A Search for IceCube Neutrinos from the First 33 Detected Gravitational Wave Events

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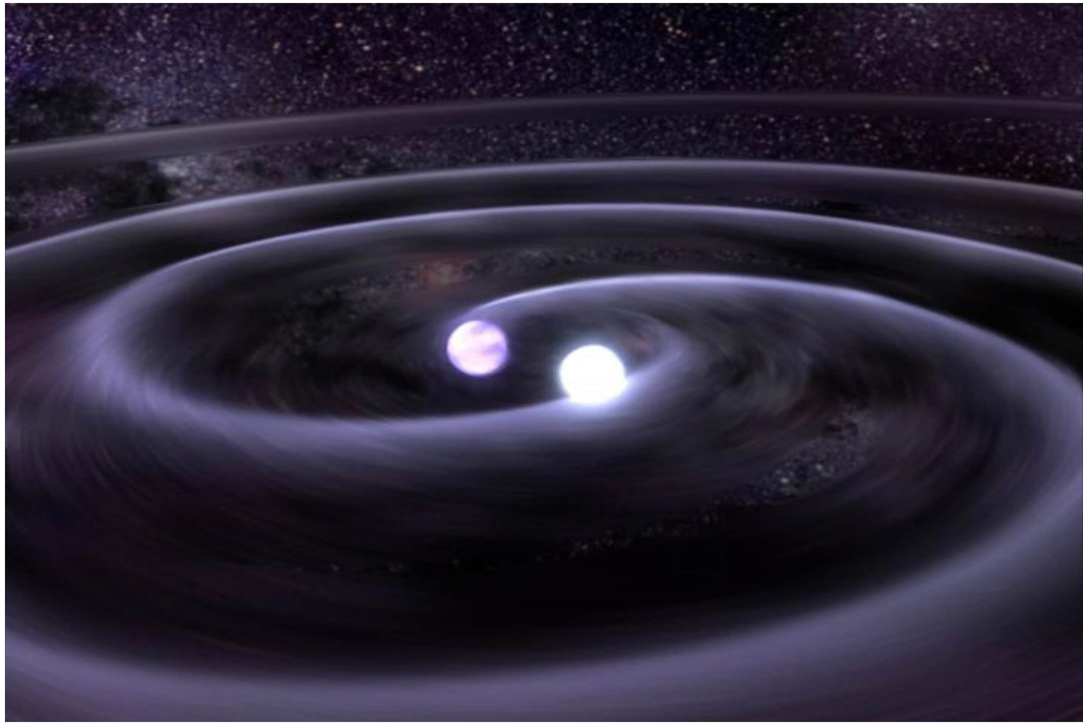
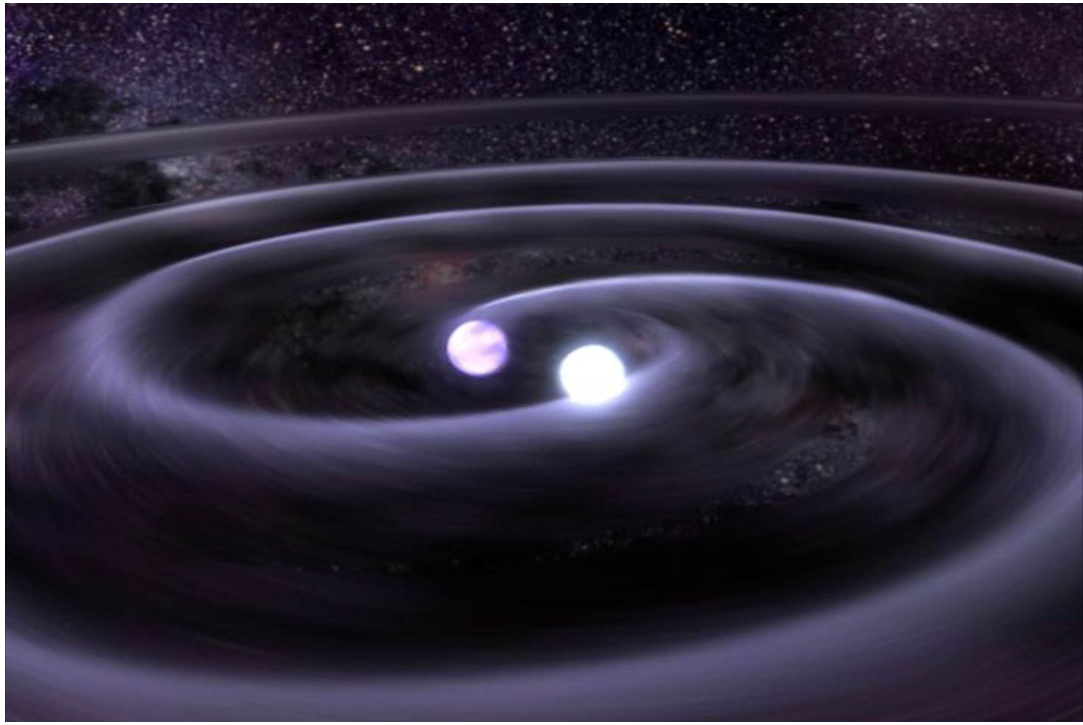
Motivation

- The merging of compact objects produces large amounts of gravitational waves (GWs) detectable by LIGO-Virgo Collaboration (LVC)
- These mergers can also produce neutrinos via relativistic jets or kilonovae
- LVC has reported 33 detections as of July 30th, 2019
  - 28 binary black hole mergers
  - 3 binary neutron star merger candidates
  - 2 terrestrial events



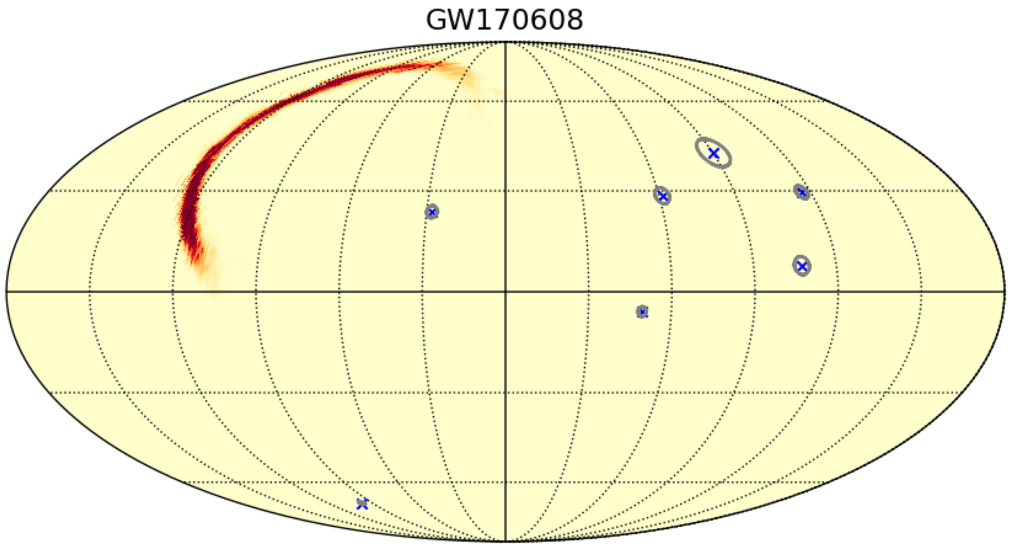
Motivation

- We search for neutrino emission from GW events detected by LVC during the O1,O2, and O3 observing runs
- Use unbinned maximum likelihood method with localization skymaps provided by LVC as spatial priors
- Search 1000 second time window centered around GW event time
- Another realtime analysis in IceCube uses a Bayesian approach to quantify the probability of a joint GW and Neutrino detection: PoS(ICRC2019)930



Analysis Procedure

1. Consider 1000 second time window centered around GW event
2. Perform all-sky scan over full sky
3. Weight results by spatial prior
4. Record best fit TS value (max TS of scan)
5. Perform 30k neutrino scrambles with fixed skymap



Example: GW170608

Event Sample:

- Gamma-ray follow up (GFU) neutrino sample
- 6.7mHz all sky rate
- Median angular error <1° for neutrino energies >1TeV

Likelihood Construction

Likelihood:

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

Test Statistic

$$TS = 2ln\left(\frac{\mathcal{L}}{\mathcal{L}(n_s=0)}\right)$$

Likelihood Construction

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Signal and Background PDFs

$$S_i = \frac{1}{2\pi\sigma^2} e^{\frac{\Delta\psi^2}{2\sigma^2}} \varepsilon(\delta|\gamma)$$

$$B_i = \frac{1}{2\pi} B_{space}(\delta)\, \varepsilon(\delta)$$

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Likelihood Construction

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Poisson Probability

Signal and Background PDFs

$$S_i = \frac{1}{2\pi\sigma^2} e^{\frac{\Delta\psi^2}{2\sigma^2}} \varepsilon(\delta|\gamma)$$

$$B_i = \frac{1}{2\pi} B_{space}(\delta)\, \varepsilon(\delta)$$

n_s, n_b : Expected number of signal and background events

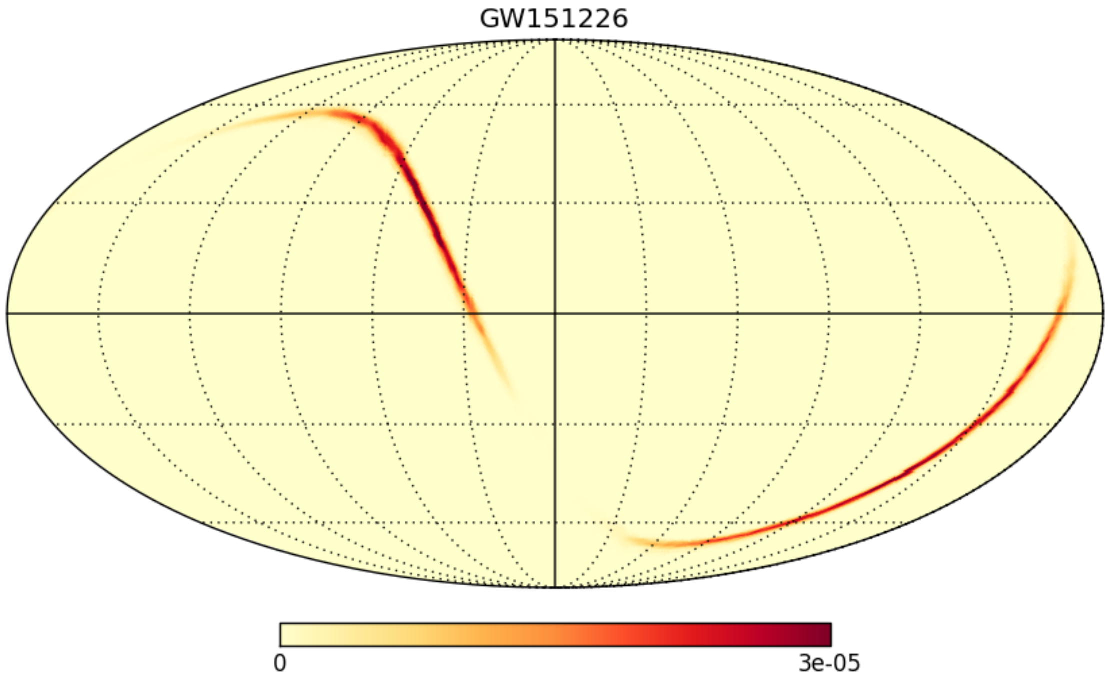
Test Statistic

$$TS = 2ln\left(\frac{\mathcal{L}}{\mathcal{L}(n_s = 0)}\right)$$

Free Parameters:
n_s, γ

Adding Spatial Prior

We incorporate the LVC probability skymap as a spatial prior to the likelihood at every point in the sky:



$$w_L = \frac{Ligo\ Prob}{Pixel\ Solid\ Angle}$$

$$\downarrow$$

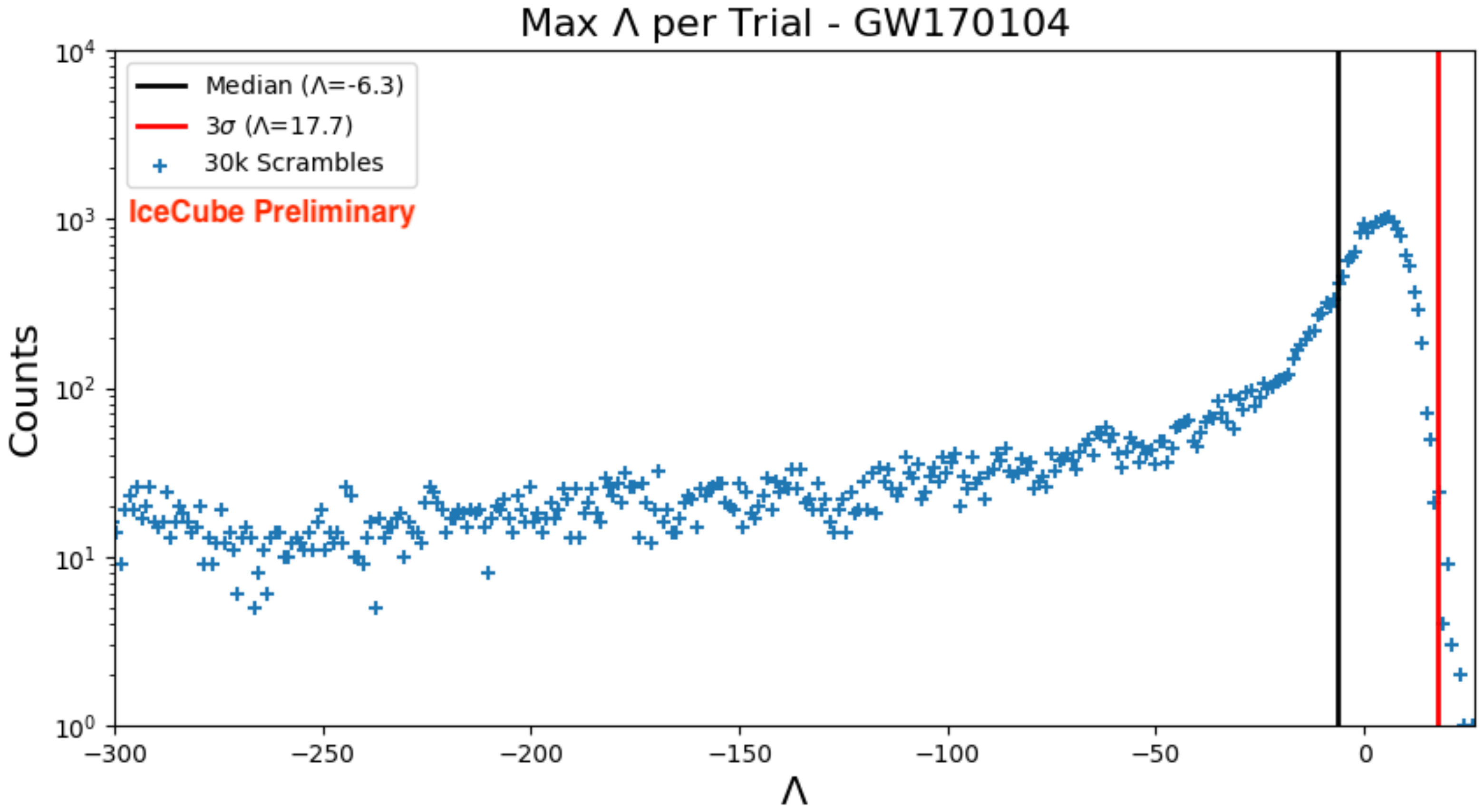
$$\Lambda = 2\ln\left(\frac{\mathcal{L}\cdot w_{\mathrm{L}}}{\mathcal{L}(n_s = 0)}\right)$$

$$\downarrow$$

$$\Lambda = \mathrm{TS} + 2\ln(w_{\mathrm{L}})$$

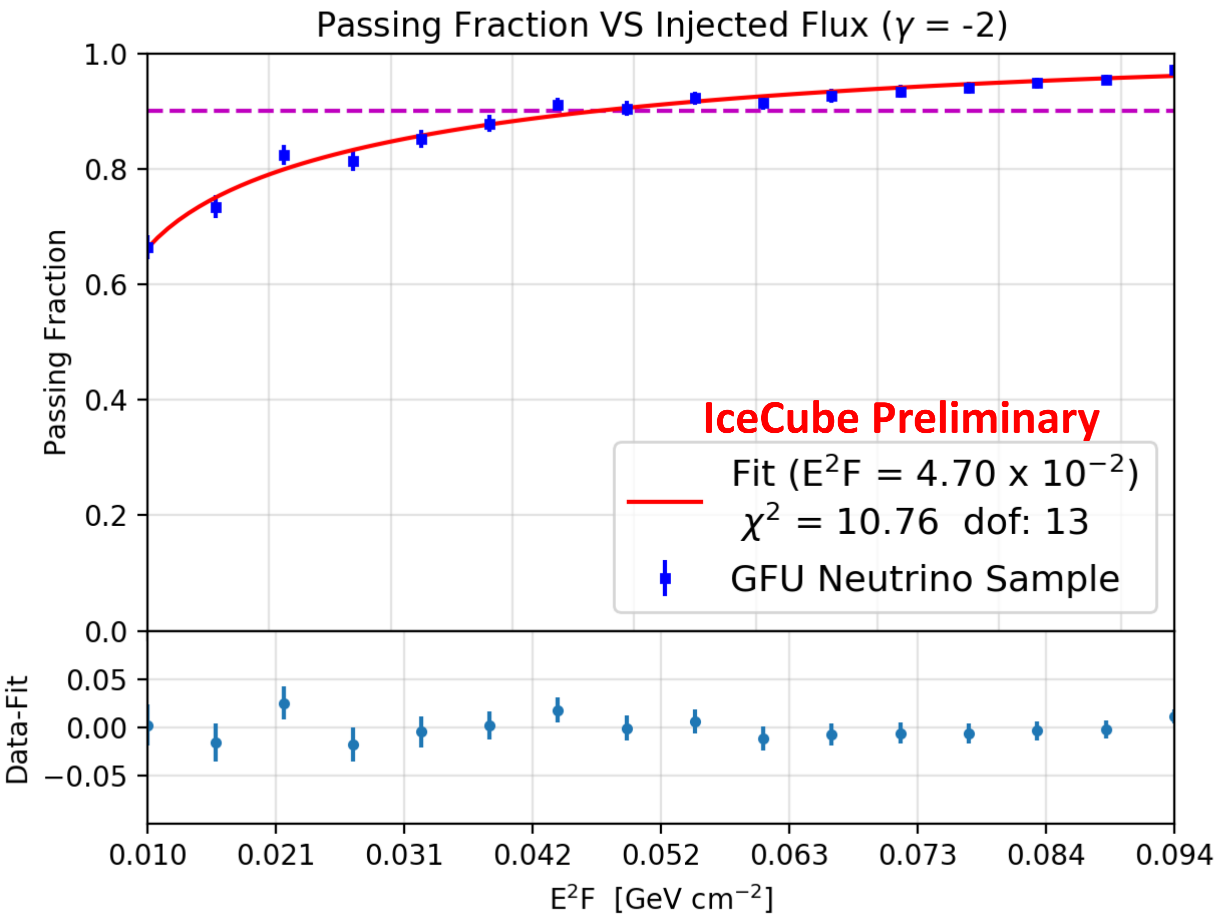
Example: GW170104

For every GW event we build a background Λ distribution using 30k neutrino scrambles and a fixed GW skymap

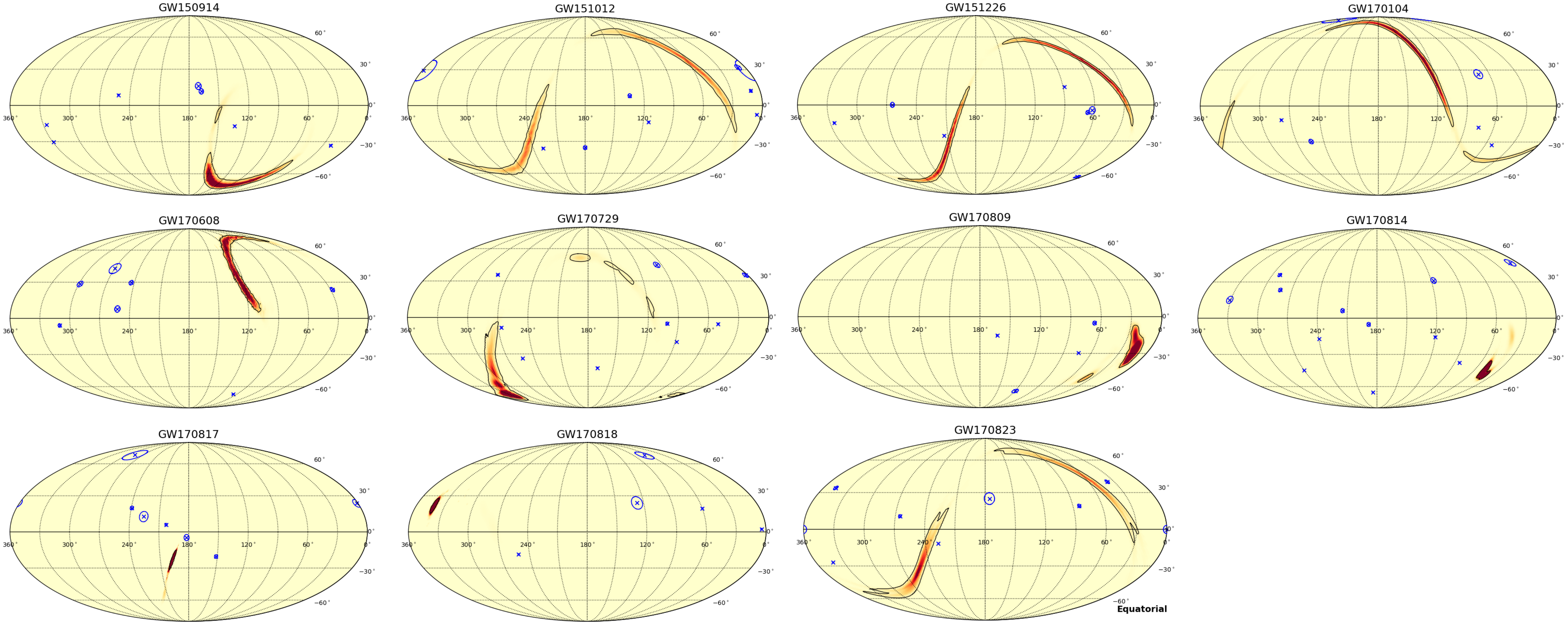


Example: GW170104

- Compute 90% C.L. sensitivity flux, E^2F, by injecting neutrinos from Monte Carlo
- Inject neutrinos until 90% of trials return a Λ greater than the median of the background
- <u>For Upper Limits:</u>
  - For upper limits we use the observed Λ as the threshold rather than the median
  - If $\Lambda_{obs} < \Lambda_{median}$ then we use Λ_{median} as the threshold to be conservative

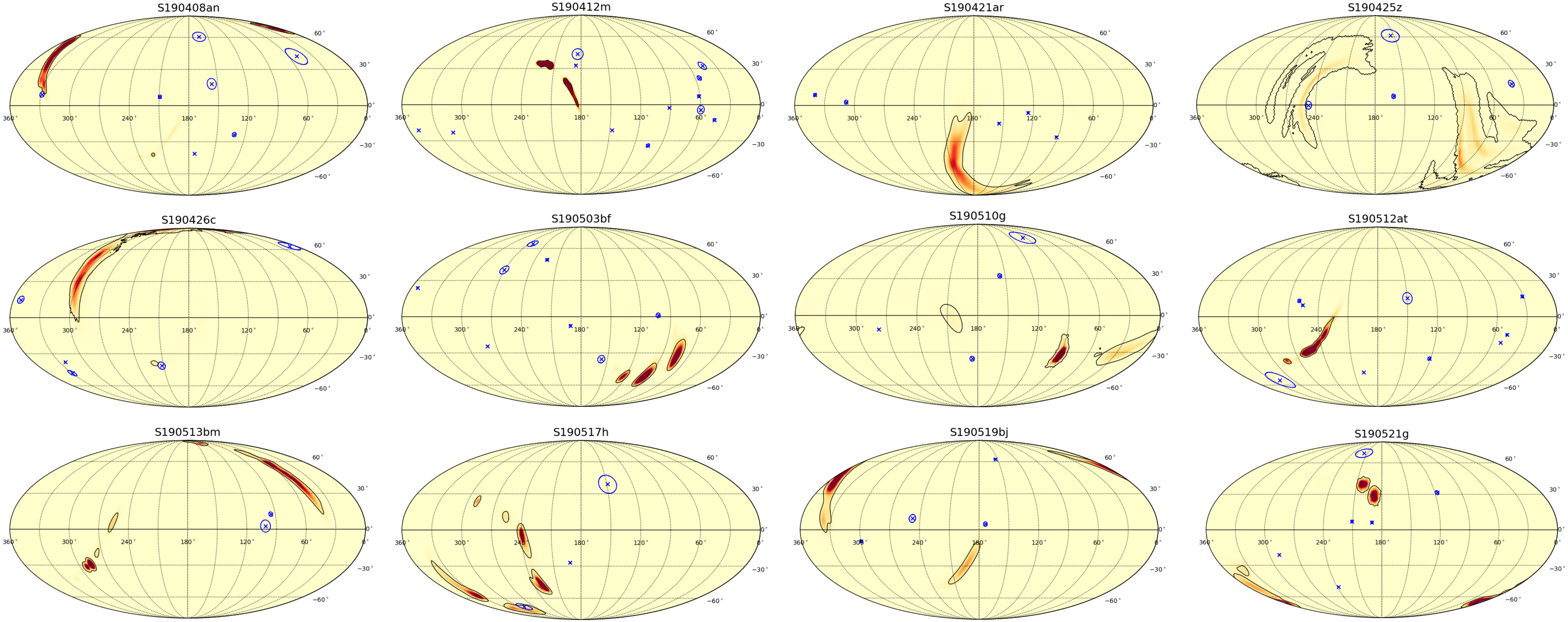


Results: O1+O2



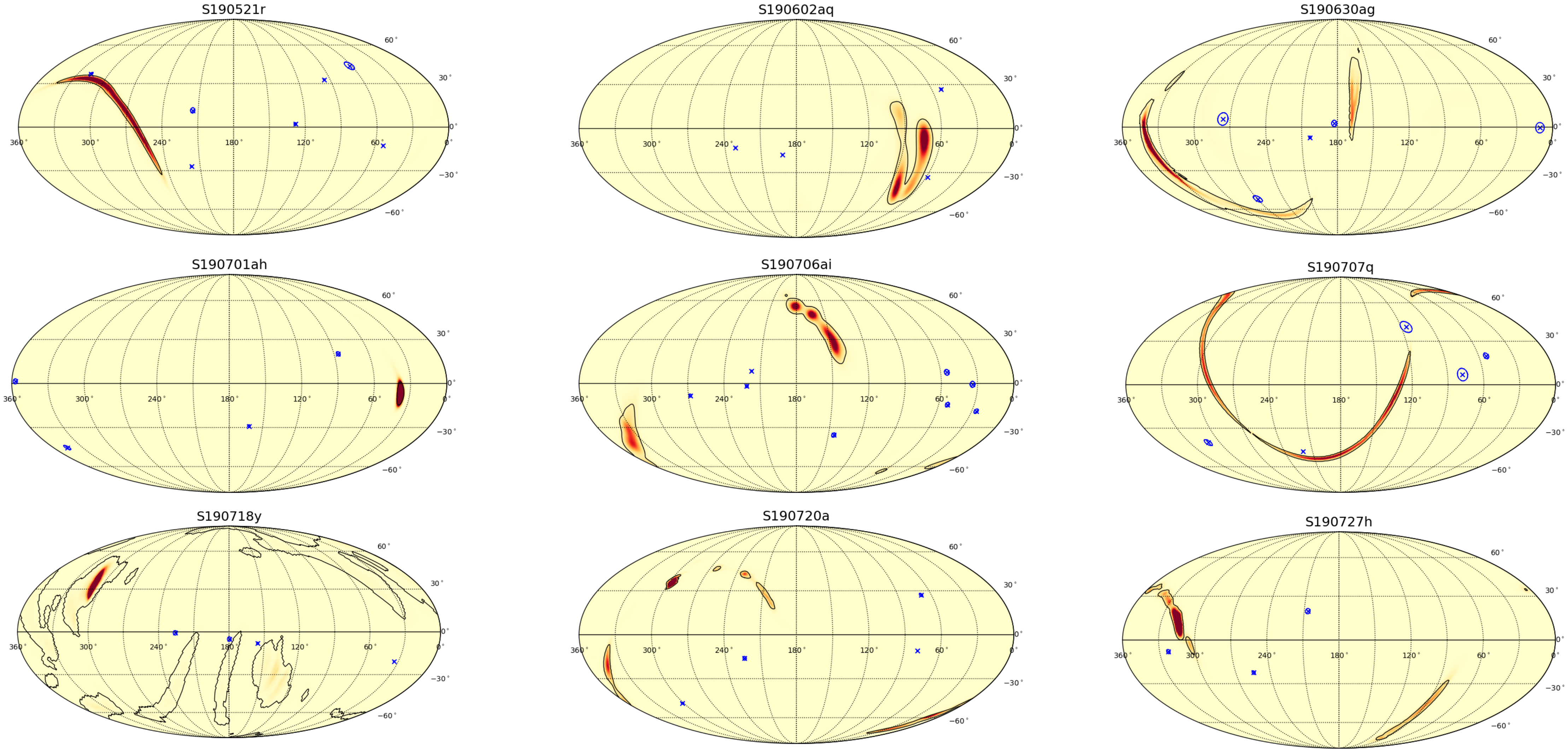
IceCube Preliminary

Results: O3



IceCube Preliminary

Results: O3



IceCube Preliminary

Results O1+O2

No significant neutrino correlation is found for the 33 GW events analyzed. Below are the results for the O1 + O2 observing run

GW Event List								
Event	Type	Ω (deg^2)	FAR (yr^{-1})	p-Value	90% U.L. ($GeVcm^{-2}$)	90% U.L.$_{min}$ ($GeVcm^{-2}$)	90% U.L.$_{max}$ ($GeVcm^{-2}$)	E_{iso} (ergs)
GW150914	BBH	180	<1.00 x 10^{-7}	0.62	0.579	0.0296	1.03	1.60 x 10^{52}
GW151012	BBH	1555	7.92 x 10^{-3}	0.71	0.182	0.0286	0.821	8.14 x 10^{52}
GW151226	BBH	1033	<1.00 x 10^{-7}	0.68	0.156	0.0286	0.904	1.45 x 10^{52}
GW170104	BBH	924	<1.00 x 10^{-7}	0.54	0.0470	0.0286	0.667	7.11 x 10^{52}
GW170608	BBH	396	<1.00 x 10^{-7}	0.61	0.0360	0.0309	0.0821	9.40 x 10^{51}
GW170729	BBH	1033	1.80 x 10^{-1}	0.21	0.619	0.0286	1.02	5.39 x 10^{53}
GW170809	BBH	340	<1.00 x 10^{-7}	0.60	0.263	0.0568	0.758	8.21 x 10^{52}
GW170814	BBH	87	<1.00 x 10^{-7}	0.83	0.461	0.488	0.711	2.94 x 10^{52}
GW170817	BNS	16	<1.00 x 10^{-7}	0.19	0.277	0.180	0.429	1.37 x 10^{50}
GW170818	BBH	39	4.20 x 10^{-5}	0.52	0.0275	0.0364	0.0431	9.04 x 10^{52}
GW170823	BBH	1651	<1.00 x 10^{-7}	0.75	0.180	0.0286	0.796	2.46 x 10^{53}

FAR: False Alarm Rate of GW ; E_{iso}: Isotropic equivalent energy emitted by GW source

Results: O3

U.L. min and max are U.Ls assuming point source hypothesis in 90% GW contour

E_{iso} U.L is computed by computing the expected number of events at IceCube, marginalized over the 3D position of the GW source

Event	Type	Ω (deg^2)	FAR (yr^{-1})	p-Value	90% U.L. (GeVcm^{-2})	90% U.L.$_{min}$ (GeVcm^{-2})	90% U.L.$_{max}$ (GeVcm^{-2})	E_{iso} (ergs)
S190408an	BBH	387	<1.00 x 10^{-7}	0.13	0.0625	0.0337	0.606	1.81 x 10^{53}
S190412m	BBH	156	<1.00 x 10^{-7}	0.18	0.0423	0.0286	0.048	5.39 x 10^{52}
S190421ar	BBH	1444	4.70x 10^{-1}	0.79	0.652	0.0420	1.15	1.65 x 10^{53}
S190425z	BNS	7461	1.43 x 10^{-5}	0.87	0.383	0.0286	1.06	1.90 x 10^{51}
S190426c	BNS	1131	6.14 x 10^{-1}	0.12	0.0685	0.0286	0.583	1.10 x 10^{52}
S190503bf	BBH	448	5.16 x 10^{-2}	0.49	0.581	0.227	0.821	1.43 x 10^{52}
S190510g	Ter	1166	2.79 x 10^{-1}	0.86	0.401	0.0286	0.610	2.76 x 10^{51}
S190512at	BBH	252	6.00 x 10^{-2}	0.84	0.341	0.0286	0.568	1.51 x 10^{53}
S190513bm	BBH	691	1.18 x 10^{-5}	1.0	0.187	0.0286	0.505	3.16 x 10^{53}
S190517h	BBH	939	7.49 x 10^{-2}	0.21	0.613	0.0286	1.06	5.78 x 10^{53}
S190519bj	BBH	967	1.80 x 10^{-1}	0.45	0.108	0.0286	0.639	8.15 x 10^{53}
S190521g	BBH	765	1.20 x 10^{-1}	0.61	0.538	0.0391	0.966	1.14 x 10^{54}
S190521r	BBH	488	1.00 x 10^{-2}	0.095	0.0654	0.0286	0.456	1.07 x 10^{53}
S190602aq	BBH	1172	<1.00 x 10^{-7}	0.15	0.344	0.0286	0.732	4.84 x 10^{52}
S190630ag	BBH	1483	4.53 x 10^{-6}	0.63	0.307	0.0286	0.977	6.73 x 10^{52}
S190701ah	BBH	67	6.04 x 10^{-1}	1.0	0.0530	0.0286	0.176	2.81 x 10^{53}
S190706ai	BBH	1100	6.00 x 10^{-2}	1.0	0.199	0.0350	0.881	2.09 x 10^{54}
S190707q	BBH	1375	1.66 x 10^{-4}	0.55	0.334	0.0286	0.763	4.99 x 10^{52}
S190718y	Ter	7246	1.15	0.67	0.135	0.0286	1.15	1.42 x 10^{51}
S190720a	BBH	1559	0.120	0.96	0.358	0.0286	1.08	6.29 x 10^{52}
S190727h	BBH	841	4.34 x 10^{-3}	0.77	0.592	0.0350	0.983	9.83 x 10^{52}
S190728q	BBH	104	<1.00 x 10^{-7}	0.014	0.0520	0.0295	0.0404	6.83 x 10^{52}

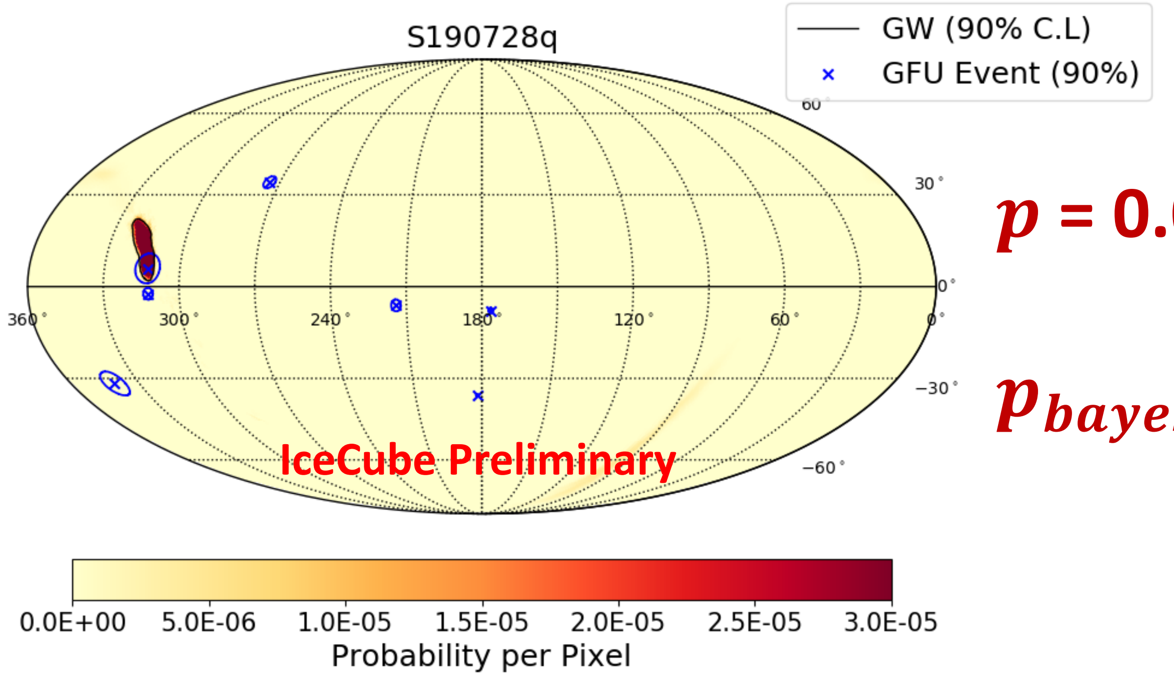
Most Significant Event

Early Sunday morning, LVC sent a notice for a potential NS-BH merger event

Neutrino follow up resulted in most significant p value of all events to date

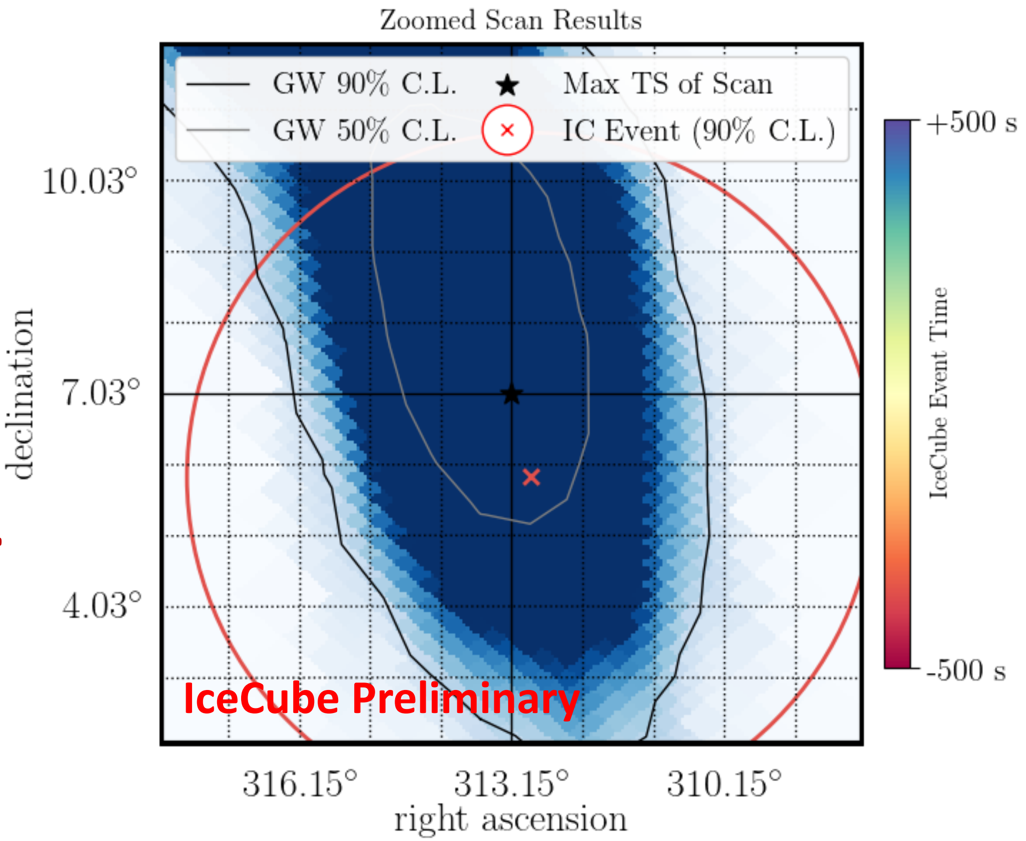
GCN Circular was sent with results from both follow up analyses

GCN: https://gcn.gsfc.nasa.gov/gcn3/25210.gcn3



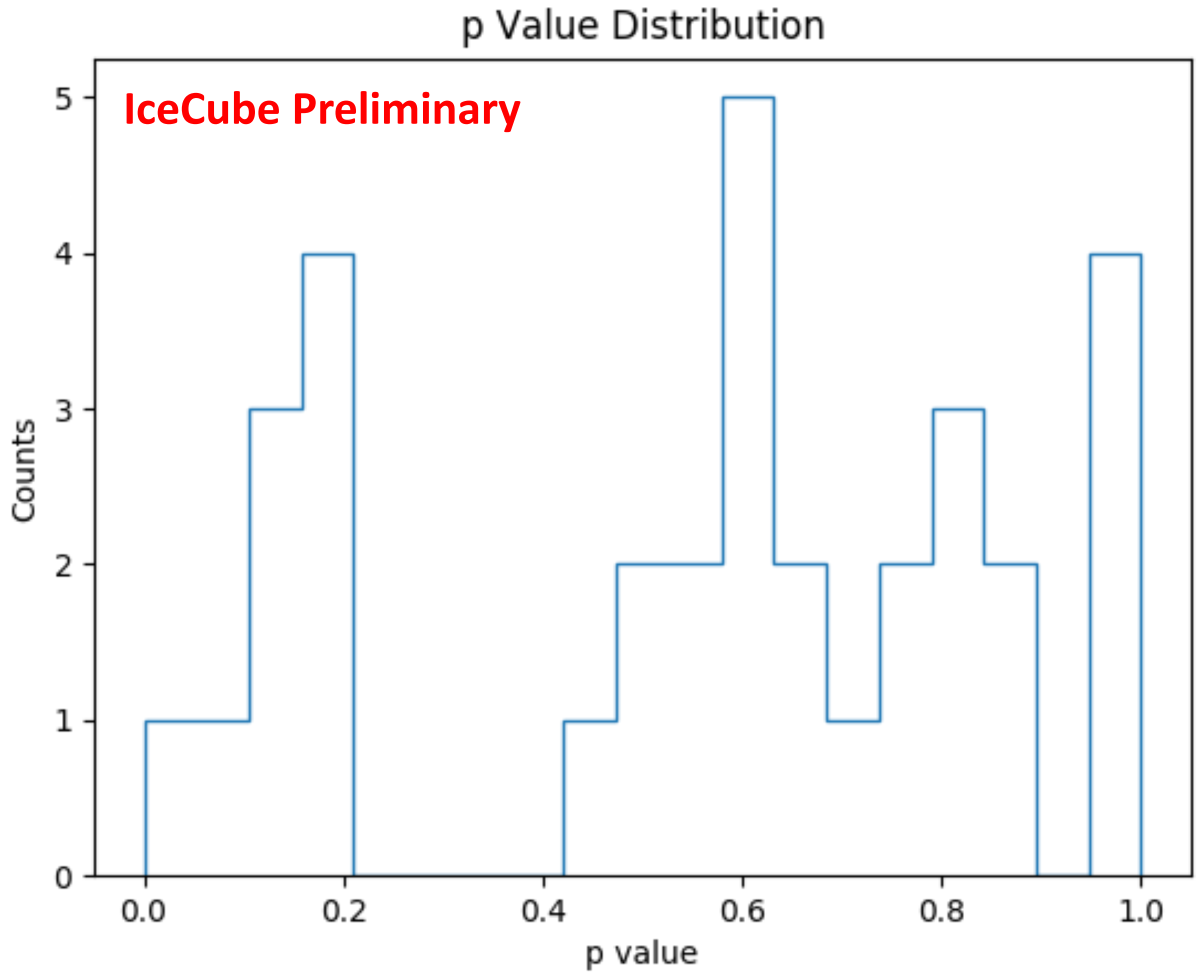
$p = 0.0136$

$p_{bayes} = 0.0102$



Realtime O3 Analyses

- This analysis is run in realtime to respond to GW events during the O3 science run
- Bayesian analysis runs in parallel
- For each event in O3, a GCN circular is sent with results from both analyses
- So far, p values seem uniformly distributed. More stats are needed to study population of GW events



Summary

- Performed neutrino follow up to all reported GW events
  - No significant neutrino correlation is found

- Automated analysis responds to GW events with low latency
  - GCN circulars are sent with results from both realtime analyses
  - 22 GW events so far
  - Estimated rates at start of 03 run:
    - BBH: ~1/week
    - BNS: ~1/month

- Planning another analysis searching for neutrino emission over longer timescales
  - If neutrino emission occurs during kilonova phase of BNS merger, a dedicated long timescale analysis would be far more sensitive