UPPSALA UNIVERSITET

IceCube Neutrino Observatory

Partikeldagarna 2021
22-23 November

ANKUR SHARMA

A MODEL-INDEPENDENT ANALYSIS OF NEUTRINO FLARES FROM X-RAY SELECTED BLAZARS

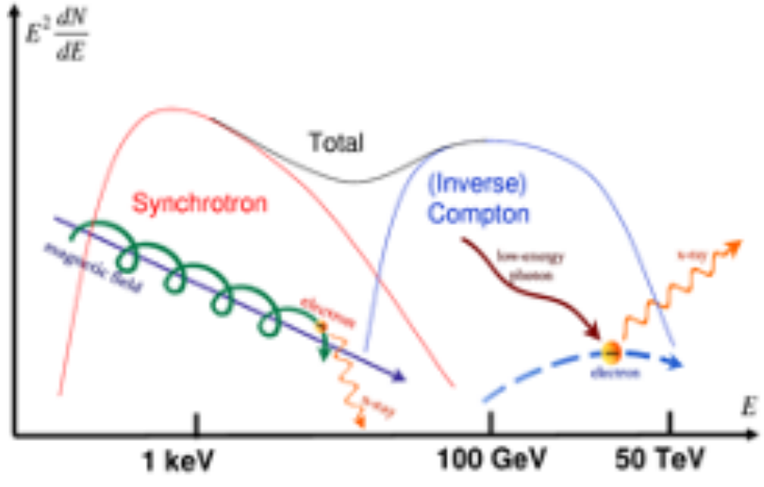
Credit: DESY

Blazars are Active Galactic Nuclei (AGN) with their jets pointed towards the Earth

Spectral Energy Distribution (SED):

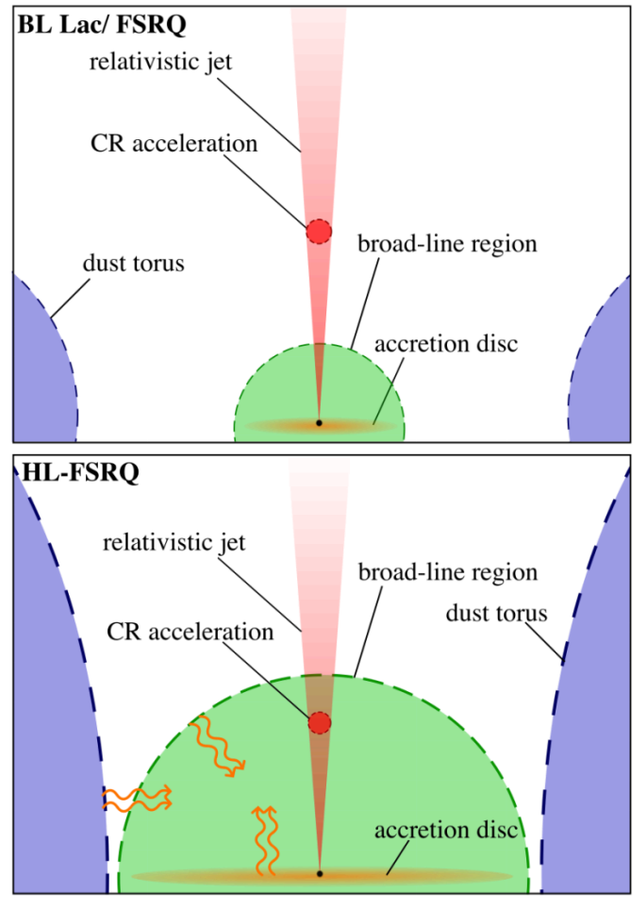
Non-thermal emission over a broad range of the EM spectrum. Two major humps:

1. **Electron Synchrotron**: Emission from relativistic e- gyrating under high magnetic fields inside jets
2. **Leptonic/hadronic**: Compton up-scattering of the synchrotron photons/hadronic gamma-rays



BL Lacs -- High optical polarisation
weak emission lines

FSRQs -- More luminous
strong optical emission lines
prominent Compton hump in SED



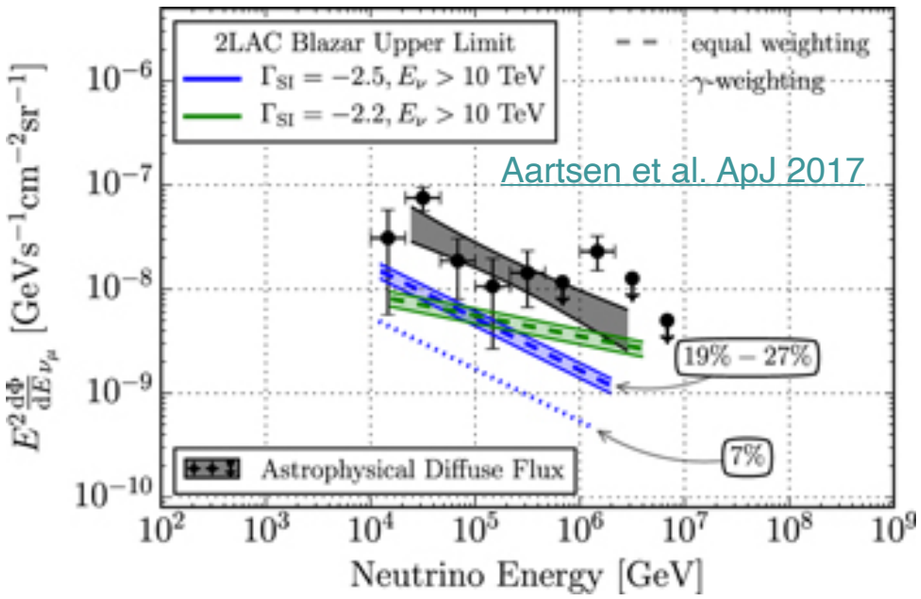
Difference between the two sub-classes possibly based on jet-power and mass of central engine

Rodrigues et al. ApJ 2018

SOURCES OF NEUTRINOS

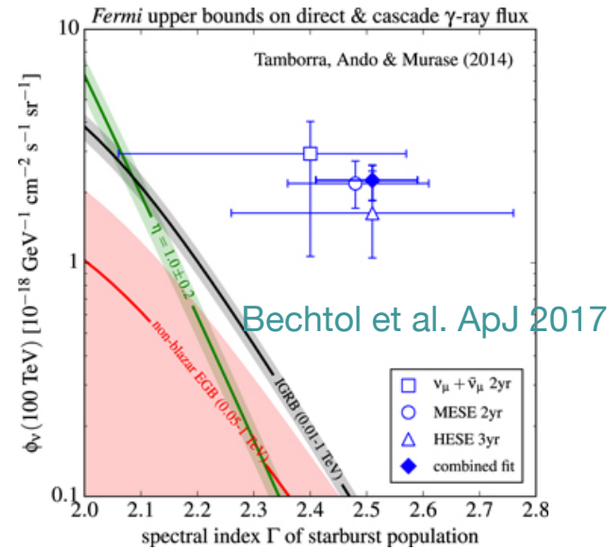
Expectations from most of the source classes suspected of producing the extra-galactic ν-flux constrained by **IceCube** and others:

AGN [> 15%]



Blazar AGNs can contribute only <u>upto 30%</u> of the observed IceCube diffuse flux

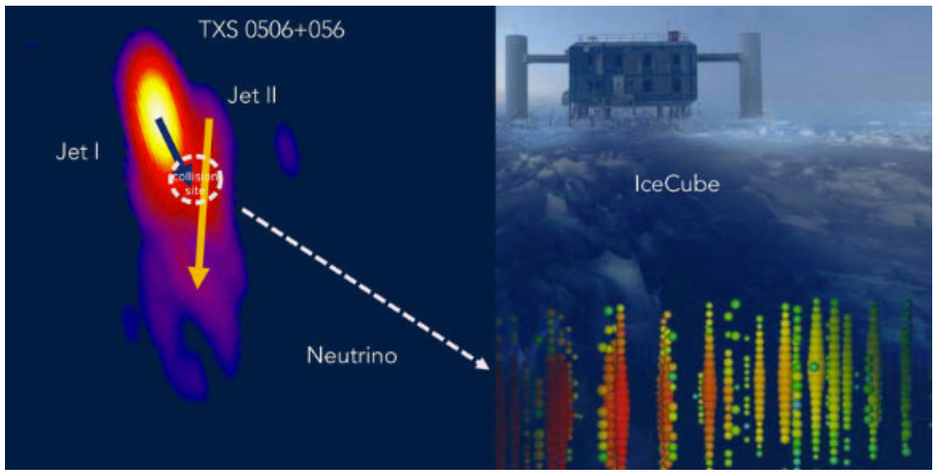
GRBs (transients) [< 1%]

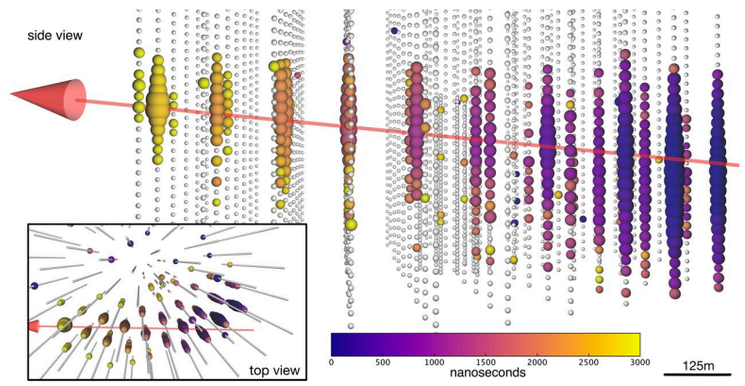


(Prompt phase only)

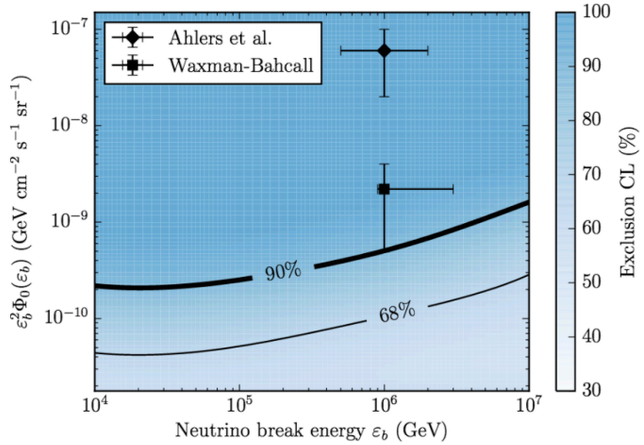
IceCube's first candidate source of high energy neutrinos was a blazar!

TXS 0506+056 (z = 0.336)





Star-forming galaxies (SFGs) [10 - 30%]



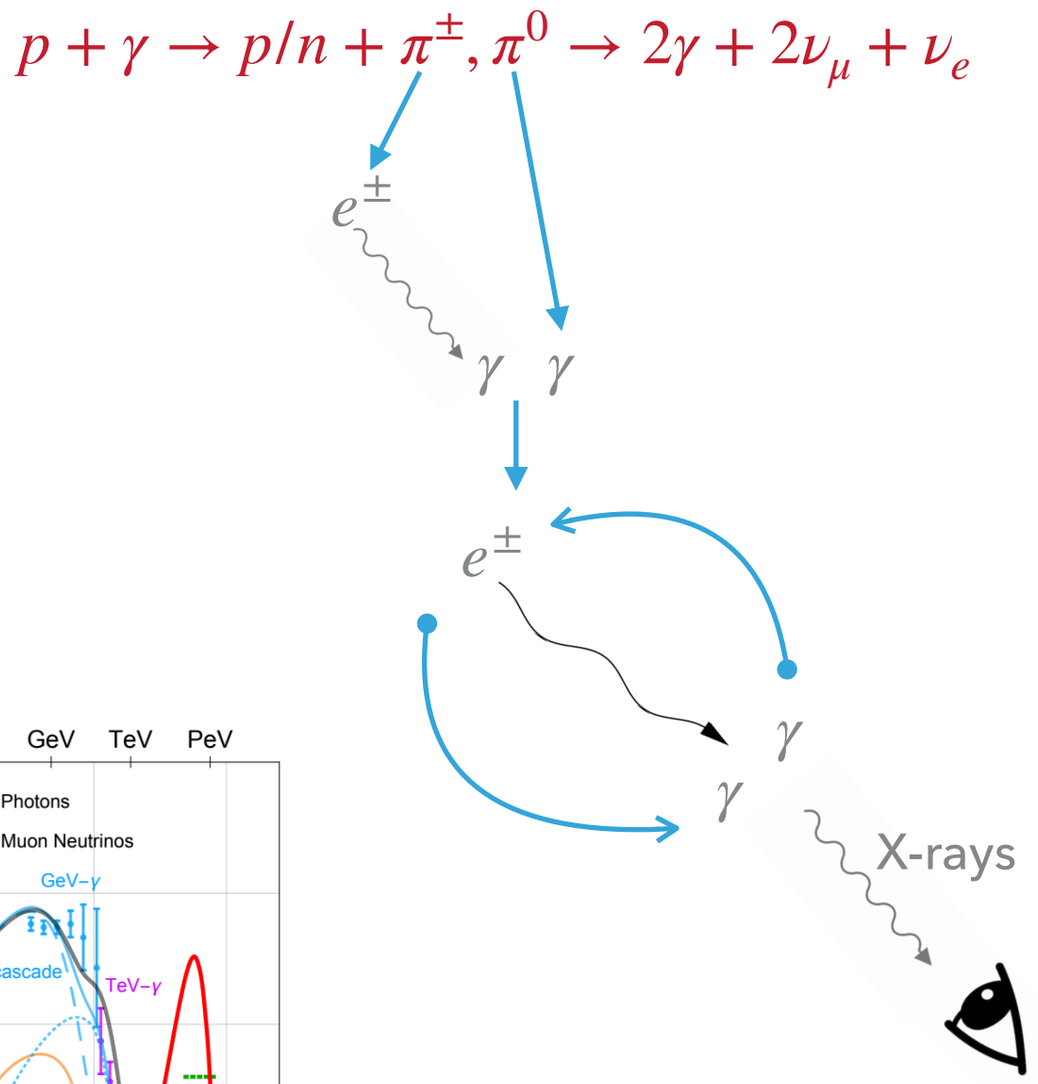
<u>Aartsen et al. ApJ 2016</u>

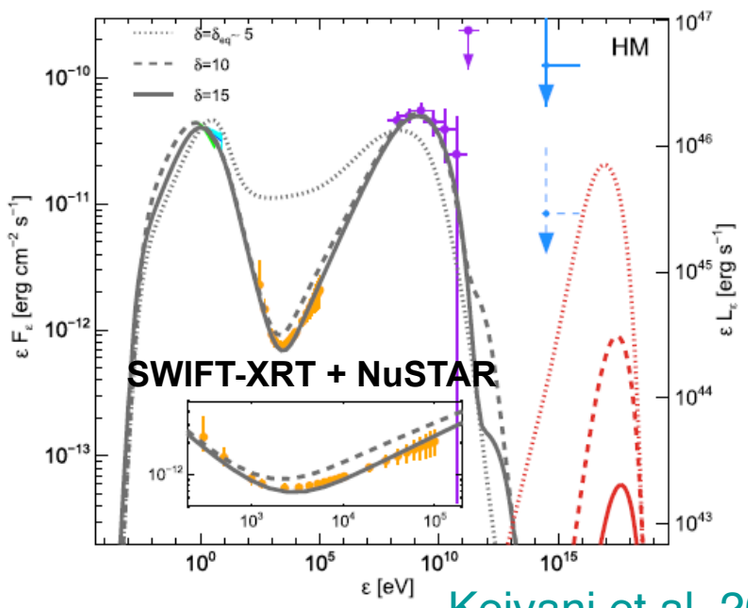
MOTIVATION

Tight correlations b/w radio core and soft-X-ray observations from radio-loud AGN suggest soft- X-rays produced in the jet

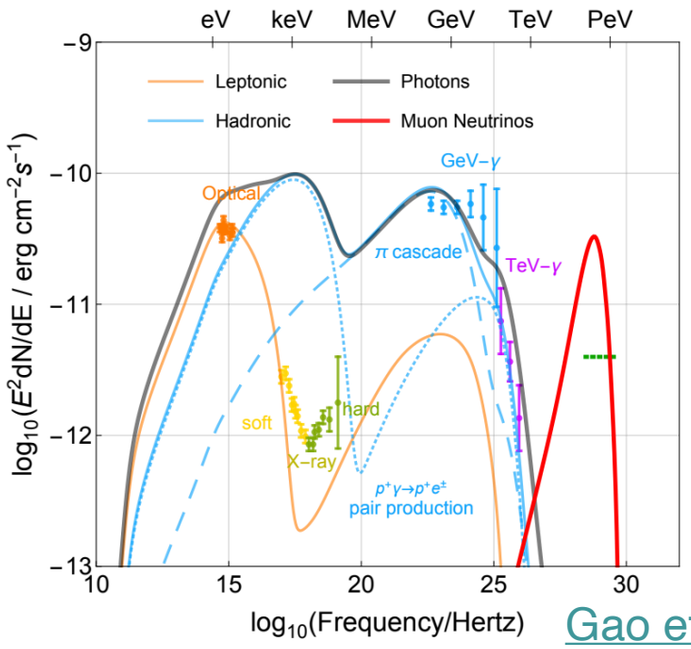
Proton Induced Cascades (PIC) :

- Secondary $e^{\pm}$ pairs generated by pion decay shift the extreme proton energies down to the X-ray band





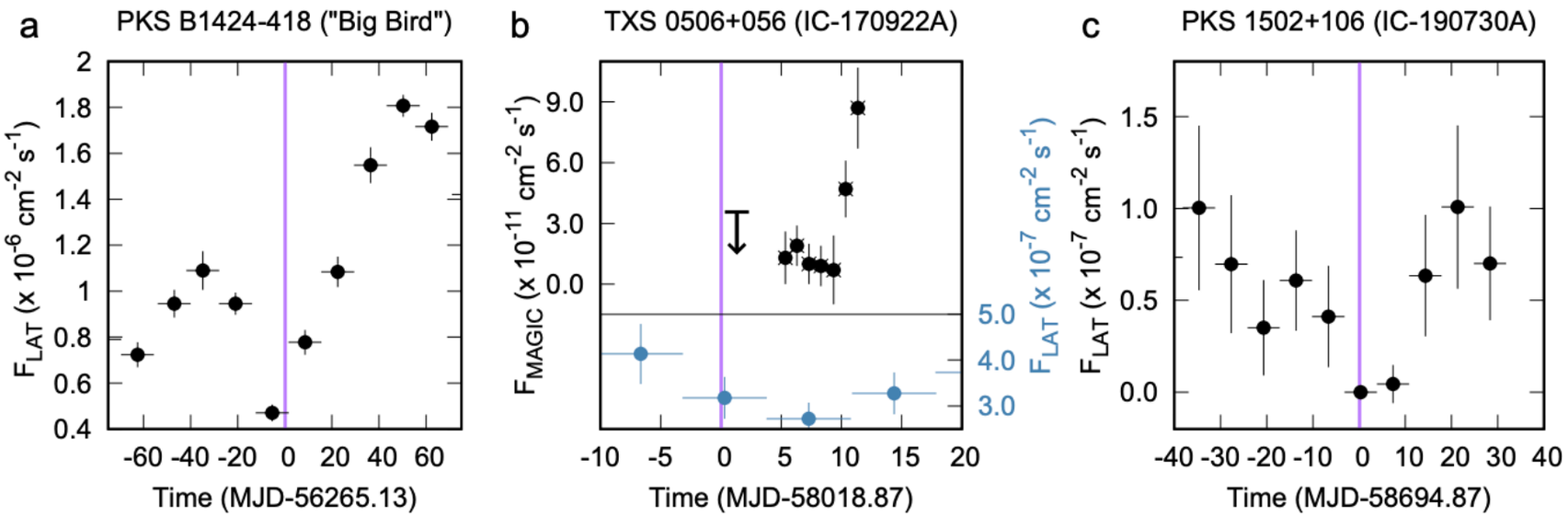
Keivani et al. 2018



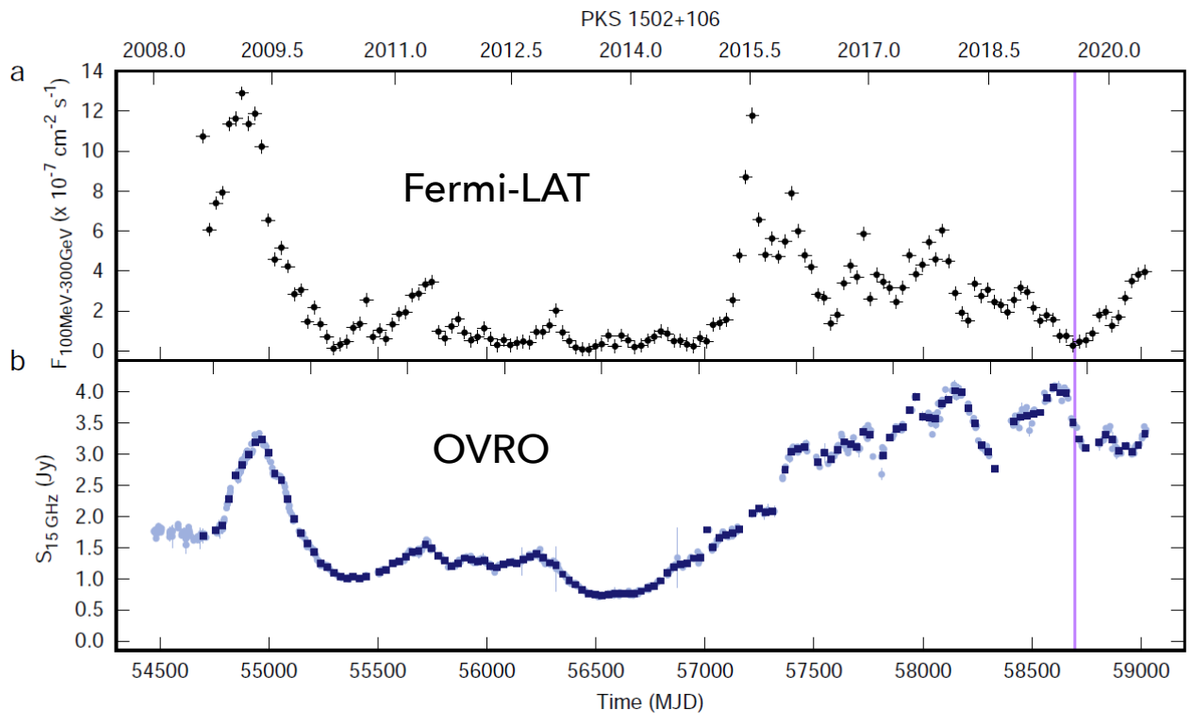
Gao et al. 2018

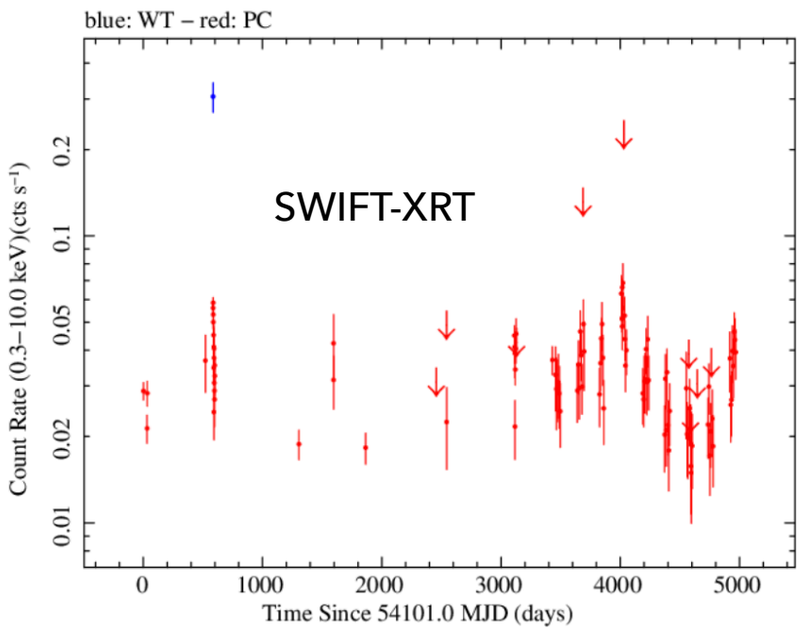
X-rays from PIC can be used to constrain the expected neutrino flux from source, if a hadronic contribution is assumed

Recent investigations observe spatially coincident neutrinos from sources in a γ-suppressed state….



….but an increased X-ray and radio flux is still expected





arXiv:2009.09792

ANALYSIS OVERVIEW

Objective: Search for correlation between X-ray selected blazars and IceCube neutrinos

We want to test the hypothesis that **X-ray bright blazars can be potential sources of high energy astrophysical neutrinos**….
…..under the assumption that **blazars can flare > 2 times on average in 10 years**

A **model independent,** time-dependent untriggered multi-flare search:

- ➡ search for neutrino flares in 10 years of IceCube data from each source in a catalog of blazars curated based on X-ray flux
- ➡ obtain a p-value for each source using the **multi-flare TS**
- ➡ perform a population test using the binomial test statistic to determine the sub-population with statistically significant emission

Test for Northern sky, and by categories of blazars:

1. **Northern BL Lacs**
2. **Northern FSRQs**
3. **Northern blazars (all)**

Dataset	LLH	Catalog
High-Energy Tracks (6th April 2008 - 8th July 2018)	**Un-binned**	**RomaBZCat (1k northern sky blazars)**

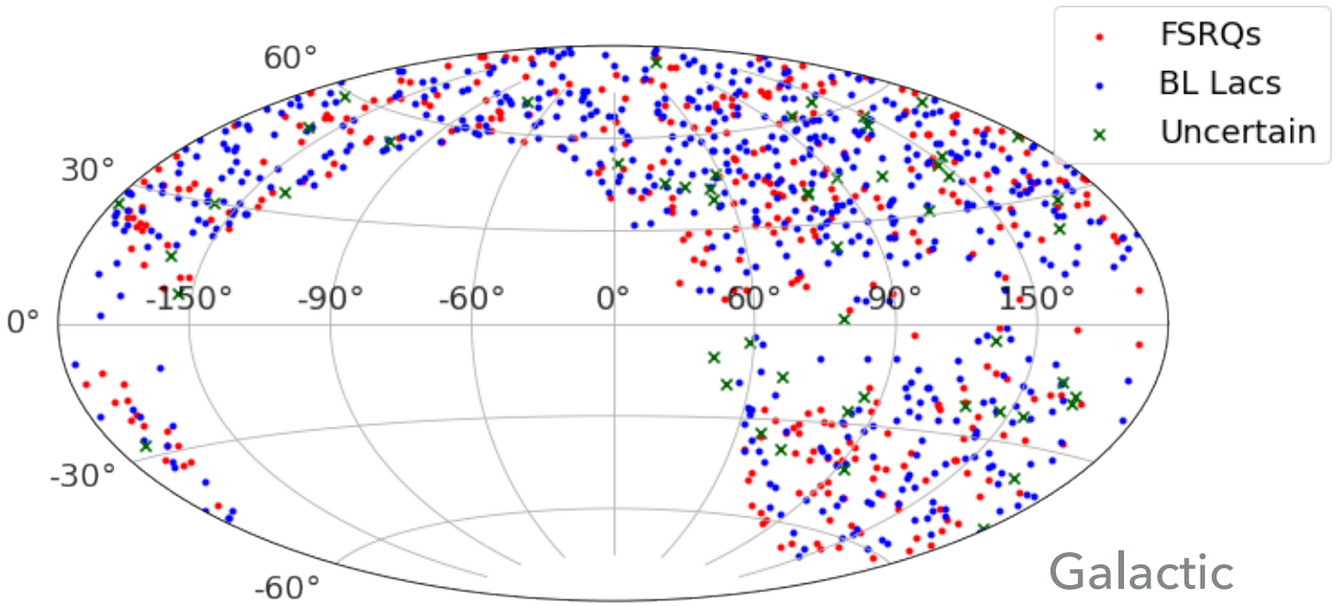
SOURCE SELECTION

ROMABZCAT 5TH EDITION (2015)

- Multi-frequency blazar catalog with fluxes in **radio** (1.4 GHz), **microwave** (143 GHz), **X-ray** (0.1 - 2.4 keV) and **γ-ray** (1 - 100 GeV) frequencies
- **3561 blazar AGNs:** BL Lacs, FSRQs and blazars of uncertain type
- X-ray fluxes taken from **ROSAT**

CATALOG DOWN-SELECTION

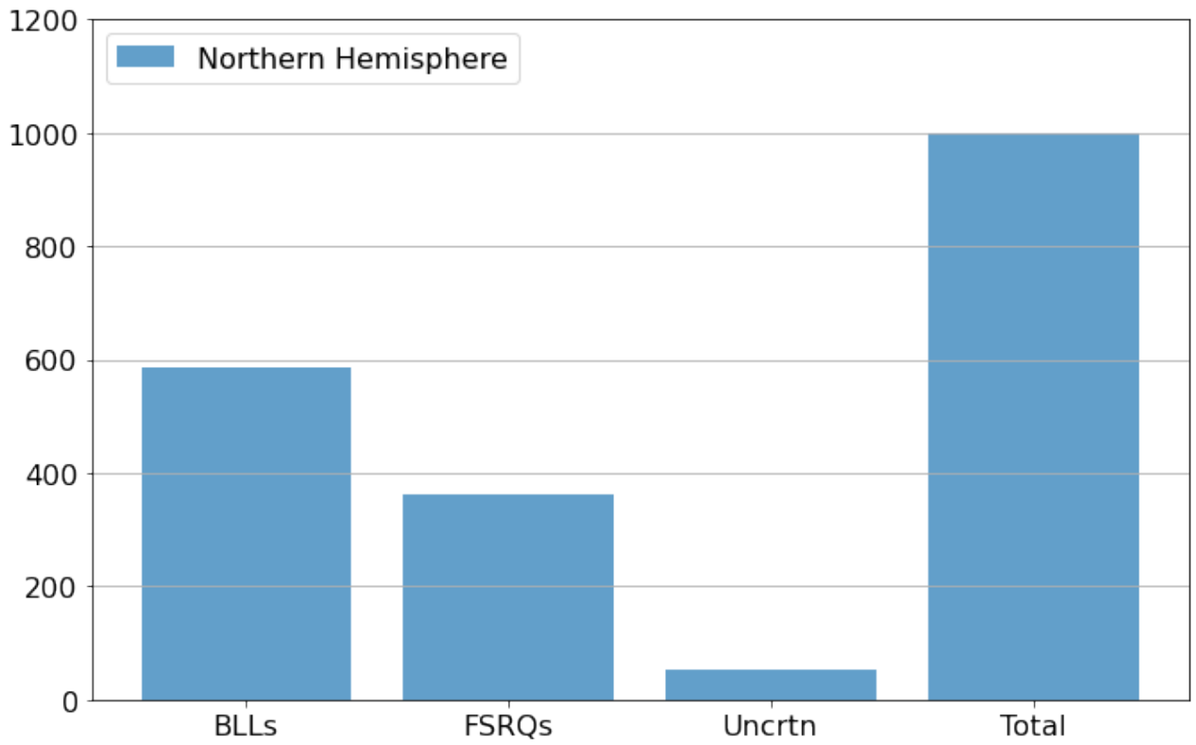
✓ We select 1000 blazars from the Northern hemisphere (-5, +85) with the highest X-ray fluxes in the catalog

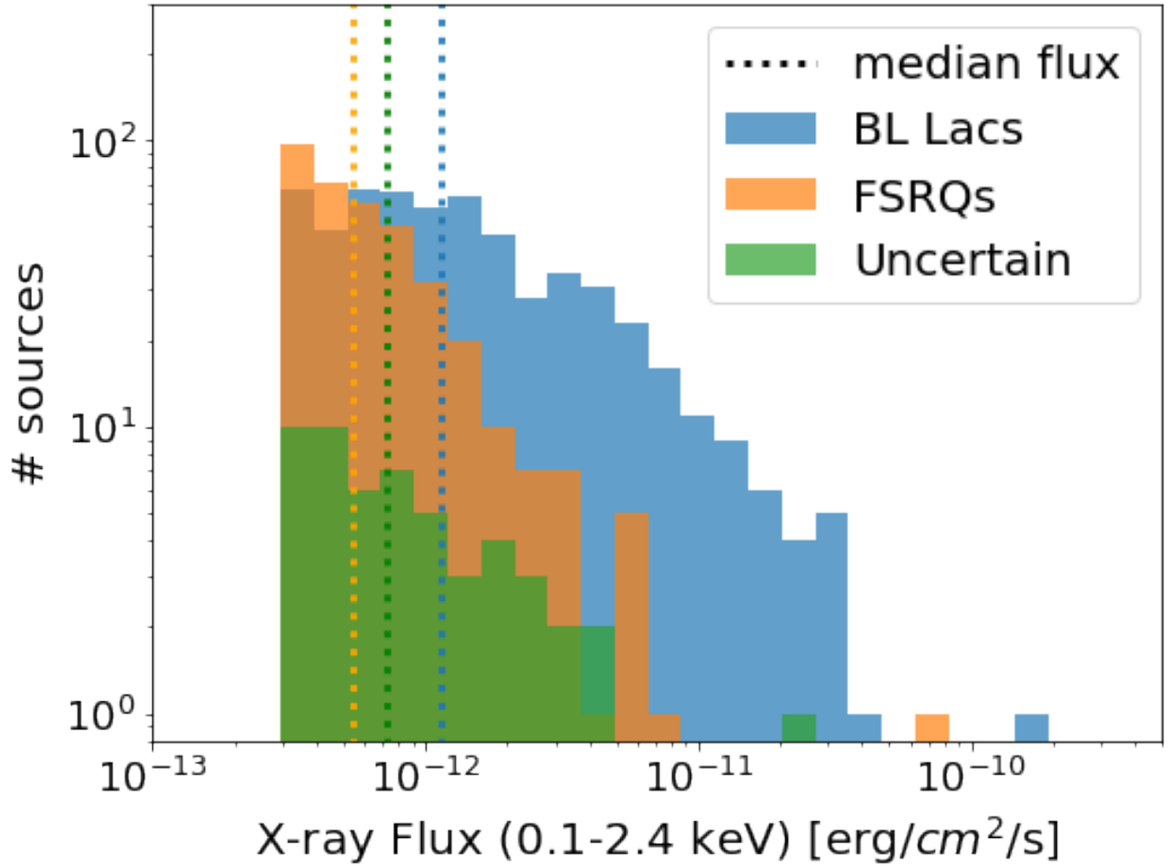


ROMABZCAT 5 : AFTER SELECTION CUTS

After selection cuts:

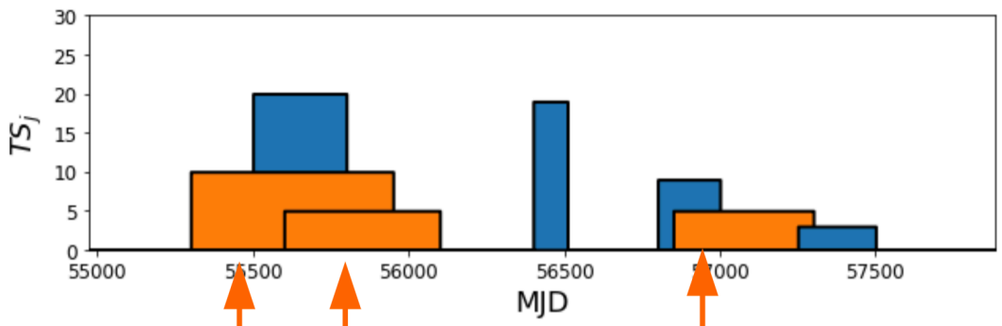
- **BL Lacs: 586, FSRQs: 361, Uncertain type: 53**
- **~5% overlap with SWIFT-BASS 70 month catalog blazars arXiv:2107.08366**
- **X-ray fluxes between: 3.1e-13 to 1.8e-10 erg/cm²/s**





MULTI-FLARE METHOD

- Blazars are variable sources. If neutrino flares behave like EM flares, **can expect > 1 flare on avg. from sources over the period IceCube has been taking data**
- Method already established by previous searches in IceCube:
  - ➡ Test flare windows for each source direction using seed events that pass the S/B threshold
  - ➡ Remove overlapping flares by selecting the flare with the highest significance
  - ➡ Stack the significance of all the remaining flares to obtain the **multi-flare TS**

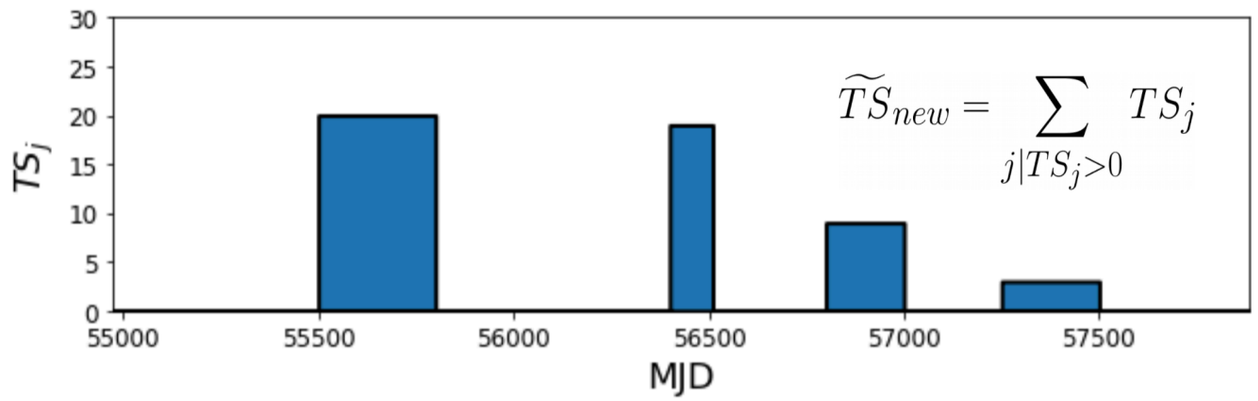


These flare candidates overlap with a more significant flare candidate that isn't going to be removed. Remove these.

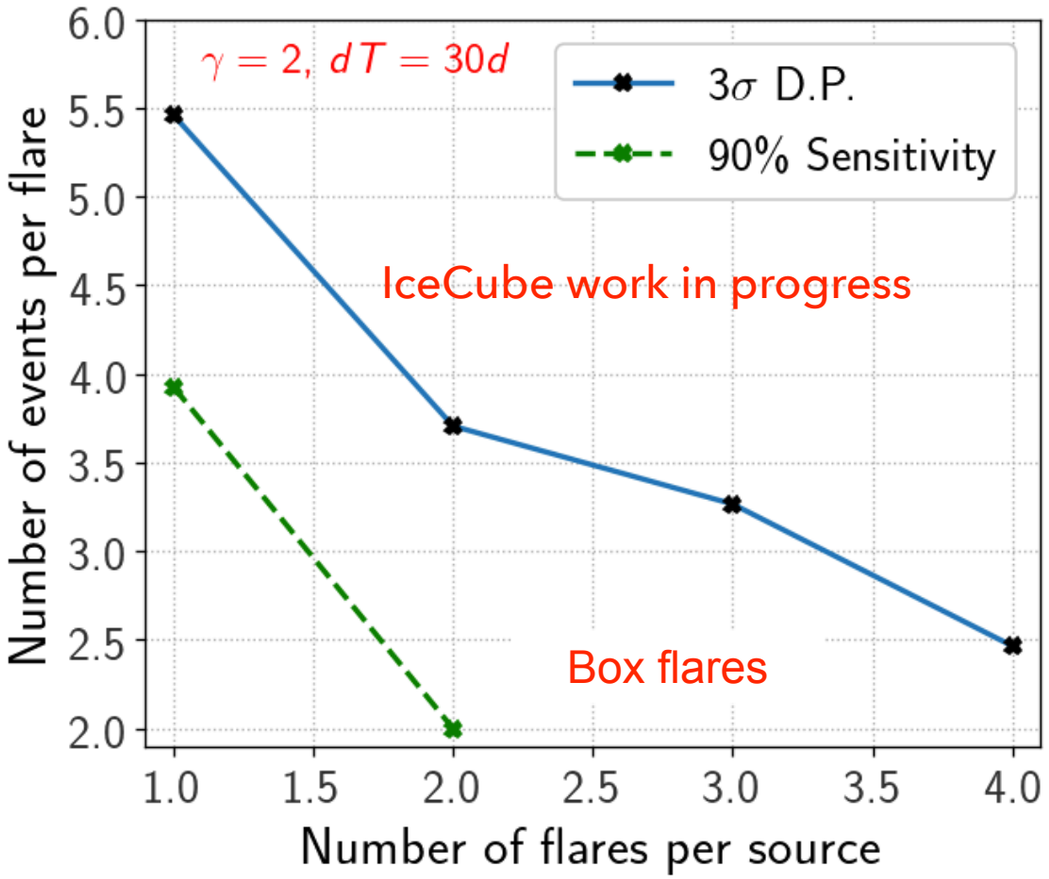
Credit: Will Luszczak

$$\mathcal{L}(n_s, \gamma, \Delta t_j) = \prod_{i=1}^{N} \frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i$$

$$\mathrm{TS}_j|_{\Delta t_j} = -2 \log \left[\frac{\Delta T_{\mathrm{data}}}{\Delta t_j} \times \frac{\mathcal{L}(\vec{x}_s, n_s = 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma}_s)} \right]$$



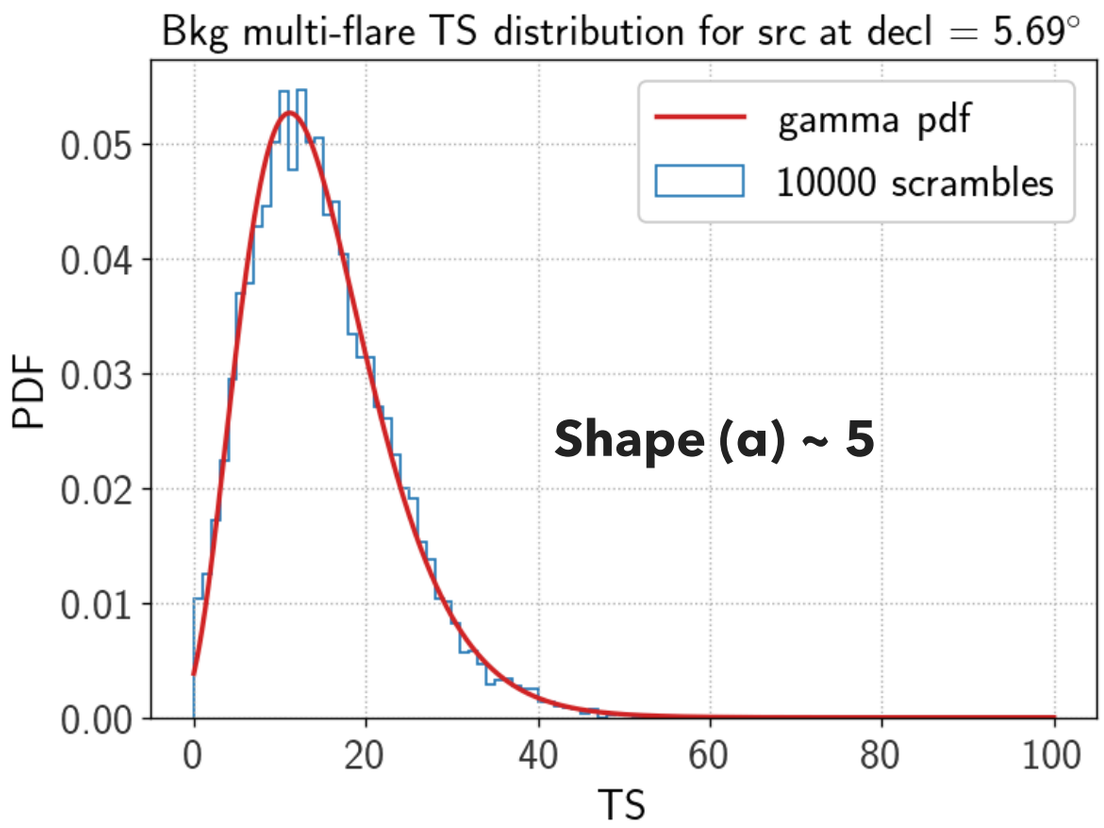
PRELIM RESULTS – PER SOURCE SENSITIVITY



- 10k scrambles for a single source location (at the declination of TXS)
- With and without injections (background trials)
- Box profile flares
- Fixed spectral index and injected flare duration (**γ = 2, dT = 30 days**)
- S/B = 2000 & Max. Flare duration = 1000 days

Strength of individual flares from a single source required to obtain a final discovery potential (D.P.) of 3-sigma, and a 90% C.L. sensitivity

Background multi-flare TS distribution for the declination of TXS across 10k trials



BINOMIAL TEST

Tests the compatibility of a known catalog with background-only hypothesis

- if a sub-population within the catalog has statistically significant emission, it can tell how many and which sources are of interest

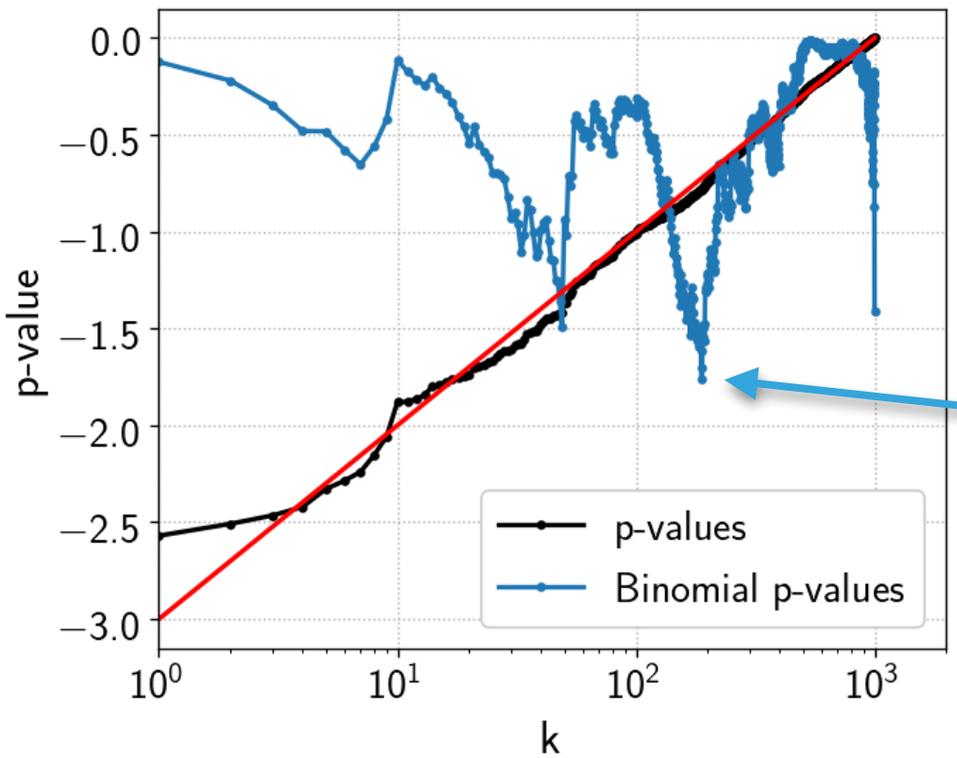
$$P(k) = \sum_{m=k}^{N} \binom{N}{m} p_k^m (1 - p_k)^{N-m}$$

For an ordered set of p-values, it determines the binomial probability P(k) at each source k, to obtain k or more p-values equal or lower than the local p-value at k

Good initial guess at the sub-population => better results

➡ **test separately for all sub-categories i.e. BL Lacs, FSRQs etc.**

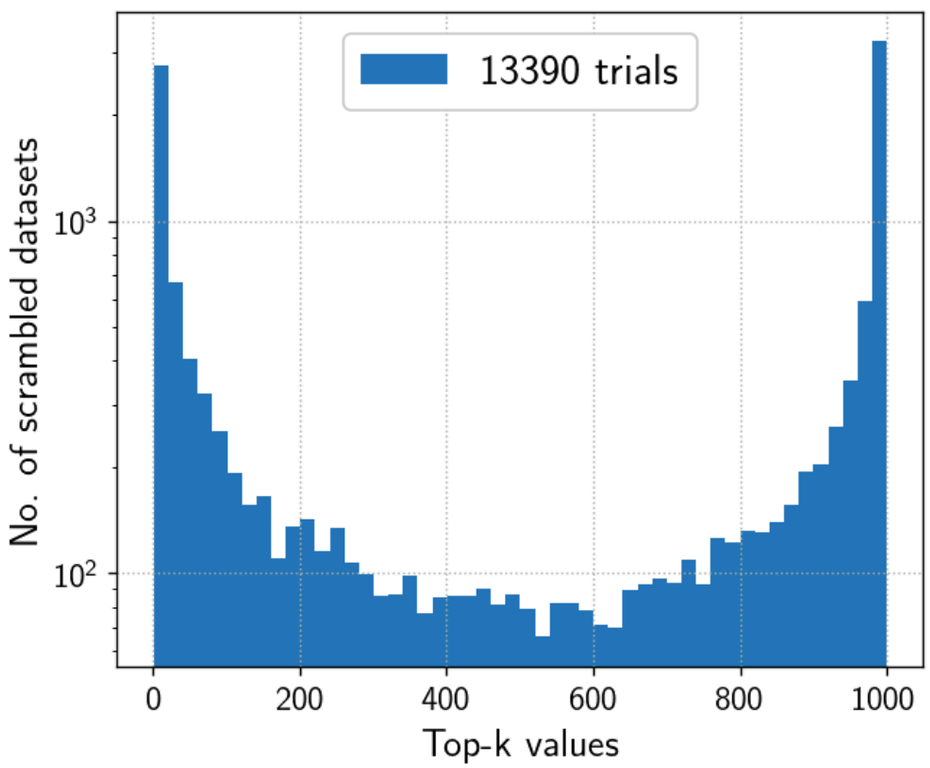
BINOMIAL TEST: DISTRIBUTIONS



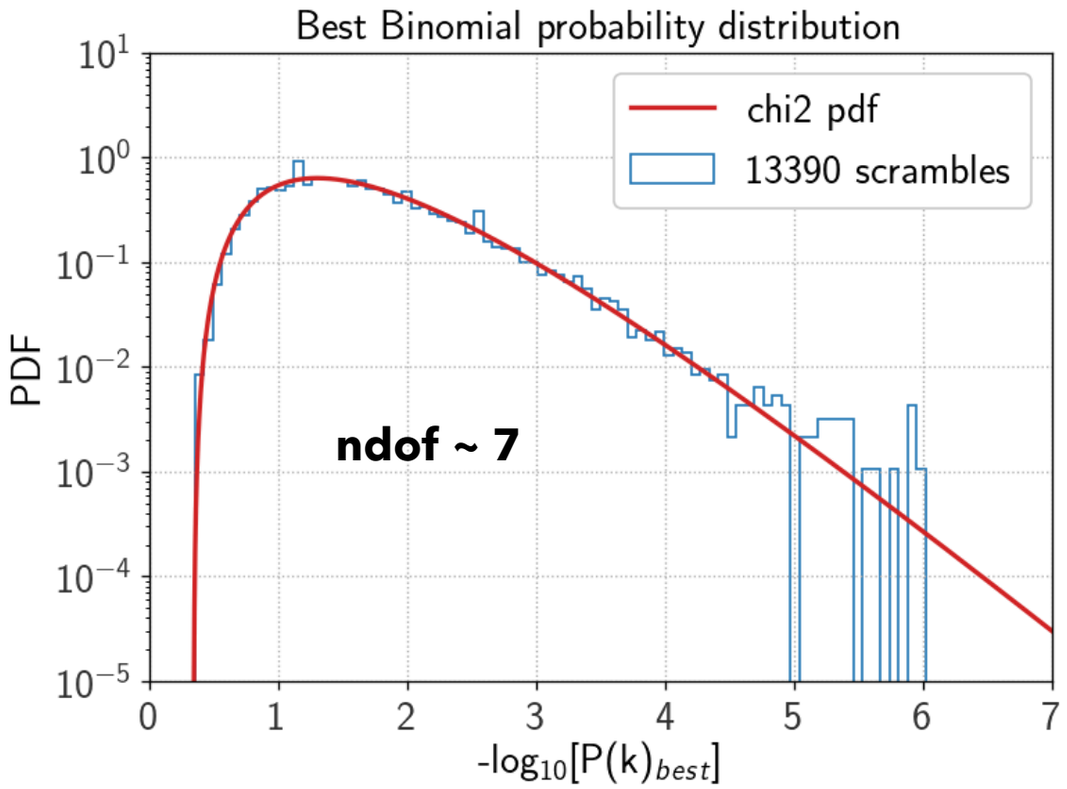
Binomial probability distribution (Binomial p-values) for a single binomial test on 1000 sources

Best case 'k' : 196

Best Binomial p-value: 0.016



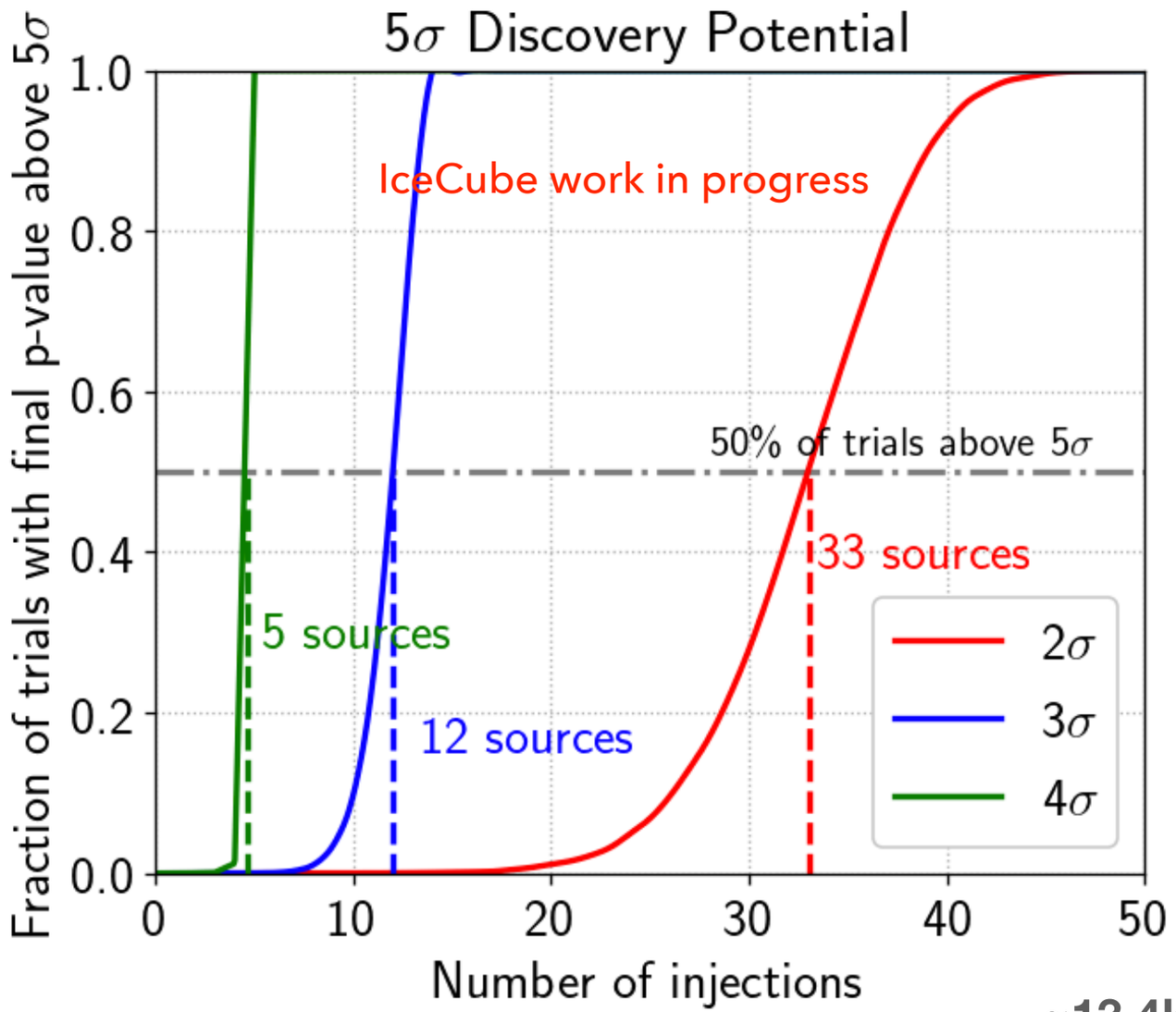
Top 'k' value distribution for 13.4k trials



$P(k)_{best}$ distribution for 13.4k trials

BINOMIAL TEST : POST-TRIAL SIGNIFICANCE

Final significance considering we are testing many sources



~13.4k background scrambles

33 (12, 5) sources of 2σ (3σ, 4σ) individual significance required to obtain a 5σ final significance from the analysis

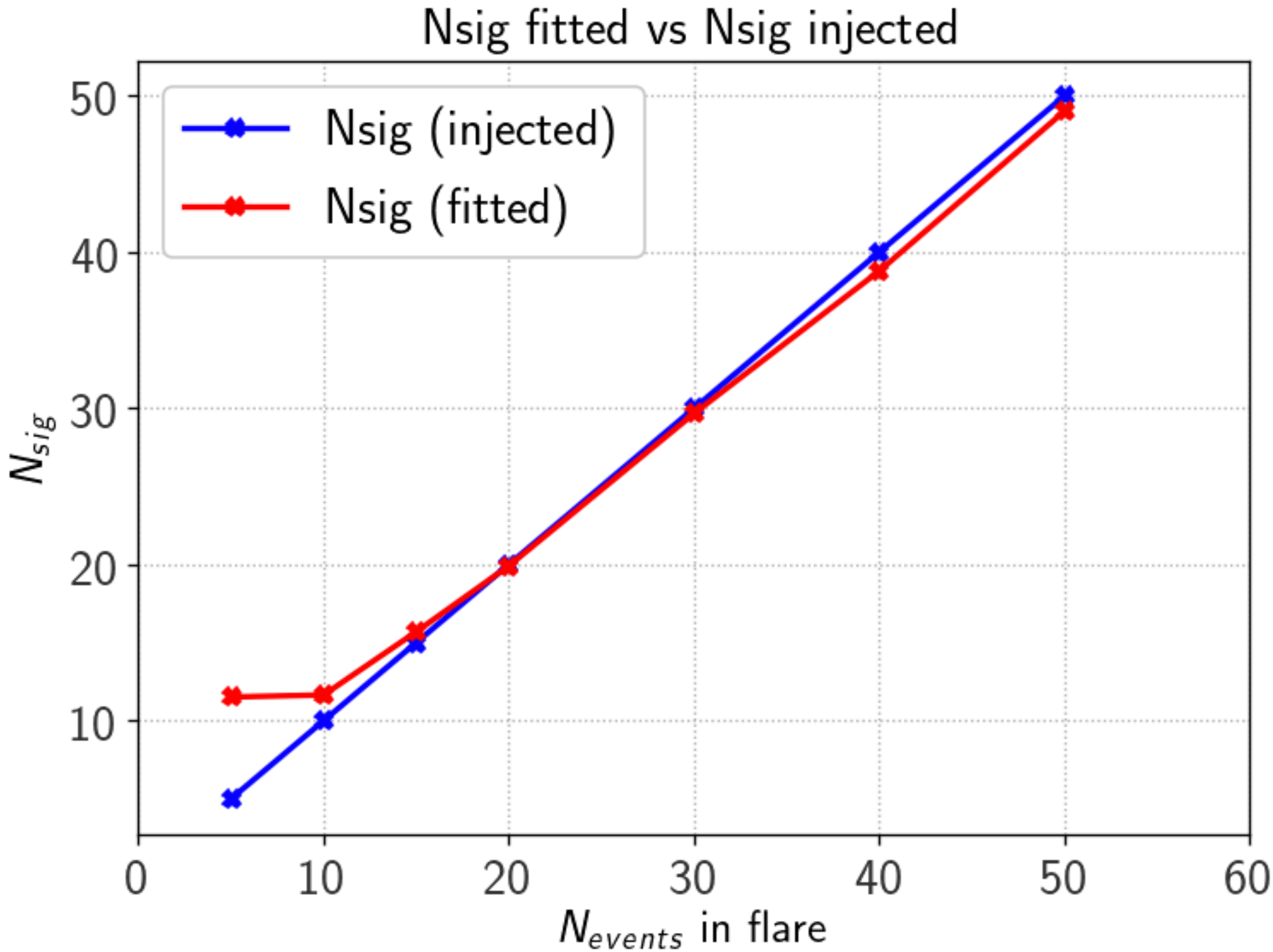
SUMMARY

- Testing correlation between X-ray bright blazars and IceCube neutrinos
- Stack individual flares from each direction to boost significance
- 1000 Northern sky blazars from RomaBZCat; 10 year IceCube track-like events
- Population test using binomial test statistic
- Sensitivities and post-trial significance estimated based on background scrambles; pending unblinding approval

Thank You!

BACKUP

FIT BIAS

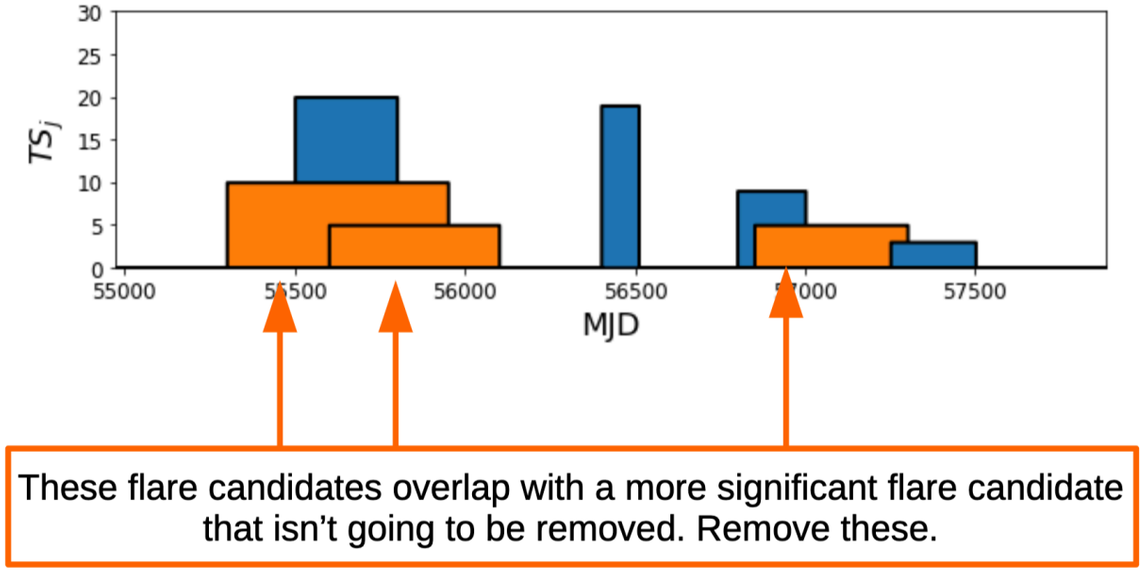


Single flare; gamma = 2, Flare duration = 30 days

DECORRELATIONS

Correlation between flares from a single source:

➡ remove all overlapping flares except the most significant one!

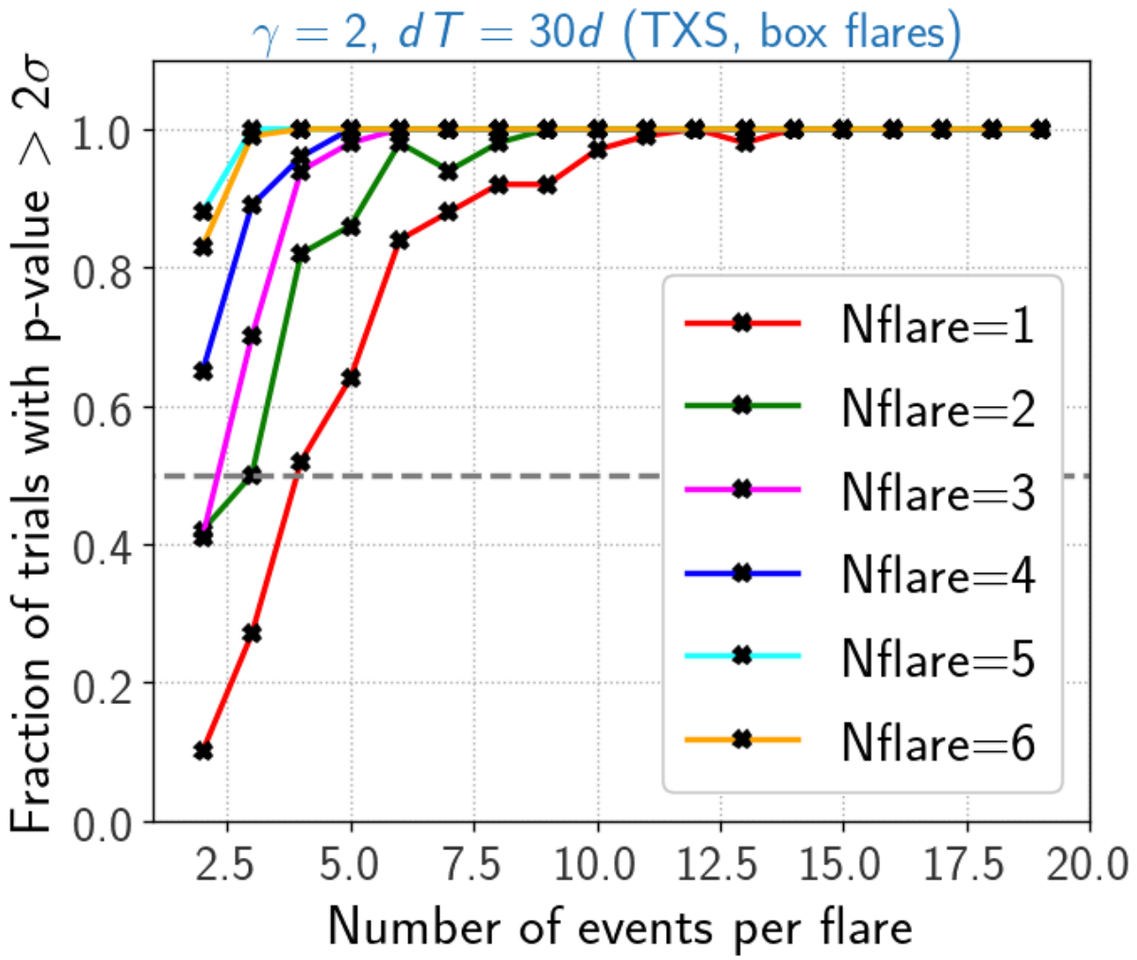


Correlation between events from different sources?

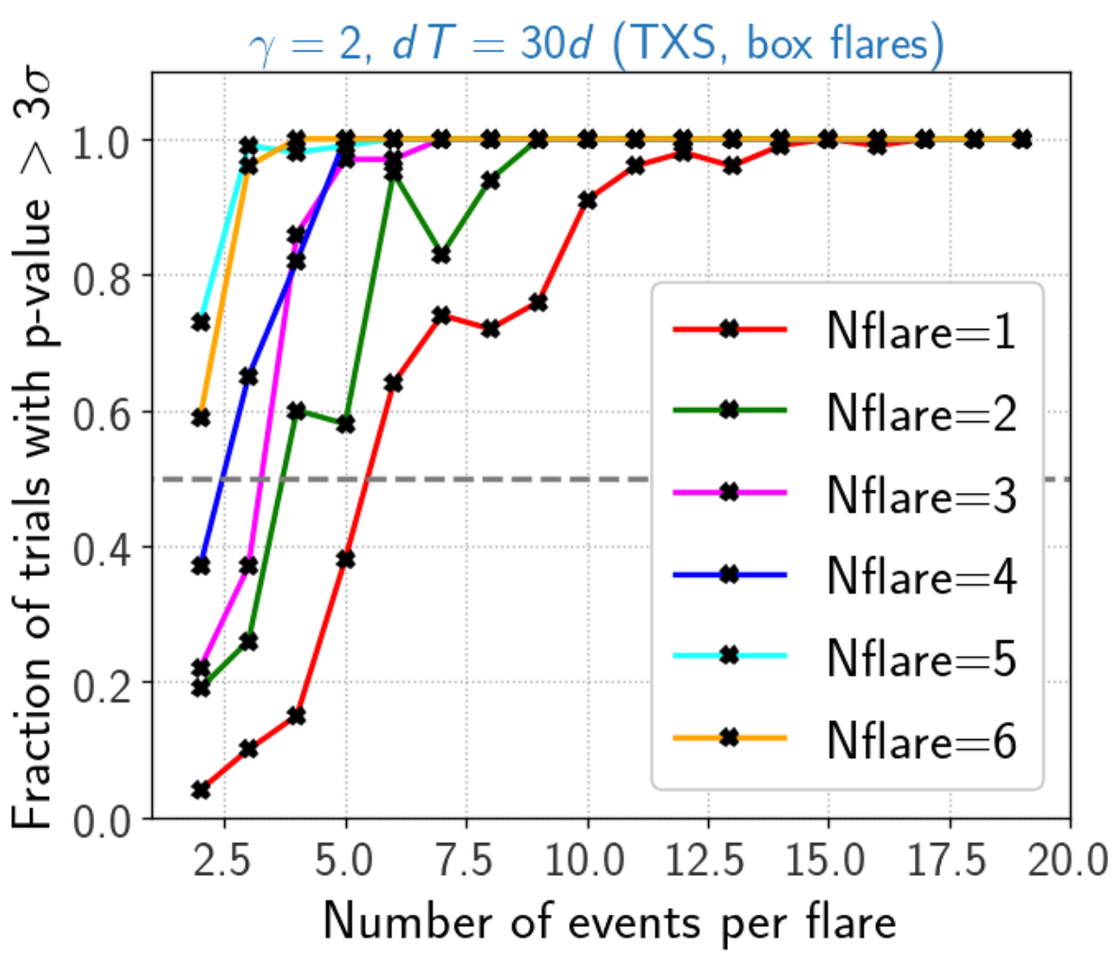
➡ 1000 sources in the catalog
➡ A single neutrino event can be counted as signal from more than one source due to large uncertainty in position, or sources in close proximity

☑ **Simulate the background scrambles with the entire catalog at once. Any correlations between sources would be present in the background trials as well, and hence accounted for**

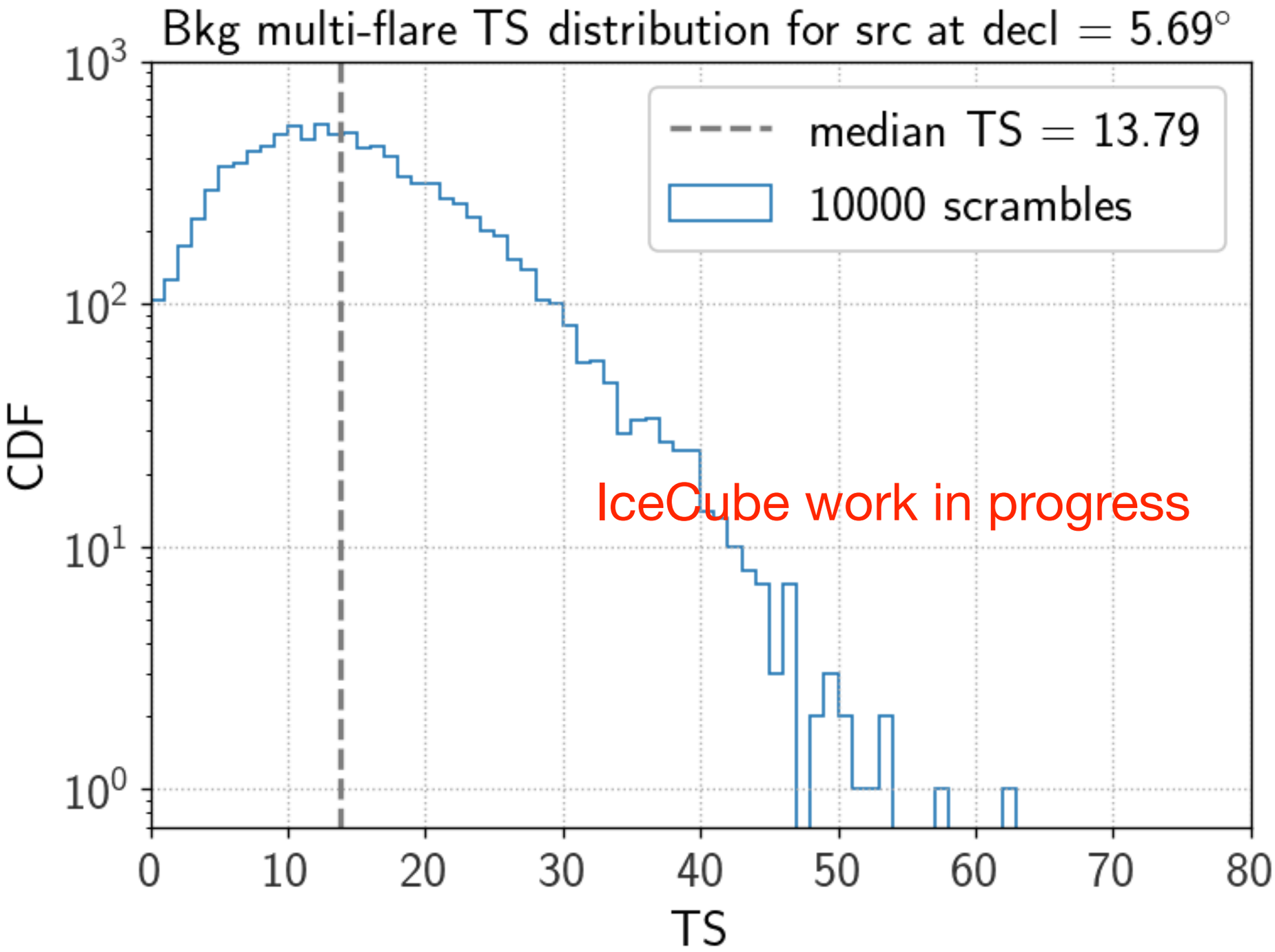
PER SOURCE SENSITIVITY



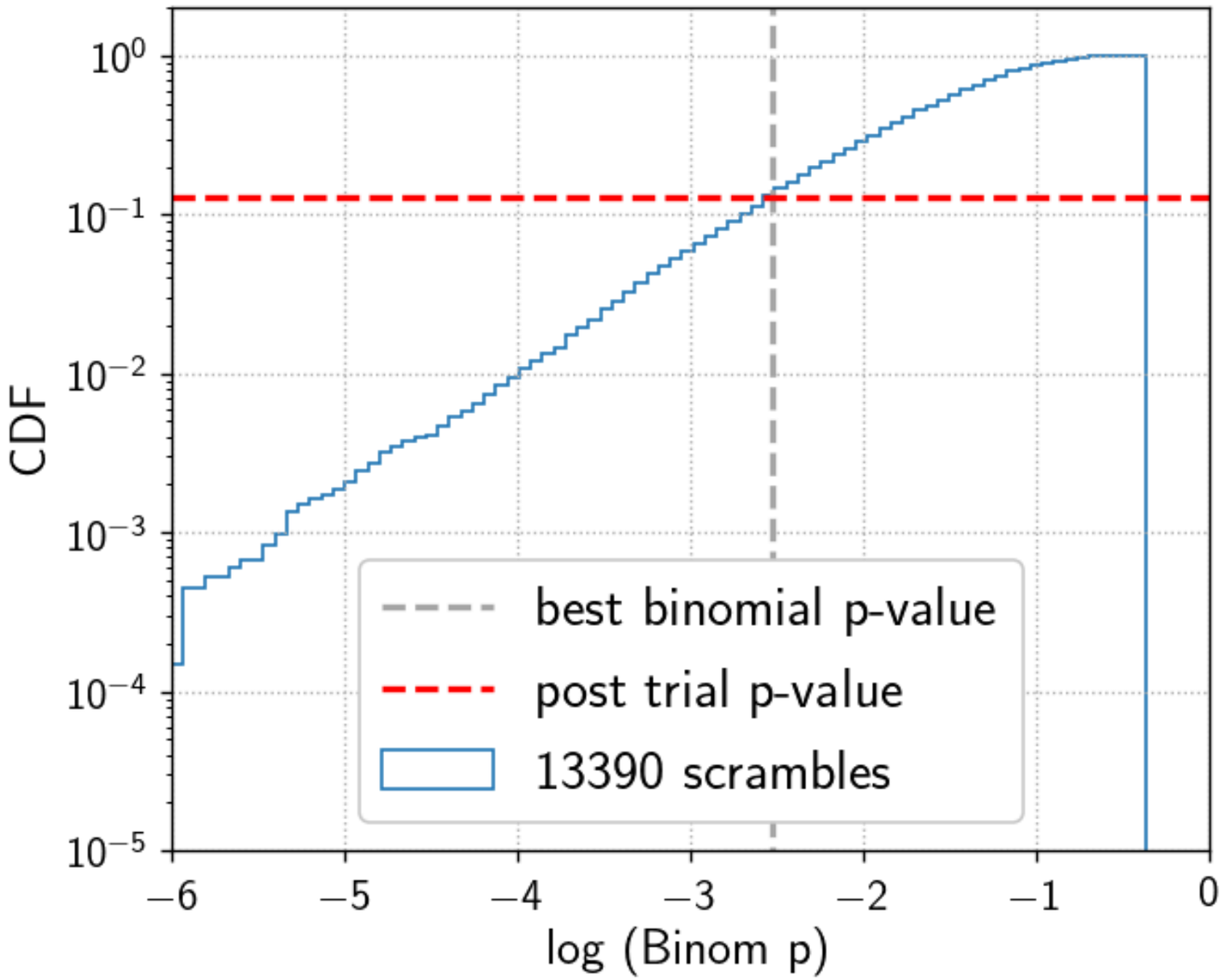
Number of events required for different values of NFlare to obtain 50% trials with p-value > 2-sigma and 3-sigma



SINGLE SOURCE BKG TS DISTRIBUTION



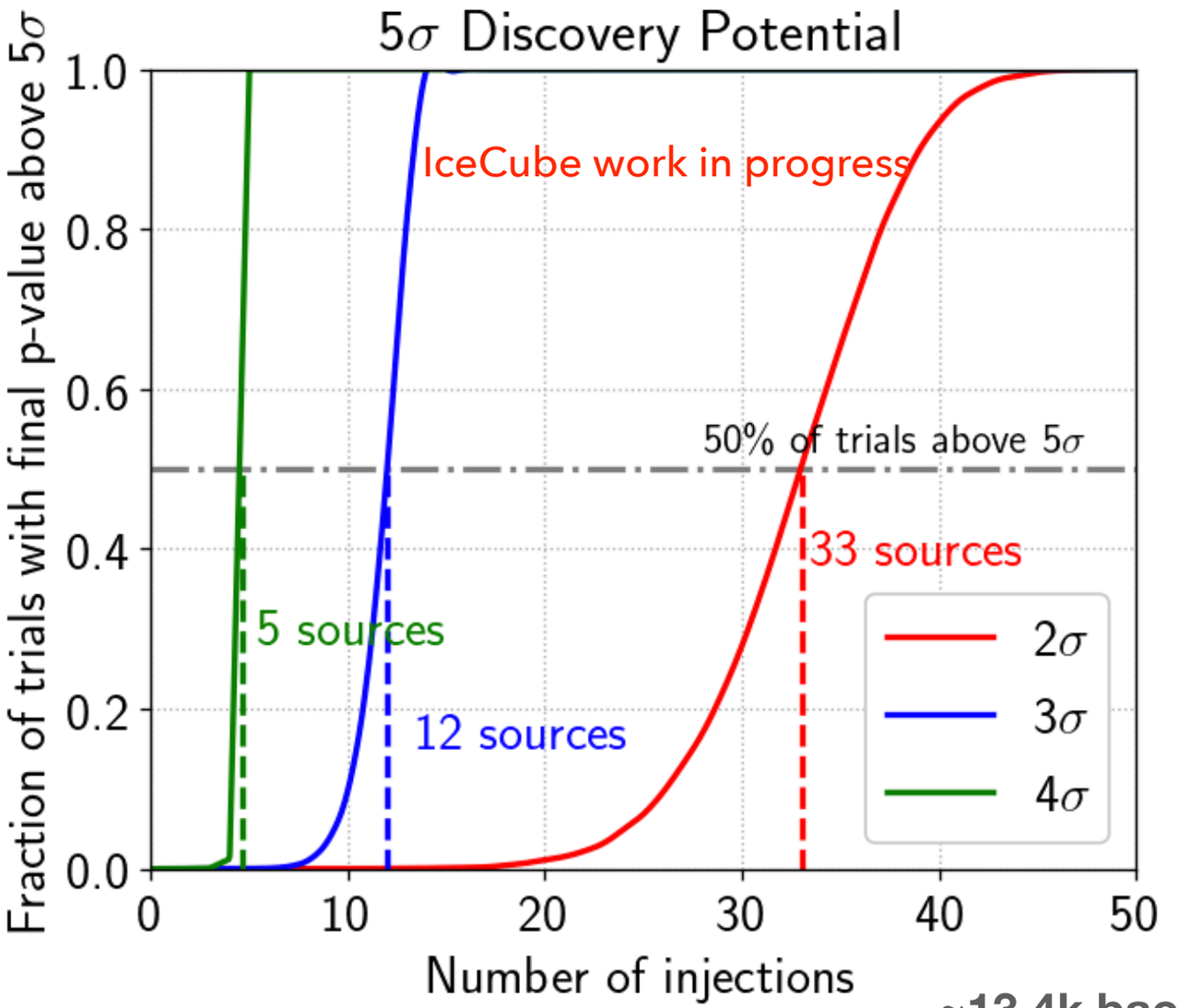
POST-TRIAL P-VALUE CALCULATION



Calculation of post-trial p-value from binomial tests performed on background scrambles

BINOMIAL TEST : POST-TRIAL SIGNIFICANCE

Final significance considering we are testing many sources



- Calculate (pre-trial) p-values for all sources over ~ 13.4k bkgd scrambles, using the **multi-flare TS**
- Perform **binomial tests** on these p-values to get a bkgd distribution of best binomial probabilities **(P_{best})**
- For each scramble, **inject** upto (m= {1,50}) n-sigma sources (where n=2,3,4) and perform binomial tests on these modified sets
- Obtain post-trial p-values for each of the injected best binomial probabilities, and compare the fraction of trials that give a **post-trial p-value** > 5σ

~13.4k background scrambles

33 (12, 5) sources of 2σ (3σ, 4σ) individual significance required to obtain a 5σ final significance from the analysis

OVERLAPS

RomaBZCat has nearly 1/3rd of the sources in common with 3LAC and 3FHL Fermi catalogs

- Overlap with **3FHL** : 392 sources **(~ 22%)**
- Overlap with **3LAC** : 608 sources **(~ 34%)**
- Overlap with (**3FHL + 3LAC**) : 645 sources **(~ 36%)**

Overlap with previous studies