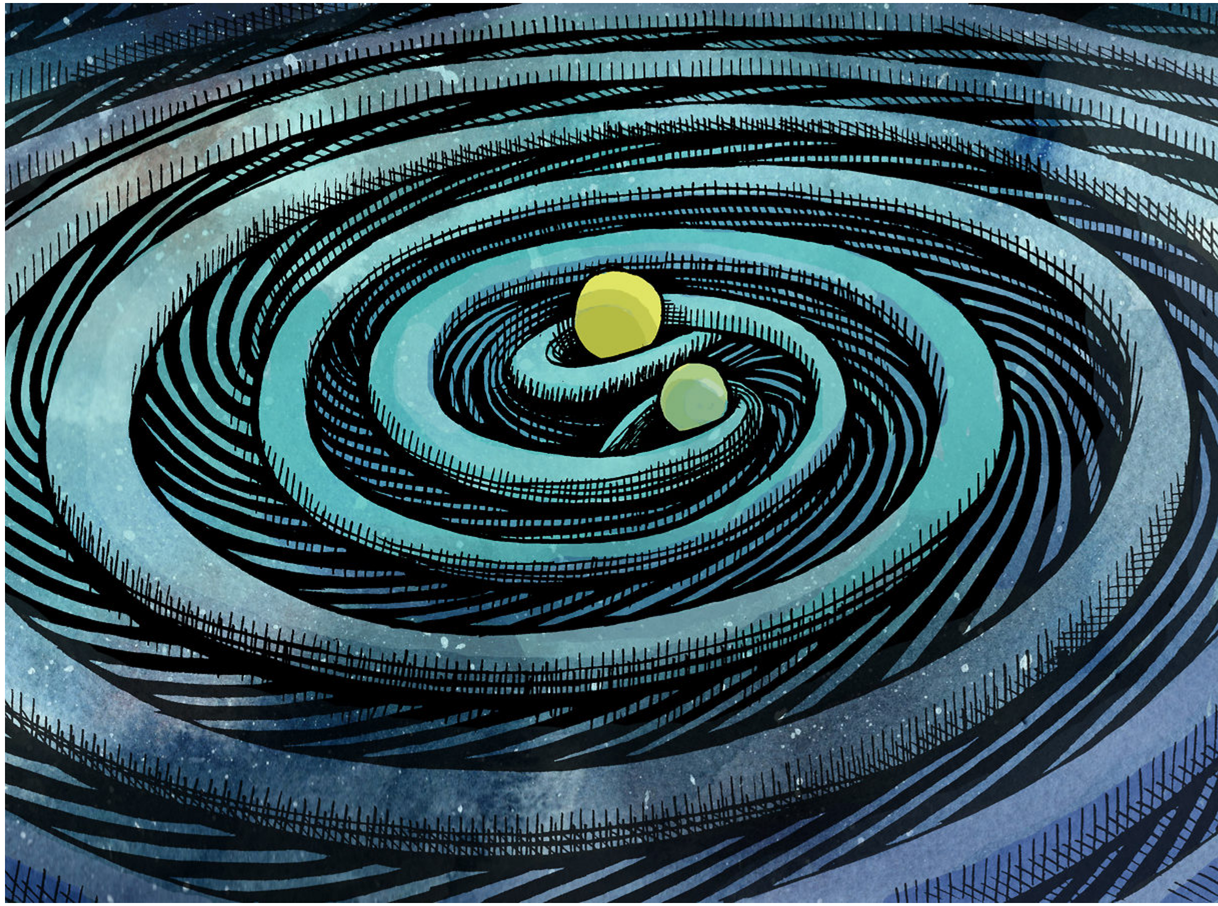
IceCube Analysis Example

Raamis Hussain

IceCube Bootcamp 2020

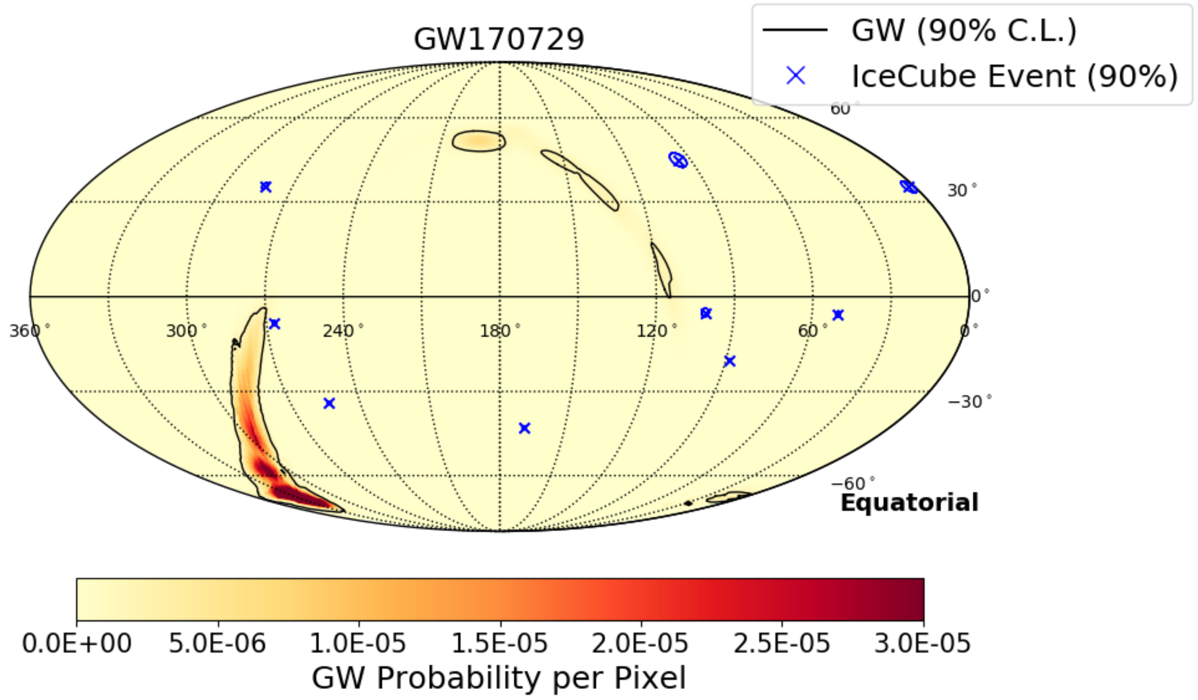
Motivation

- Gravitational waves (GWs) are ripples in spacetime caused by the acceleration of massive objects
- LIGO-Virgo detects GWs during compact binary mergers
  - Binary black hole mergers
  - Binary neutron star mergers
  - Neutron star - black hole mergers
- During these mergers, particles may be accelerated to very high energies
- High-energy proton interactions lead to neutrino production which can be detected by IceCube



Analysis Overview

- We develop an analysis to search for neutrinos correlated with gravitational wave events observed by LIGO-Virgo
- Use an unbinned maximum likelihood analysis with a spatial weight derived from the GW skymap
- Neutrinos near the higher probability region on the skymap will be more significant
- Search a ± 500 second time window centered around the GW merger time



Example of GW with neutrinos overlaid

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

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

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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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n_s, n_b : Expected number of signal and background events

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Free Parameters:
n_s, γ

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Test Statistic

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Signal Hypothesis

Null Hypothesis

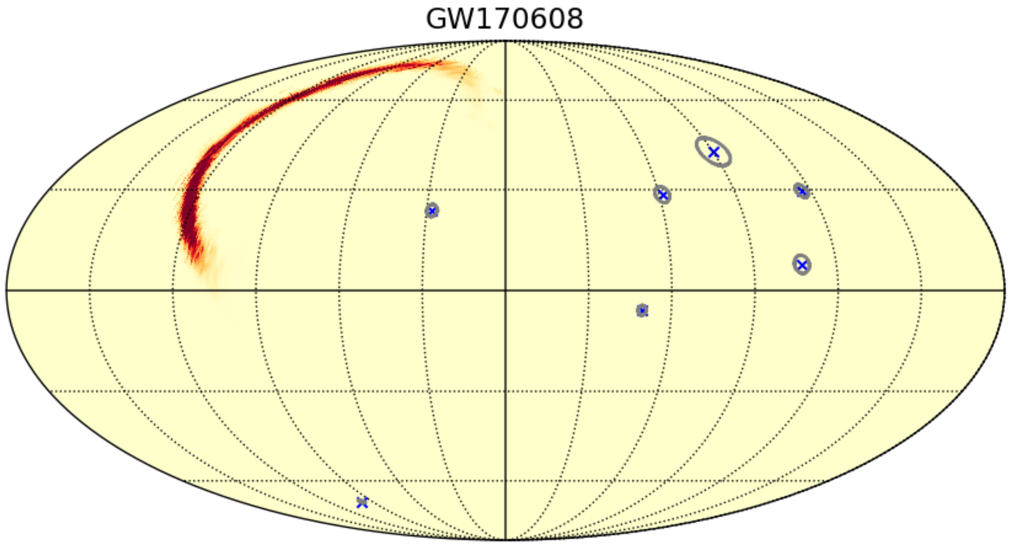
Free Parameters:

n_s, γ

Spatial Weight

Notice we have not added any information about the gravitational wave event thus far. We have a general transient point source likelihood. To add the GW information we define a per pixel spatial weight based on the GW probability skymap

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



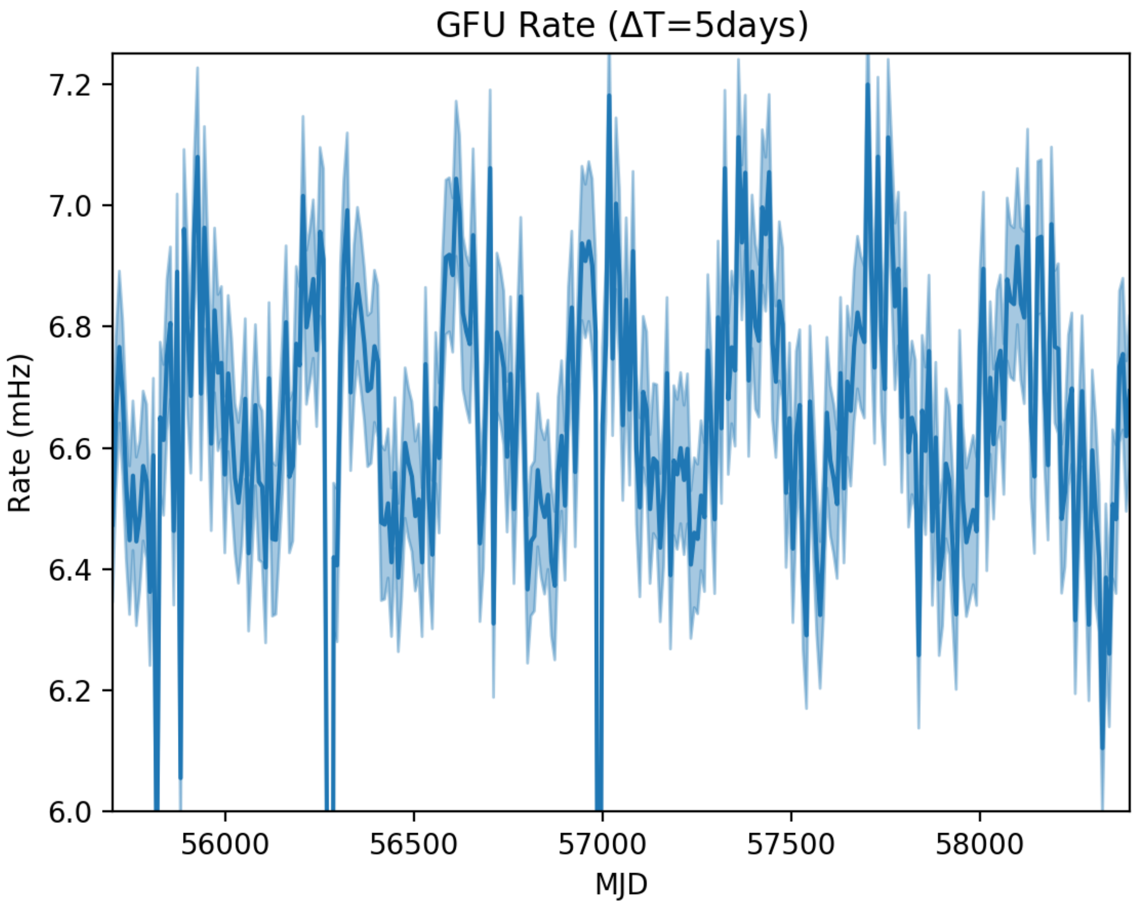
Example: GW170608

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

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

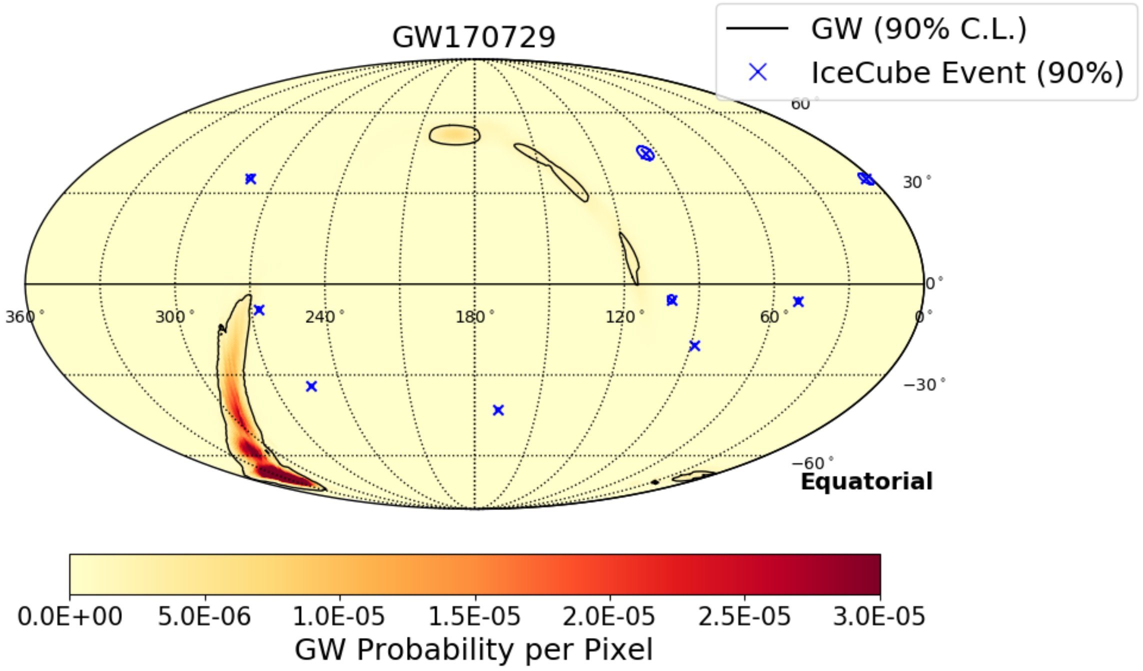
Estimating Background

- In the transient likelihood, we need to have an estimate for n_b, the expected number of background events. We can compute this directly from our data
- GFU sample is a dataset consisting of high-energy muon tracks that are commonly used in point source analyses in IceCube
- The GFU rate as a function of time is roughly sinusoidal due to the seasonal temperature variations of the atmosphere at the south pole
- We can use this curve to estimate the amount of expected background events in our 1000 second time window based on the time of the year the GW occurs



Analysis Procedure

1. Consider ±500 second time window
2. Maximize log-likelihood at every pixel in the sky
3. Weight resulting test statistic (TS) by spatial prior
4. Record maximum TS value in the sky
5. Perform 30k neutrino scrambles with fixed skymap



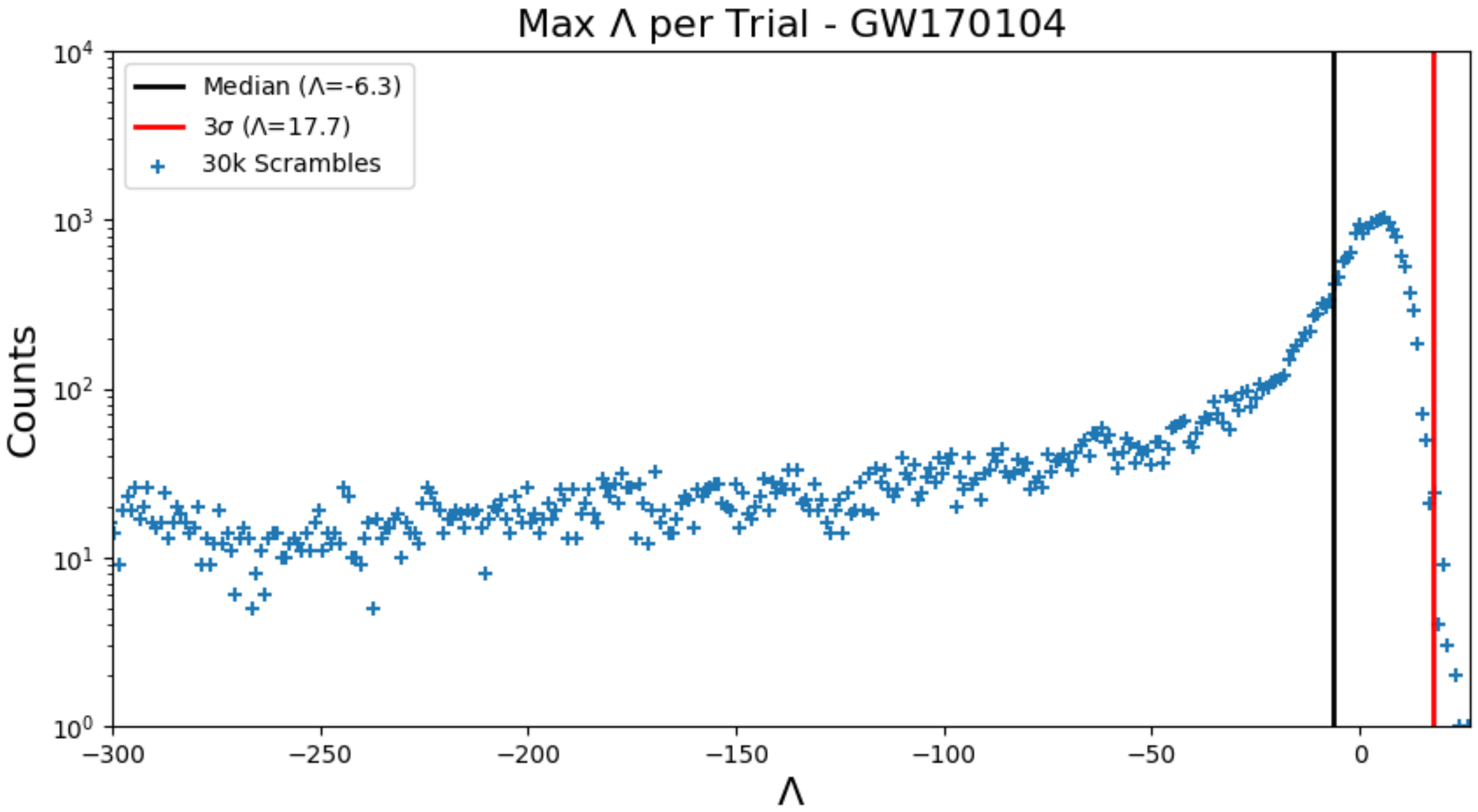
Example: GW170608

<u>Event Sample:</u>

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

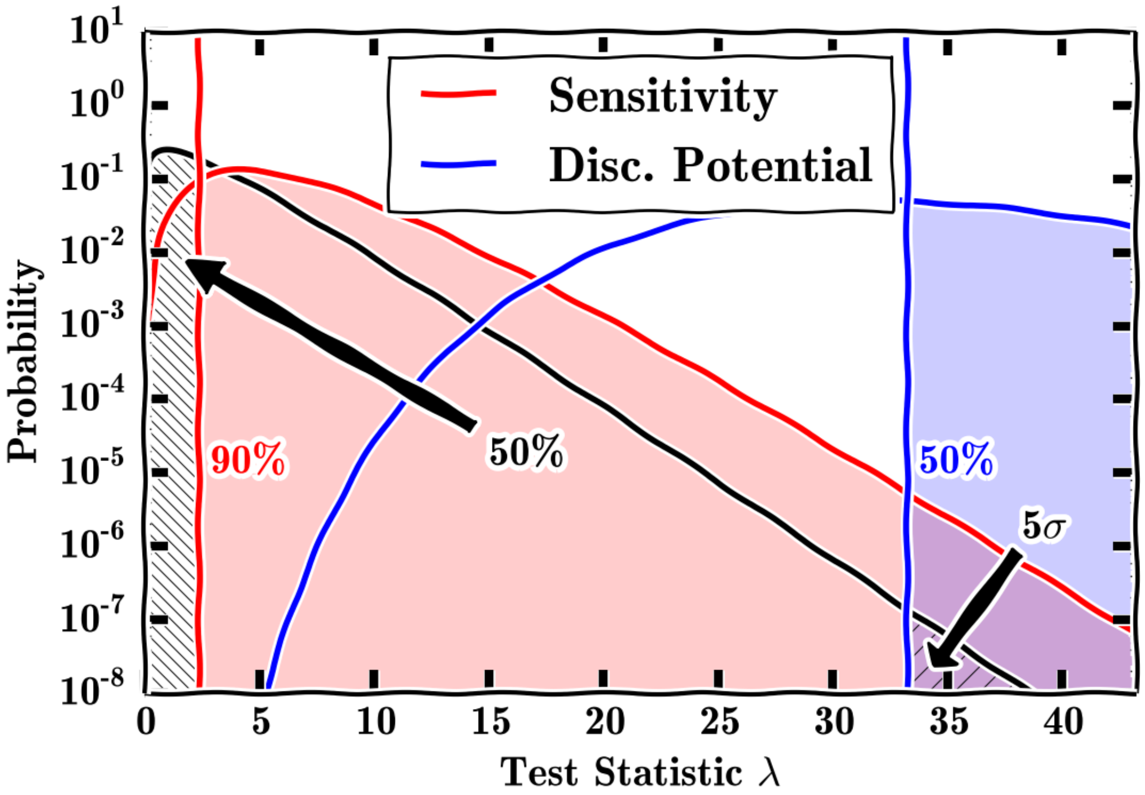
Test statistic distribution (background only)

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



Calculating the neutrino flux sensitivity

- 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



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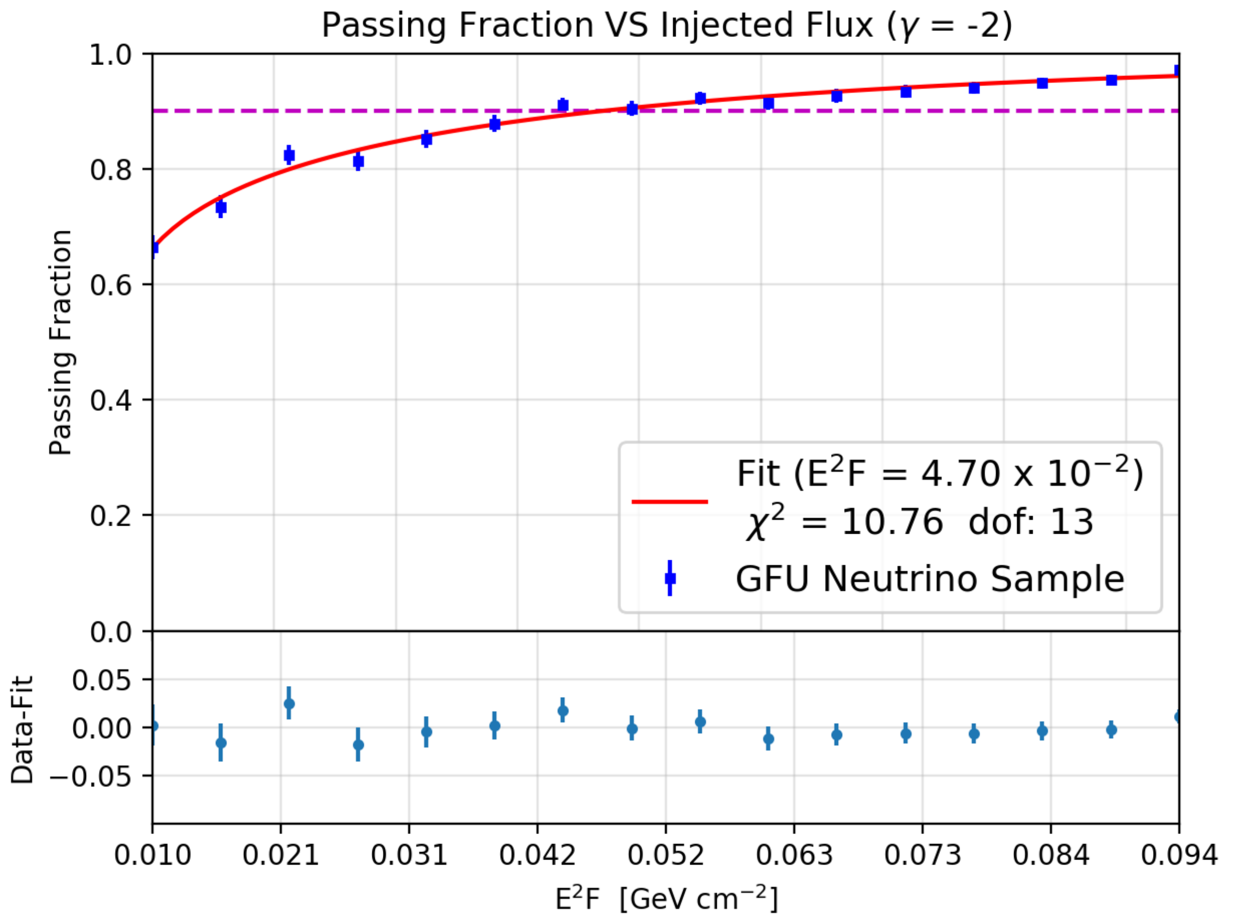
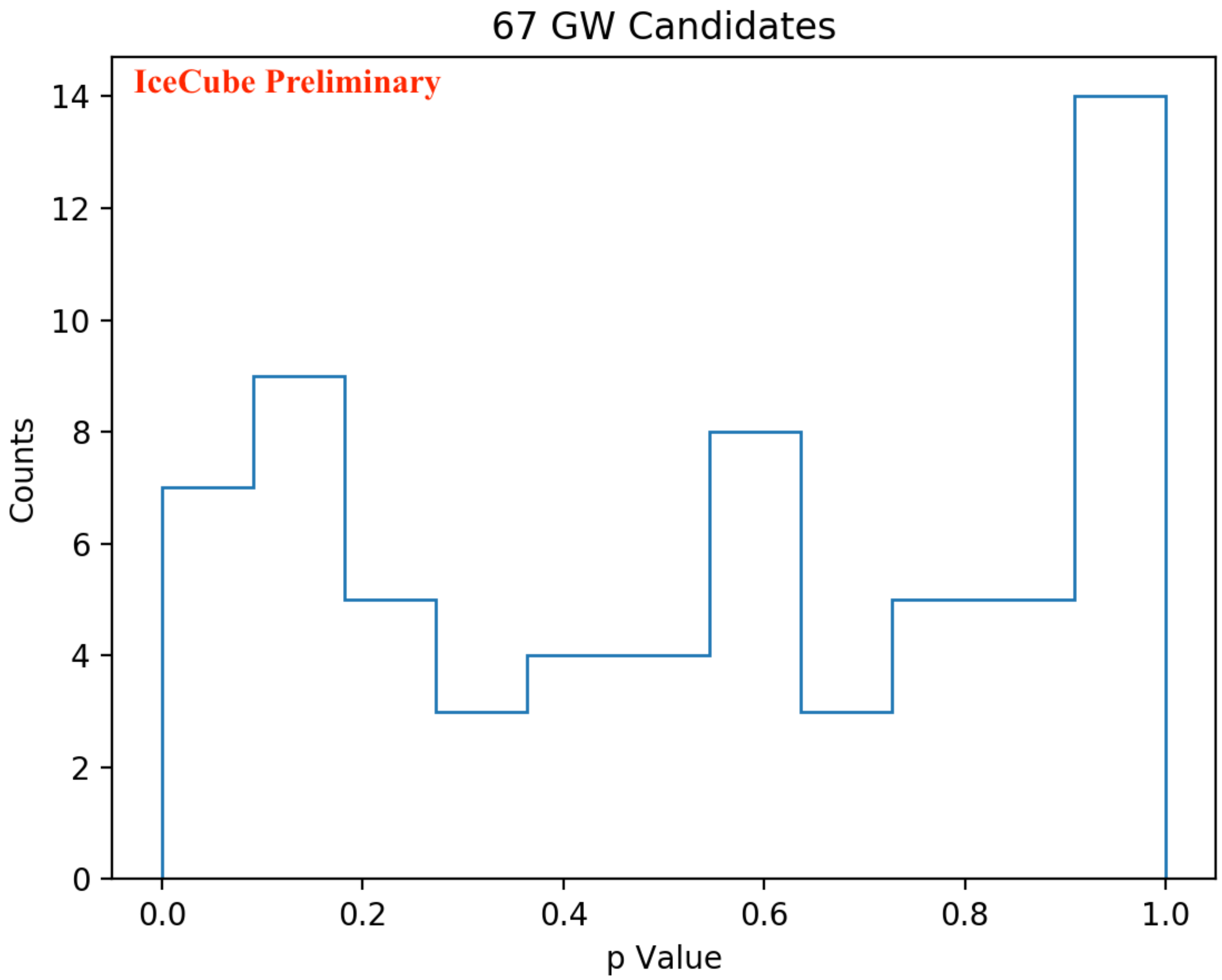


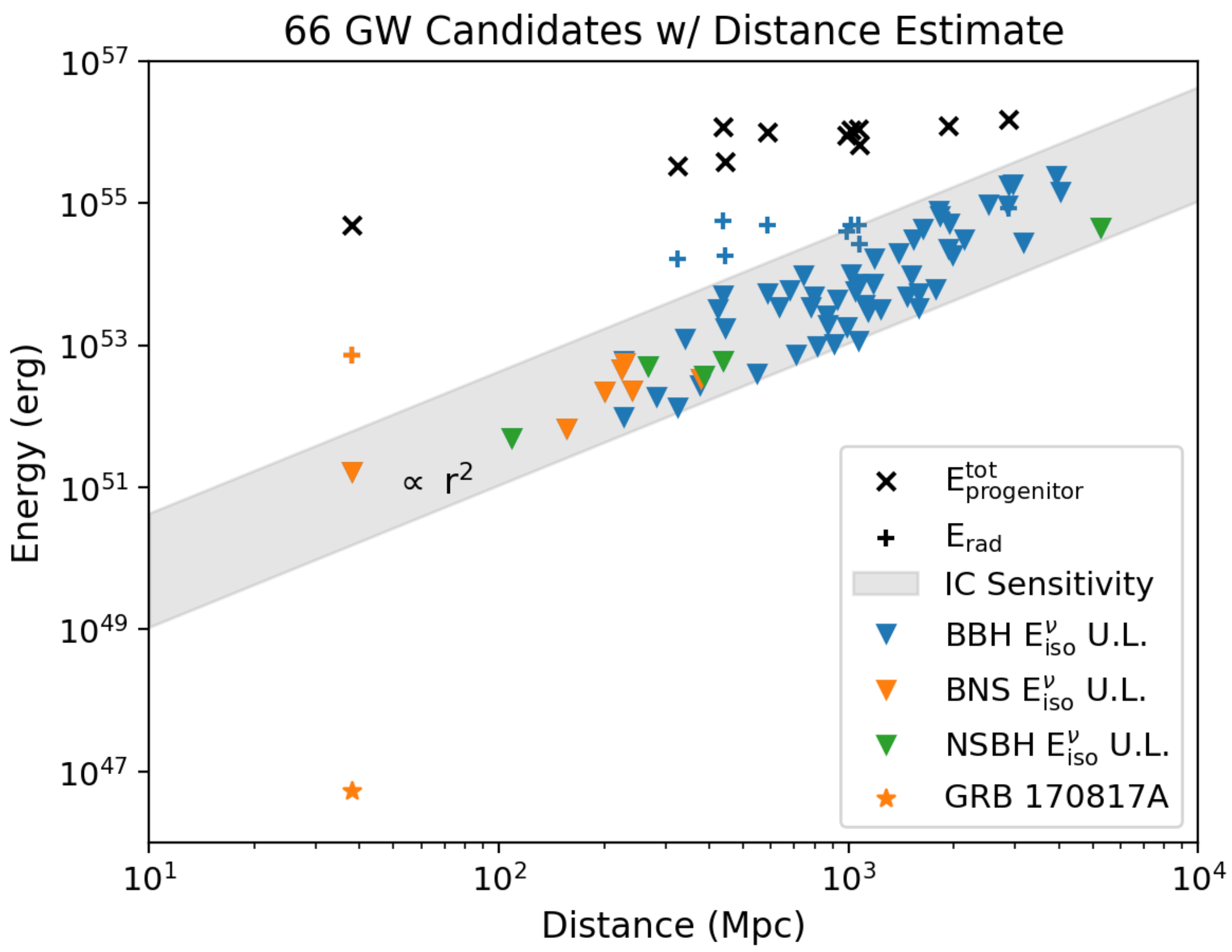
Unblinding Results

- We followed up a total of 67 GW events from the O1, O2, and O3 observing runs
- We found no evidence of neutrino emission from any of the 67 events
- The p value distribution shown on the right is consistent with a uniform distribution which is expected from background
- We set 90% upper limits on the time integrated flux scaled by energy, E^2F, as well as the total isotropic equivalent energy emitted in high-energy neutrinos



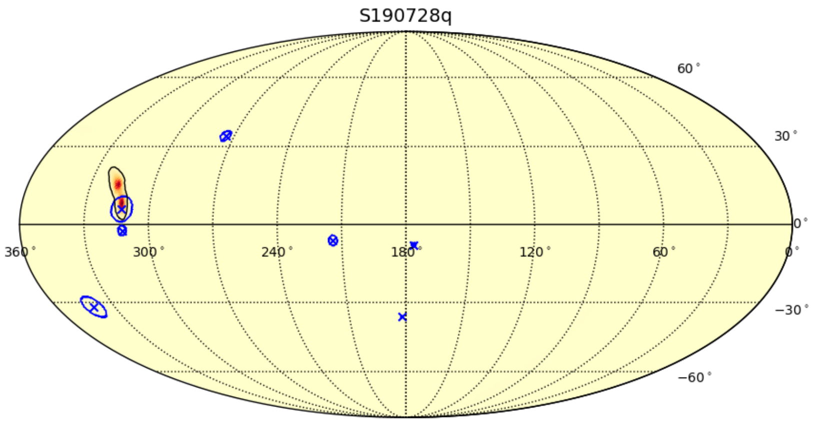
Unblinding Results

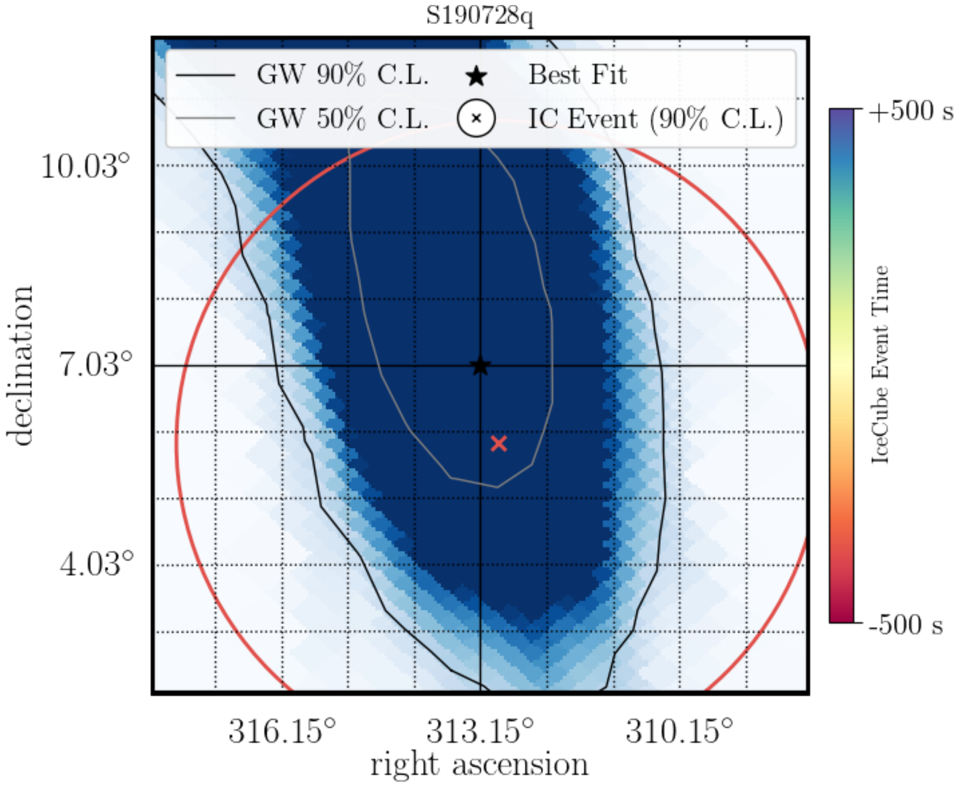
- 90% Upper limits on isotropic equivalent energy, E_{iso}, as a function of distance to the GW source
- The gray band shows IceCube's best and worst point source sensitivity
- Shown for reference are other relevant energy scales in the system
  - Total progenitor rest mass energy
  - Total energy radiated by the binary system



Example Neutrino Coincidence

- On July 28th, 2019, LIGO-Virgo sent an automated notice to announce the detection of a gravitational wave event they had just observed
- Our analysis monitors GCN circulars and automatically starts a follow up analysis of every reported GW event
- We found a neutrino within the 50% containment region of the GW event, with a p value of p = 0.0136
- We sent the direction of this neutrino via GCN circular
  - Swift follow up of IceCube neutrino region overlapping with GW yielded no results





Summary

- We developed an analysis searching for neutrino emission from gravitational wave sources observed by LIGO-Virgo
- We also developed a realtime analysis which responded to GW detections in realtime during the O3 observing run
- 67 GW candidates were followed up with no statistically significant results
  - Paper on archival search on first 11 GW events is now accepted for publication in ApJL
  - https://arxiv.org/pdf/2004.02910.pdf
- Future analyses are in the works
  - Longer timescale analysis searching for neutrino emission over a 2 week time window
  - Analysis using a cascade event selection rather than a track selection