XIX International Workshop on Neutrino Telescopes

UNTRIGGERED MULTIPLE FLARE NEUTRINO SEARCH FROM A SOURCE CATALOG WITH 10 YEARS OF ICECUBE DATA

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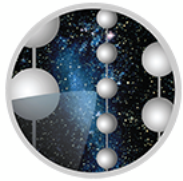
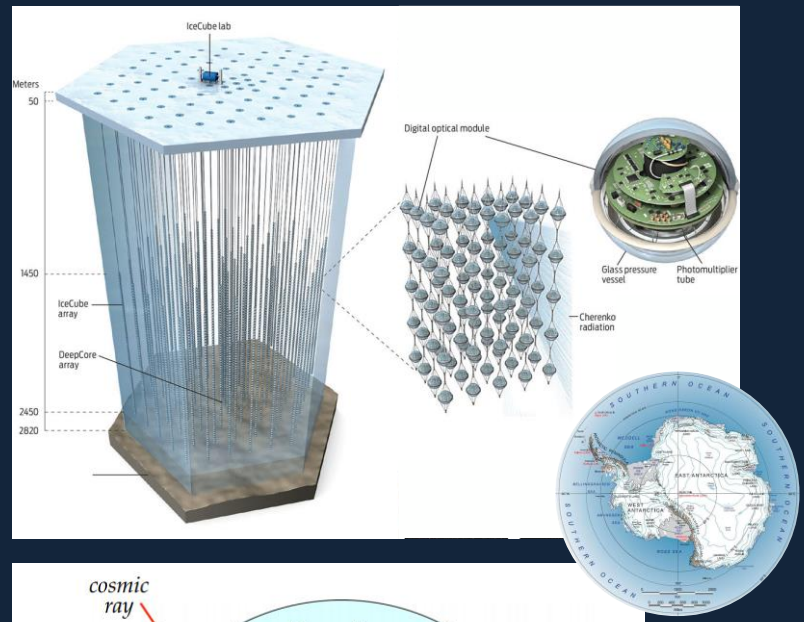


IceCube
South Pole Neutrino Observatory

Introduction

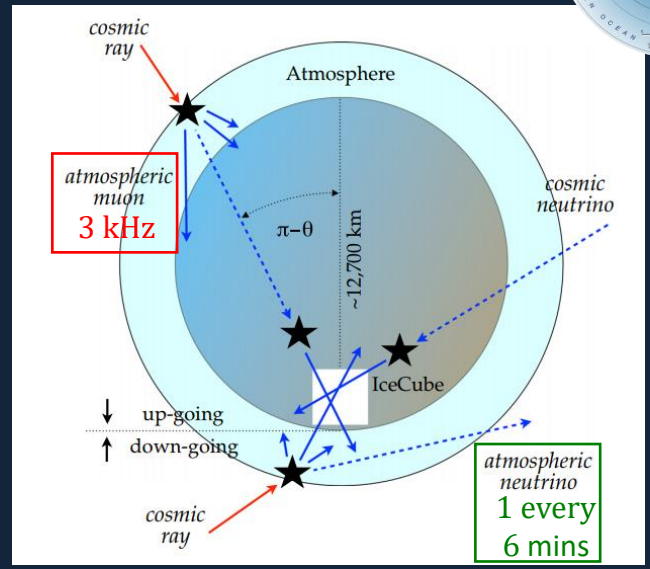
About this analysis:

- Point-source: it searches for astrophysical sources of neutrinos
- Multimessenger: sources are selected based on γ-ray observations
- Time-dependent: It looks for astrophysical neutrino flares from the source directions
- Multi-flare: It looks for all possible neutrino flares from a single given direction

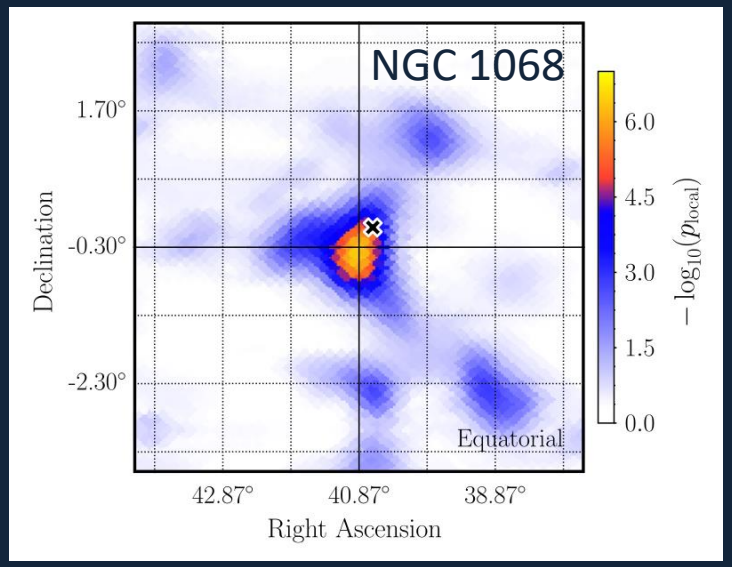


Main background:

- Atmospheric muons
  It affects mostly the southern hemisphere
- Atmospheric neutrinos
  It affects both hemispheres. It is the main component in the North

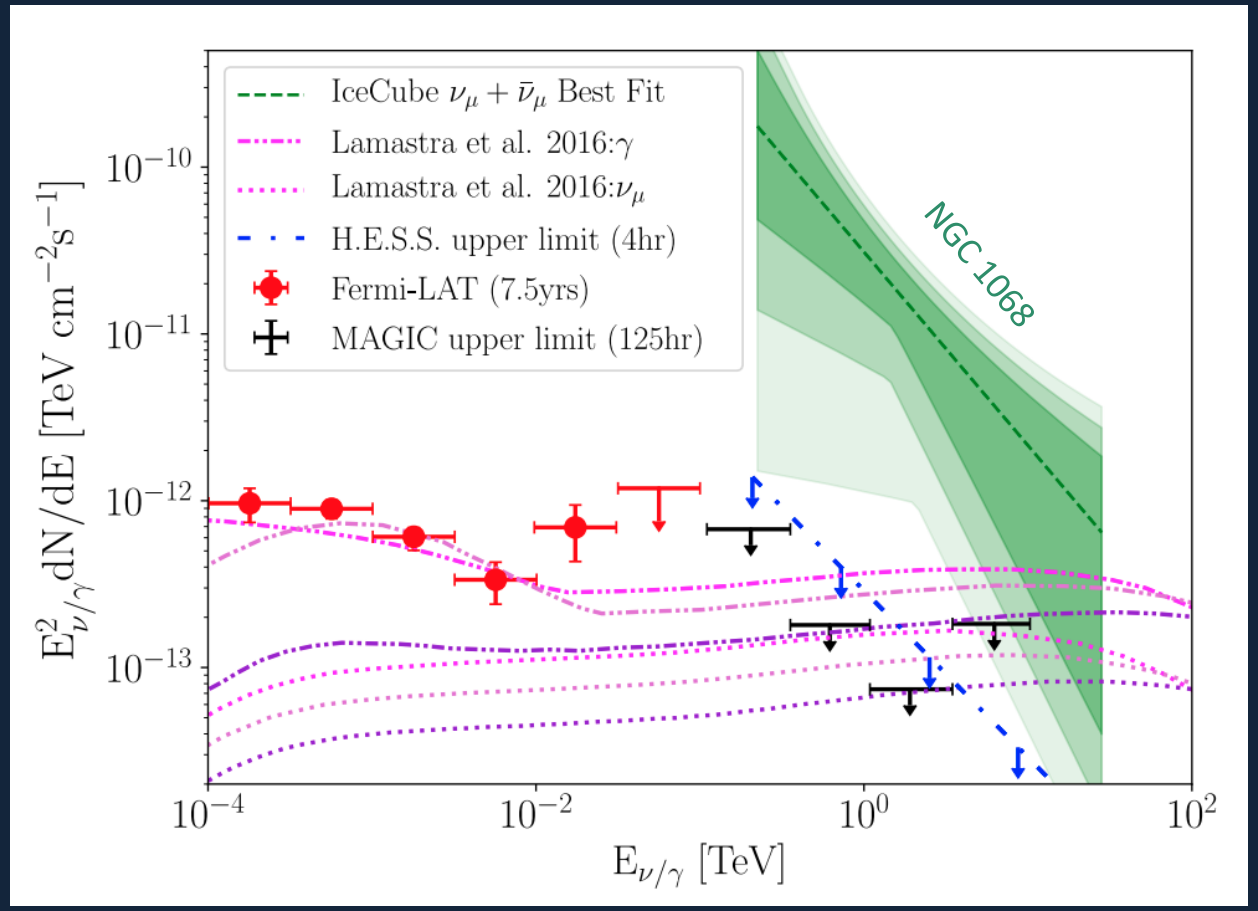


Past Search for Time-Integrated Neutrino Emission



A recent IceCube analysis looked for time-integrated neutrino emission from a catalog of γ-ray emitters.

γ-ray emitters are chosen based on the γ flux and IceCube sensitivity



2 searches were made, separately in each hemisphere:

1. Hottest source
   Looks for most significant source of the catalog
   Result (north): NGC 1068 (2.9σ post-trial)

2. Sub-threshold population analysis
   Looks for excess of neutrinos from sub-threshold sources of the catalog
   Result (north): 3.3σ neutrino excess from 4 sources (NGC 1068, TXS 0506+056, PKS 1424+240, GB6 J1542+6129)

https://link.aps.org/doi/10.1103/PhysRevLett.124.051103

Analysis Strategy: Likelihood

$$\mathcal{L}(\vec{n}_s, \vec{\gamma}, \vec{t}_0, \vec{\sigma}_T) = \prod_{i=\text{events}} \left\{ \sum_{f=\text{flares}} \left[\frac{n_s^{(f)}}{N} S_i^{(f)}(\gamma^f, t_0^f, \sigma_T^f) \right] + \left(1 - \sum_f \frac{n_s^{(f)}}{N} \right) B_i \right\}$$

Single-flare signal PDF

Multi-flare signal PDF

Background PDF

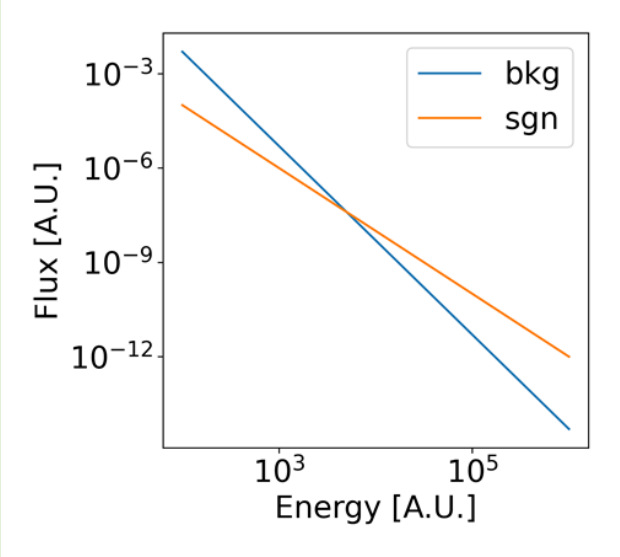
Analysis Strategy: Signal and Background PDFs

$$\mathcal{L}(\vec{n}_s, \vec{\gamma}, \vec{t}_0, \vec{\sigma}_T) = \prod_{i=\text{events}} \left\{ \sum_{f=\text{flares}} \left[\frac{n_s^{(f)}}{N} S_i^{(f)}(\gamma^f, t_0^f, \sigma_T^f) \right] + \left(1 - \sum_f \frac{n_s^{(f)}}{N} \right) B_i \right\}$$

Energy PDF

Signal: power-law $\propto E^{-\gamma^f}$

Background: data-driven



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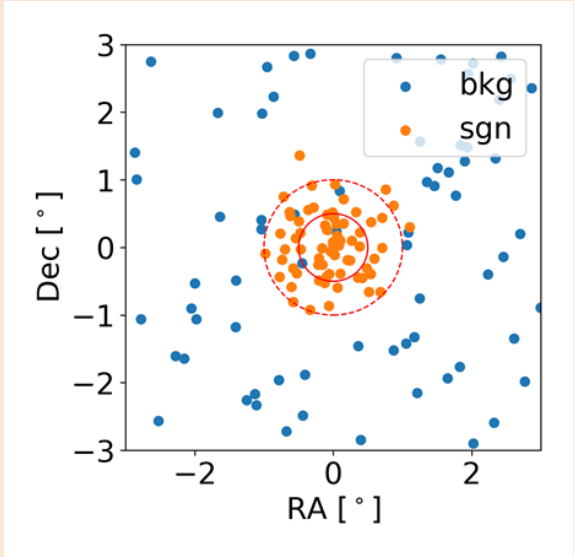
Spatial PDF

Signal: 2D Gaussian $\frac{1}{2\pi\sigma_i^2} \exp\left[-\frac{|\vec{x}_i - \vec{x}_S|^2}{2\sigma_i^2} \right]$

Background: data-driven



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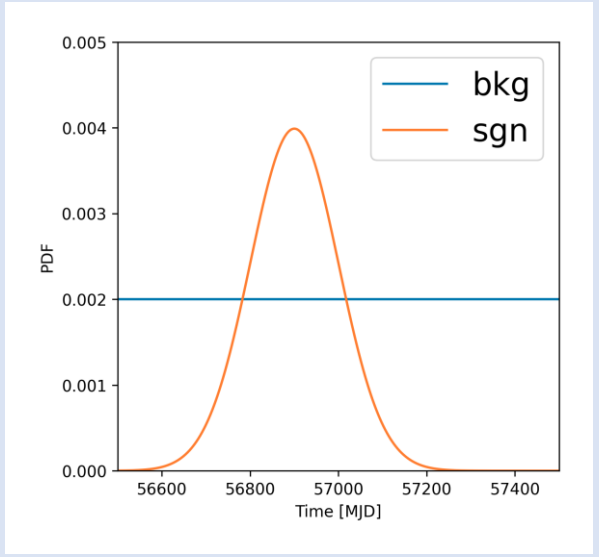
Time PDF

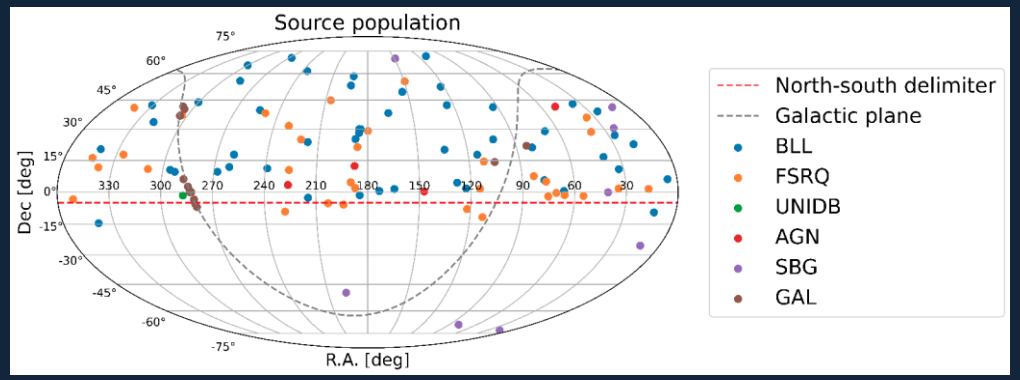
Signal: Gaussian $\propto \exp\left[\frac{(t_i - t_0^f)^2}{2\sigma_T^{f2}} \right]$

Background: uniform



Search Methods

- The catalog of 110 gamma-ray emitters is tested with the multiflare analysis.
- Each hemisphere is considered individually
- Two searches are made:



Search 1: hottest source

Looks for the most significant source

1. The TS (log-likelihood ratio) is calculated from the directions of the sources
2. The pre-trial p-values p_k are evaluated from the observed TS and a background distribution of TS
3. The post-trial p-value is estimated for the most significant source in each hemisphere

Search 2: sub-threshold population test

Looks for a global excess of neutrino emission

1. p-values p_k of the N sources are ranked in significance
2. A binomial p-value is computed for each source index k

$$P_{bin}(k) = \sum_{m=k}^{N} \binom{N}{m} p_k^m (1-p_k)^{N-m}$$

It is the probability that the background produces k or more sources with p-values smaller than p_k

3. The smallest binomial p-value in each hemisphere is reported as post-trial

Search 1: Hottest Source (Results)

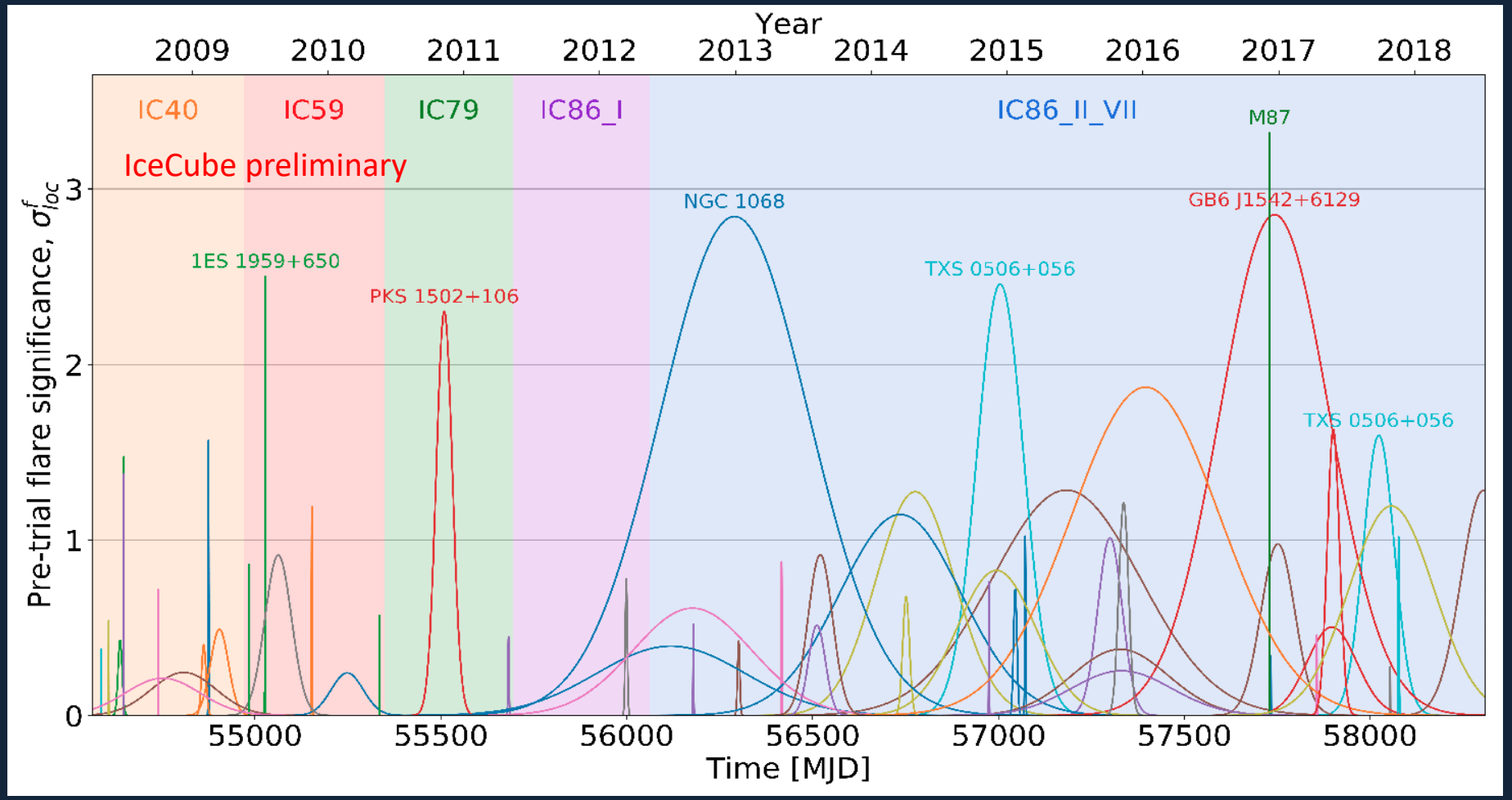
North

Hottest source: M87 (1.7σ Post-trial)

Two flares reconstructed from **TXS 0506+056**

South

Hottest source: PKS 2233-148 (post-trial $p_{val} = 0.72$)



Best-fit flares of the sources of the catalog and pre-trial flare significance

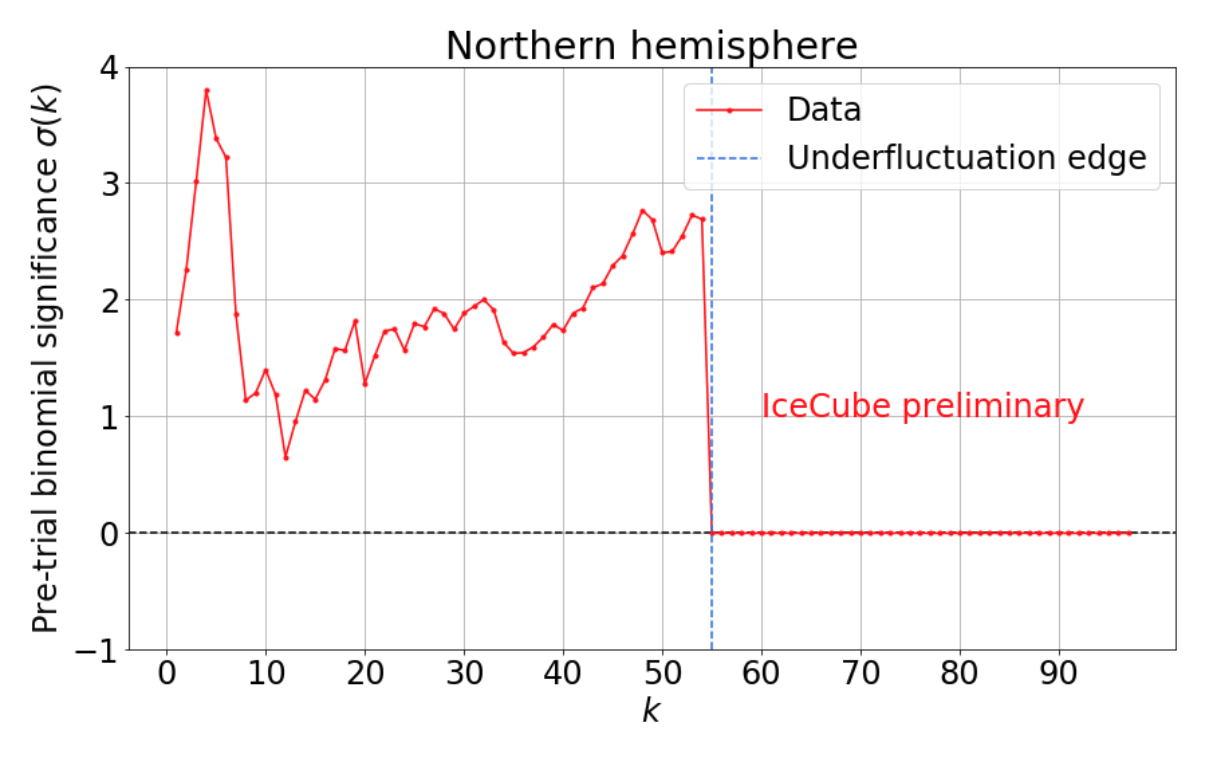
Search 2: Sub-Threshold Population Test (Results)

North

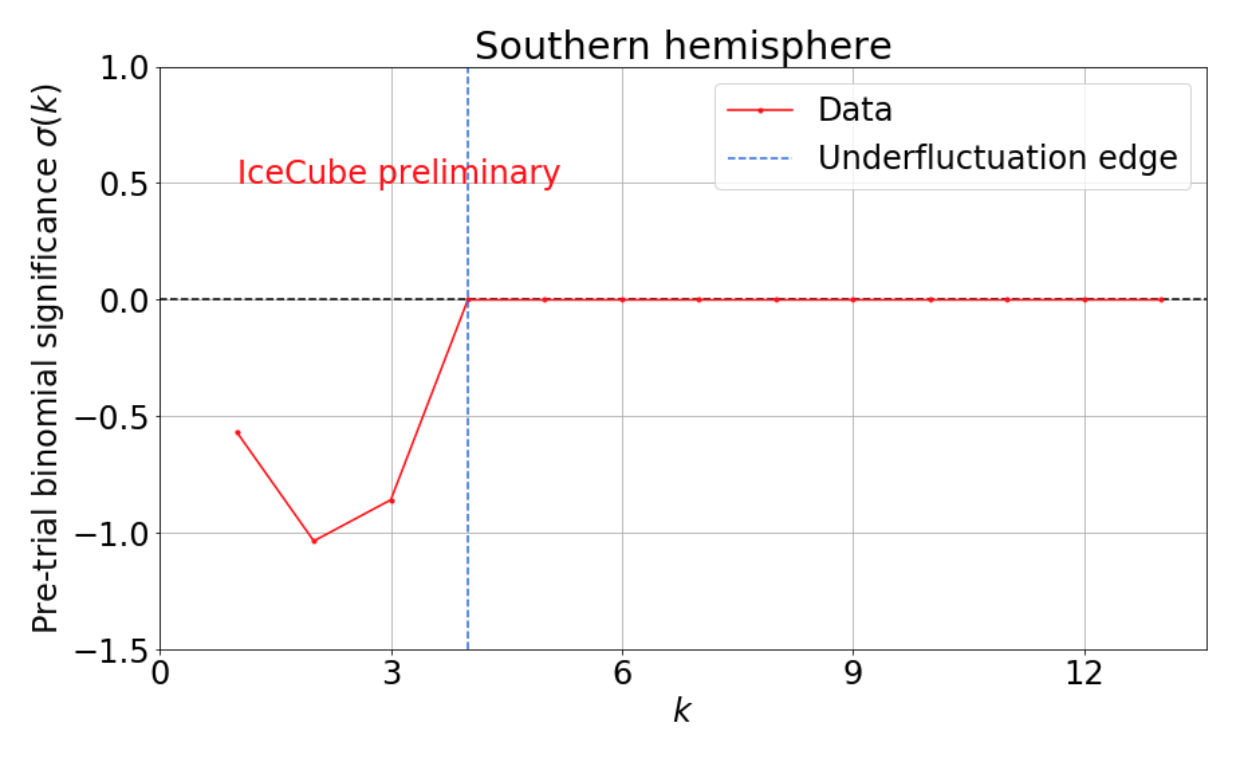
3.0σ post-trial from 4 sources:
M87, NGC 1068, TXS 0506+056, GB6 J1542+6129

South

Post-trial $p_{val} = 0.89$ from 1 source (PKS 2233-148)



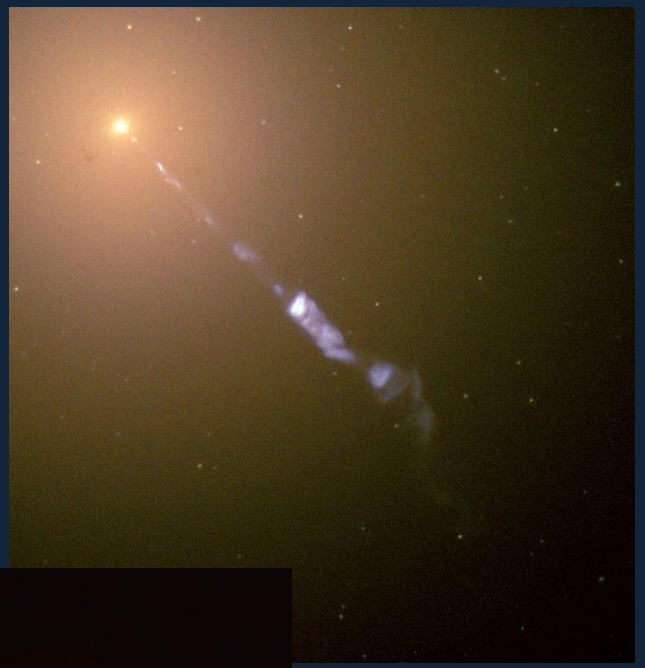
Significance of the binomial p-value in the northern hemisphere

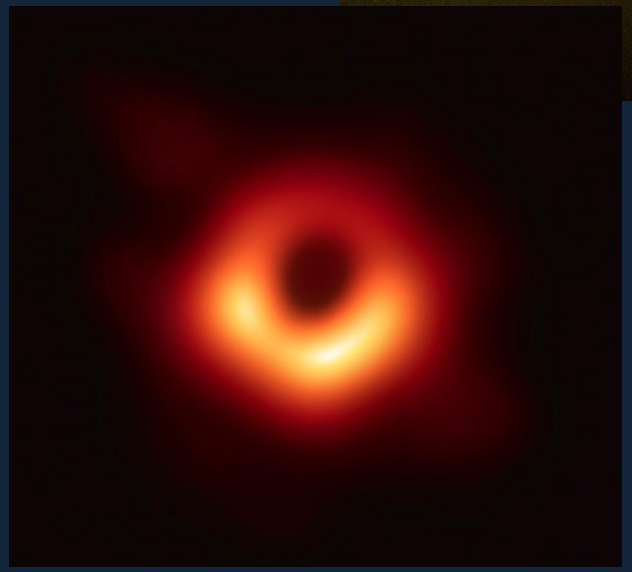


Significance of the binomial p-value in the southern hemisphere

Conclusions

- This search confirms a significant neutrino excess from the catalog in the northern sky
  - 3 out of 4 potential sources that mostly contribute to this excess are the same as the time-integrated excess
  - After NGC 1068 ($z = 0.0038$), a new potential source emerges: M87
- M87 is the most significant source of the catalog
  - It is a close galaxy ($z = 0.0043$)
  - It is a known source of ultrarelativistic ejecta
  - It hosts the first photographed black hole
- No strong time-dependent structure for neutrino emission from NGC 1068





So far no evidence can be provided, but unexpected surprises might be just behind the corner.

Stay tuned!

Thank you for your attention

Backup

Analysis Strategy: Test Statistic

A Test Statistic is defined to evaluate the significance of each tested source

$$\mathrm{TS} = -2\log\left[\frac{1}{2}\left(\prod_{f=\mathrm{flares}} \frac{T_{10\,yr}}{\sigma_T^f\, I\left[\hat{t}_0^f, \hat{\sigma}_T^f\right]}\right)\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\vec{\hat{n}}_s, \vec{\hat{\gamma}}, \vec{\hat{t}}_0, \vec{\hat{\sigma}}_T)}\right]$$

A marginalization term is introduced to correct a natural preference of the TS towards shorter flares, where

$$I\left[\hat{t}_0^f, \hat{\sigma}_T^f\right] = \int_{T_{10\,yr}} \frac{1}{\sqrt{2\pi}\hat{\sigma}_T^f} \exp\left[-\frac{\left(t - \hat{t}_0^f\right)^2}{2\hat{\sigma}_T^{f\,2}}\right]$$

Multiflare Algorithm

The number of flares is fixed at fit-time and determined at pre-fit:

1. Preselection
   Events with S/B ratios above a given threshold are considered

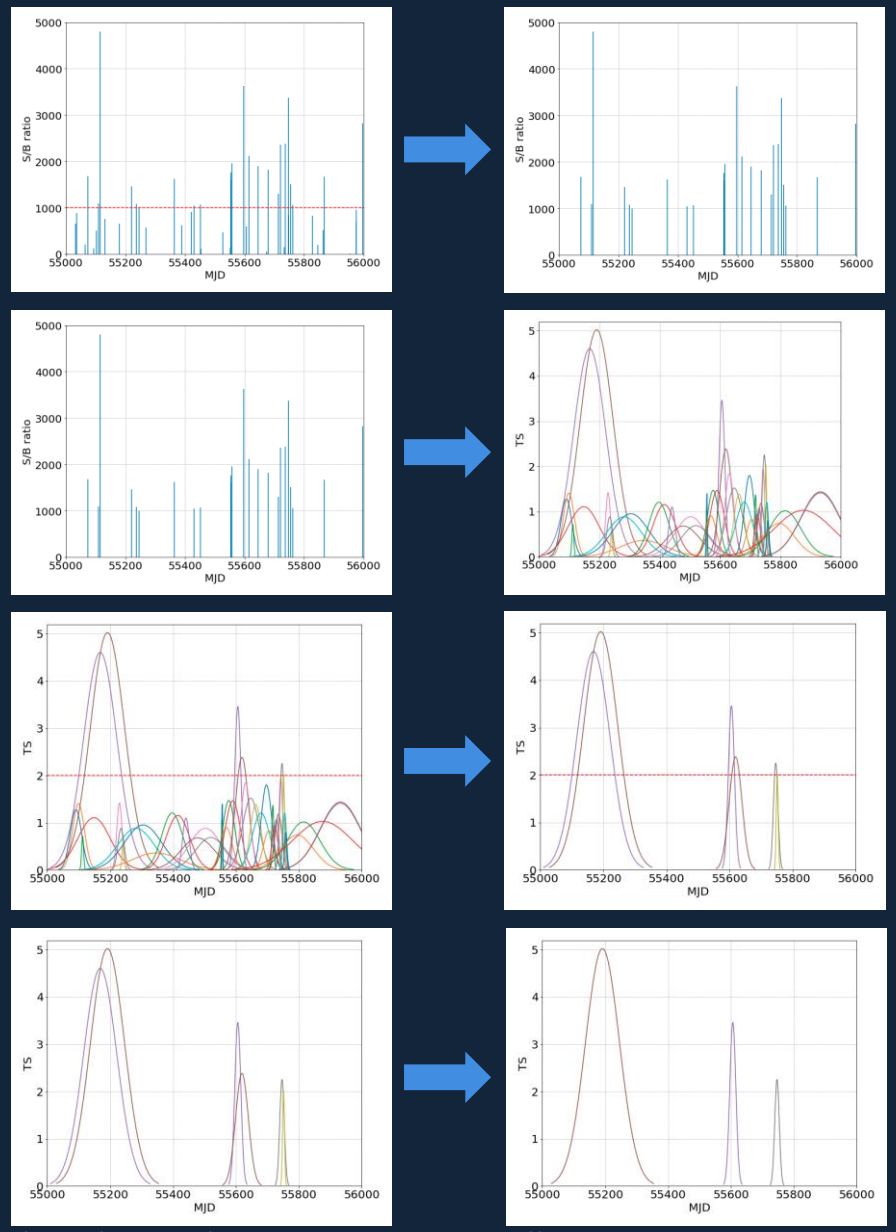
2. Event grouping and TS evaluation
   Consecutive events are collected in groups of 2, 3, 4, ...
   Each group is a possible flare with:
   - central time t_0^f = average event times
   - duration σ_T^f = RMS of event times

   The single-flare TS of each group is evaluated for some values of n_s^f and γ^f

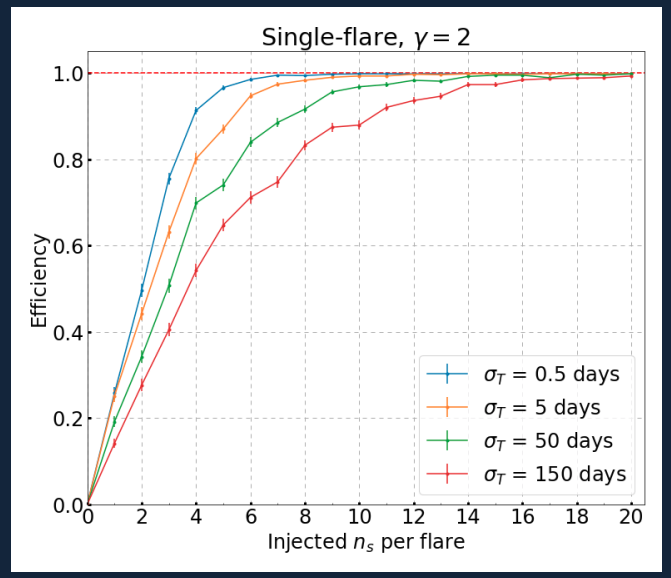
3. Flare selection
   Flares with single-flare TS larger than a given threshold are retained and referred to as candidate flares. If there are no flares above the TS threshold, only the one flare with the highest TS is retained.

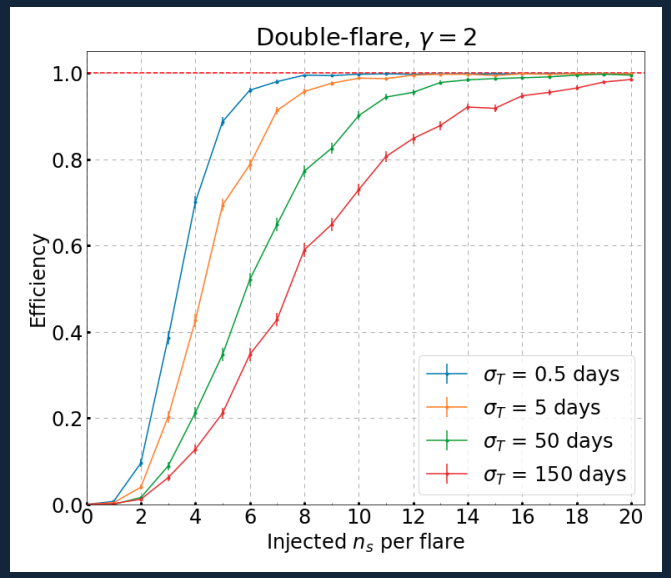
4. Overlap removal
   If two or more candidte flares overlap within their $\pm 4\sigma_T^f$ ranges with respect to their central time, the flares with the lowest TS are removed

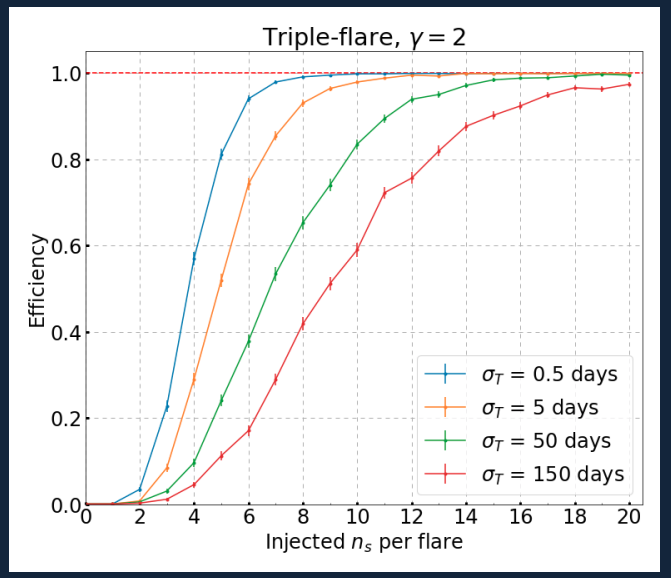
The survival flares provide the number of flares

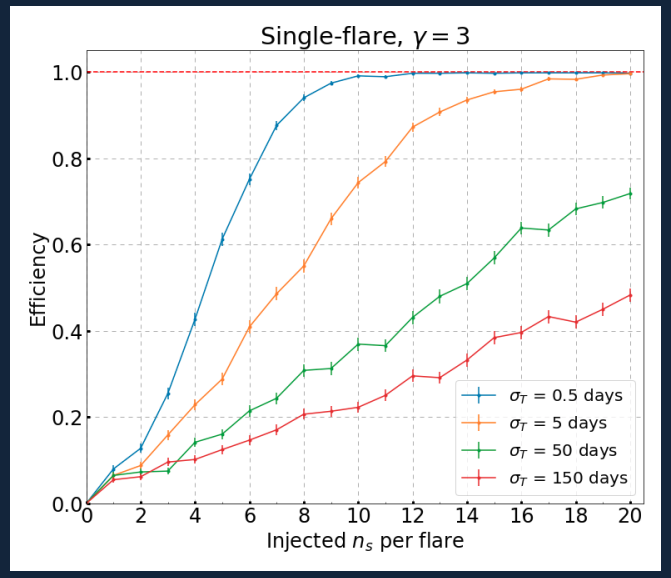


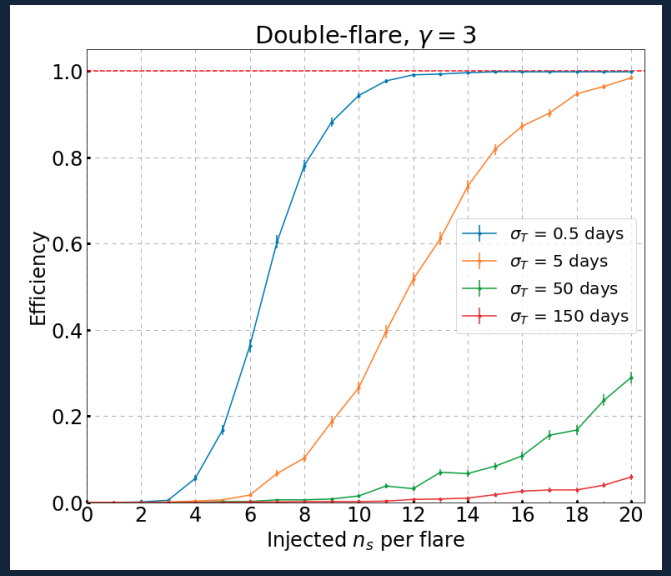
Multiflare Algorithm: Efficiency

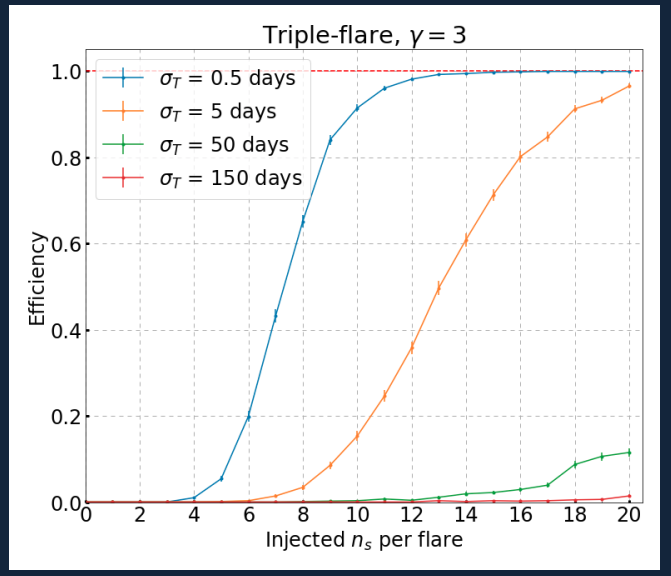




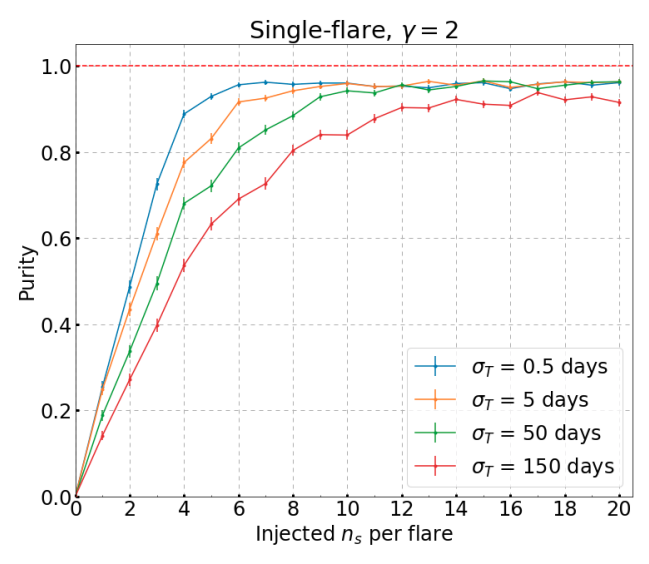


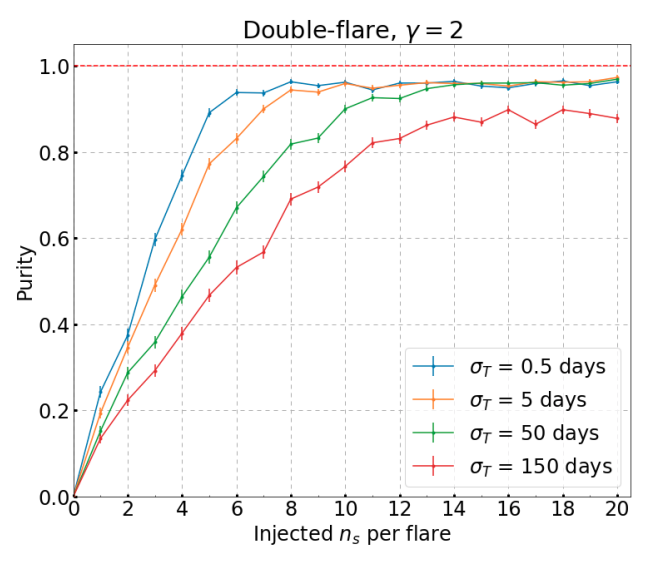


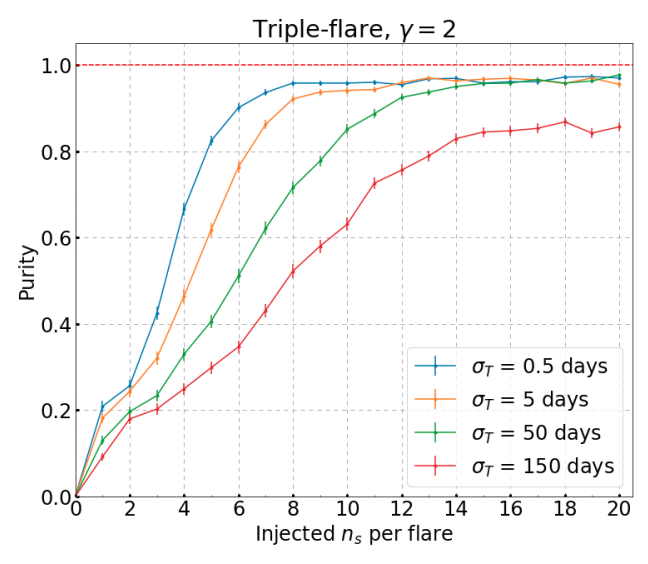


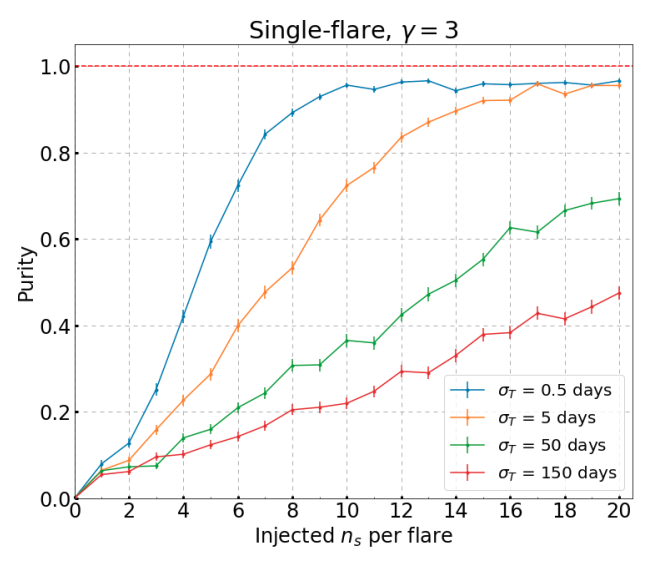


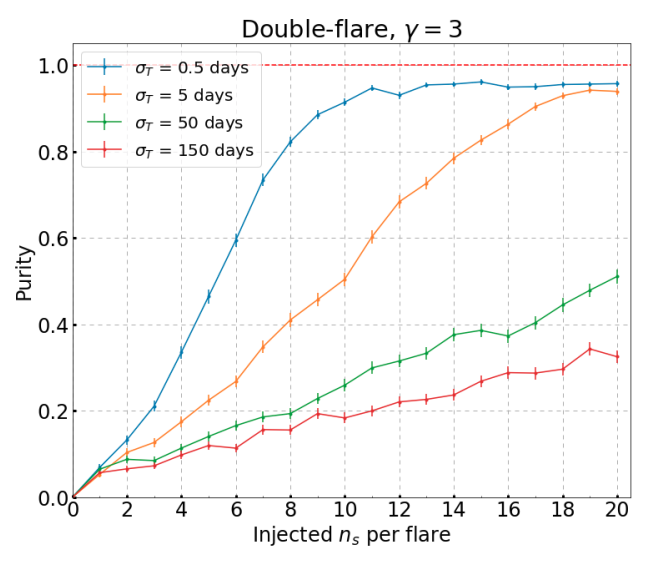
Multiflare Algorithm: Purity

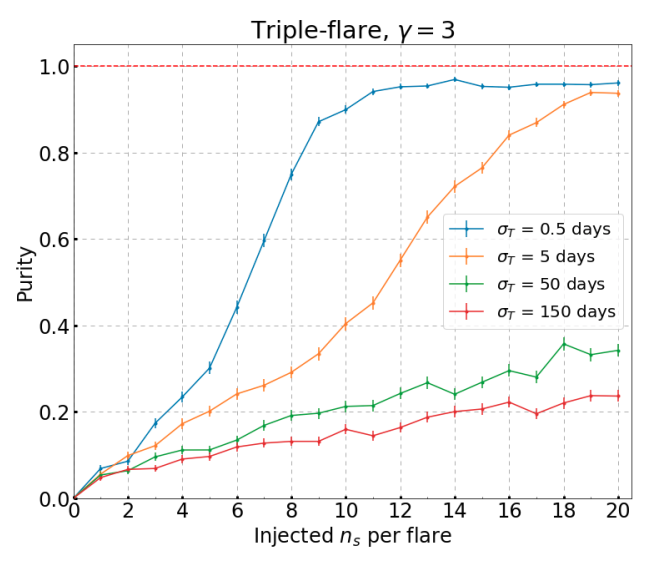




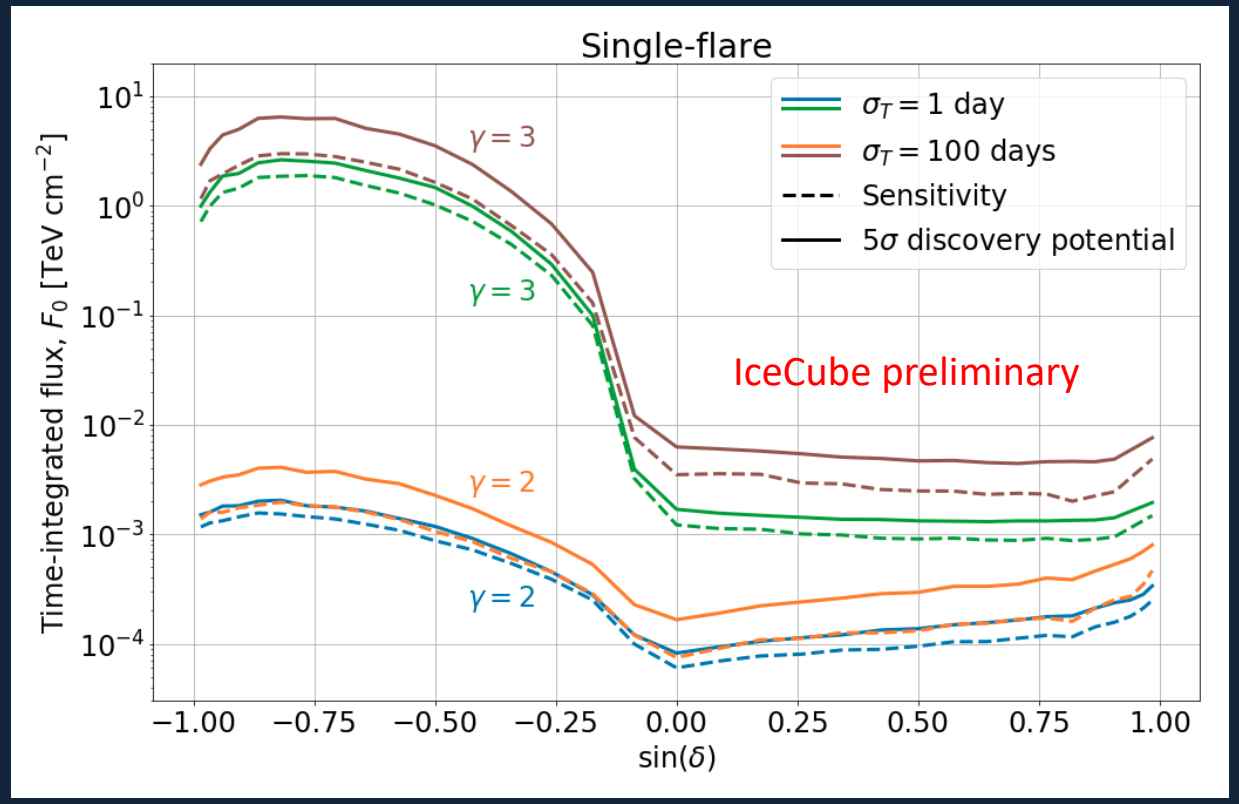


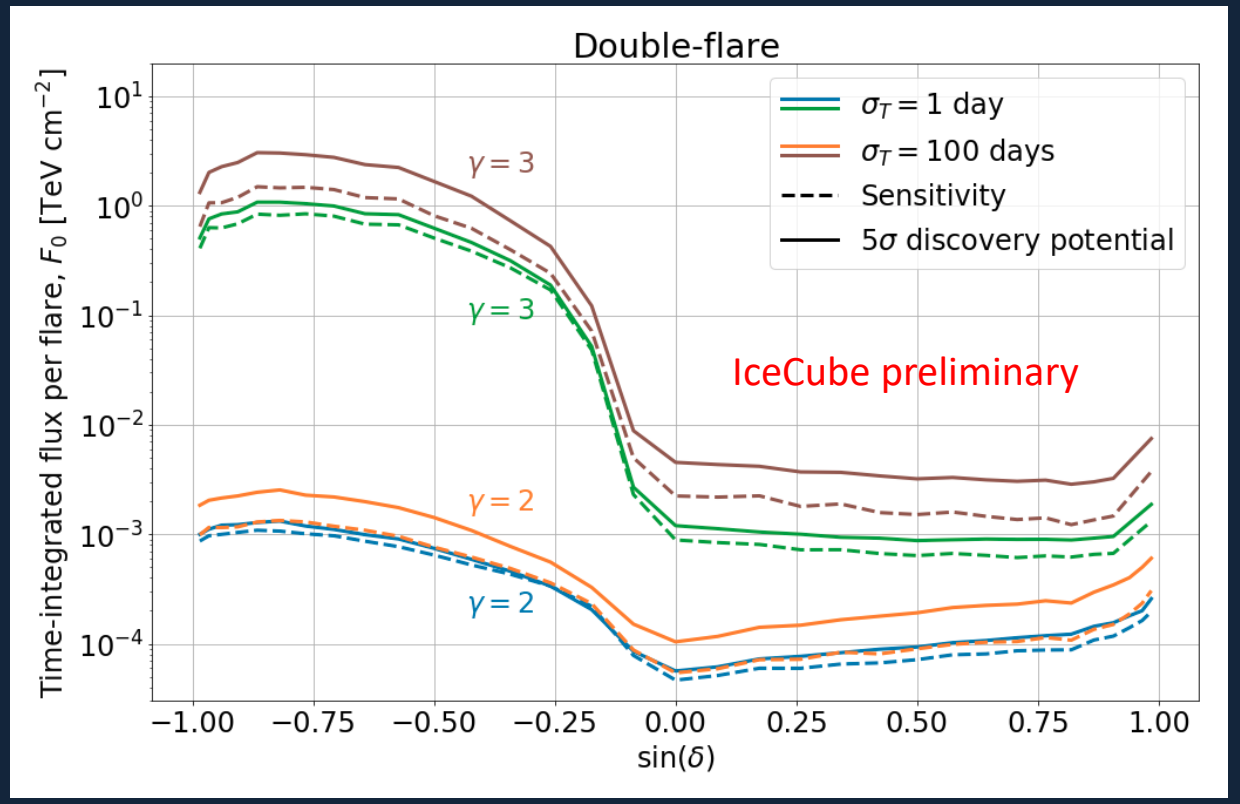




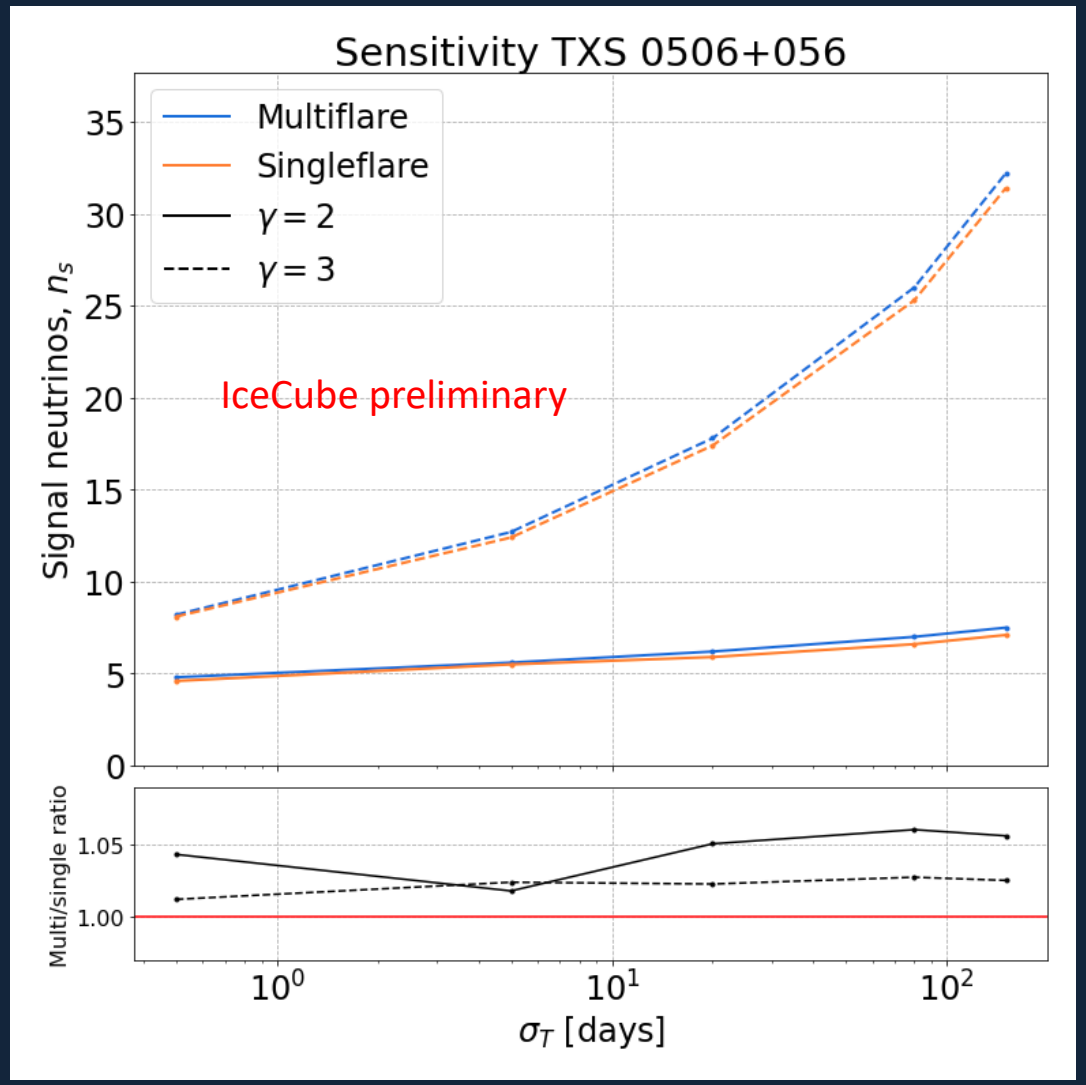


All-sky Multiflare Sensitivity





Multiflare VS Singleflare Sensitivity



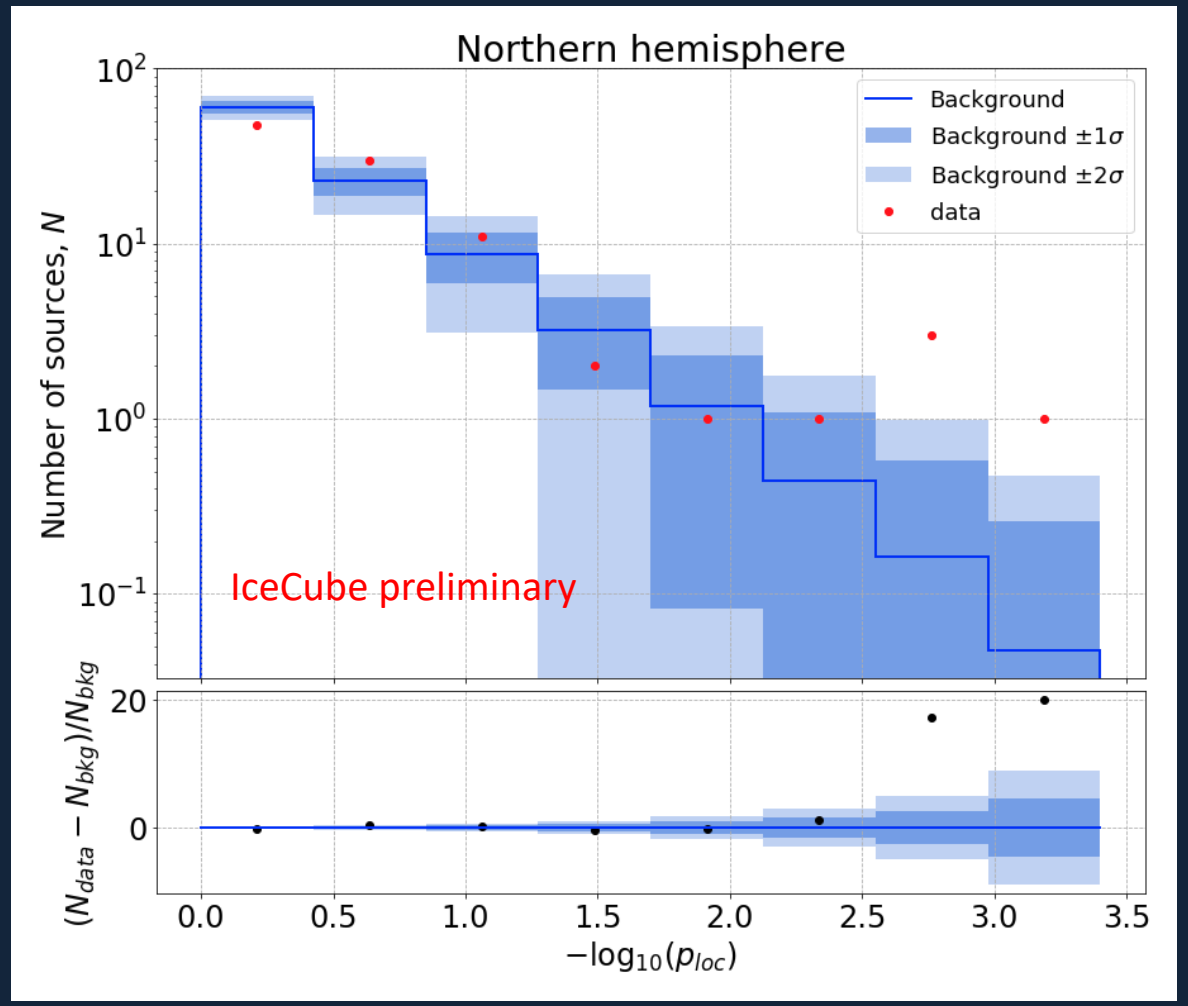
Catalog Results

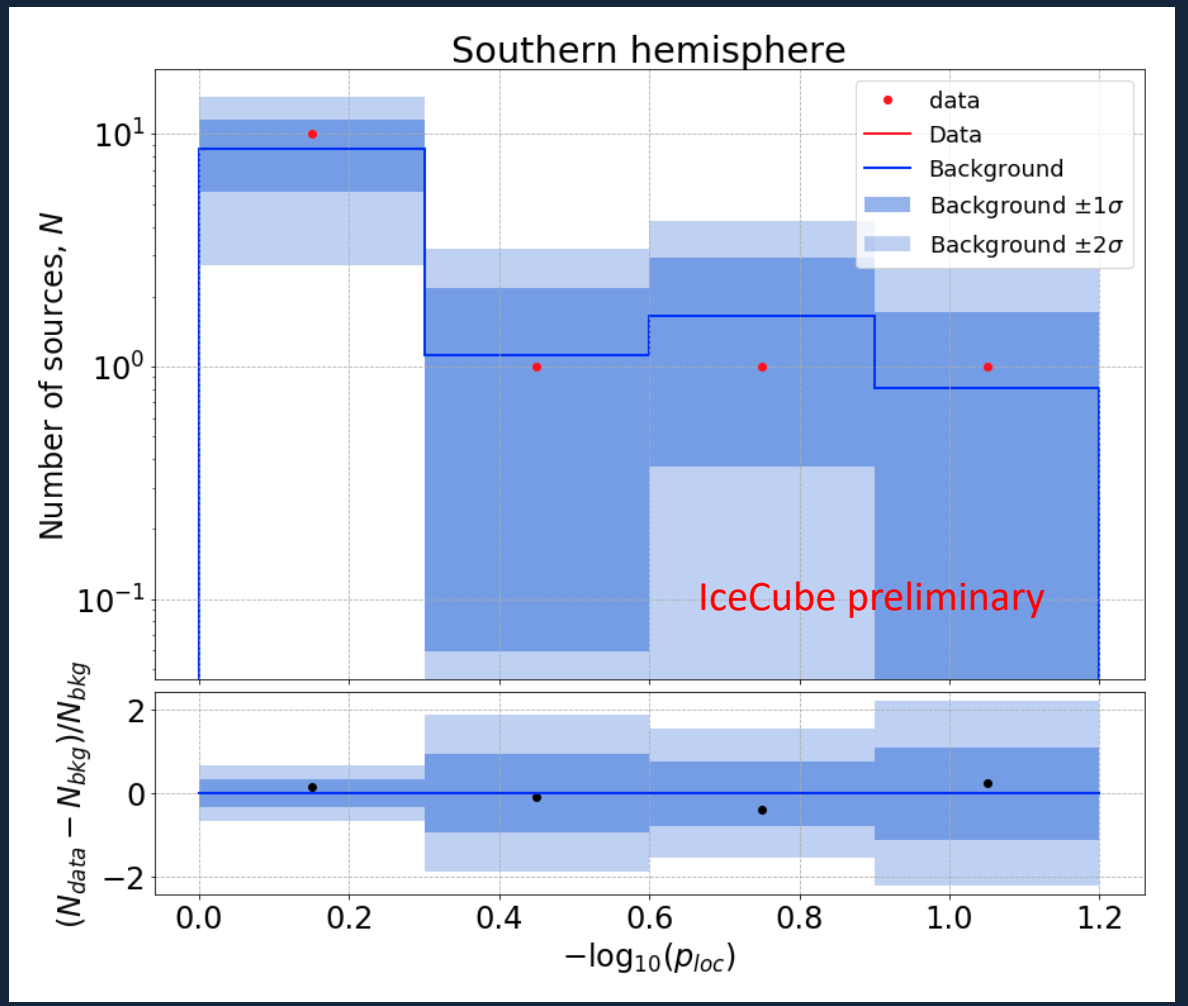
Fit results of the most significant sources of the catalog

Catalog results								
Source	R.A. [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$\hat{t}_0$ [MJD]	$\hat{\sigma}_T$ [days]	$-\log_{10}(p)$	$F_{90\%}$ [TeV cm^{-2}]
1ES 1959+650	300.01	65.15	$3.9^{+2.1}_{-1.9}$	$3.3^{+0.9}_{-0.9}$	$55028.4^{+0.1}_{-0.1}$	$1.8^{+1.1}_{-0.3} \times 10^{-1}$	2.21	3.8
GB6 J1542+6129	**235.75**	**61.50**	$\mathbf{23.7^{+9.7}_{-7.9}}$	$\mathbf{2.7^{+0.5}_{-0.3}}$	$\mathbf{57740^{+80}_{-60}}$	$\mathbf{147^{+110}_{-25}}$	**2.67**	**5.3**
M87	**187.71**	**12.39**	$\mathbf{3.0^{+2.0}_{-1.4}}$	$\mathbf{4.0^{+0.9}_{-0.9}}$	$\mathbf{57730.031^{+0.001}_{-0.001}}$	$\mathbf{1.4^{+1.3}_{-0.4} \times 10^{-3}}$	**3.35**	**0.9**
PKS 1502+106	226.10	10.50	$9.8^{+4.2}_{-3.9}$	$2.5^{+0.3}_{-0.4}$	55510^{+9}_{-10}	$21.6^{+9.0}_{-3.0}$	1.97	1.8
TXS 0506+056	**77.35**	**5.70**	$\mathbf{10.0^{+5.2}_{-4.2}}$ $\mathbf{7.6^{+6.1}_{-5.8}}$	$\mathbf{2.2^{+0.3}_{-0.3}}$ $\mathbf{2.6^{+0.5}_{-0.6}}$	$\mathbf{57000^{+30}_{-30}}$ $\mathbf{58020^{+40}_{-40}}$	$\mathbf{62^{+27}_{-27}}$ $\mathbf{42^{+42}_{-28}}$	**2.77**	**1.7**
NGC 1068	**40.67**	**-0.01**	$\mathbf{23.0^{+8.7}_{-7.9}}$	$\mathbf{2.8^{+0.3}_{-0.3}}$	$\mathbf{56290^{+90}_{-80}}$	$\mathbf{198^{+64}_{-64}}$	**2.65**	**1.9**
PKS 2233-148	339.14	-14.56	$2.0^{+1.8}_{-1.1}$	$2.8^{+0.8}_{-0.8}$	$54877.516^{+0.004}_{-0.001}$	$2.6^{+4.1}_{-1.4} \times 10^{-3}$	1.04	12.0

Table 1: Coordinates (Right Ascension R.A. and declination δ), flare parameters and the logarithm of the local pre-trial p-values p of the sources of the catalog and the 90% CL upper limits on the time-integrated flux $F_{90\%}$, defined for a spectrum $E^2 dN/dE = F_{90\%}(E/\text{TeV})^{2-\gamma} \times 10^{-4}$ with $\gamma = 2$, in units of TeV cm^{-2}. The likelihood parameters are reported together with their 68% confidence interval.

Pre-trial p-value Distributions



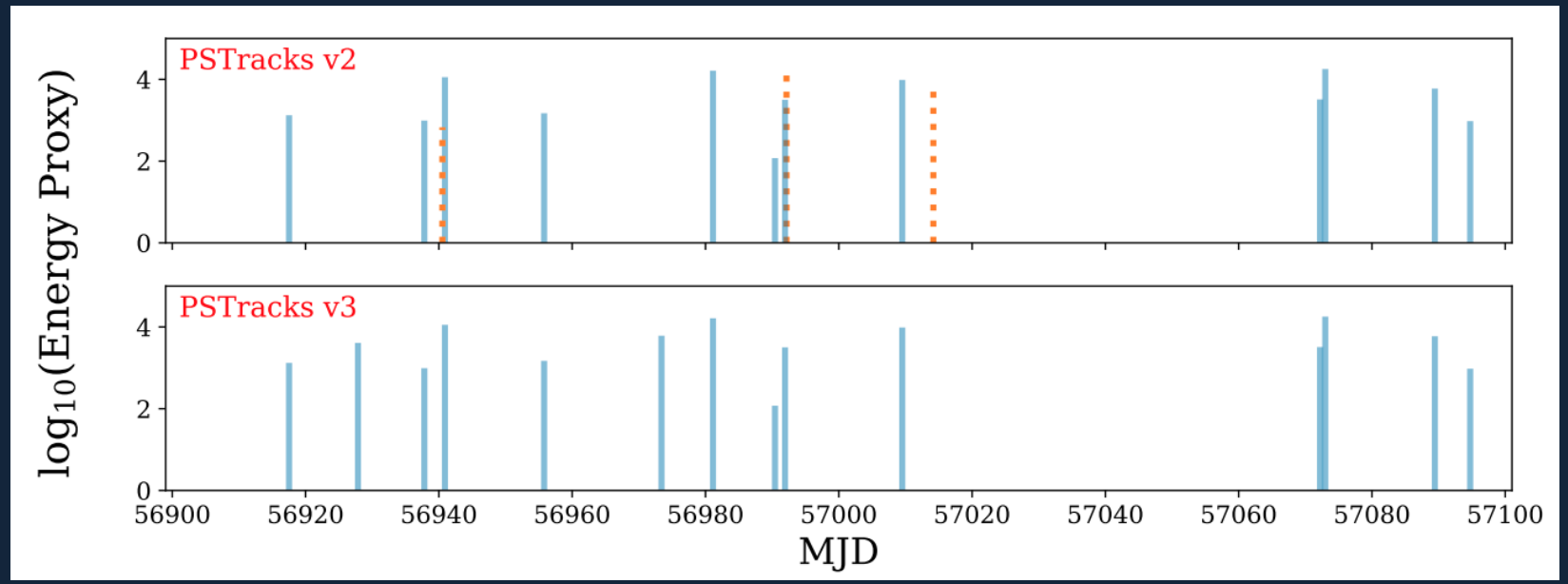


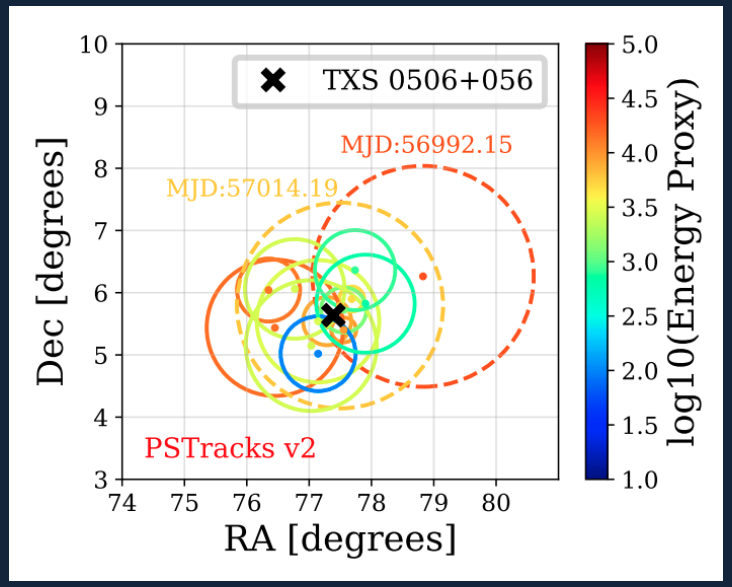
TXS 0506+056

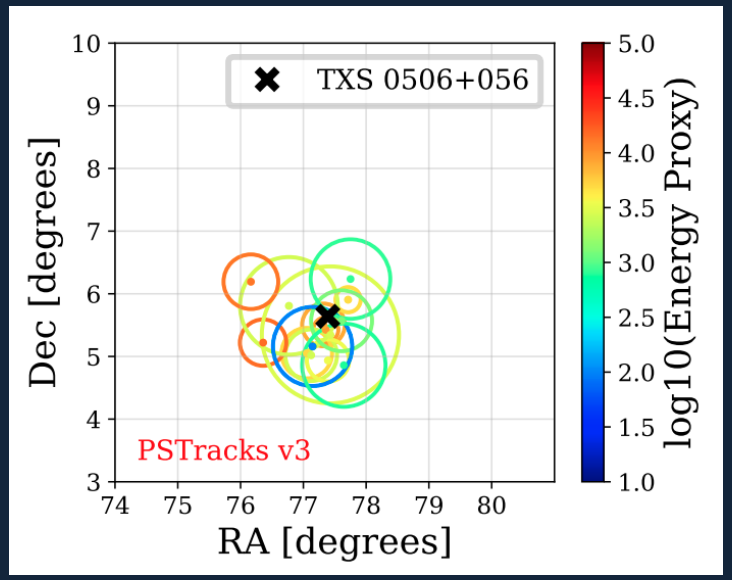
The data sample (psTracks v3) used for this analysed is different from the data sample (psTracks v2) used for the archival result

The new data sample differs mostly for an updated event reconstruction

The change in significance from the direction of TXS 0506+056 is almost entirely due to it







https://arxiv.org/pdf/2101.09836.pdf