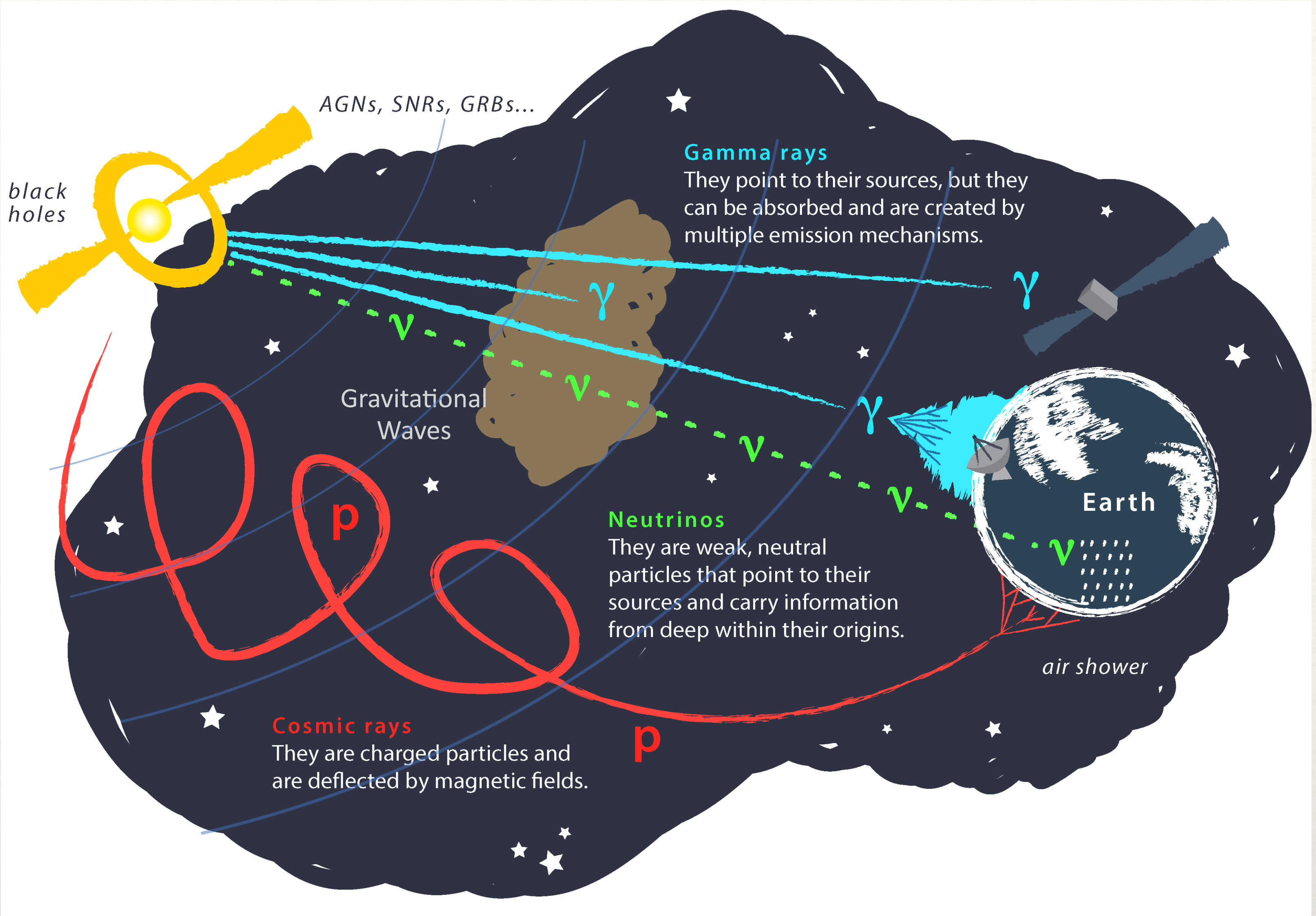

Testing The AGN Radio And Neutrino Correlation Using The MOJAVE Catalog

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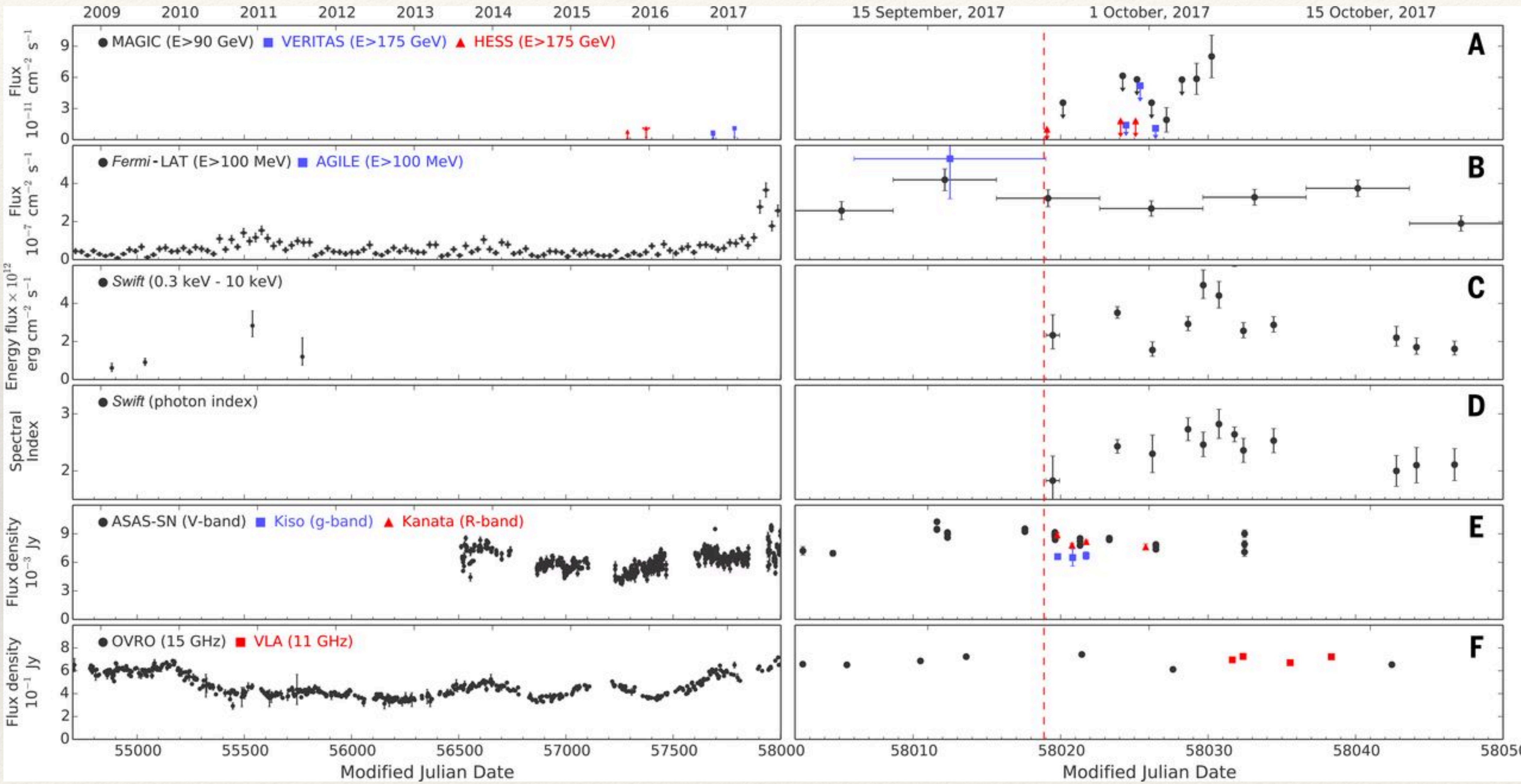
Jets 2021

Why AGN Became So Interesting For Neutrino Studies:

- Neutrino Alert: IC-170922A (Red dashed line); AGN: TXS 0506+056



The IceCube Collaboration. Science 2018, 361

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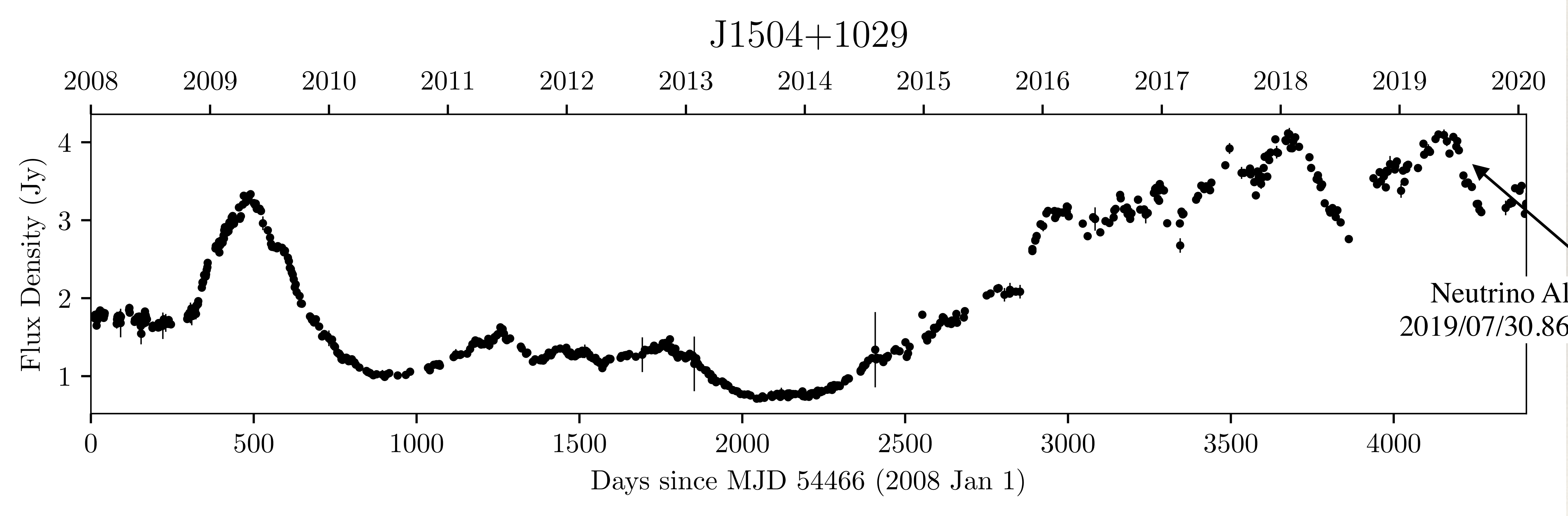
Motivation For Radio-Neutrino Correlation Studies:

- The blazar PKS1502+106 was found to have a possible correlation with an IceCube alert (IC190730A: ATel #12967) .
- At the time of the alert, the radio observations of the FSRQ were seen reaching an all time peak flux of 4 Jy (S. Kiehlmann et al. ATel #12996) (See Below).
- Moreover, a positive correlation will help us better understand possible neutrino production processes in AGN (as also discussed in Plavin et al. 2020 ApJ 894,101).



Data taken from the OVRO 40-m monitoring program

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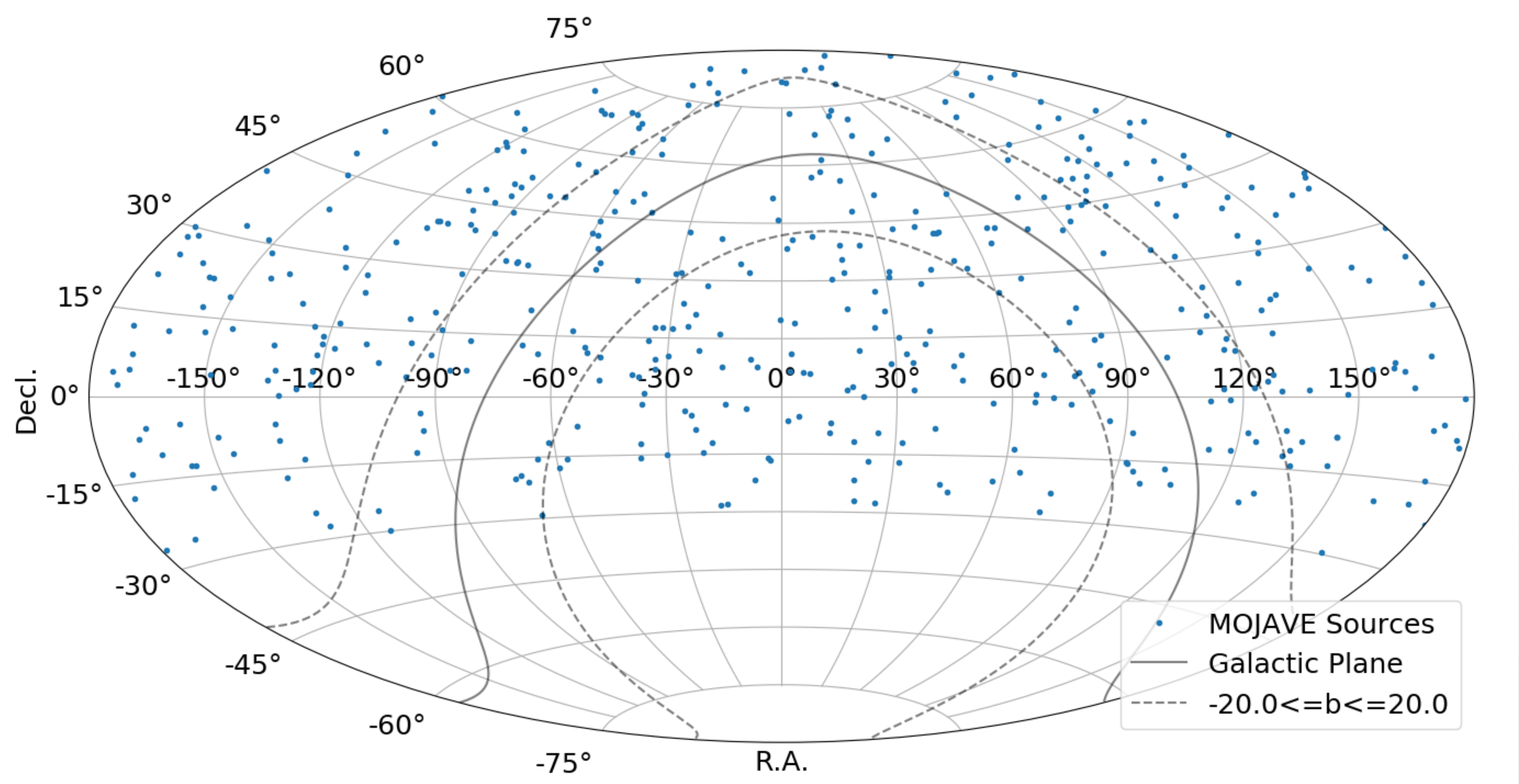
MOJAVE Sample: Source Distribution



- ~75% of the MOJAVE XV (Lister et al. 2018 ApJS 234, 12) source sample consists of sources with declination>0 degree, rest of the sources lie in between 0 and -30 degrees declination.
- The MOJAVE dataset consists of 5321 observations of 437 AGNs in the 15 GHz band, obtained between 1996 January 19 and 2016 December 26 with the VLBA in full polarization mode.

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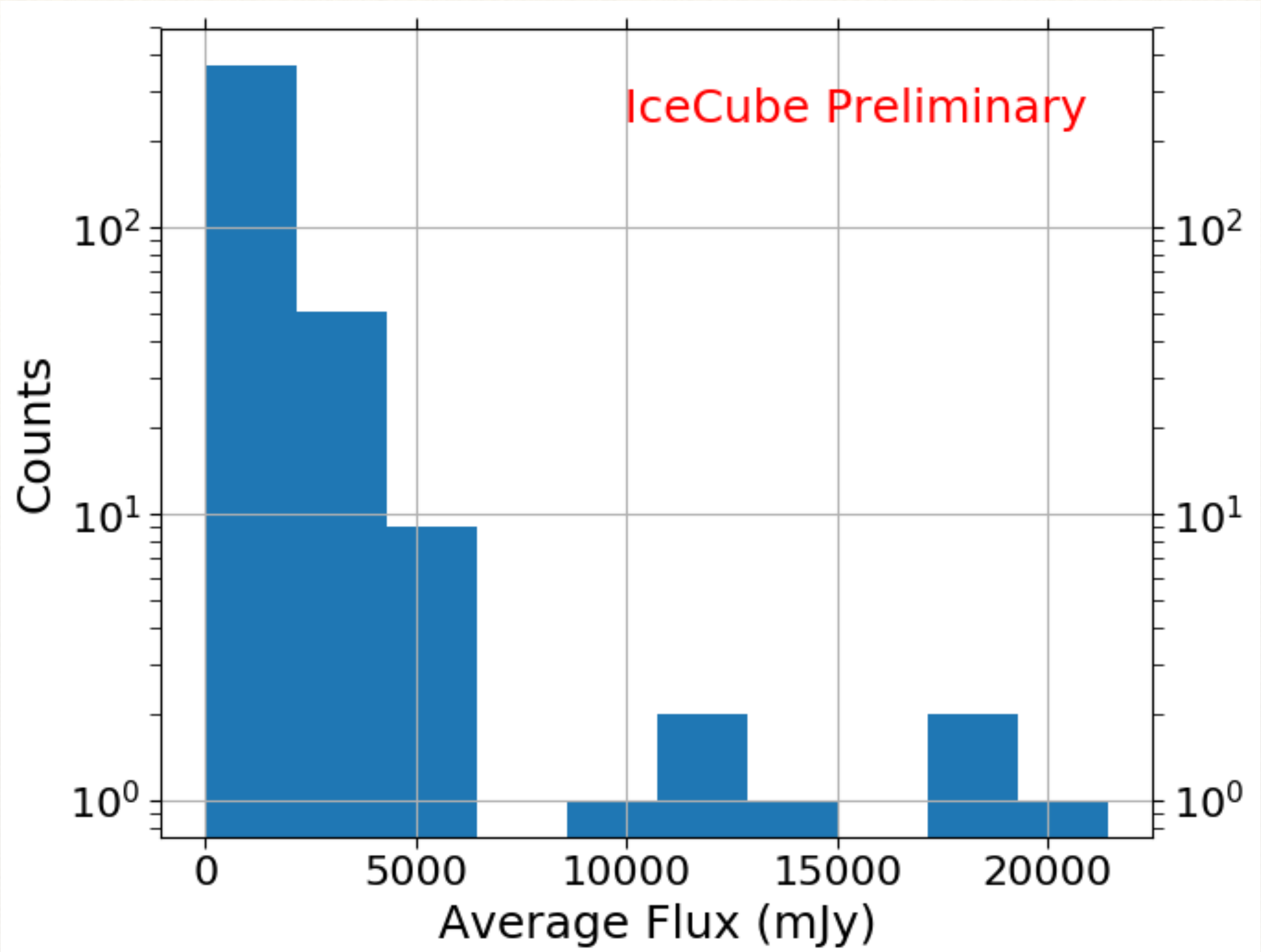
Stacking Analysis

Time averaged analysis

$F_\nu \propto F_R: \ (w_i = F_{Ri})$

- We make use of the average flux of each source as the weight to be used in stacking.
- As the sample size is relatively small (437) we make use of all the sources in our analysis.



Stacking Analysis

- For each event i, the number of associated signal neutrinos (n_s), the event location (x), source location (x_S) , reconstruction accuracy (sigma), energy (E), declination (delta), and spectral index (gamma) of the source are used to derive the likelihood using the following un-binned likelihood equation:

$$\mathscr{L} = \prod_i \left(\frac{n_s}{N} \mathcal{S}_i \left(\mathbf{x}, \mathbf{x_S}; \sigma, E, \delta, \gamma \right) + \left(1 - \frac{n_s}{N} \right) \mathscr{B}_i (\delta; E) \right)$$

- To boost sensitivity, we stack the signal using weights. We use the average radio flux of the MOJAVE source observed at 15 GHz to test the hypothesis of a direct correlation of the radio and neutrino flux. Stacking of the signal is done using:

$$\mathcal{S}_i \rightarrow \frac{\sum_i \omega_i \mathcal{S}_i \left(\mathbf{x}_i \right)}{\sum_i \omega_i}$$

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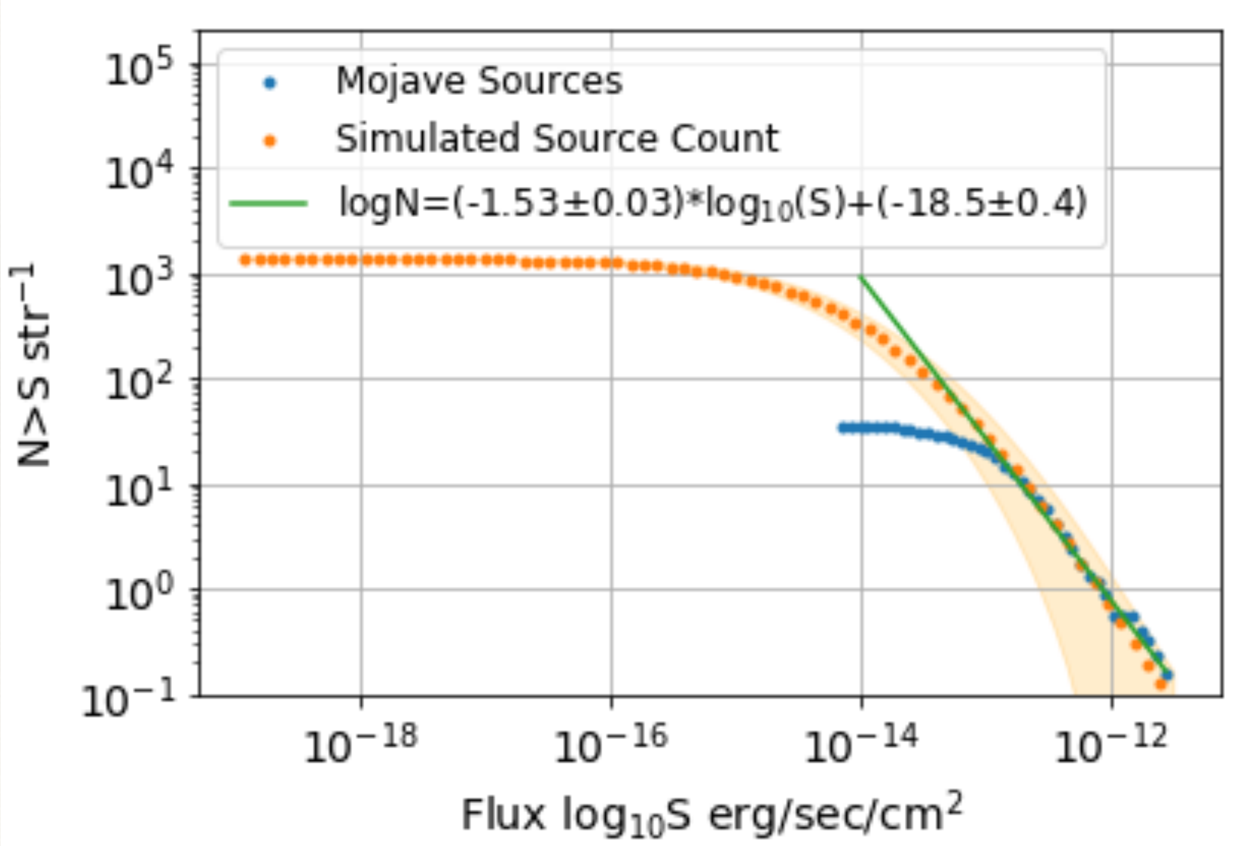
Completeness Calculation:

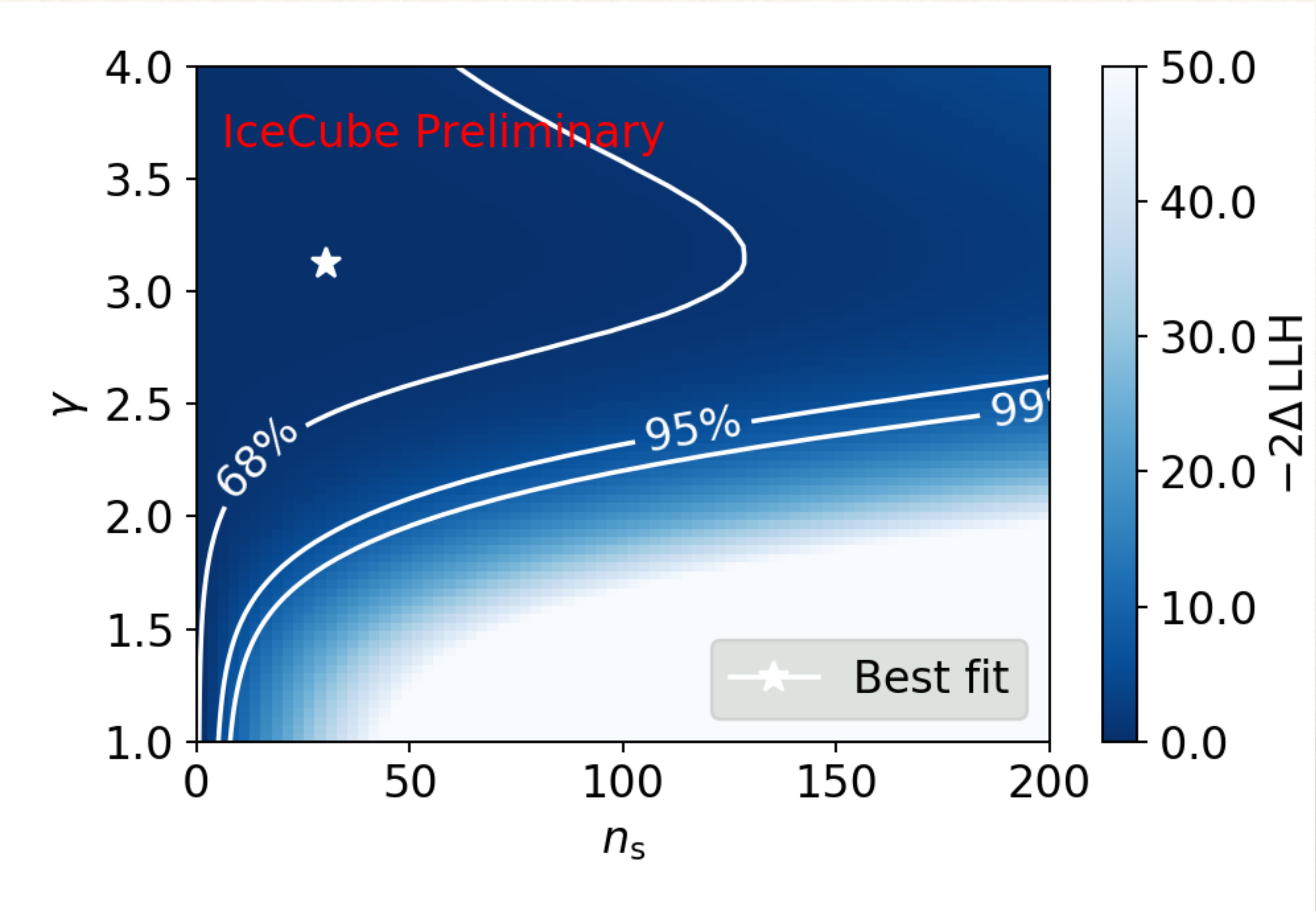
- The source count distribution is estimated using the luminosity function parameters presented in the MOJAVE XVII work. (Lister et al. 2019 ApJ 874, 43).
- The Lorentz factor and the viewing angles are allowed to vary randomly based on the limits discussed, and for each flux value the process is repeated multiple times.
- After calculating the area under the curve for the two cases to derive completeness, the whole process is repeated multiple times to derive the uncertainty.
- The MOJAVE catalog completeness is calculated to be (44.7+-11.2)% .
- The orange shaded portion shows the 1 sigma uncertainty of the N>S values because of variation of Doppler factor.
- Because the MOJAVE catalog is blazar dominated, the completeness shown here is also for a blazar dominated sample.



Stacking Results:

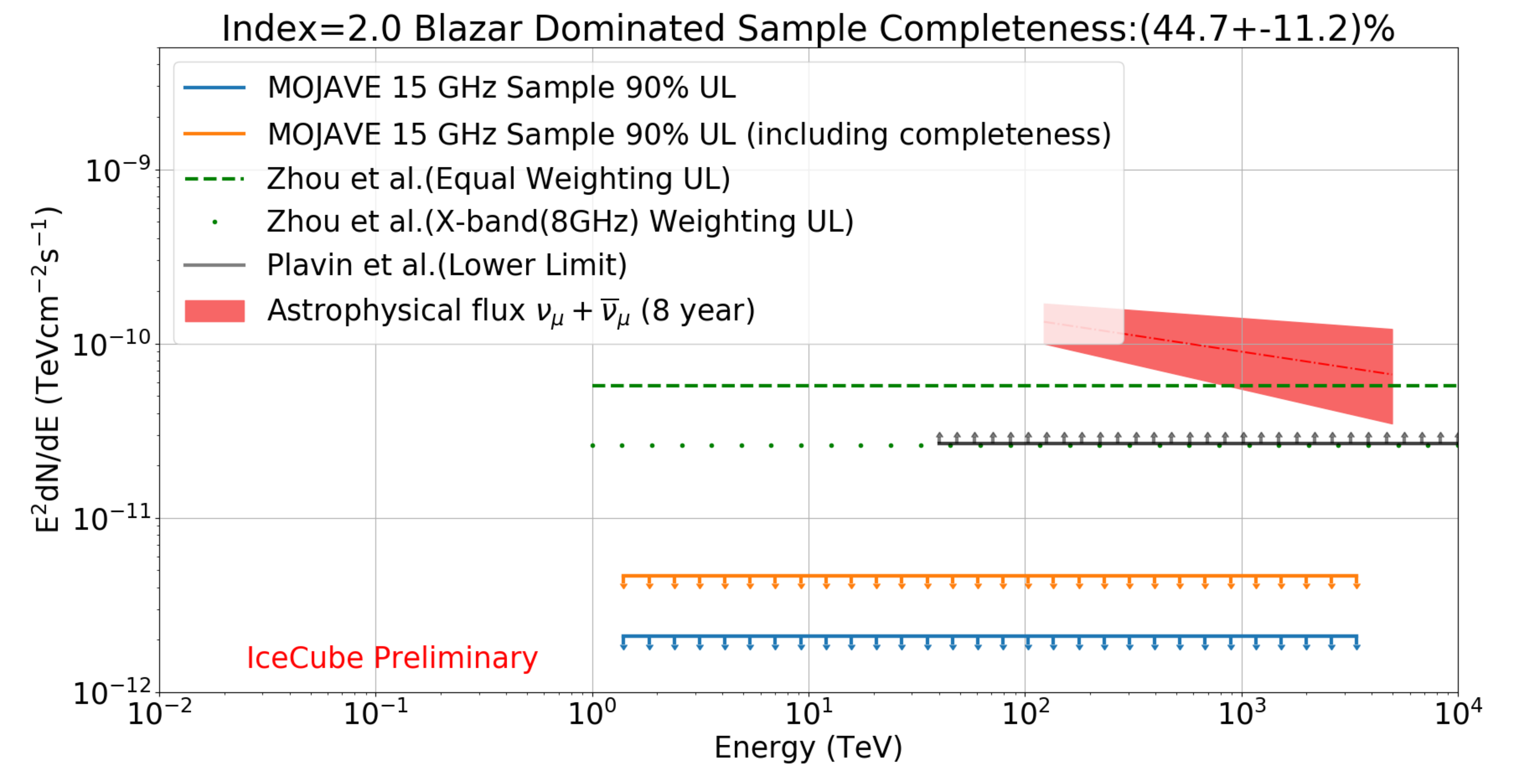
- Unblinding results:

n_s	31.56
Gamma	3.14
TS	0.09
p-value	0.49
Significance	0.69 sigma



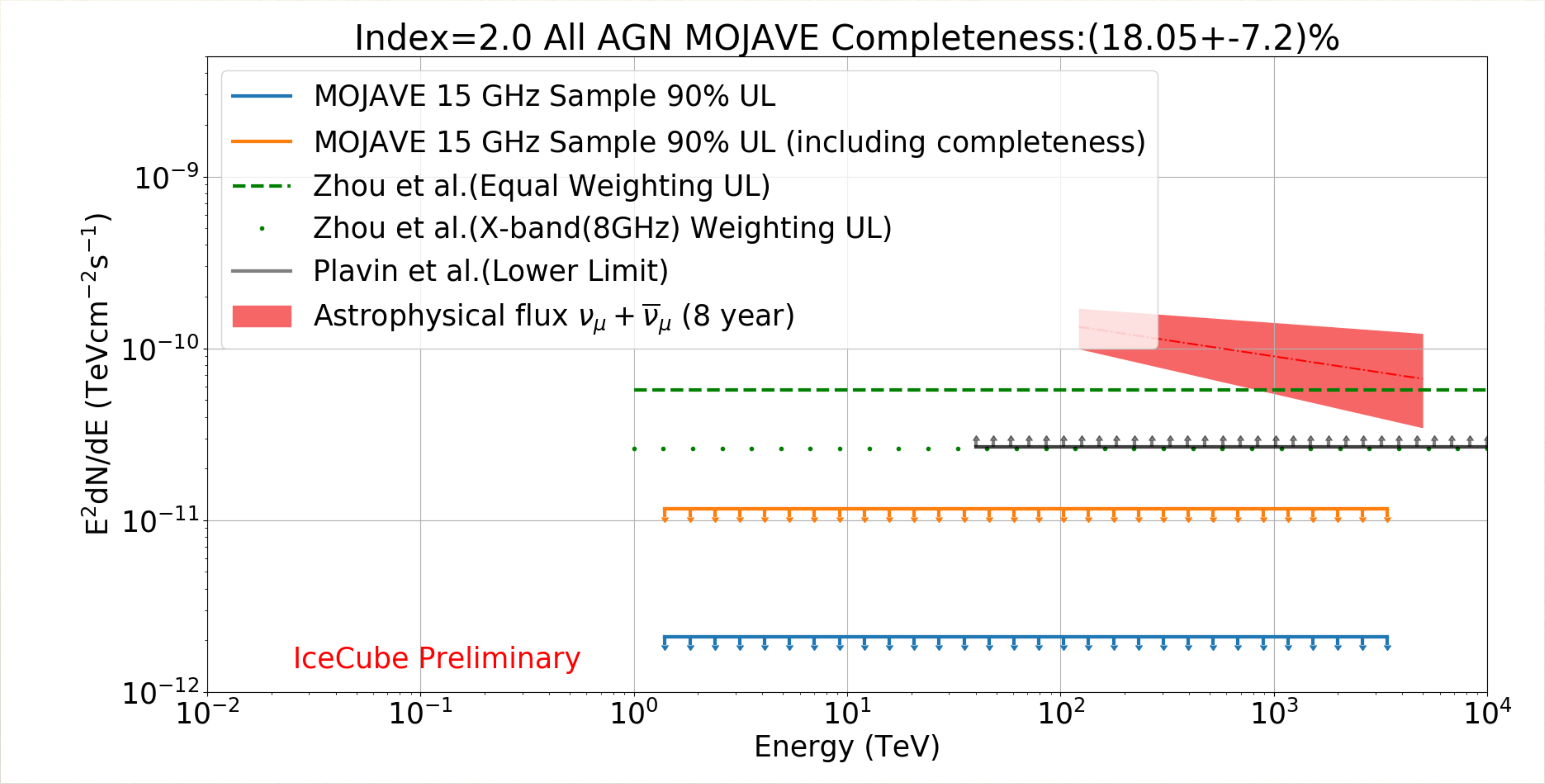
- The contours in the above ns-gamma likelihood plot show the 1,2 and 3 sigma values from the best fit assuming Wilk's with 2 degrees of freedom.
- We get a p value of 0.49 as our unblinded result. So, we set an upper limit on neutrino flux from these sources.

Upper Limits



- Zhou et al. 2021 makes use of 3388 sources listed in the Radio Fundamental Catalog and a weighting of radio fluxes measured at ~8 GHz to derive an upper limit at 95% C.L. (we use 15 GHz data to derive a limit at 90% C.L.).
- Both Zhou et al. 2021 and Plavin et al. 2020a2020b do not have the same constraints as the MOJAVE sample which is dominated by Blazars.

Upper Limits



- Zhou et al. 2021 makes use of 3388 sources listed in the Radio Fundamental Catalog and a weighting of radio fluxes measured at ~8GHz to derive an upper limit at 95% C.L. (we use 15 GHz data to derive a limit at 90% C.L.).
- This completeness percentage is calculated by taking into account the parent population (AGN) distributions causing the completeness value being lower than the previous case

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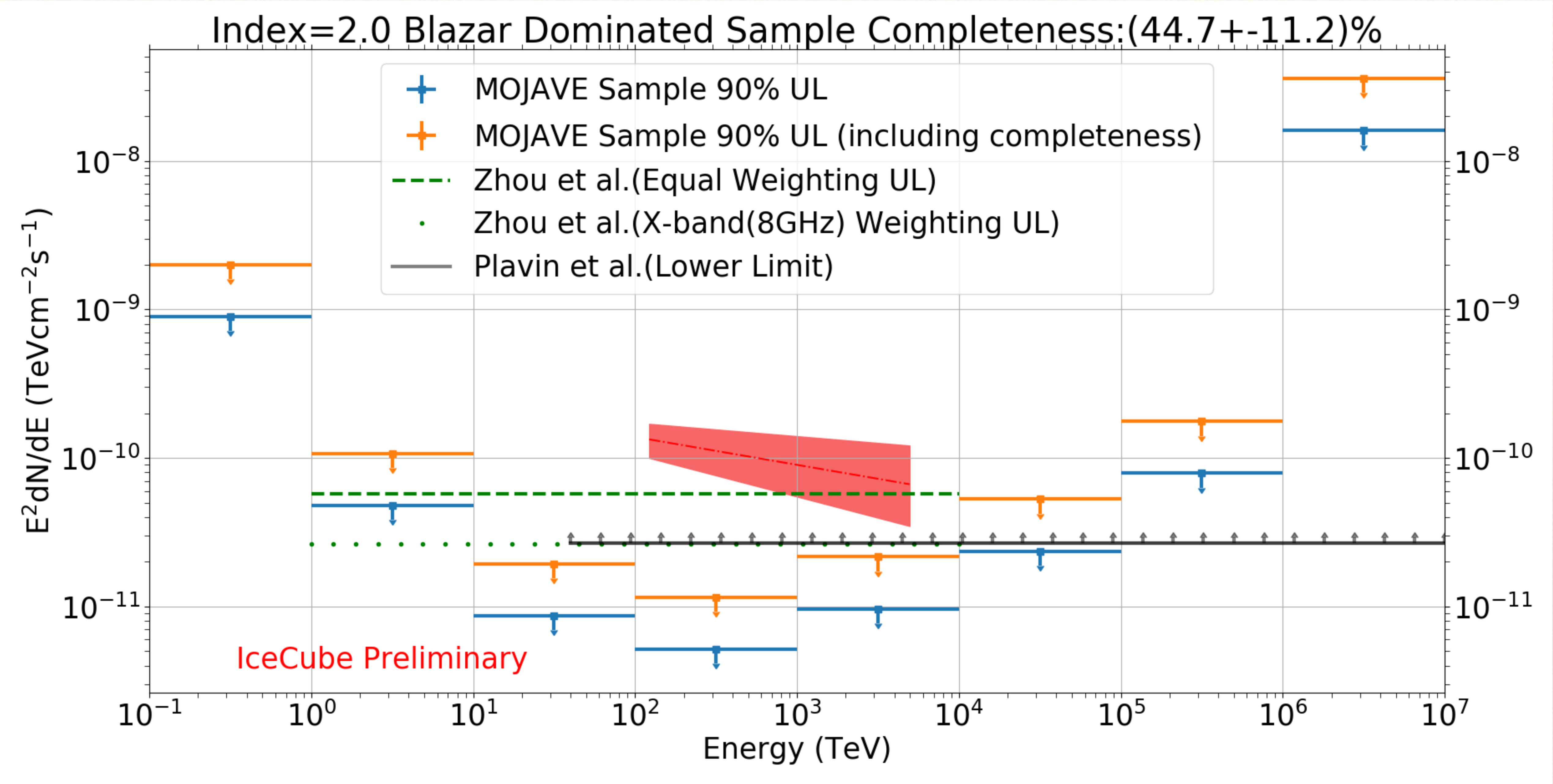
Differential Upper Limits



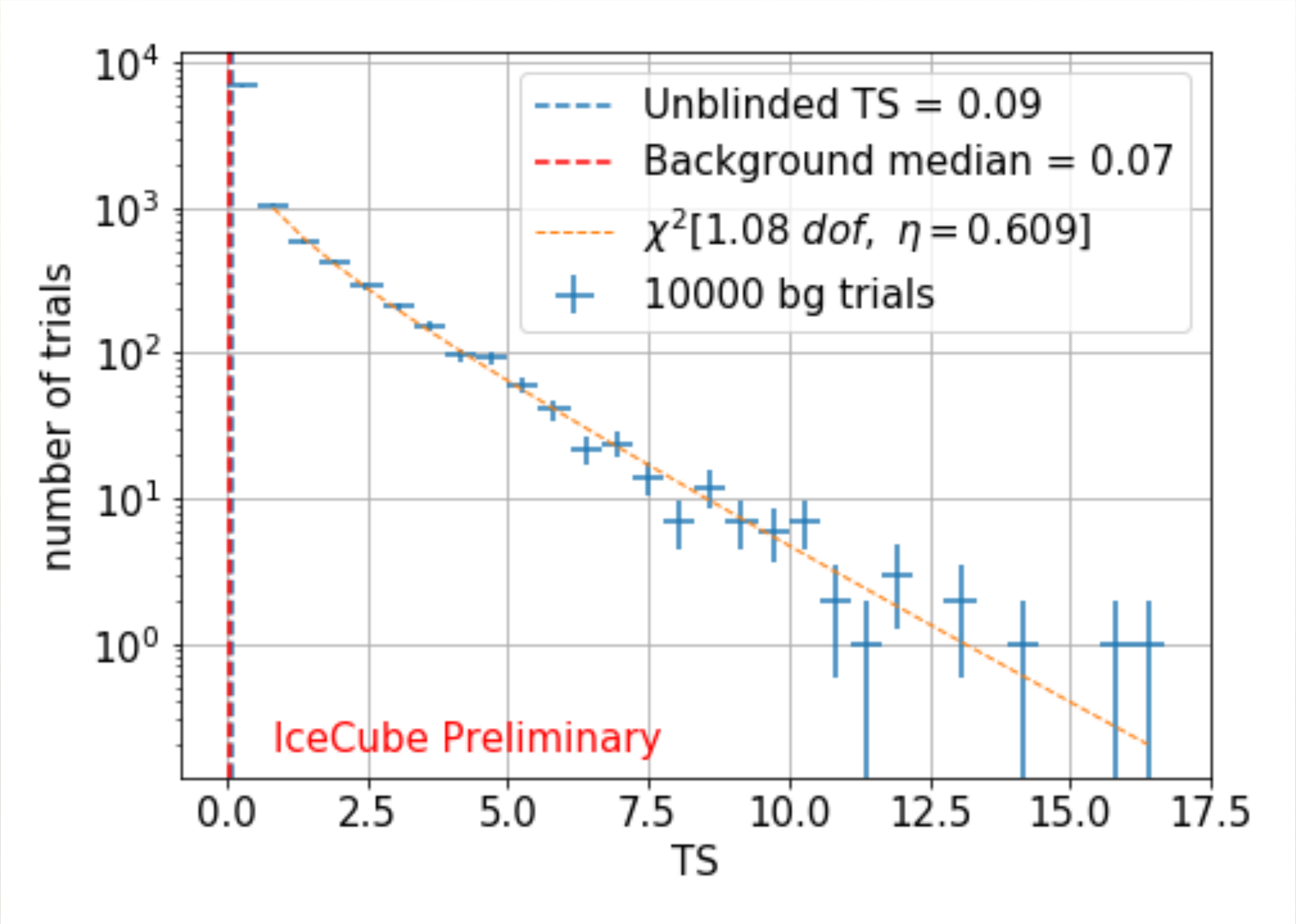
- The plot shows the 90% differential upper limits derived by stacking the MOJAVE sources using the average radio flux as the weights for each energy bin.

Summary:

- We perform a time averaged stacking analysis using the MOJAVE catalog.
- We report here the upper limit results for a radio-neutrino correlation analysis which focuses on a blazar dominated AGN sample.
- We are also in process of working on a time dependent analysis which makes use of the light curves observed by MOJAVE as weights for the stacking.

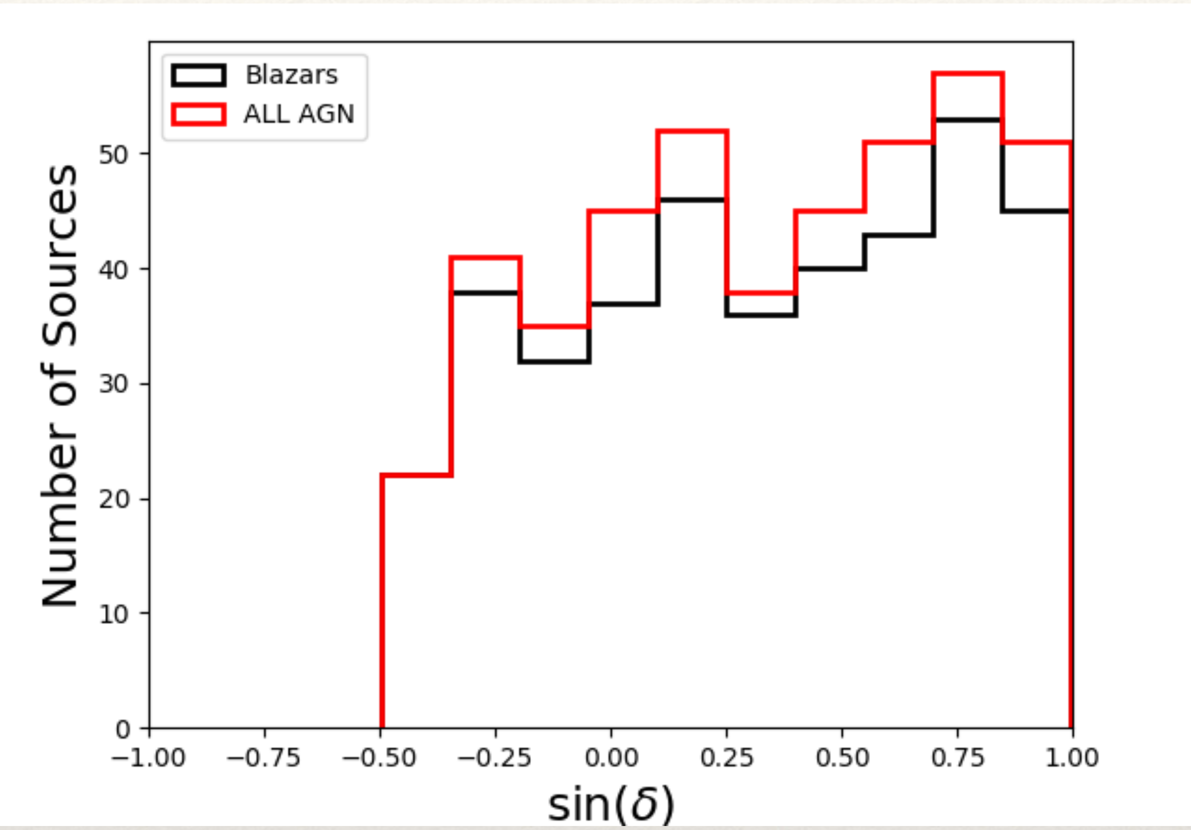
Backup

Unblinded result compared to Background distributions:

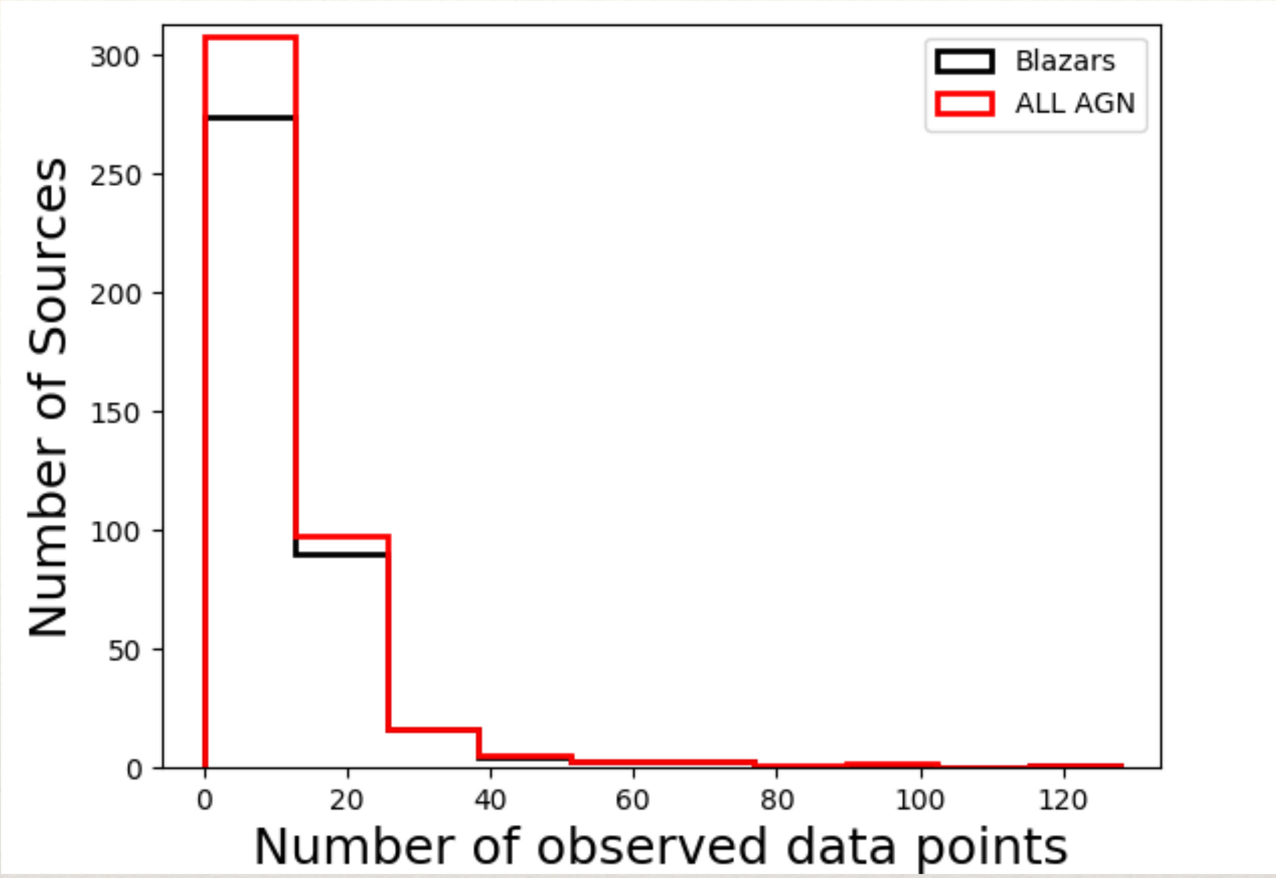


- The unblinded TS is shown as compared to the background median on the background TS distributions.

Backup Slide: Distribution of the MOJAVE source sample



Distribution of the source sample in sin(declination) taken from the MOJAVE XV catalog



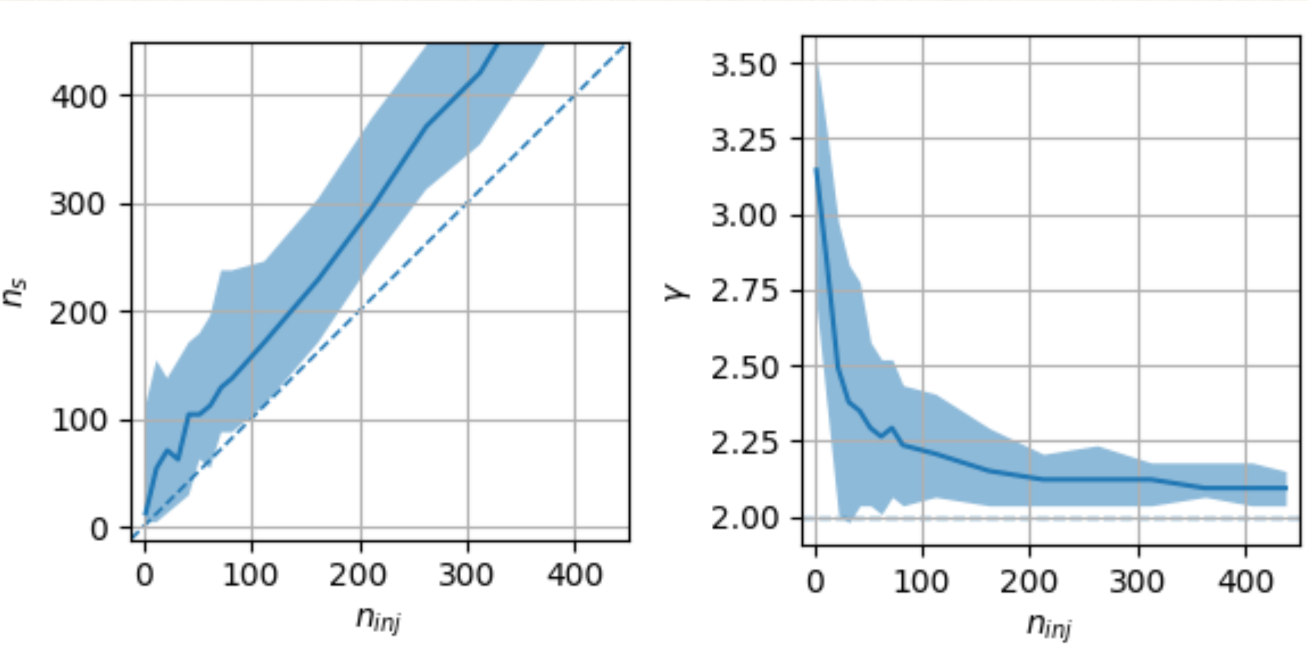
Distribution of the 5321 observations for the MOJAVE XV sources

Information from the MOJAVE XVII paper

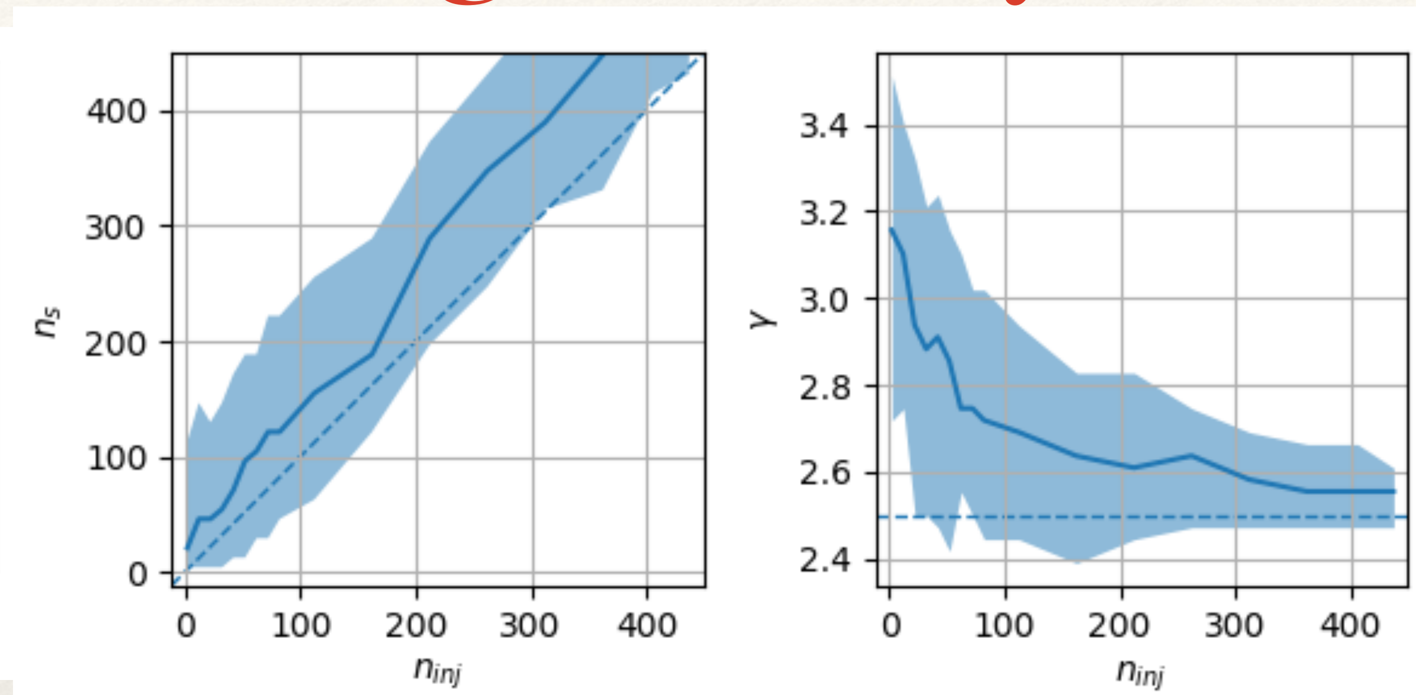
Jet Property	Distribution	Fixed parameters	Free parameter ranges
Lorentz factor	$N(\Gamma)d\Gamma \propto \Gamma^b$	$\Gamma_{\rm min} = 1.25$ $\Gamma_{\rm max} = 50$	$-1.8 \leq b \leq -0.2$, step = 0.2
Luminosity function	$\Phi(L,z) \propto \Phi(L/e(z))$ $e(z) = (1+z)^k e^{z/\eta}$ $\Phi(L/e(z=0)) \propto L^\gamma$	$L_{\rm min} = 10^{24}$ W Hz^{-1} $L_{\rm max} = 10^{31}$ W Hz^{-1}	$-0.65 \leq \eta \leq -0.25$, step = 0.05 $4.5 \leq k \leq 8.5$, step = 0.5 $-3.2 \leq \gamma \leq -2.4$, step = 0.1
Beamed luminosity	$P = L\delta^p$	$p = 2+\alpha$	$\alpha = -0.5, 0, 0.22$
Viewing angle	$p(\theta)d\theta = \sin\theta$	$\theta_{\rm min} = 0°$ $\theta_{\rm max} = 90°$	$\cdots$

- MOJAVE XVII: Link
- Above table shows the jet properties of the AGN sample used in the analysis. These are used to compute the completeness of the MOJAVE sample.

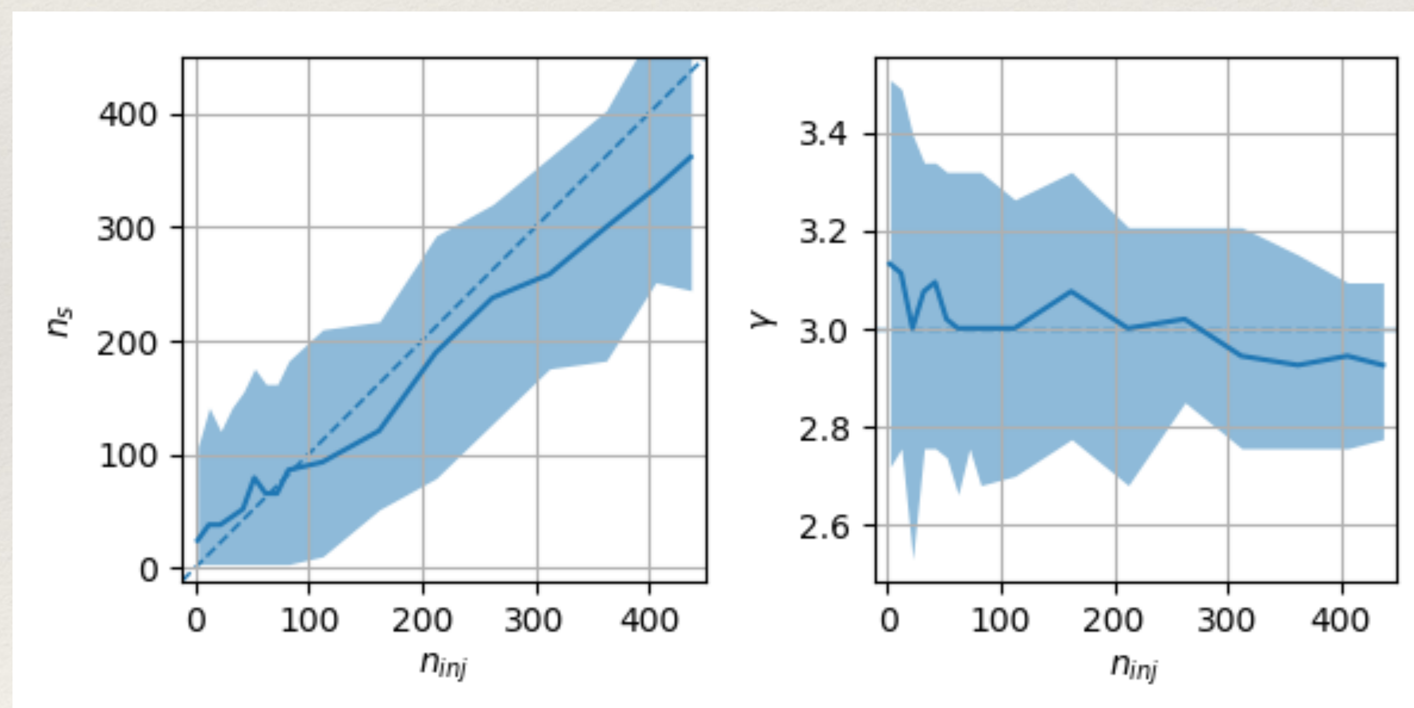
N Bias Test (Time averaged analysis)



- Index=2.0



- Index=2.5



- Index=3.0

- The shaded region depicts the 1 sigma containment.
- n_s gives the number of neutrino events derived when $N_{injected}$ number of signal events are injected
- If we find a significant detection while unblinding using a 3 sigma threshold, the bias will be calibrated.

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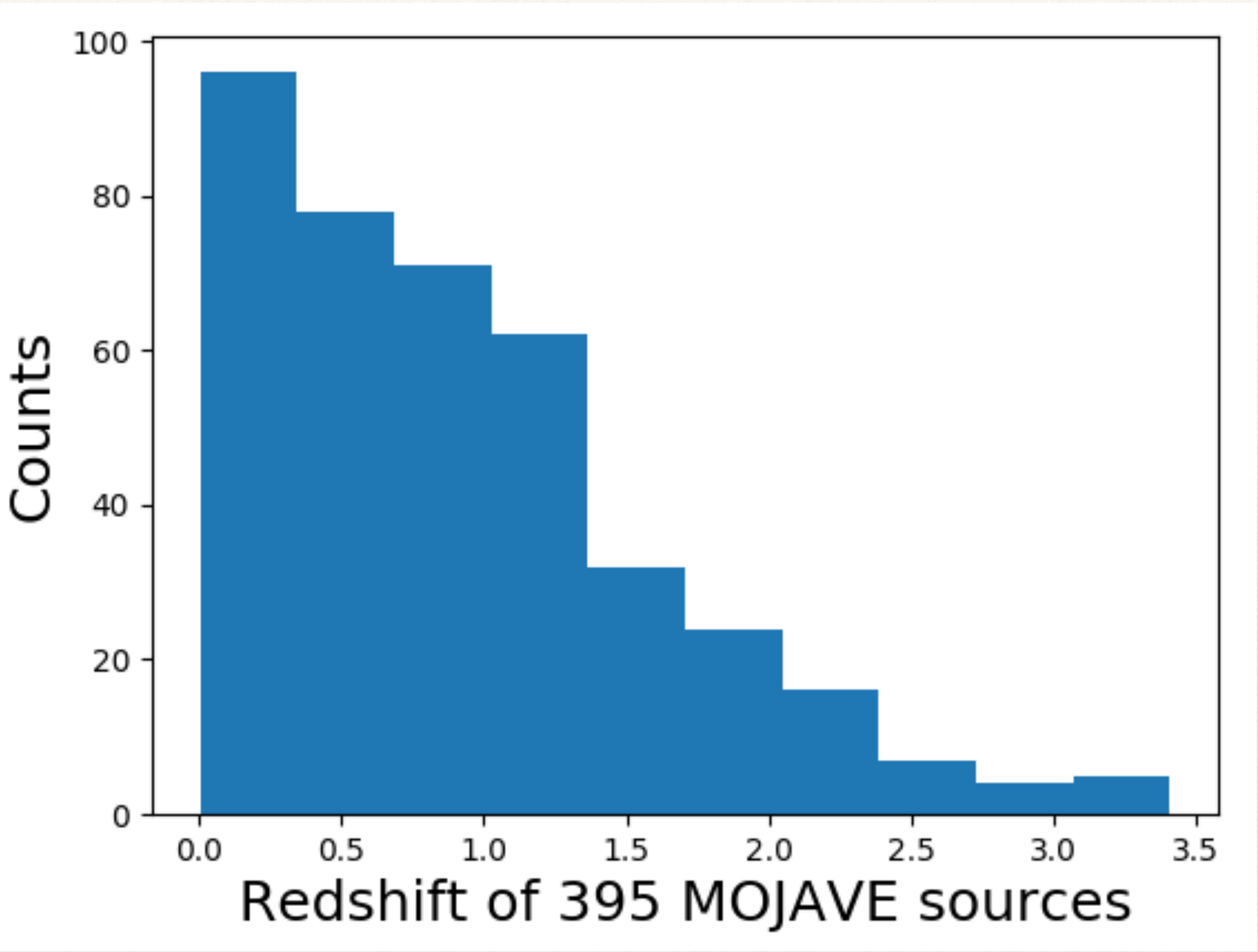
Redshift Distribution



sample, 395 sources

Relevant Literature talking about this correlation

- Using Catalog and public IceCube alerts
  - Plavin,et al.,2020a
  - Plavin,et al.,2020b
  - OVRO 2020
  - Giommi,et al.,2020
  - Zhou et al. 2021
- Some (of the many) interesting papers talking about this correlation while not using any large (radio) source population:
  - Kun,et al.,2020 (Neutrino emission during Gamma ray suppressed state in AGN)
  - Markus Boettcher 2019
  - Blandford,Meier and Readhead 2018
  - Murase, Inoue and Dermer 2014
  - Mannheim,Stanev and Biermann 1992

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Comparison With Individual Potential Neutrino Sources

- Possible coinciding IceCube alerts and AGN source directions
  - TXS0506+056 (IC170922A) Mojave avg rd flux: 593 mJy
  - 1WHSP J104516.2+275133/NVSS J104516+275136 (IC190704A): Not Present. (Not in any of the catalogs MOJAVE is made from)
  - PKS1502+106 (IC190730A) MOJAVE avg rd flux: 1423 mJy
  - NVSS J151100+054916 (IC191119A) Not Present. (Not in any of the catalogs MOJAVE is made from)
  - 3HSP J095507.9+355101 (IC200107A): Not Present. (Not in any of the catalogs MOJAVE is made from)
  - TXS 1100+122 (IC200109A) (Not in any of the catalogs MOJAVE is made from)
- 10 yr PS analysis (Most significant sources)
  - NGC1068 Not present in MOJAVE because no detection at 15GHz (link)
  - PKS 1424+240 Mojave avg rd flux: 275 mJy
  - GB6 J1542+6129 Mojave avg rd flux: 152 mJy

Back-of-the-envelope calculation for completeness :

- Say there are nsim=16pi number of sources in the sky while a catalog sees n_catalog=6pi. And say the coverage of the catalog is 50% of the sky. (Notice it is not equal to nsim/2 so there is an additional factor apart from sky coverage effecting completeness)
- Based on the calculation I did earlier for the N>S value, if the whole catalog is depicted by 1 flux bin, the N>S (str-1) will be n_catalog/4pi = 6pi/4pi = 3/2
- The N>S (str-1) for the simulated/complete sample will be nsim/4pi = 16pi/4pi = 4
- The completeness will then be N>S_catalog/N>S_sim giving (3/2)/4=37.5% complete.
- If this is true then n_catalog/completeness should give the total number of sources in the sky (nsim)—-> 6pi/0.375 = 16 pi
- So both the sky coverage and flux coverage is included.

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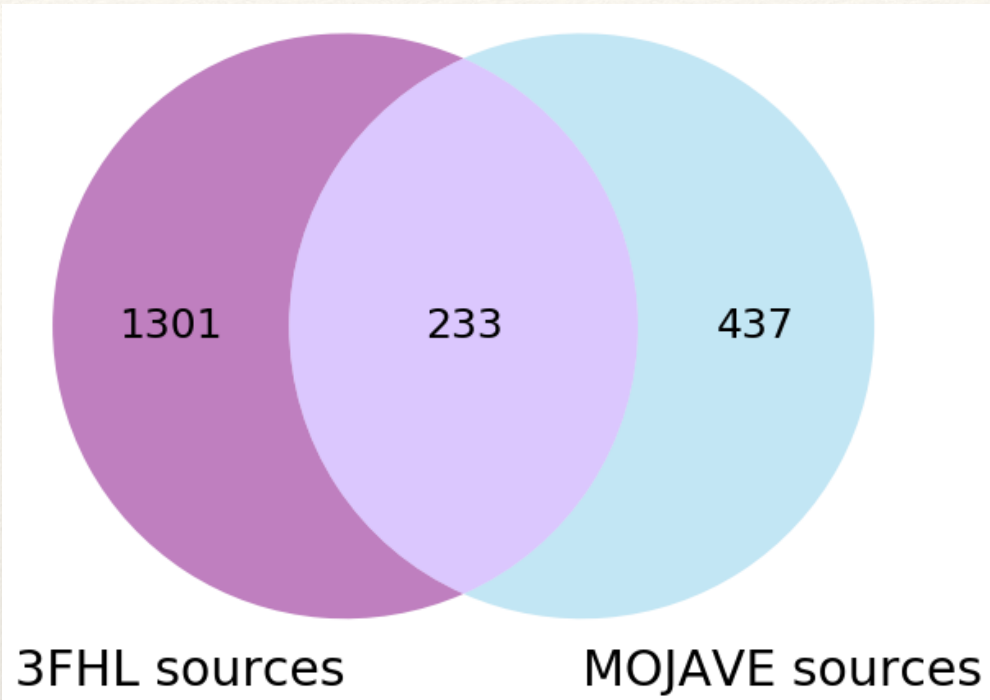
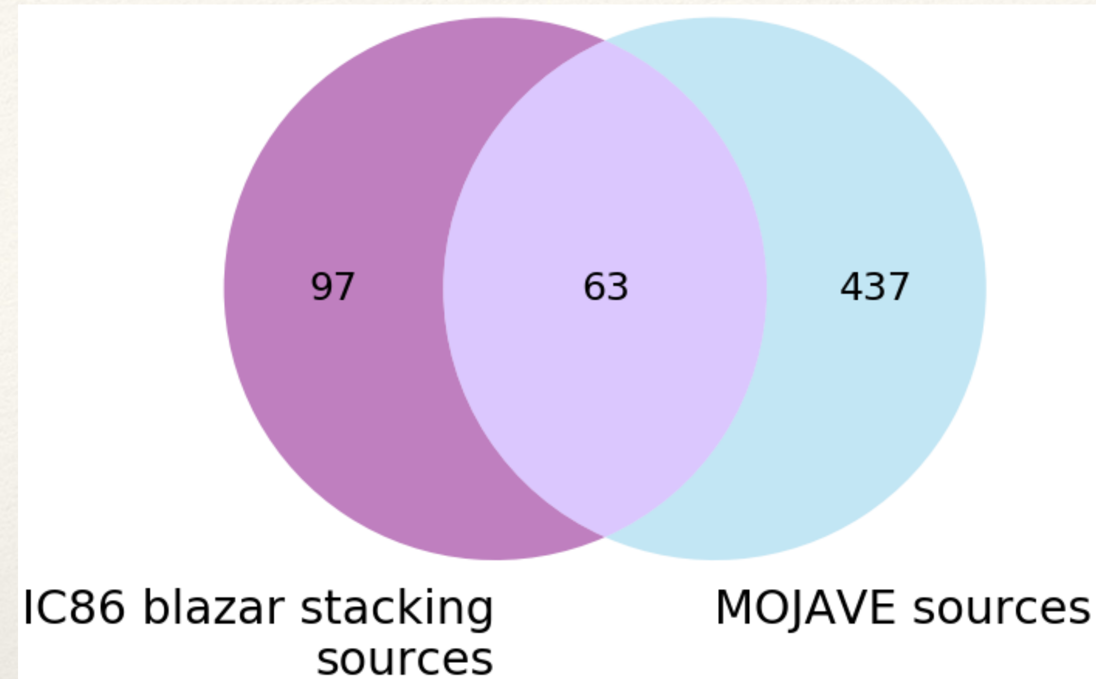
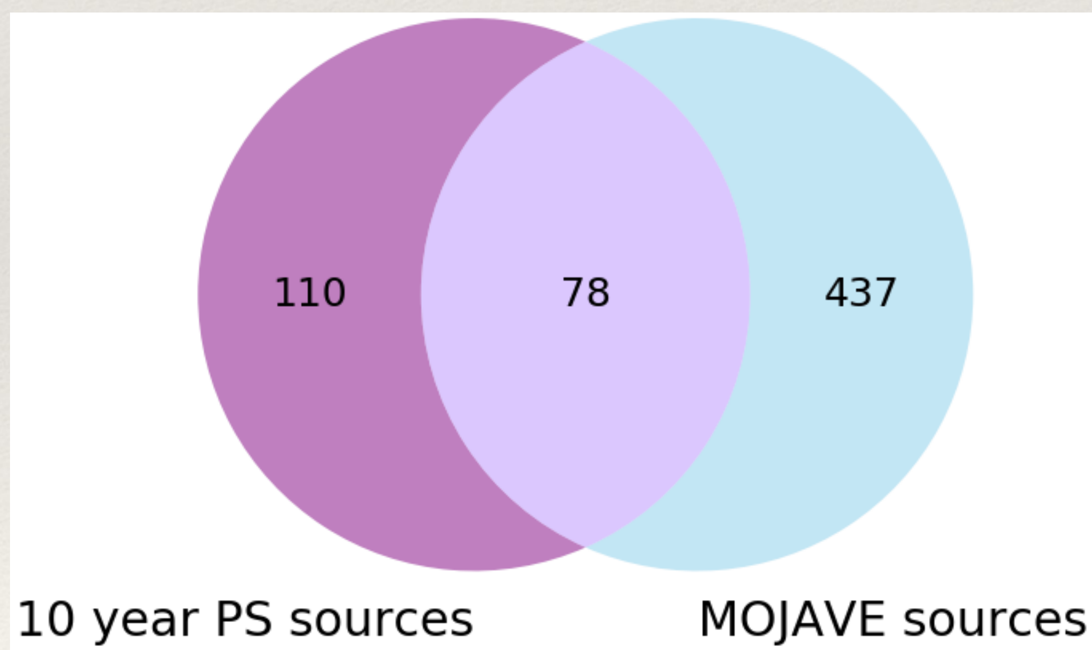
Comparison With Other Stacking Analysis



https://wiki.icecube.wisc.edu/index.php/3FHL_Blazar_Stacking



https://wiki.icecube.wisc.edu/index.php/IC86_Blazar_Stacking



https://wiki.icecube.wisc.edu/index.php/Ten_Year_Time_Integrated_Point_Source_Searches