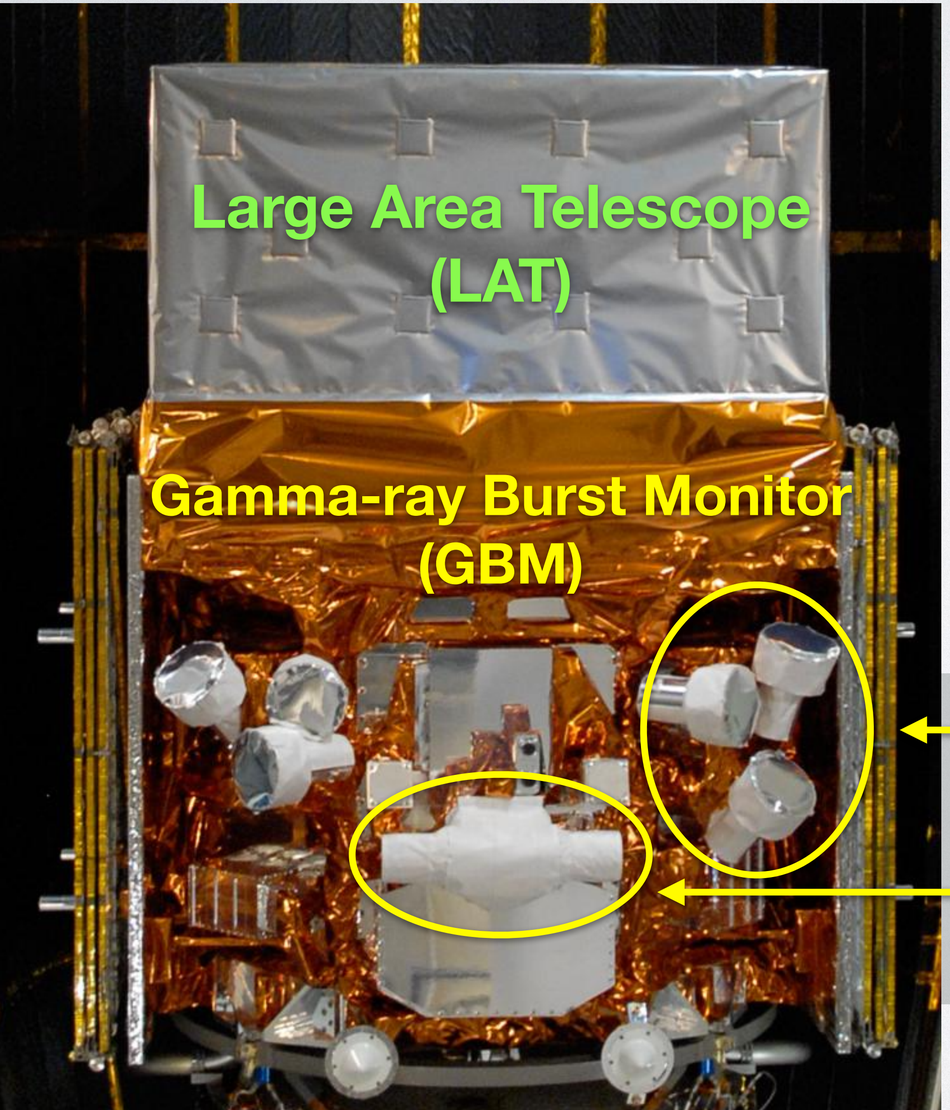
Multimessenger Follow-up of High Energy Neutrino Events using Fermi-GBM

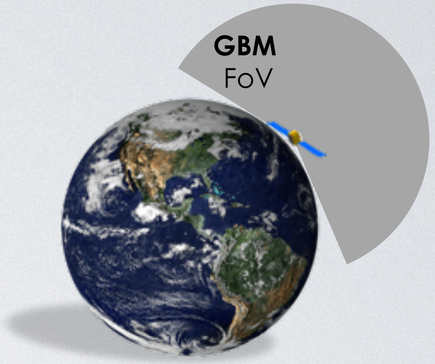
Joshua Wood
NASA/MSFC

Fermi Gamma-ray Burst Monitor (GBM)

http://gammaray.nsstc.nasa.gov/



- GBM monitors for gamma-ray transients with its >8sr FOV. Covers entire sky every ~90 min.
- **It is the most prolific GRB detector (~240 GRBs detected on-board per year)**
- Spatial localizations within ~few deg
- Also has follow-up programs looking for subthreshold events that don't trigger on-board analysis:



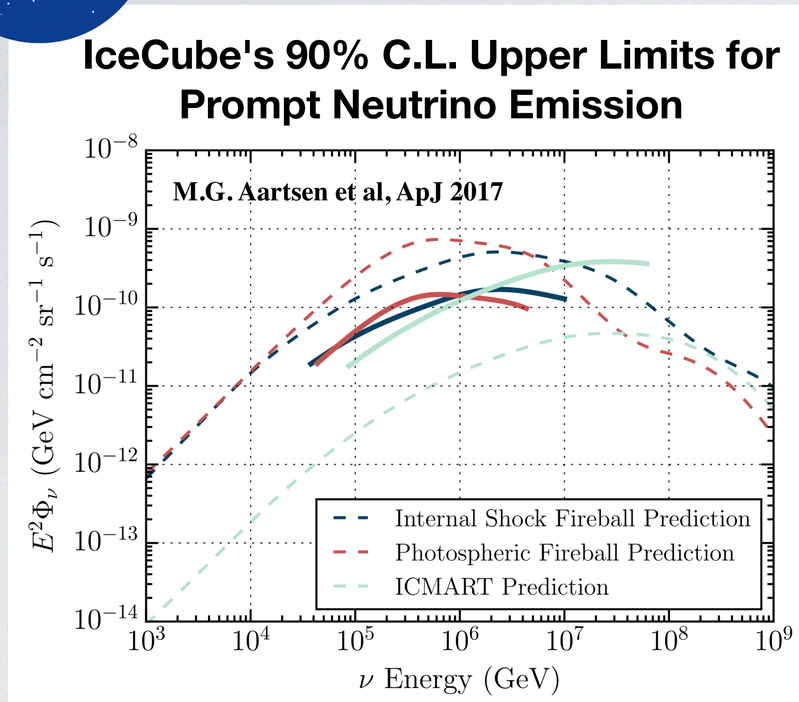
12 NaI Detectors (8 keV - 1 MeV)

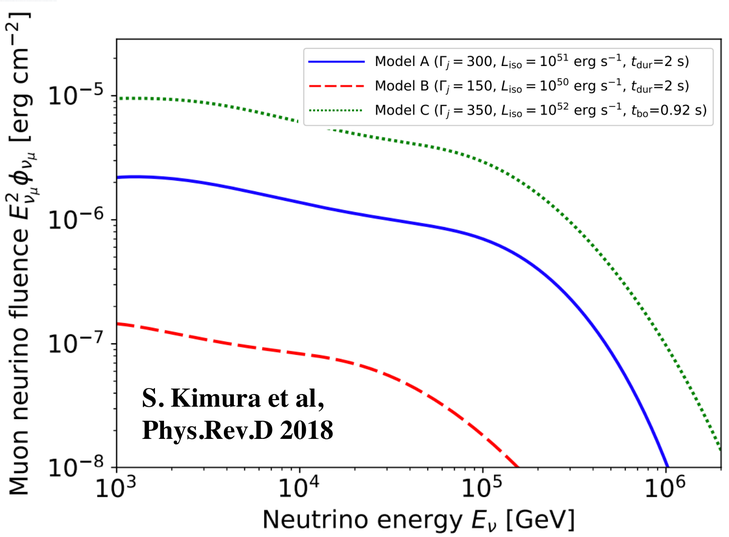
2 BGO Detectors (200 keV - 40 MeV)

(1) targeted search for short transients near the time of an external trigger

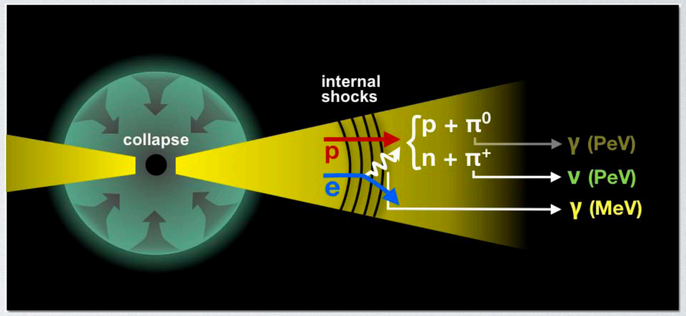
(2) untargeted search for short transients identified in offline reconstructions

The Neutrino-GRB Connection





- GRBs are promising sources for high energy neutrino production based on energetics alone, but their connection remains elusive

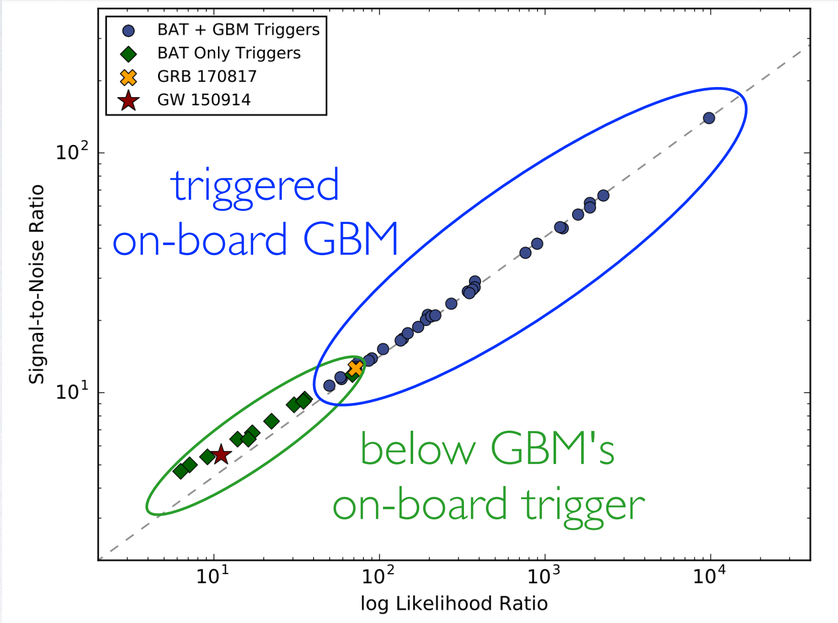


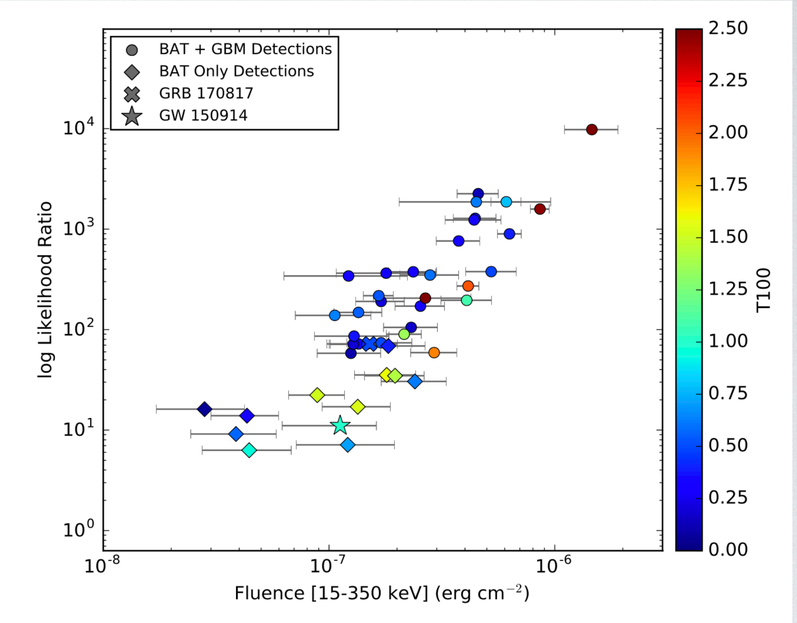
- High energy neutrino emission is constrained well below model expectations by IceCube measurements during the prompt emission phase of typical, bright GRBs
- However, low luminosity and choked GRBs may produce neutrinos detectable by IceCube/IceCube-Gen2
- Particularly interesting scenarios similar to GRB170817A/GW170817 could result in a BNS detection in GW, EM, and neutrinos
- Weak EM emission may prove tricky to detect on-board Fermi-GBM → highlights importance of on-ground analysis

The Benefits of On-Ground Analysis

Kocevski et al. *ApJ.* (2018)

- **<u>GBM's targeted search method</u>** used ground data to recover bursts well below GBM's on-board threshold
- Formulates a likelihood ratio test for the presence of a short gamma-ray transient on top of modeled backgrounds.





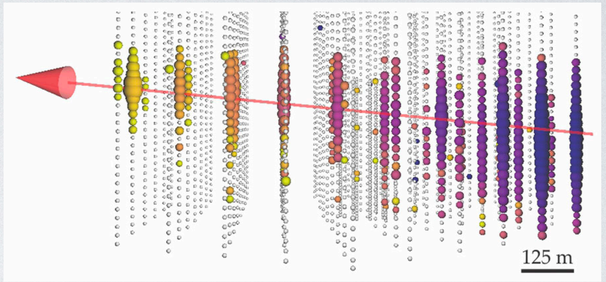
- Examines continuous time tagged events (CTTE) data within +/- 30 seconds of an external trigger
- A separate, **<u>untargeted search method</u>** continuously scans CTTE for subthreshold candidates. The public results (link) can be used to look for counterparts with larger time offsets.

further details: 80 candidates / year (~2x short GRB on-board trigger rate) with ~1/3 of high reliability candidates confirmed by other instruments

- However, it's still important to look at **<u>on-board triggers</u>** as well (example: GRB170817A)

GBM Neutrino Follow-up Program

- Currently consists of real-time follow-up to track-like high energy neutrino events publicly reported by IceCube as [Gold/Bronze events through GCN]



Similar to IC170922A

- Uses the same automated tools developed for analysis of gravitational wave events to:

1. Capture GCN Notices

Subject **GCN/ICECUBE_ASTROTRACK_GOLD**
Date Feb 10th

NOTICE TYPE: ICECUBE_ASTROTRACK_GOLD

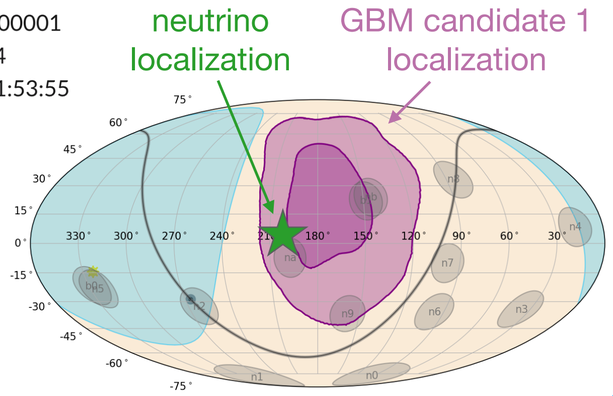
UTC Time: 2021-02-10T11:53:55.64
RA (J2000): 206.1922 [deg]
Dec (J2000): 4.7734 [deg]
Error (90%): 0.5134 [deg]
Energy: 287.41 [TeV]
FAR: 0.4645 [per year]
Prob. Astro.: 0.65
Type: Gold
Event: 134979_17138286
Rev: 0

2. Complete a targeted search for GRB-like transients near the trigger time using on-ground data

Event ID: 134979_17138286

Search MET: 634650840.6400001
Search GPS: 1296993253.64
Search UTC: 2021-02-10T11:53:55

Candidate 1:
Offset: 13.920 s
Duration: 0.064 s
Spectrum: norm
LogLR: 7.29
CoincLR: 8.79
FAR: 3.7e-03 Hz
Pspatial: 78.1 %



3. Have a human write a circular

```
NUMBER:  29464
SUBJECT: IceCube-210210A: Upper limits from Fermi-GBM Observations
DATE:    21/02/10 18:34:54 GMT
FROM:    Christian Malacaria at NASA-MSFC/USRA  <cmalacaria@usra.edu>

C. Malacaria (NASA-MSFC/USRA) reports on behalf of the Fermi-GBM Team:

For the IceCube high-energy neutrino candidate event 210210A (GCN 29454),
at the event time Fermi-GBM was observing the reported neutrino location at:
RA: 206.06 (+1.40 -0.95 deg 90% PSF containment) J2000
Dec: 4.78  (+0.62 -0.56 deg 90% PSF containment) J2000

There was no Fermi-GBM onboard trigger around the event time of the
neutrino candidate. An automated, blind search for short gamma-ray bursts
below the onboard triggering threshold in Fermi-GBM also identified no
counterpart candidates. The GBM targeted search, the most sensitive,
coherent search for GRB-like signals, was run from +/-30 s around the
neutrino candidate time. From this search, no significant signal was found
related to IceCube-210210A.

We set upper limits on impulsive gamma-ray emission. Using the
representative soft, normal, and hard GRB-like templates
(arXiv:1612.02395), we report the following 3 sigma flux upper limits over
10-1000 keV (in units of 10^-7 erg/s/cm^2):

Timescale  soft     norm     hard
---------------------------------------

0.128 s: 8.5 12. 21.
1.024 s: 2.7 3.4 6.3
8.192 s: 1.1 1.6 3.4
```

T_0 + 60 sec

T_0 + 4-5 hours

T_0 + 5-6 hours

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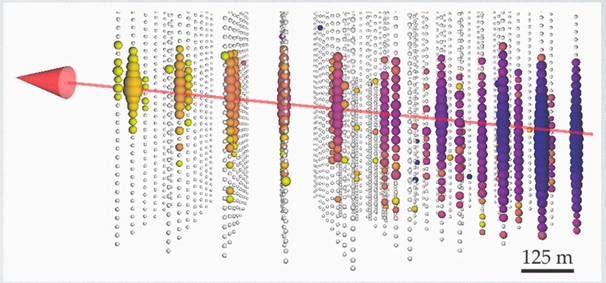

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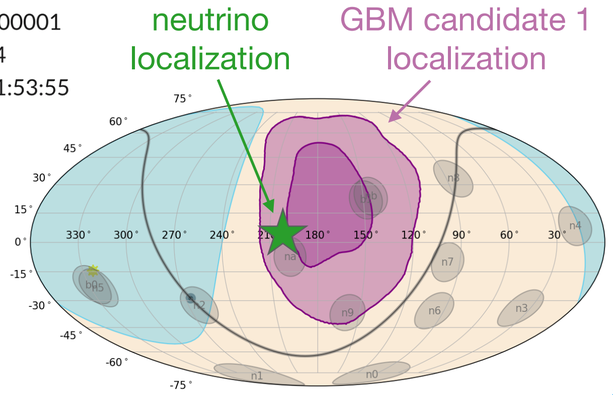

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```

Main Take-away:
we look for counterparts with:

- targeted search within +/-30 sec
- nearby untargeted search candidates
- nearby on-board triggers

```
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1.024 s: 2.7 3.4 6.3
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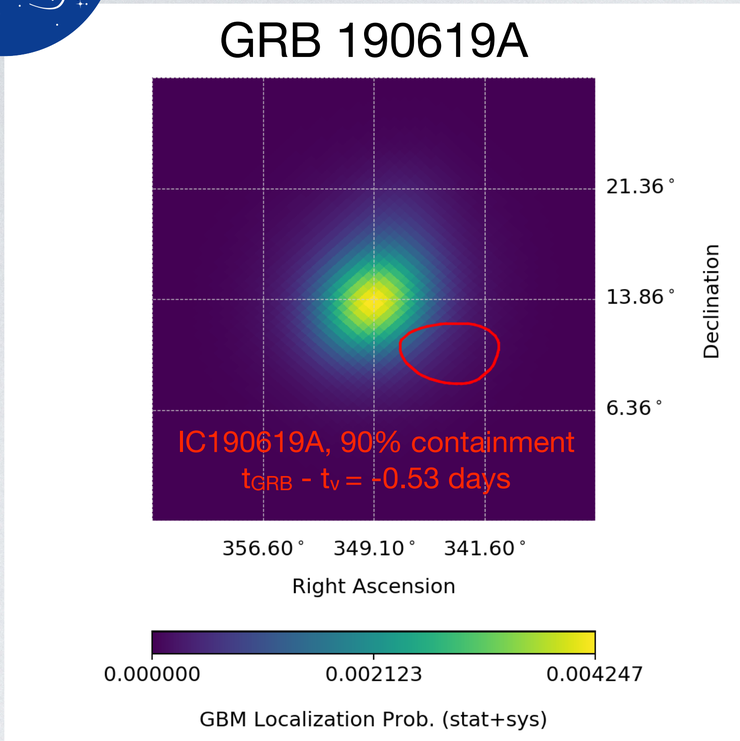
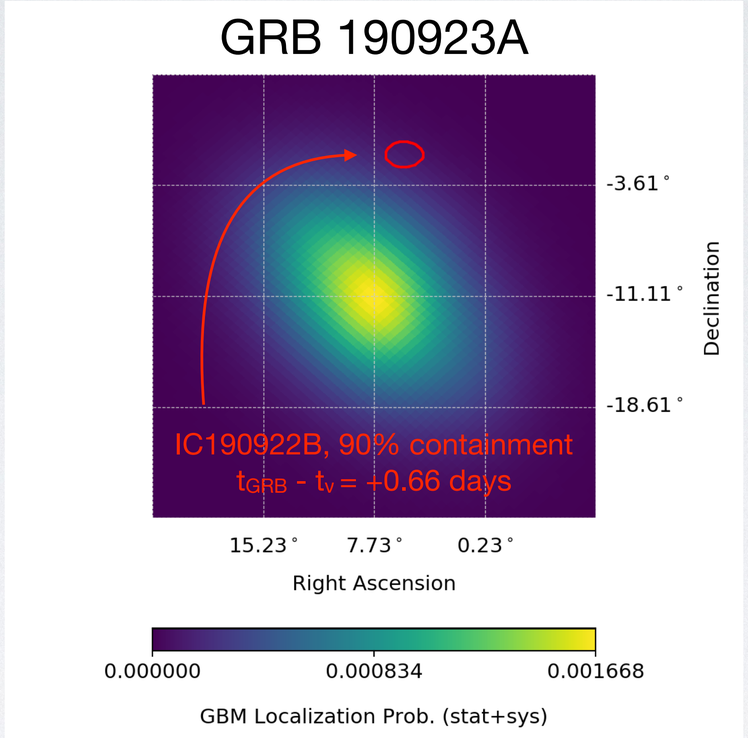
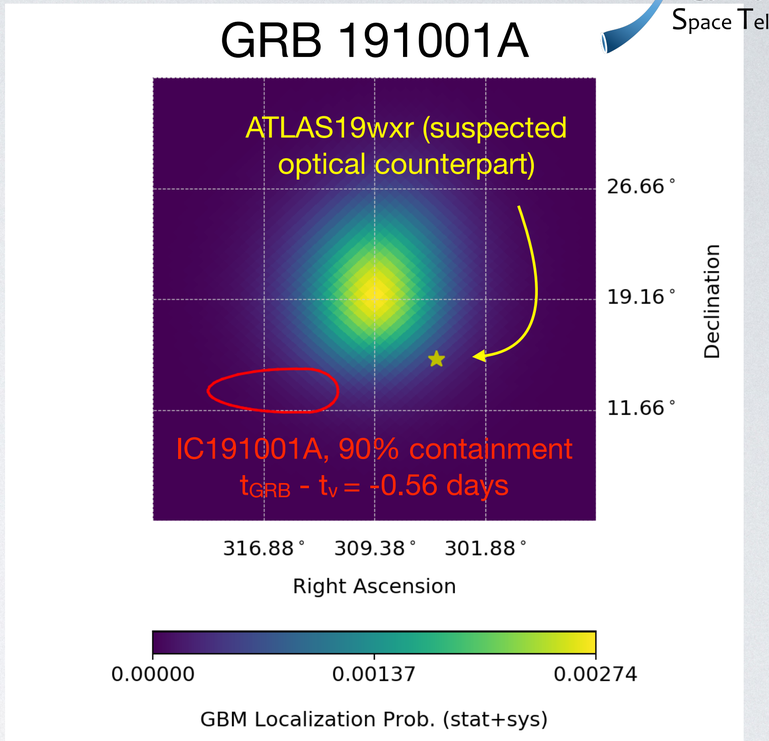
An Interesting Surprise



99% Spatial Assoc. Prob.



96% Spatial Assoc. Prob.

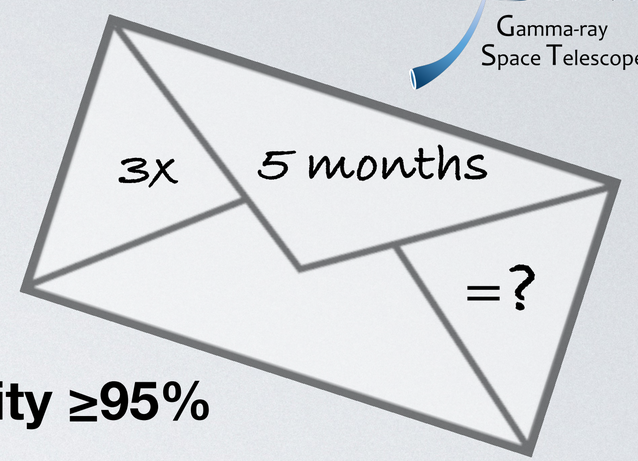


96% Spatial Assoc. Prob.

- The start of Gold/Bronze event reporting from IceCube provided **three on-board GRB detections** within +/-1 day of Gold neutrinos with spatial associations of >95%
- These GRBs were not seen by Swift
- Interesting because there were no spatial associations >90% within +/- 1 day of an on-board GRB prior to the start of Gold/Bronze reporting out of 10 HESE, 7 EHE neutrino events reported through GCN

details on slide 10

Back of the Envelope Significance



- Preliminary analysis performed by scrambling the 9 neutrino events and GRB localizations during first ~5 months of public Gold/Bronze reporting estimated that there should be **0.13 chance correlations***
- ***Correlation = a neutrino event with a spatial association probability ≥95% within +/-1 day of a GRB**

One sided Poisson p-value: $P(\geq 3, \mu=0.13) = 3.3 \times 10^{-4}$ ⟶ **3.4σ**

Caveats: not a blind analysis, plenty of things we could do better, not accounting for trials of older public HESE/EHE events

- Less interesting as time has gone on since there were no additional correlations over the first ~2 years of Gold/Bronze reporting ⟶ reduces the estimated significance to **1.8σ**
- But... still highlights the need to reliably quantify the significance of joint associations between GBM detections and neutrino events

Work in Progress: A Likelihood Approach

- Currently developing a likelihood based approach to fit for the number of high energy neutrino events associated with a Fermi GBM detection/GRB-like candidate

$$\mathcal{L}(n_\nu) = \prod_{i=1}^{N} \left(\frac{n_\nu}{N} S + (1 - \frac{n_\nu}{N}) B \right)$$

background PDF for uniform background

source PDF incorporating GRB location, time

Number of neutrinos associated with the GRB detection/candidate

Total number of reported Gold/Bronze neutrinos

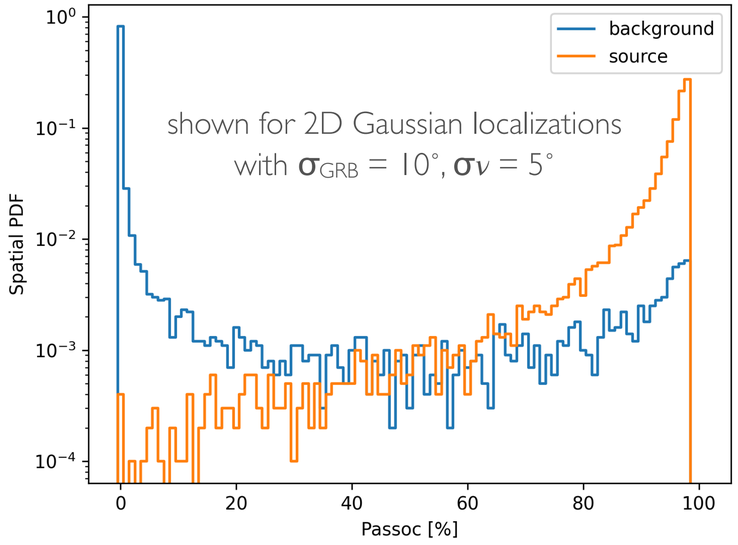
- Maximizing the test statistic *TS*, defined as the logarithm of a ratio of likelihoods, yields the best-fit value for n_ν

$$TS = 2 \log \left(\frac{\mathcal{L}(n_\nu)}{\mathcal{L}(n_\nu = 0)} \right)$$

Work in Progress: A Likelihood Approach

- The source (S) and background (B) terms are the products of PDFs for three variables:

Spatial Association Probability



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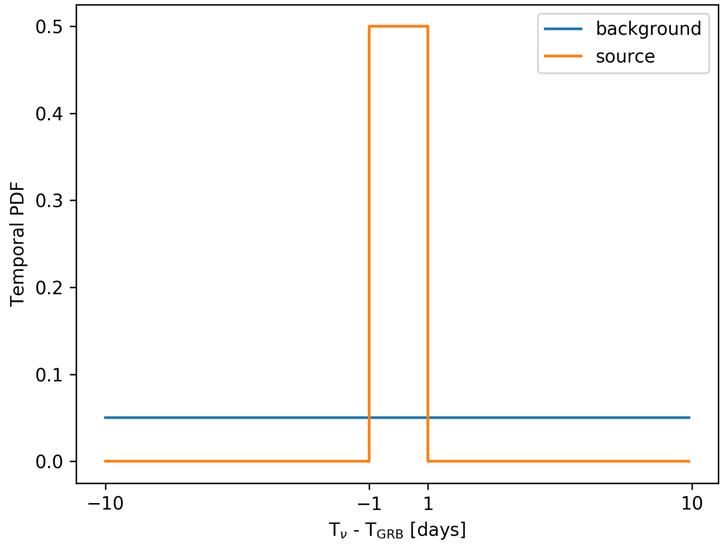
Time Offset



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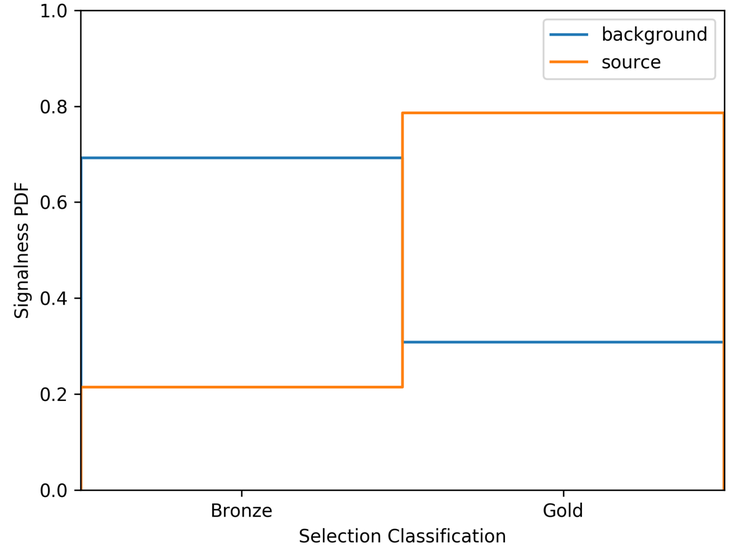
Astrophysical Probability of the neutrino (Signalness)



$$P_{\text{assoc}} = \frac{P_{\text{GBM}} \cdot P_{\nu}}{P_{\text{GBM}} \cdot P_{\nu} + P_{\text{GBM}} \cdot P_{\text{uniform}}}$$

GBM localization probability map

neutrino localization probability map

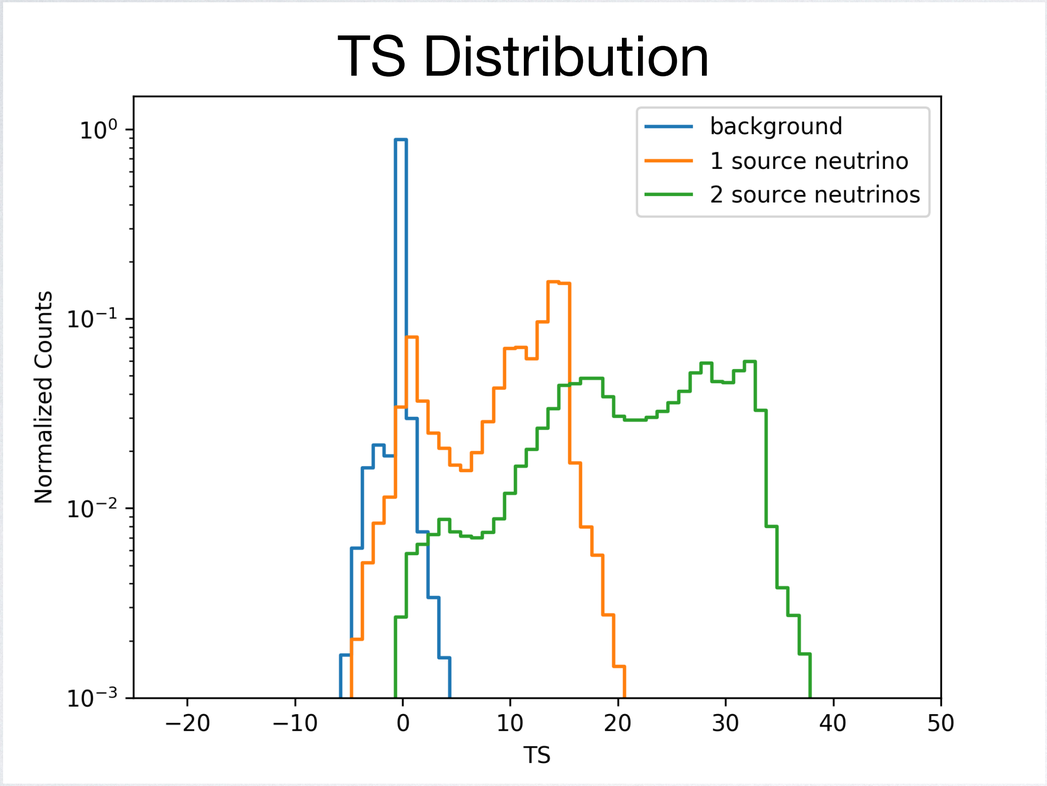
uniform probability over the full sky

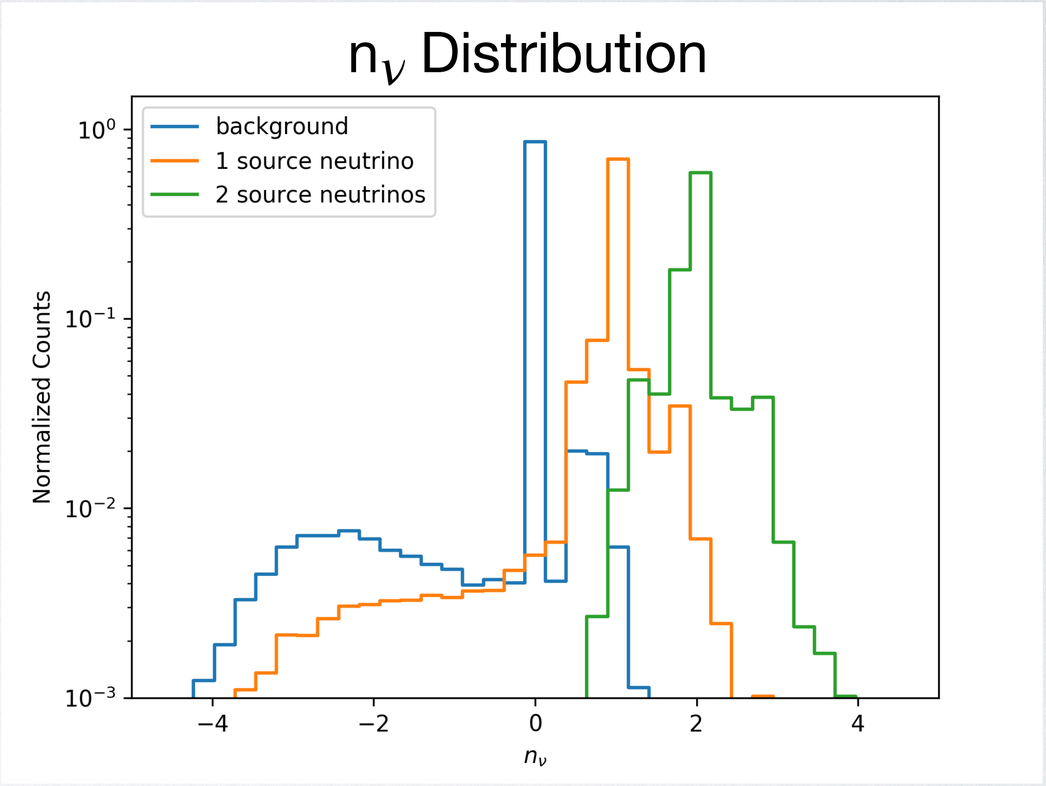
derived from event rates in the Gold/Bronze event documentation

"energy proxy"

Work in Progress: A Likelihood Approach

- Demonstration from fitting a GRB via a toy model for 2 years of neutrino alerts





Details

- 100,000 trials with a randomly selected GRB and a set of neutrinos matching the Gold/Bronze event rate
- Signal neutrinos are drawn from same position & time as the GRB, background neutrinos drawn from uniform distributions
- Simplified 2D Gaussian models for localization errors with $\sigma_{GRB} = 3.75^\circ$, $\sigma\nu = 0.75^\circ$, designed to reproduce median 90% containment areas of real GRB and neutrino localizations

Summary

- Fermi-GBM is actively expanding its multimessenger follow-up program to search for GRB counterparts to high energy neutrino events using the same tools developed for analyzing GW events
- Currently analyzing Gold/Bronze events from IceCube but we will also plan to incorporate additional neutrino data products (IceCube Cascades, NU-EM alerts, etc.) in the future
- Working on a likelihood formalism to quantify the significance of associations between neutrino events and an individual GRB
- Plenty Still To Do:
  - Need to incorporate IceCube's declination dependence into the spatial association variable, background modeling, and signal injection
  - Build realistic localization errors into the background and signal studies on slide 11
  - Work on a method to derive population level information from sets of individual fits

Thanks!

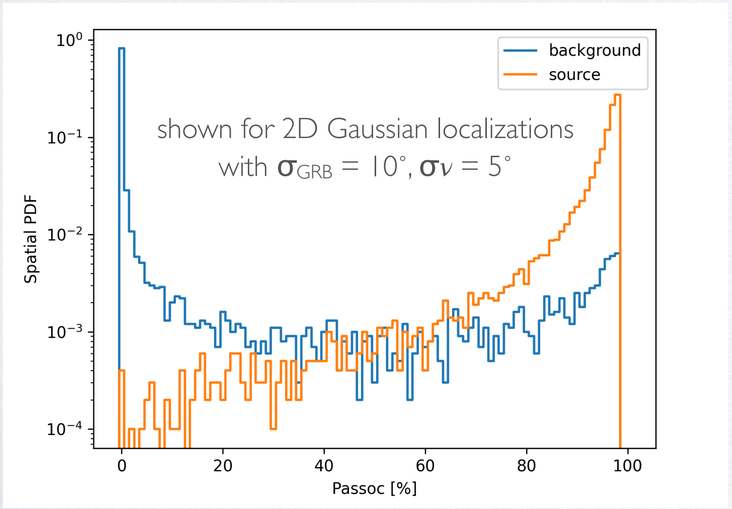
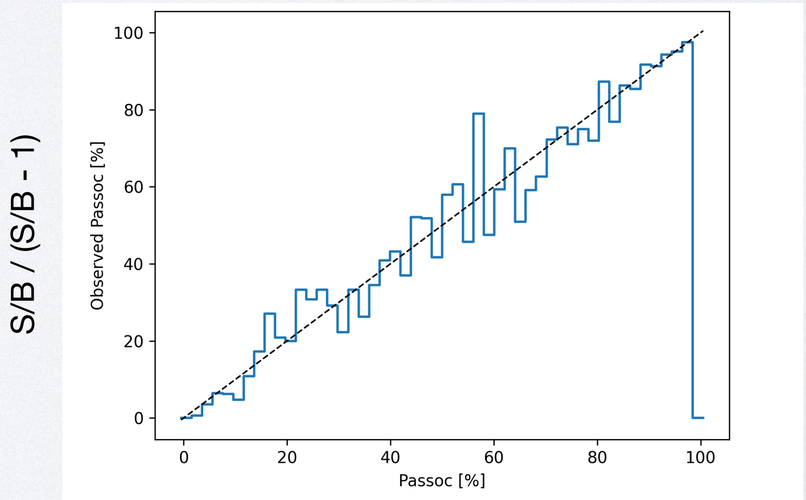
Backup

More Details on P_{assoc}

$$P_{\rm assoc} = \frac{P_{\rm GBM} \cdot P_{\nu}}{P_{\rm GBM} \cdot P_{\nu} + P_{\rm GBM} \cdot P_{\rm uniform}}$$

- $P_{\rm GBM}$: GBM localization probability map
- P_{ν}: neutrino localization probability map
- $P_{\rm uniform}$: uniform probability over the full sky

- The spatial association probability incorporates both the uncertainty in the localization of the GRB and the uncertainty of an individual neutrino event

- It considers two cases:
  (case 1) both localizations derive from the same point source at single location
  (case 2) the neutrino localization is unrelated and could have come from anywhere in the sky. To be realistic, the "uniform" probability should reflect the declination dependence of a uniform background in IceCube

- P_{assoc} is directly related to the ratio of source / background PDFs: $P_{\rm assoc} = \frac{S/B}{S/B - 1}$