Searches for GeV to PeV neutrinos from gravitational sources with IceCube

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for the IceCube collaboration

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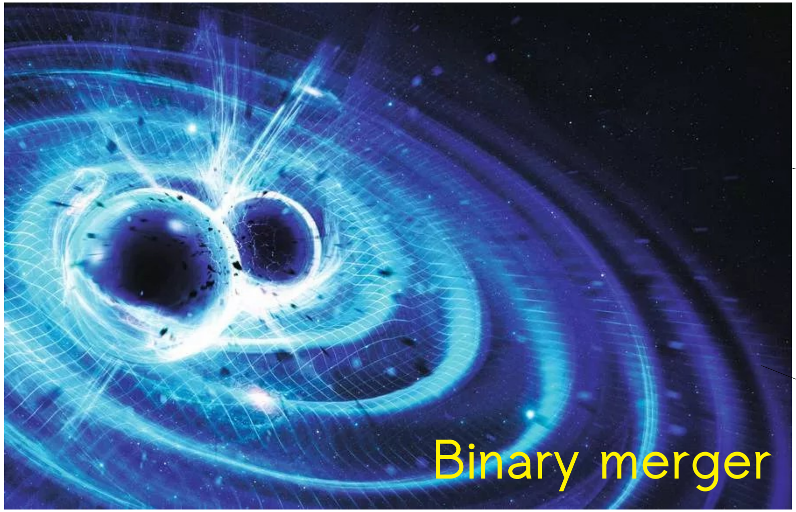
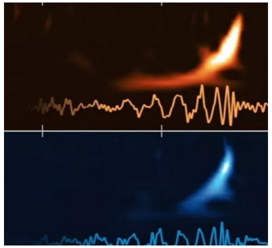
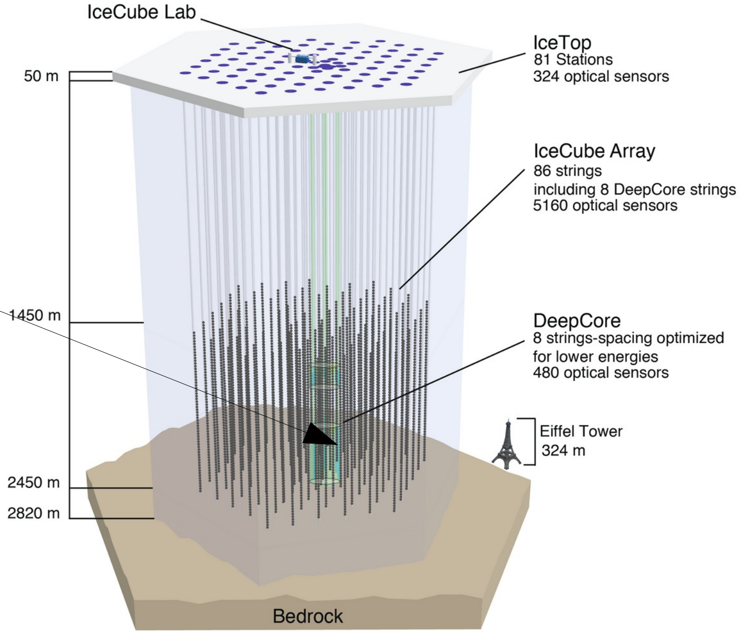




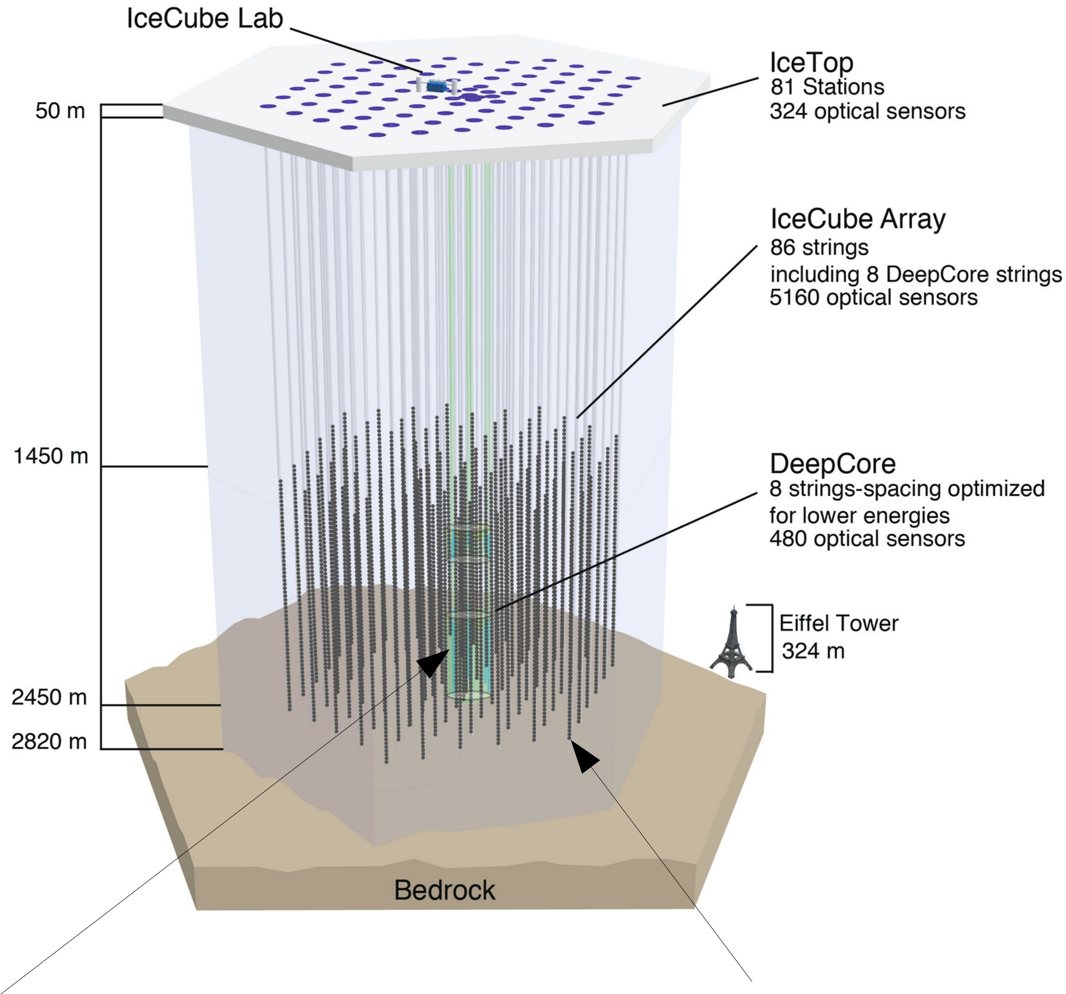
Gravitational waves

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 nutrinos
- We search for neutrino events from GW events detected by LIGO-Virgo
- Searches done both in the high energy (> 1 TeV), low energy (<1 TeV) and extremely low energy (< 5 GeV) regime

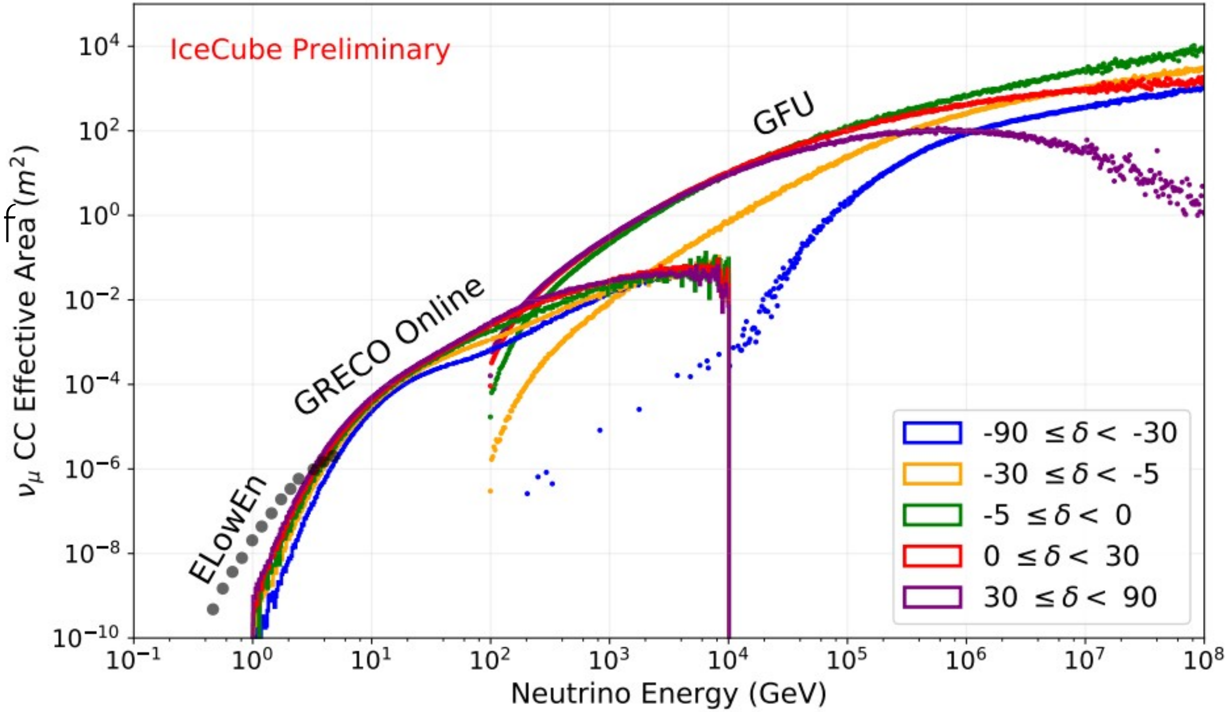


DeepCore to detect low energy neutrinos

High energy neutrinos from the whole detector

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

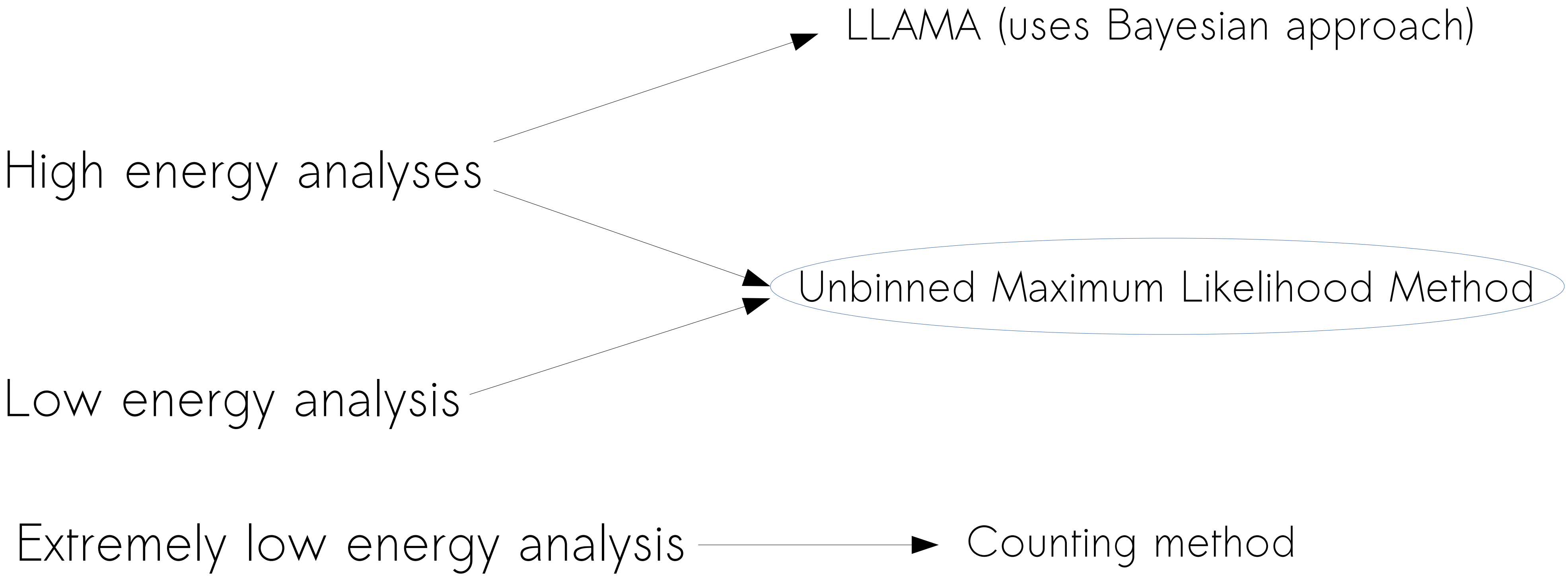


PoS(ICRC2021)1131

Summary of the GW events

- We want to follow up GW events in O1, O2 and O3a runs of LIGO-Virgo
- GWTC-1 catalog: O1+O2 (Sept. 12 2015 - Jan. 19 2016 + Nov. 30 2016 - Aug. 25 2017)
- GWTC-1 contains 11 GW events
- GWTC-2 catalog: O3a (April 1 2019 - Oct. 12019)
- GWTC-2 catalog has 39 events
- An updated catalog GWTC-2.1available
- Revised version of GWTC-2; with 44 GW events (37 events from GWTC-2 and 8 new events)
- Working on following-up this revised catalog
- In this talk: GWTC-1 +GWTC-2

Analysis approaches



The unbinned maximum likelihood 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

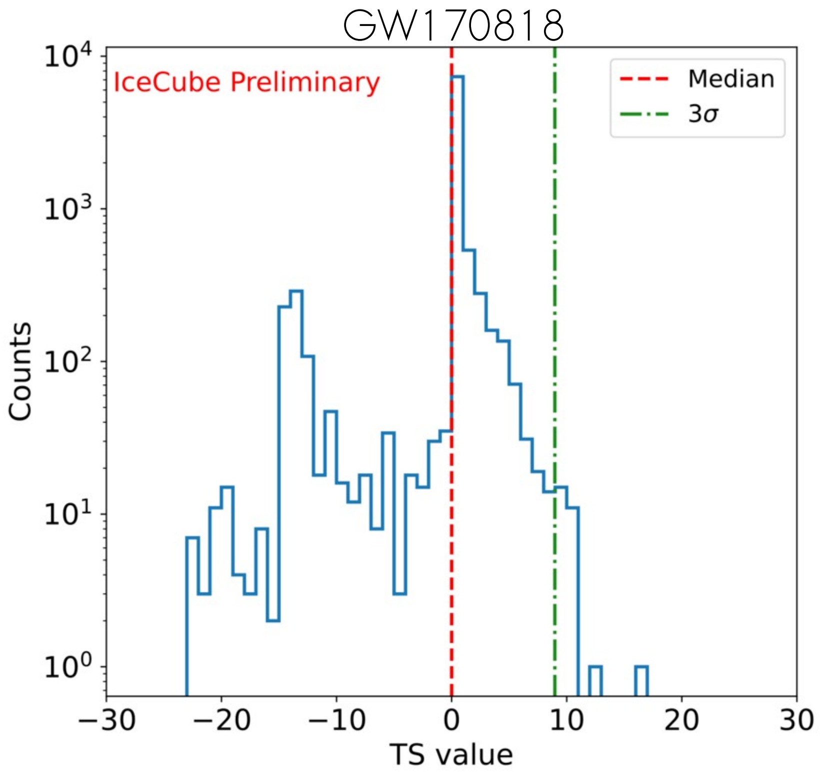
Likelihood $$\mathcal{L} = \frac{(n_s + n_b)^N}{N!} e^{-(n_s+n_b)} \prod_{i=1}^{N} \left(\frac{n_s \mathcal{S}_i}{n_s + n_b} + \frac{n_b \mathcal{B}_i}{n_s + n_b} \right)$$

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

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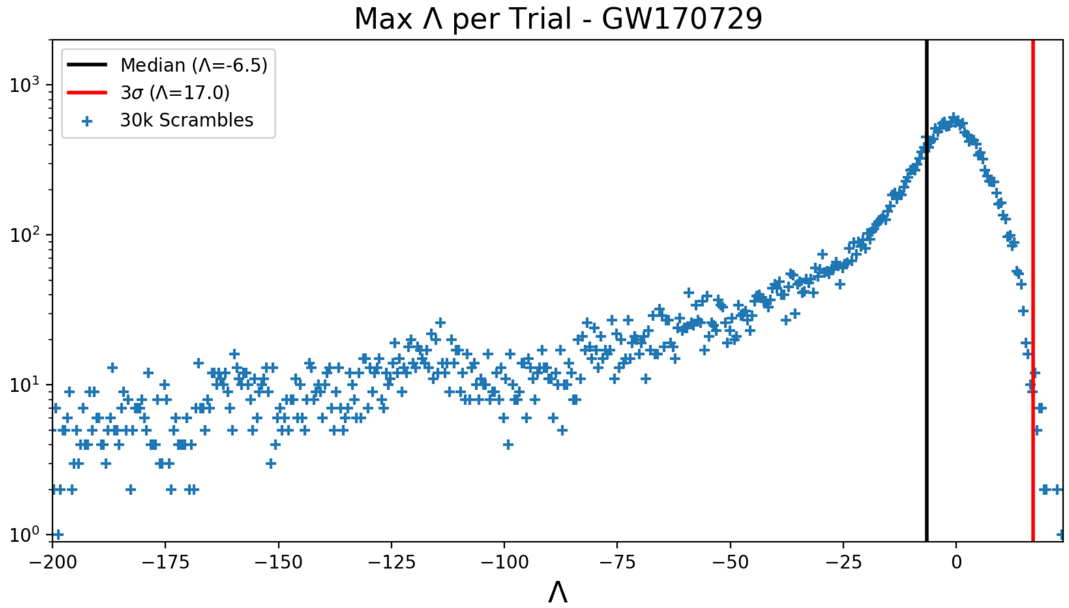
A background TS distribution is built for each GW by scrambling data

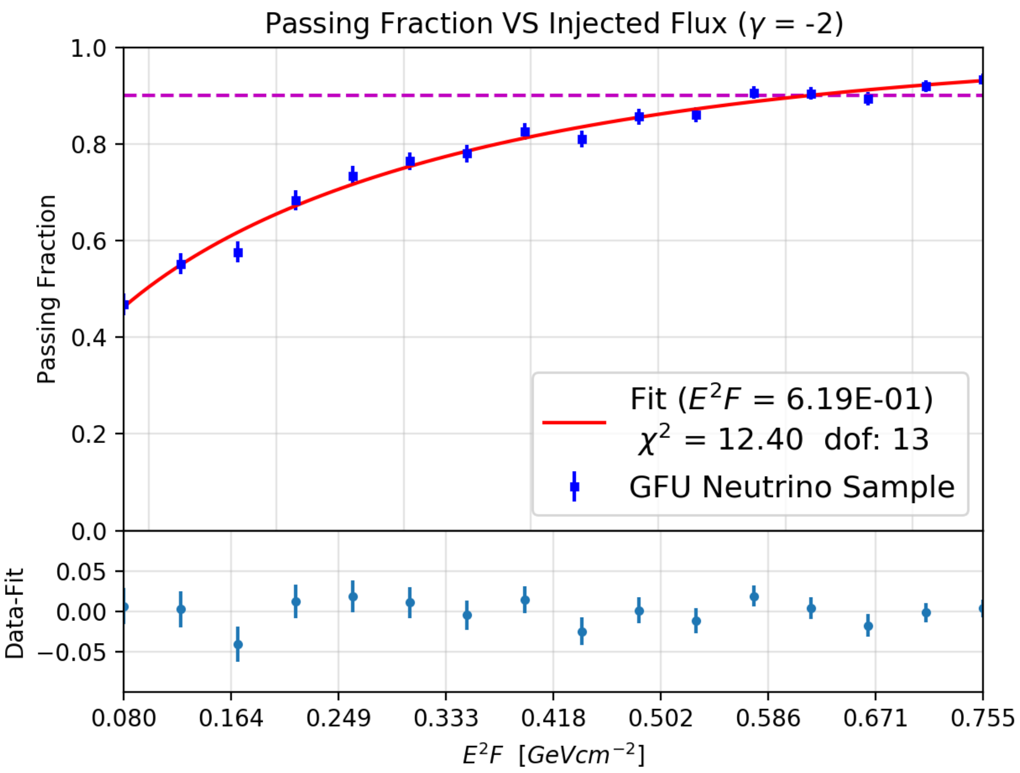


High energy UML analysis

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 $\chi 2$ cdf; PF = 0.9 gives the 90% sensitivity
- Calculated for all GW events



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Sensitivities (O1&O2)

Sensitivity: 90% C. L. above the median

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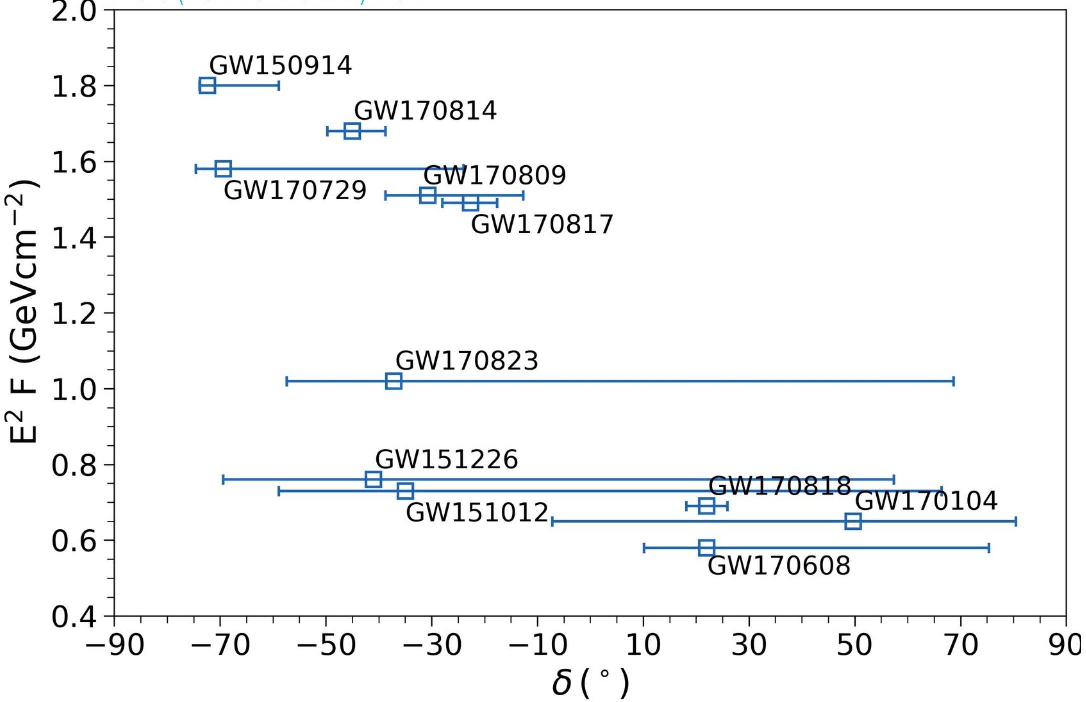
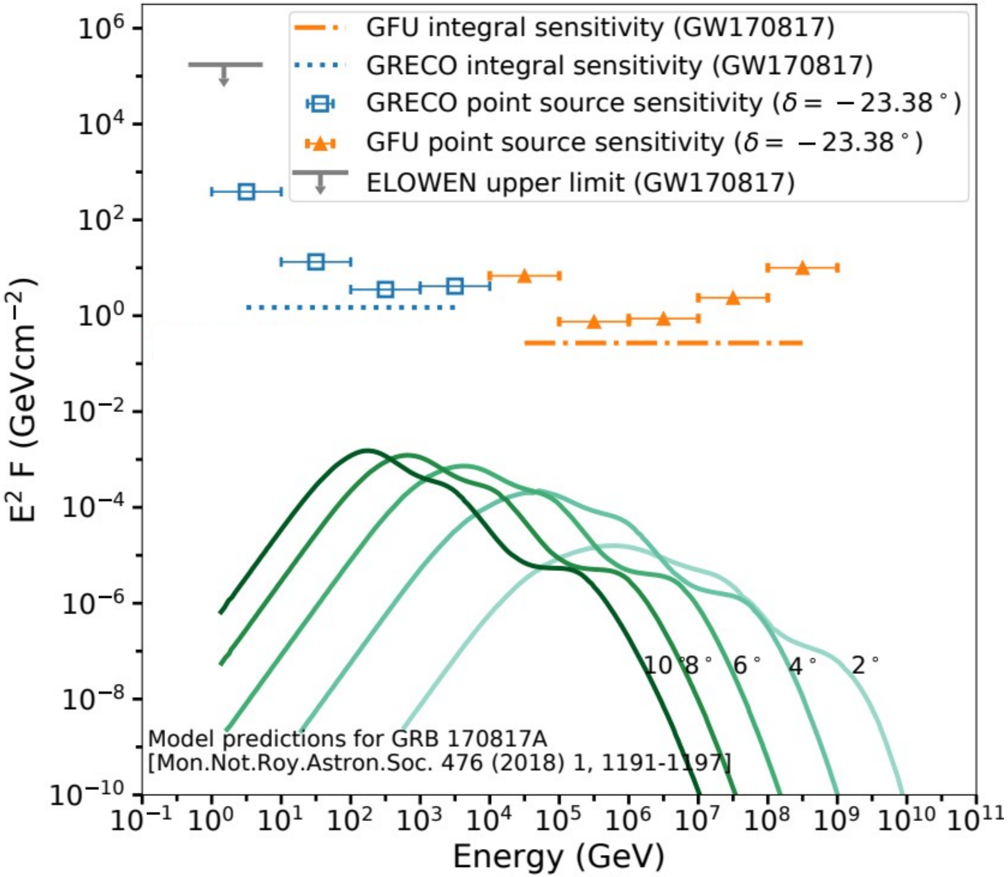


Integral sensitivity of low-energy analysis to GW events in O1 & O2 vs declination of pixels with max. prob. in the skymap (markers), and 68% prob. regions (error bars)



Comparison of differential sensitivites of various GW follow-up analyses, with model predictions

Results: High Energy Analysis

- No significant neutrino emission was seen in O1+O2

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O1 and O2 Detections										
						Maximum Likelihood			LLAMA	
Event	Type	Detectors	Ω (deg^2)	D_L (Mpc)	UL Range (GeVcm^{-2})	p-value	UL (GeVcm^{-2})	$E_{\rm iso}$ UL (erg)	p-value	UL (GeVcm^{-2})
GW150914	BBH	LH	182	440^{+150}_{-170}	0.0296 - 1.03	0.51	0.66	5.10×10^{53}	0.29	0.70
GW151012	BBH	LH	1523	1080^{+550}_{-490}	0.0286 - 0.821	0.83	0.16	7.50×10^{53}	0.82	0.18
GW151226	BBH	LH	1033	450^{+180}_{-190}	0.0286 - 0.904	0.74	0.22	1.74×10^{53}	0.26	0.21
GW170104	BBH	LH	921	990^{+440}_{-430}	0.0286 - 0.667	0.54	0.044	1.81×10^{53}	0.16	0.055
GW170608	BBH	LH	392	320^{+120}_{-110}	0.0309 - 0.0821	0.61	0.037	1.37×10^{52}	0.97	0.038
GW170729	BBH	LH	1041	2840^{+1400}_{-1360}	0.0286 - 1.02	0.21	0.62	1.80×10^{55}	0.17	0.62
GW170809	BBH	LH	308	1030^{+320}_{-390}	0.0568 - 0.758	0.60	0.27	1.02×10^{54}	0.83	0.26
GW170814	BBH	LHV	87	600^{+150}_{-220}	0.488 - 0.711	0.83	0.45	5.47×10^{53}	1.0	0.43
GW170817	BNS	LHV	16	40^{+7}_{-15}	0.180 - 0.429	0.19	0.27	1.67×10^{51}	0.94	0.25
GW170818	BBH	LHV	39	1060^{+420}_{-380}	0.0364 - 0.0431	0.58	0.028	1.17×10^{53}	0.40	0.028
GW170823	BBH	LH	1666	1940^{+970}_{-900}	0.0286 - 0.796	0.75	0.18	2.33×10^{54}	0.25	0.18

Results: High Energy Analysis

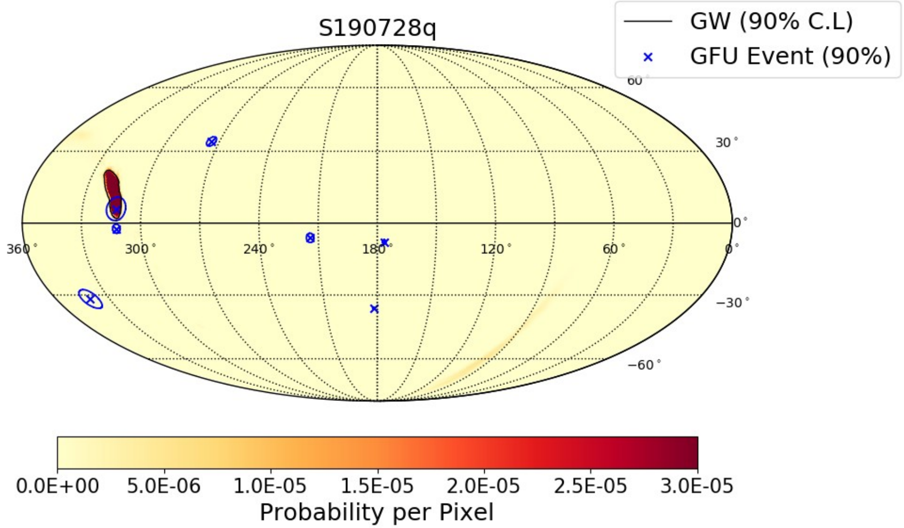
- No significant neutrino emission was seen in O3a
- One event with p-value < 0.1 in UML method (also in LLAMA method)

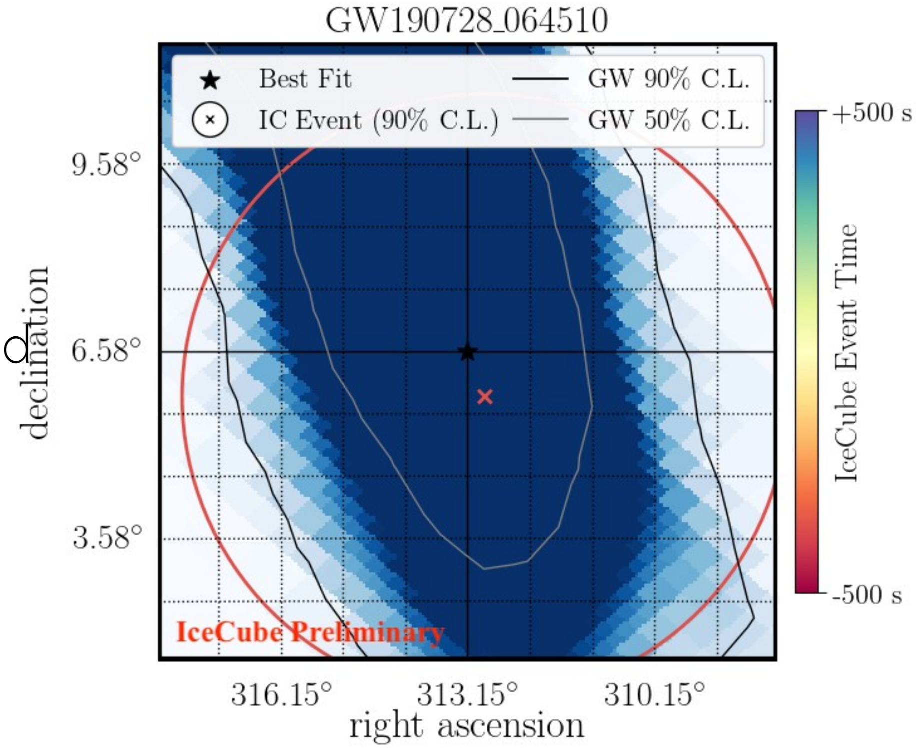
[PoS(ICRC2021)950]

		LLAMA		UML		
Event	Type	*p*-value	E^2F UL [$\mathrm{GeV cm^{-2}}$]	*p*-value	E^2F UL [$\mathrm{GeV cm^{-2}}$]	E_{iso} UL [erg]
GW190408_181802	BBH	0.16	0.048	0.17	0.0512	4.85×10^{53}
GW190412	BBH	0.19	0.041	0.13	0.0459	8.31×10^{52}
GW190413_052954	BBH	0.21	0.087	0.28	0.133	7.01×10^{54}
GW190413_134308	BBH	0.18	0.34	0.34	0.270	2.84×10^{55}
GW190421_213856	BBH	0.77	0.46	0.56	0.393	1.40×10^{55}
GW190424_180648	BBH	0.58	0.32	0.23	0.233	5.37×10^{54}
GW190425	BNS	0.16	0.22	0.94	0.176	1.66×10^{52}
GW190426_152155	NSBH	0.12	0.082	0.12	0.0942	5.65×10^{52}
GW190503_185404	BBH	0.87	0.54	0.34	0.584	4.99×10^{54}
GW190512_180714	BBH	0.67	0.23	0.85	0.199	1.74×10^{54}
GW190513_205428	BBH	0.97	0.043	0.94	0.0514	6.73×10^{53}
GW190514_065416	BBH	0.28	0.089	0.44	0.0453	3.96×10^{54}
GW190517_055101	BBH	0.14	0.48	0.26	0.366	6.05×10^{54}
GW190519_153544	BBH	0.063	0.15	0.21	0.0914	3.20×10^{54}
GW190521	BBH	0.47	0.37	0.63	0.359	1.90×10^{55}
GW190521_074359	BBH	0.16	0.049	0.15	0.0451	2.36×10^{53}
GW190527_092055	BBH	0.61	0.41	0.88	0.326	1.01×10^{55}
GW190602_175927	BBH	0.22	0.34	0.17	0.370	9.73×10^{54}
GW190620_030421	BBH	0.15	0.36	0.23	0.121	4.13×10^{54}
GW190630_185205	BBH	0.38	0.15	0.81	0.427	5.31×10^{53}
GW190701_203306	BBH	1.0	0.039	0.87	0.0385	7.65×10^{53}
GW190706_222641	BBH	0.99	0.036	0.92	0.0356	3.17×10^{54}
GW190707_093326	BBH	0.43	0.24	0.63	0.202	4.74×10^{53}
GW190708_232457	BBH	0.11	0.11	0.56	0.0720	1.62×10^{53}
GW190719_215514	BBH	0.79	0.054	0.91	0.0512	4.90×10^{54}
GW190720_000836	BBH	0.98	0.13	0.94	0.0872	5.34×10^{53}
GW190727_060333	BBH	0.79	0.38	0.74	0.324	1.53×10^{55}
GW190728_064510	BBH	0.013	0.89	0.04	0.315	6.36×10^{53}
GW190731_140936	BBH	0.29	0.93	0.61	0.385	1.81×10^{55}
GW190803_022701	BBH	0.21	0.037	0.64	0.0354	1.69×10^{54}
GW190814	BBH	1.0	0.24	1.0	0.259	5.68×10^{52}
GW190828_063405	BBH	0.86	0.21	0.98	0.178	2.74×10^{54}
GW190828_065509	BBH	0.72	0.38	0.84	0.368	3.73×10^{54}
GW190909_114149	BBH	0.56	0.11	0.39	0.136	1.33×10^{55}
GW190910_112807	BBH	0.16	0.45	0.77	0.177	1.90×10^{54}
GW190915_235702	BBH	0.40	0.036	0.44	0.0354	3.61×10^{53}
GW190924_021846	BBH	0.038	0.037	0.23	0.0346	4.46×10^{52}
GW190929_012149	BBH	0.091	0.34	0.22	0.276	–
GW190930_133541	BBH	0.19	0.038	0.31	0.0427	1.05×10^{53}

Results: High Energy Analysis

- Neutrino arrived 360 s before the GW merger
- Had a reconstructed energy of 601 GeV
- No counterparts found from other observatories
- Event also found in realtime follow-up, and a GCN circular was sent

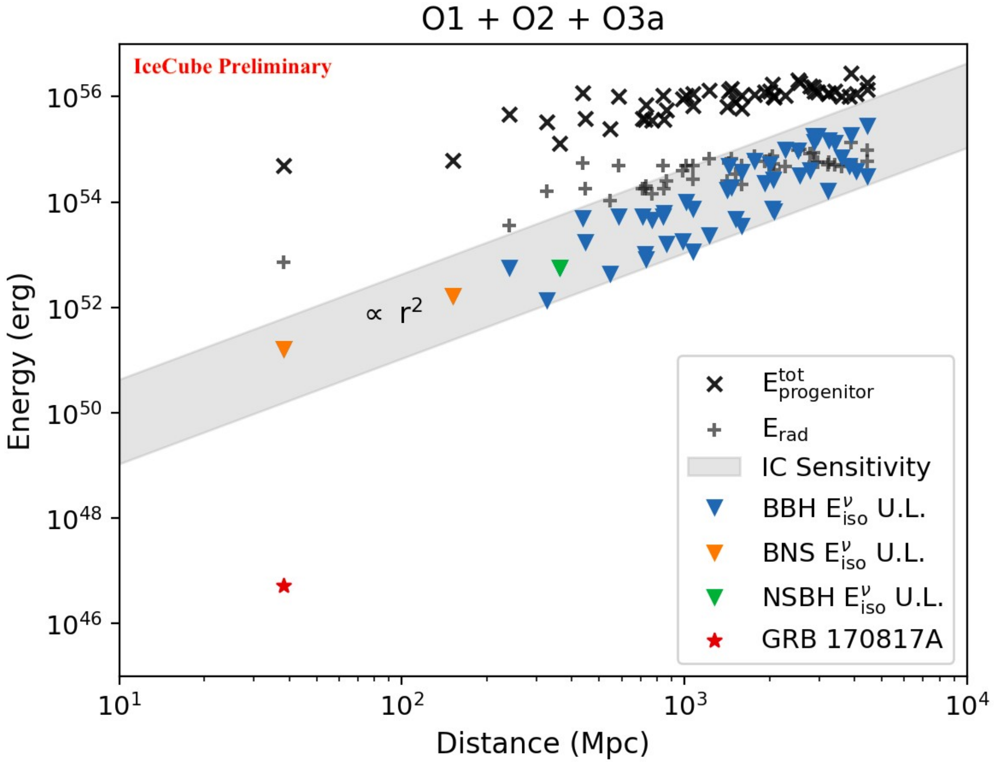




Sky localization of the most significant event

[PoS(ICRC2021)950]

Eiso upper limits



With GFU dataset
[PoS(ICRC2021)950]

- 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)
- Eiso UL on GRB170817A is 4 orders of magnitude lower than that on neutrinos

Two week follow-up

- 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 [GeV cm^{-2}]
GW190425	BNS	0.43	0.661
GW190426_152155	NSBH	0.21	0.248
GW190814	BBH	0.59	0.309

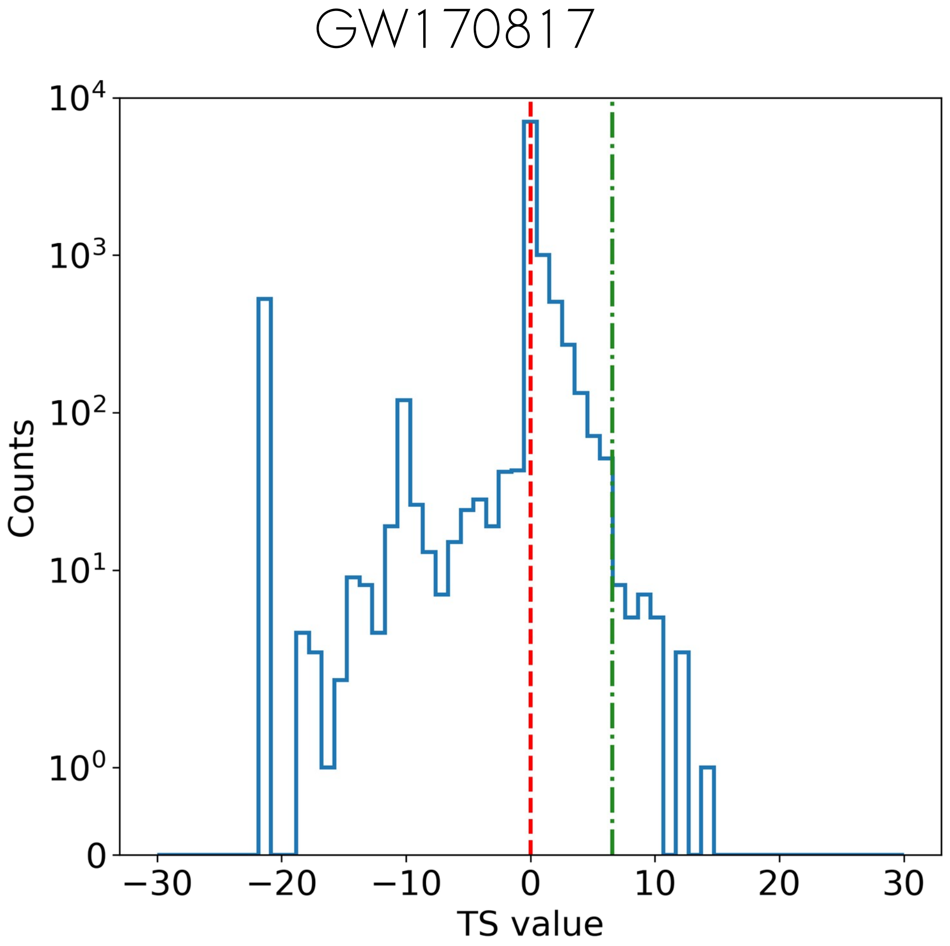
Summary

- We search for neutrino counterparts to GWs in the < 1TeV and > 1 TeV energy regimes
- Follow-up of events in GWTC-1 and GWTC-2 detected by LIGO-Virgo is done
- Sensitivities with unbinned maximum likelihood method (for high and low energy follow-up analyses) shown here
- Unblinded results of high energy neutrino search presented
- No significant emission found
- Stay tuned for more on this

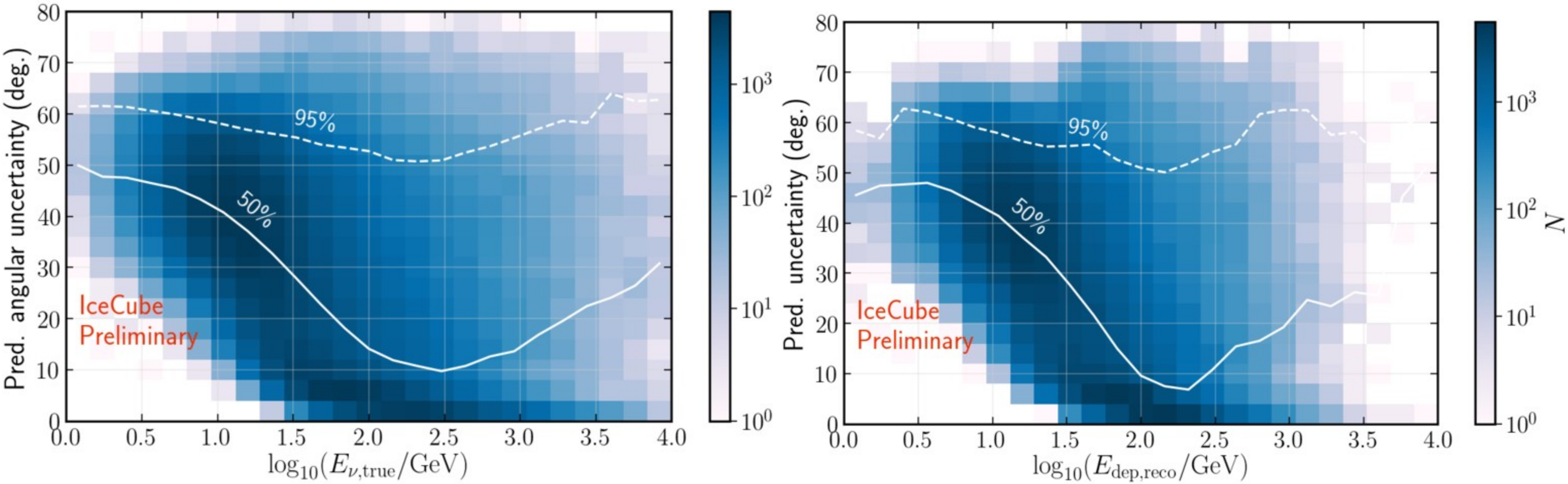
Backup

Background TS distribution

- Determined by running 10000 trials for each GW event
- Prior derived from corresponding GW skymap
- Negative values in the TS distribution arise from the spatial prior
- All -inf values set at -21 for pictorial representation
- Get the median/3 sigma from the background TS distribution for sensitivity/discovery potential calculations



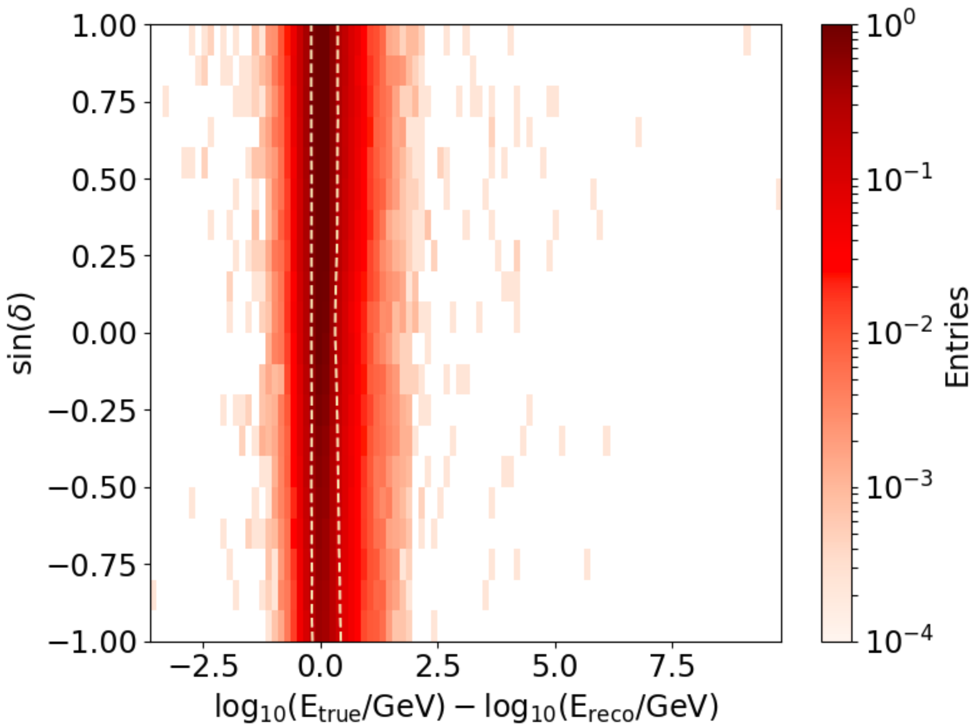
Angular uncertainty from Random Forest



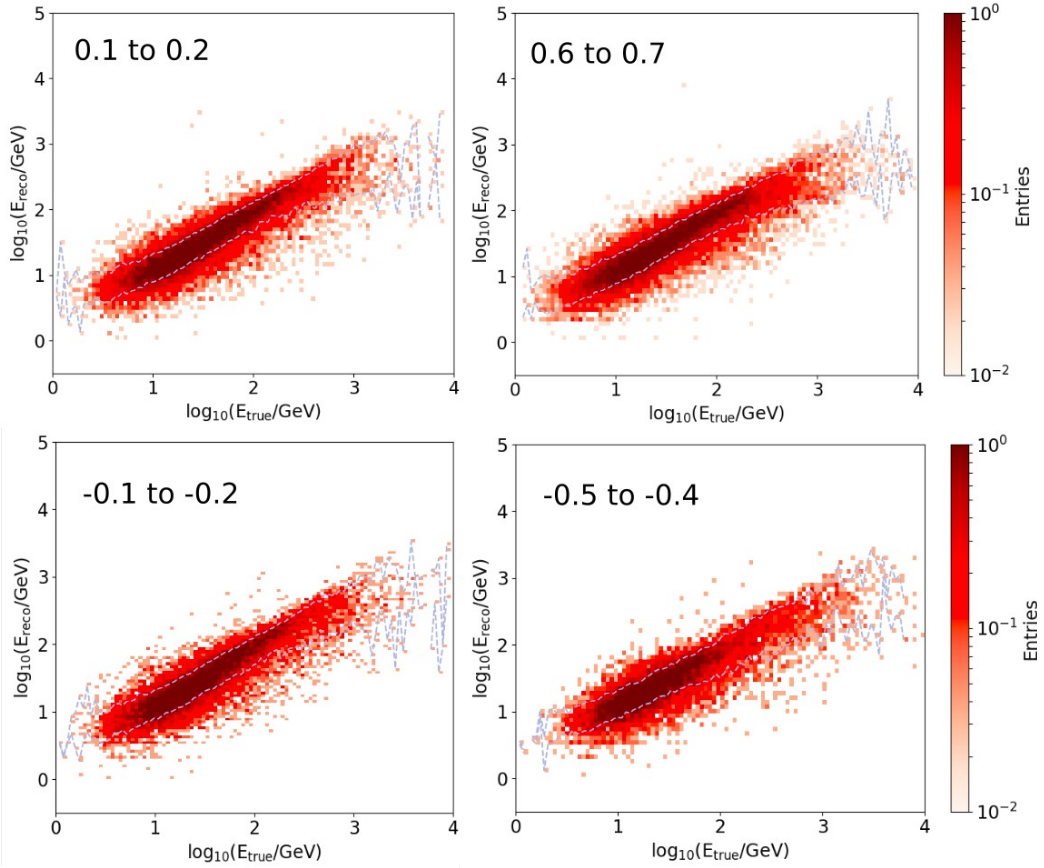
For muon neutrinos and anti neutrinos

[Alex Pizzuto]

Energy resolution



Energy resolution at different sin(δ) bins, with 68% contours



True vs reconstructed energy at different sin(δ), along with 68% contours

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

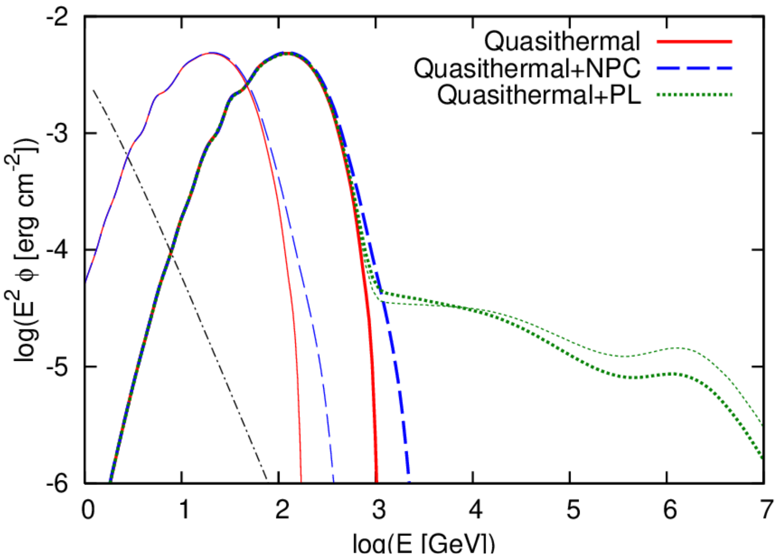
BNS and NSBH events

- O2: GW170817--> BNS
- O3a: GW190426_152155--> NSBH in GWTC-2, rejected in GWTC-2.1 since pastro < 0.5
- O3a: 190917_114630--> NSBH in GWTC-2.1
- O3a: 190725_174728--> one of the two objects with solar mass between 2 and 5 (but still classified as BBH)

GeV neutrino emission from mergers

Predictions of GeV neutrino emission

- BNS, BHNS mergers mainly with GRB progenitors
- Produced in subphotospheric region
- P and n decouple (either during acceleration stage or later) have inelastic collisions (pion production)
- Neutrino emission in GeV range



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- N. Fraija, MeV-GeV neutrino propagation as a signal of magnetic field amplification in neutron star merger , Journal of High Energy Astrophysics, Vol. 11-12, 2016, Pg. 29-43
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