameter): 44 events, 3 removed from GWTC-2 (1 NSBH also removed); 1 new NSBH and 43 BBH

  Links: GWTC-1, GWTC-2, GWTC-2.1

Results (low-energy)

IceCube paper in preparation

GW	Type	Area	p-value	Upper Limit ($E^2 F$ (GeV cm^{-2}))	E_{iso} U.L. (ergs)	Pre-trial σ
GW151226	BBH	1039.0	7.83×10^{-3}	3.80	3.10×10^{54}	2.42
GW200316_215756	BBH	410.4	3.79×10^{-2}	1.71	4.47×10^{54}	1.78
GW190426_190642	BBH	8214.5	4.13×10^{-2}	2.80	3.03×10^{56}	1.74
GW190630_185205	BBH	1216.9	4.12×10^{-2}	2.83	1.21×10^{55}	1.74
GW190413_052954	BBH	1484.5	4.23×10^{-2}	2.05	1.62×10^{56}	1.72
GW190910_112807	BBH	10880.3	3.07×10^{-2}	3.04	3.74×10^{55}	1.71
GW170823	BBH	1650.0	5.07×10^{-2}	2.59	3.57×10^{55}	1.65
GW191230_180458	BBH	1012.2	5.47×10^{-2}	2.94	6.79×10^{55}	1.60
GW190930_133541	BBH	1679.6	5.48×10^{-2}	1.36	6.05×10^{54}	1.60
GW190728_064510	BBH	395.5	6.72×10^{-2}	1.98	6.83×10^{54}	1.50
GW191216_213338	BBH	480.1	6.93×10^{-2}	2.62	2.85×10^{53}	1.48
GW190425	BNS	9958.2	9.08×10^{-2}	2.49	2.82×10^{53}	1.34
GW200129_065458	BBH	81.8	9.25×10^{-2}	1.56	2.36×10^{54}	1.33
GW200220_061928	BBH	3484.7	1.03×10^{-1}	2.26	1.16×10^{56}	1.26
GW190731_140936	BBH	3387.3	1.05×10^{-1}	2.73	1.40×10^{56}	1.26
GW190503_185404	BBH	94.4	1.24×10^{-1}	2.44	2.26×10^{55}	1.16
GW170818	BBH	40.3	1.23×10^{-1}	0.88	7.56×10^{54}	1.16
GW190421_213856	BBH	1211.5	1.26×10^{-1}	2.40	8.32×10^{55}	1.14
GW200225_060421	BBH	509.0	8.55×10^{-1}	0.68	2.21×10^{54}	1.05
GW200308_173609	BBH	18705.7	1.49×10^{-1}	2.38	1.61×10^{56}	1.04
GW191103_012549	BBH	2519.6	1.58×10^{-1}	1.24	2.29×10^{54}	1.00
GW170814	BBH	88.1	1.83×10^{-1}	2.07	2.41×10^{54}	0.90
GW190925_232845	BBH	1233.5	1.84×10^{-1}	1.67	6.64×10^{54}	0.90
GW190412	BBH	20.9	1.91×10^{-1}	0.70	2.89×10^{54}	0.87
GW190521_074359	BBH	546.5	2.17×10^{-1}	0.96	8.95×10^{54}	0.78
GW190805_211137	BBH	3949.1	2.53×10^{-1}	1.59	2.78×10^{56}	0.66
GW190517_055101	BBH	473.3	2.72×10^{-1}	1.70	2.63×10^{55}	0.61
GW200220_124850	BBH	3168.9	2.77×10^{-1}	1.46	4.13×10^{55}	0.59
GW190514_065416	BBH	3009.7	2.78×10^{-1}	0.94	1.04×10^{56}	0.59
GW190915_235702	BBH	396.9	3.05×10^{-1}	0.59	1.30×10^{55}	0.51
GW190916_200658	BBH	4499.2	3.15×10^{-1}	1.33	1.87×10^{56}	0.48
GW200112_155838	BBH	4250.4	3.50×10^{-1}	1.56	3.13×10^{54}	0.39
GW190828_063405	BBH	520.1	3.59×10^{-1}	1.28	2.58×10^{55}	0.36
GW190803_022701	BBH	1519.5	3.71×10^{-1}	0.79	6.62×10^{55}	0.33
GW190917_114630	NSBH	2050.6	3.84×10^{-1}	1.12	4.06×10^{54}	0.29
GW190707_093326	BBH	1346.0	3.88×10^{-1}	1.21	3.45×10^{54}	0.28
GW190403_051519	BBH	5589.4	4.13×10^{-1}	0.98	2.40×10^{56}	0.23
GW191126_115259	BBH	1514.5	4.61×10^{-1}	0.94	3.36×10^{54}	0.09
GW200322_091133	BBH	31571.1	5.15×10^{-1}	0.95	7.44×10^{55}	-
GW191113_071753	BBH	2993.3	8.15×10^{-1}	1.38	4.67×10^{54}	-
GW191215_223052	BBH	595.8	8.48×10^{-1}	1.37	6.73×10^{54}	-
GW190602_175927	BBH	694.5	8.52×10^{-1}	1.65	5.28×10^{55}	-
GW200105_162426	NSBH	7881.8	8.55×10^{-1}	0.77	9.05×10^{52}	-
GW190521	BBH	1008.2	8.65×10^{-1}	1.48	7.27×10^{54}	-
GW200306_093714	BBH	4371.2	8.66×10^{-1}	0.68	7.08×10^{54}	-
GW191127_050227	BBH	1499.2	8.69×10^{-1}	0.86	2.31×10^{55}	-
GW190620_030421	BBH	7202.1	8.71×10^{-1}	0.91	6.16×10^{55}	-
GW200209_085452	BBH	924.5	8.73×10^{-1}	0.78	2.03×10^{55}	-
GW200210_092254	NSBH	1830.7	8.74×10^{-1}	1.21	1.65×10^{54}	-
GW150914	BBH	184.6	8.79×10^{-1}	1.80	1.13×10^{54}	-
GW190519_153544	BBH	857.1	8.78×10^{-1}	0.88	3.39×10^{55}	-
GW190706_222641	BBH	653.8	8.78×10^{-1}	0.72	1.27×10^{56}	-
GW190814	BBH	19.3	8.87×10^{-1}	1.4	2.49×10^{53}	-
GW190719_215514	BBH	2890.1	8.88×10^{-1}	0.81	6.98×10^{55}	-
GW190408_181802	BBH	148.8	8.91×10^{-1}	0.59	1.10×10^{55}	-
GW200115_042309	NSBH	511.9	8.92×10^{-1}	1.28	1.23×10^{53}	-
GW200219_094415	BBH	702.1	8.97×10^{-1}	1.38	2.41×10^{55}	-
GW190727_060333	BBH	833.8	8.98×10^{-1}	1.33	5.96×10^{55}	-
GW190720_000836	BBH	463.4	9.02×10^{-1}	1.15	6.58×10^{54}	-
GW190708_232457	BBH	13675.4	9.04×10^{-1}	0.72	3.95×10^{54}	-
GW170817	BNS	31.9	9.07×10^{-1}	1.48	7.07×10^{51}	-
GW170729	BBH	1032.3	9.08×10^{-1}	1.58	5.15×10^{55}	-
GW190513_205428	BBH	518.4	9.10×10^{-1}	0.54	1.56×10^{55}	-
GW200208_130117	BBH	38.0	9.10×10^{-1}	1.55	8.78×10^{54}	-
GW190701_203306	BBH	46.1	9.11×10^{-1}	1.20	2.05×10^{55}	-
GW190725_174728	BBH	2292.5	9.13×10^{-1}	1.07	6.65×10^{54}	-
GW190828_065509	BBH	664.0	9.15×10^{-1}	1.50	1.50×10^{55}	-
GW151012	BBH	1554.3	9.17×10^{-1}	0.65	4.30×10^{54}	-
GW200128_022011	BBH	2677.5	9.17×10^{-1}	1.06	1.58×10^{55}	-
GW200224_222234	BBH	49.9	9.19×10^{-1}	1.29	4.92×10^{54}	-
GW170809	BBH	340.7	9.26×10^{-1}	1.51	4.78×10^{54}	-
GW191204_171526	BBH	344.9	9.28×10^{-1}	1.24	5.62×10^{53}	-
GW190924_021846	BBH	357.9	9.29×10^{-1}	0.80	1.43×10^{54}	-
GW170104	BBH	935.8	9.34×10^{-1}	0.65	4.31×10^{54}	-
GW190527_092055	BBH	3662.4	9.34×10^{-1}	1.08	3.33×10^{55}	-
GW191129_134029	BBH	848.3	9.36×10^{-1}	1.16	9.4×10^{53}	-
GW191105_143521	BBH	728.7	9.38×10^{-1}	1.16	1.89×10^{54}	-
GW200202_154313	BBH	159.3	9.38×10^{-1}	0.25	2.63×10^{53}	-
GW200208_222617	BBH	1889.2	9.43×10^{-1}	0.78	3.93×10^{55}	-
GW190926_050336	BBH	2505.9	9.44×10^{-1}	1.12	1.27×10^{56}	-
GW200311_115853	BBH	35.6	9.44×10^{-1}	1.25	2.17×10^{54}	-
GW191219_163120	NSBH	2232.1	9.53×10^{-1}	0.96	4.60×10^{53}	-
GW190413_134308	BBH	730.6	9.54×10^{-1}	1.21	1.23×10^{56}	-
GW190512_180714	BBH	218.0	9.56×10^{-1}	1.27	1.40×10^{55}	-
GW200302_015811	BBH	7010.8	9.58×10^{-1}	1.04	3.69×10^{54}	-
GW191109_010717	BBH	1784.3	9.63×10^{-1}	1.28	2.66×10^{54}	-
GW190929_012149	BBH	2219.3	9.66×10^{-1}	0.83	8.66×10^{55}	-
GW191204_110529	BBH	4747.7	9.85×10^{-1}	0.84	6.52×10^{54}	-
GW200216_220804	BBH	3009.5	9.86×10^{-1}	0.52	2.46×10^{55}	-
GW170608	BBH	538.8	1.0	0.58	5.08×10^{53}	-

Results (high-energy)

GWTC-2.1			LLAMA		UML		
Event	Type	Area [deg^2]	p-value	E^2F UL [GeVcm^{-2}]	p-value	E^2F UL [GeVcm^{-2}]	$E_{\rm iso}$ UL [erg]
GW190403_051519	BBH	5589.4	0.51	0.14	0.46	0.101	1.86×10^{55}
GW190408_181802	BBH	148.8	0.22	0.048	0.17	0.0512	4.85×10^{53}
GW190412	BBH	20.9	0.27	0.041	0.13	0.0459	8.31×10^{52}
GW190413_052954	BBH	1484.5	0.30	0.087	0.28	0.133	7.01×10^{54}
GW190413_134308	BBH	730.6	0.27	0.34	0.34	0.270	2.84×10^{55}
GW190421_213856	BBH	1211.5	0.81	0.46	0.56	0.393	1.40×10^{55}
GW190425	BNS	9958.2	0.16	0.22	0.94	0.176	1.66×10^{52}
GW190426_190642	BBH	8214.5	0.42	0.17	0.18	0.282	1.25×10^{55}
GW190503_185404	BBH	94.4	0.94	0.54	0.34	0.584	4.99×10^{54}
GW190512_180714	BBH	218.0	0.81	0.23	0.85	0.199	1.74×10^{54}
GW190513_205428	BBH	518.4	0.99	0.043	0.94	0.0514	6.73×10^{53}
GW190514_065416	BBH	3009.7	0.25	0.089	0.44	0.0453	3.96×10^{54}
GW190517_055101	BBH	473.3	0.21	0.48	0.26	0.366	6.05×10^{54}
GW190519_153544	BBH	857.1	0.067	0.15	0.21	0.0914	3.20×10^{54}
GW190521	BBH	1008.2	0.62	0.37	0.63	0.359	1.90×10^{55}
GW190521_074359	BBH	546.5	0.11	0.049	0.15	0.0451	2.36×10^{53}
GW190527_092055	BBH	3662.4	0.65	0.41	0.88	0.326	1.01×10^{55}
GW190602_175927	BBH	694.5	0.31	0.34	0.17	0.370	9.73×10^{54}
GW190620_030421	BBH	7202.1	0.20	0.36	0.23	0.121	4.13×10^{54}
GW190630_185205	BBH	1216.9	0.64	0.15	0.81	0.427	5.31×10^{53}
GW190701_203306	BBH	46.1	1.0	0.039	0.87	0.0385	7.65×10^{53}
GW190706_222641	BBH	653.8	0.99	0.036	0.92	0.0356	3.17×10^{54}
GW190707_093326	BBH	1346.	0.43	0.24	0.63	0.202	4.74×10^{53}
GW190708_232457	BBH	13675.4	0.11	0.11	0.56	0.0720	1.62×10^{53}
GW190719_215514	BBH	2890.1	0.83	0.054	0.91	0.0512	4.90×10^{54}
GW190720_000836	BBH	463.4	0.99	0.13	0.94	0.0872	5.34×10^{53}
GW190725_174728	BBH	2292.5	0.048	0.19	0.59	0.0918	4.04×10^{53}
GW190727_060333	BBH	833.8	0.89	0.38	0.74	0.324	1.53×10^{55}
GW190728_064510	BBH	395.5	0.0084	0.89	0.04	0.315	6.36×10^{53}
GW190731_140936	BBH	3387.3	0.25	0.93	0.61	0.385	1.81×10^{55}
GW190803_022701	BBH	1519.5	0.31	0.037	0.64	0.0354	1.69×10^{54}
GW190805_211137	BBH	3949.1	0.74	0.20	0.93	0.180	2.56×10^{55}
GW190814	BBH*	19.3	1.0	0.24	1.0	0.259	5.68×10^{52}
GW190828_063405	BBH	520.1	0.93	0.21	0.98	0.178	2.74×10^{54}
GW190828_065509	BBH	664.0	0.84	0.38	0.84	0.368	3.73×10^{54}
GW190910_112807	BBH	10880.3	0.22	0.45	0.77	0.177	1.90×10^{54}
GW190915_235702	BBH	396.9	0.56	0.036	0.44	0.0354	3.61×10^{53}
GW190916_200658	BBH	4499.2	0.52	0.16	0.85	0.108	1.22×10^{55}
GW190917_114630	NSBH*	2050.6	0.20	0.19	0.72	0.203	6.37×10^{53}
GW190924_021846	BBH	357.9	0.031	0.037	0.23	0.0346	4.46×10^{52}
GW190925_232845	BBH	1233.5	0.39	0.11	0.59	0.0908	3.41×10^{53}
GW190926_050336	BBH	2505.9	0.13	0.78	0.33	0.280	2.30×10^{55}
GW190929_012149	BBH	2219.3	0.11	0.34	0.22	0.276	1.85×10^{55}
GW190930_133541	BBH	1679.6	0.14	0.038	0.31	0.0427	1.05×10^{53}

IceCube paper in preparation

GWTC-3			LLAMA		UML		
Event	Type	Area [deg^2]	p-value	E^2F UL [GeVcm^{-2}]	p-value	E^2F UL [GeVcm^{-2}]	$E_{\rm iso}$ UL [erg]
GW191103_012549	BBH	2519.6	0.53	0.049	0.71	0.049	1.96×10^{53}
GW191105_143521	BBH	728.7	0.27	0.28	0.54	0.267	1.28×10^{54}
GW191109_010717	BBH	1784.3	0.14	0.48	0.05	0.508	5.03×10^{54}
GW191113_071753	BBH	2993.3	0.076	0.52	0.19	0.441	3.12×10^{54}
GW191126_115259	BBH	1514.5	0.77	0.13	1.00	0.138	1.42×10^{54}
GW191127_050227	BBH	1499.2	0.38	0.078	0.83	0.081	2.96×10^{54}
GW191129_134029	BBH	848.3	0.25	0.35	0.30	0.425	8.95×10^{53}
GW191204_110529	BBH	4747.7	0.16	0.36	0.49	0.085	1.46×10^{54}
GW191204_171526	BBH	344.9	0.97	0.26	1.00	0.280	3.96×10^{53}
GW191215_223052	BBH	595.8	0.98	0.26	1.00	0.211	2.98×10^{54}
GW191216_213338	BBH	480.1	0.0049	0.093	0.10	0.071	2.57×10^{52}
GW191219_163120	NSBH	2232.1	0.09	0.26	0.71	0.219	2.80×10^{53}
GW191222_033537	BBH	2299.2	0.95	0.36	1.00	0.375	1.1×10^{55}
GW191230_180458	BBH	1012.2	0.37	0.36	0.28	0.488	3.18×10^{55}
GW200105_162426	NSBH	7881.8	0.20	0.13	0.81	0.095	2.98×10^{52}
GW200112_155838	BBH	4250.4	0.58	0.18	0.79	0.133	8.43×10^{53}
GW200115_042309	NSBH	511.9	0.34	0.038	0.45	0.045	2.12×10^{52}
GW200128_022011	BBH	2677.5	0.46	0.25	0.47	0.243	9.31×10^{54}
GW200129_065458	BBH	81.8	0.033	0.041	0.05	0.406	1.73×10^{53}
GW200202_154313	BBH	159.3	0.0057	0.039	0.06	0.038	2.43×10^{52}
GW200208_130117	BBH	38.0	0.94	0.33	1.00	0.518	9.25×10^{54}
GW200208_222617	BBH	1889.2	0.41	0.045	0.90	0.043	4.98×10^{54}
GW200209_085452	BBH	924.5	0.84	0.50	1.00	0.041	1.81×10^{54}
GW200210_092254	BBH	1830.7	0.28	0.071	0.79	0.081	2.51×10^{53}
GW200216_220804	BBH	3009.5	0.065	0.066	0.46	0.236	2.82×10^{54}
GW200219_094415	BBH	702.1	0.98	0.23	1.00	0.035	9.57×10^{54}
GW200220_061928	BBH	3484.7	0.23	0.22	0.05	0.357	4.23×10^{55}
GW200220_124850	BBH	3168.9	0.42	0.13	0.53	0.118	6.31×10^{54}
GW200224_222234	BBH	49.9	0.90	0.068	1.00	0.079	9.33×10^{53}
GW200225_060421	BBH	509.0	0.0048	0.10	0.20	0.055	3.03×10^{53}
GW200302_015811	BBH	7010.8	0.16	0.67	0.21	0.531	4.34×10^{54}
GW200306_093714	BBH	4371.2	0.15	0.074	0.57	0.046	9.99×10^{53}
GW200308_173609	BBH	18705.7	0.24	0.38	0.29	0.326	7.18×10^{55}
GW200311_115853	BBH	35.6	1.0	0.047	1.00	0.076	4.38×10^{53}
GW200316_215756	BBH	410.4	0.17	0.066	0.04	0.110	5.19×10^{53}
GW200322_091133	BBH	31571.1	0.23	0.18	0.87	0.148	4.39×10^{55}