MULTI-FLARE ANALYSIS OF X-RAY SELECTED BLAZARS

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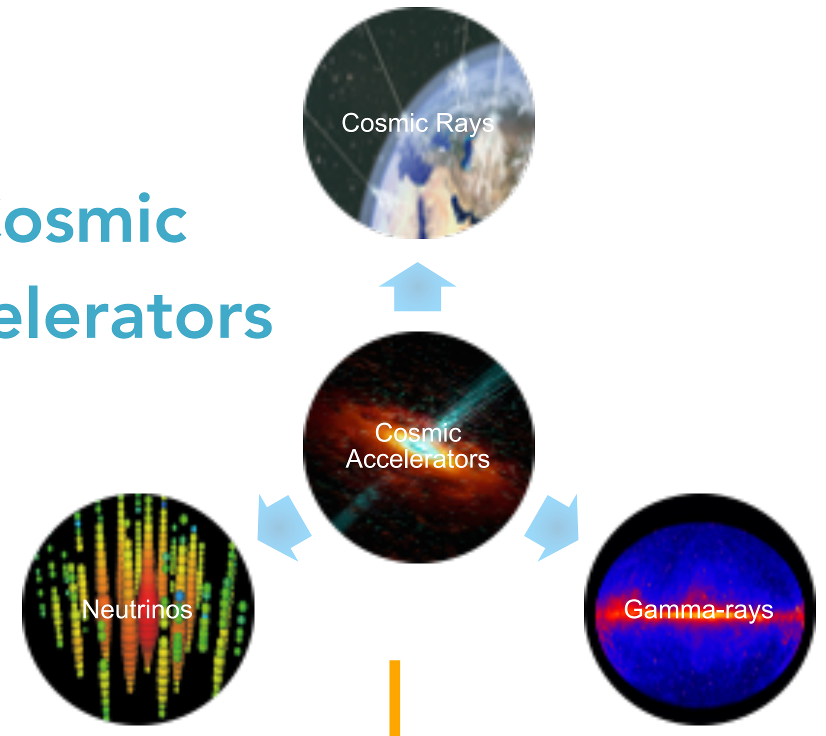
FYSIKDAGARNA | JUNE 2022 | LUND

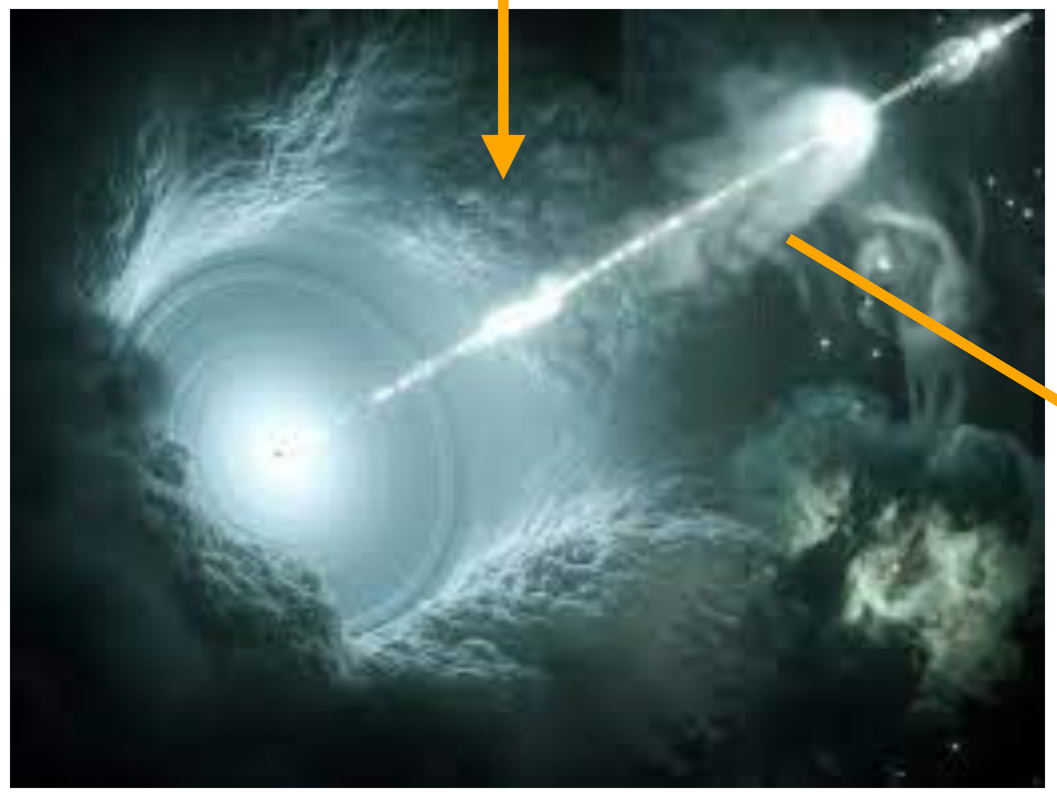
ICECUBE NEUTRINO OBSERVATORY

MULTI-MESSENGER ASTROPHYSICS

(Photons, neutrinos, cosmic rays)

Cosmic Accelerators





Active Galactic Nuclei (jetted)

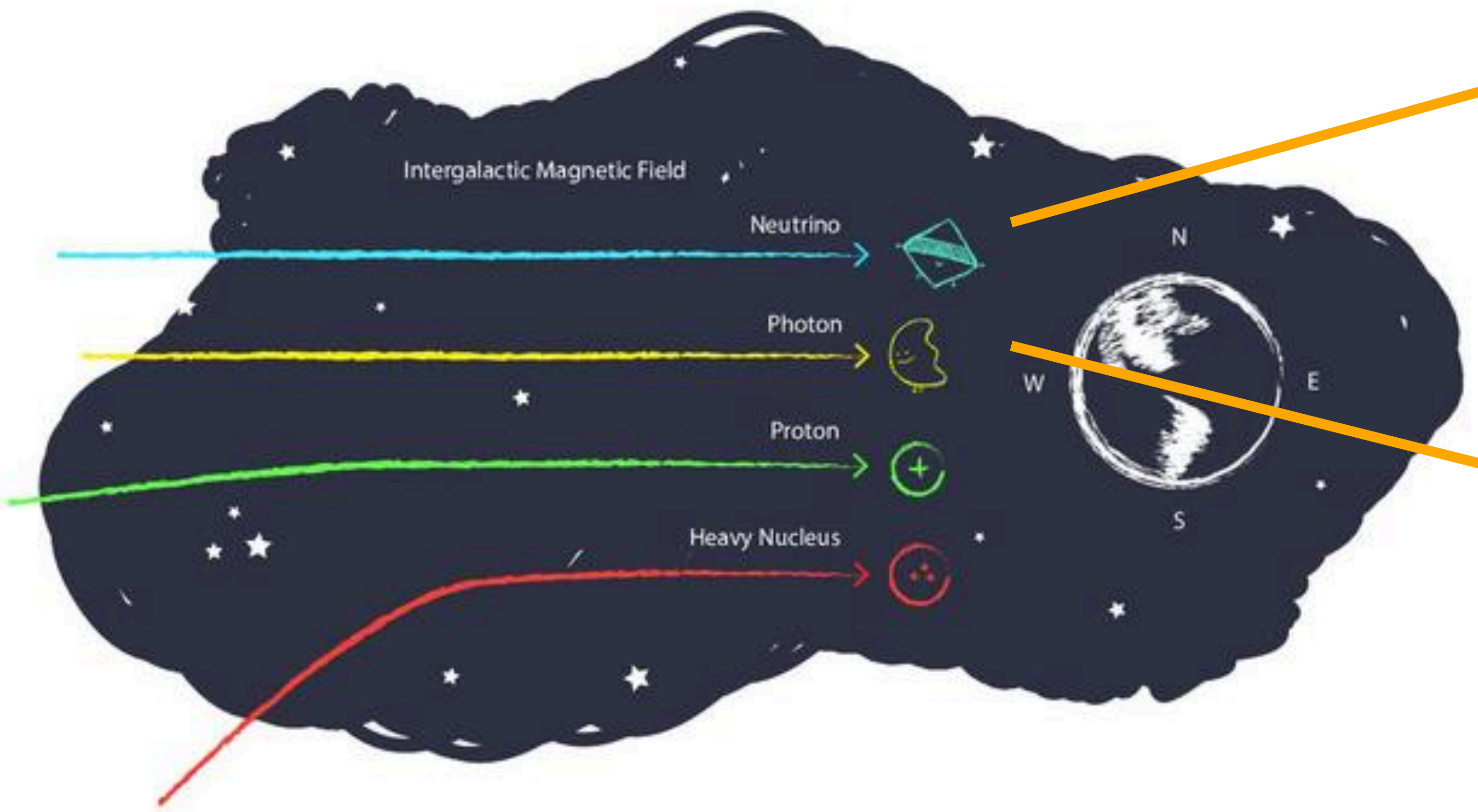
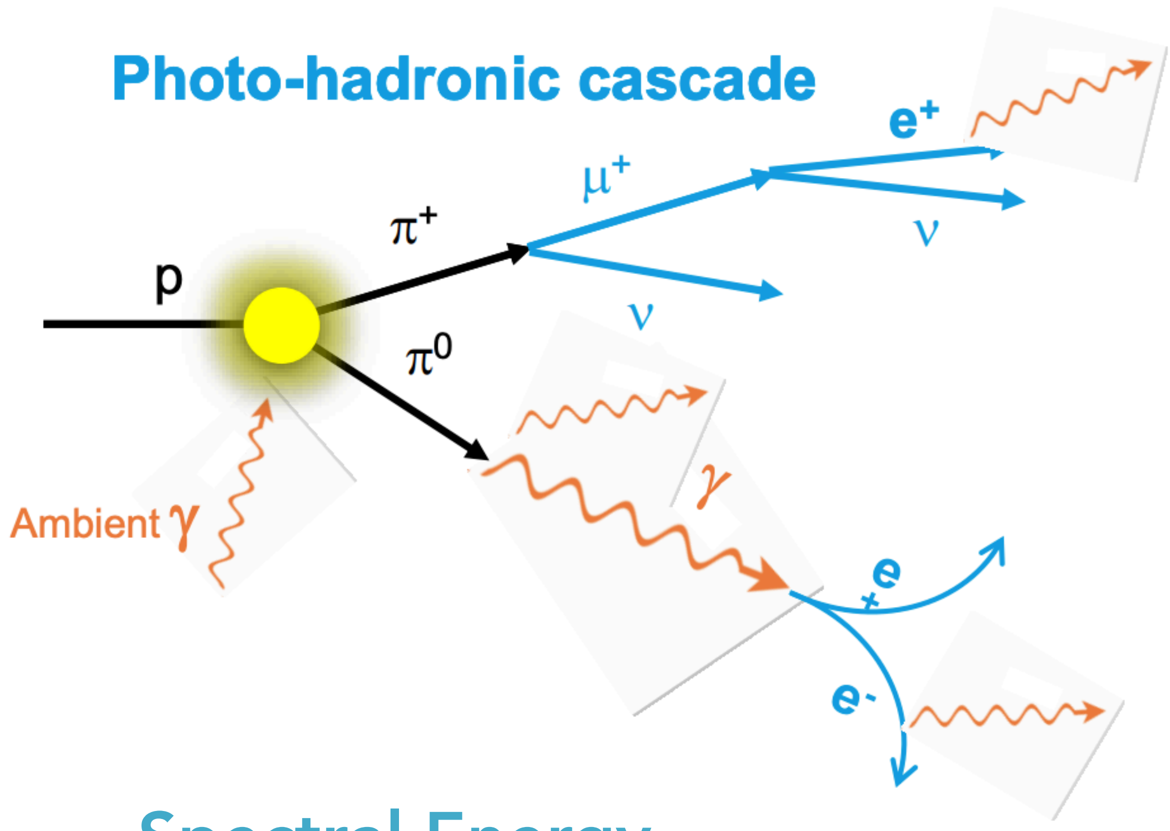
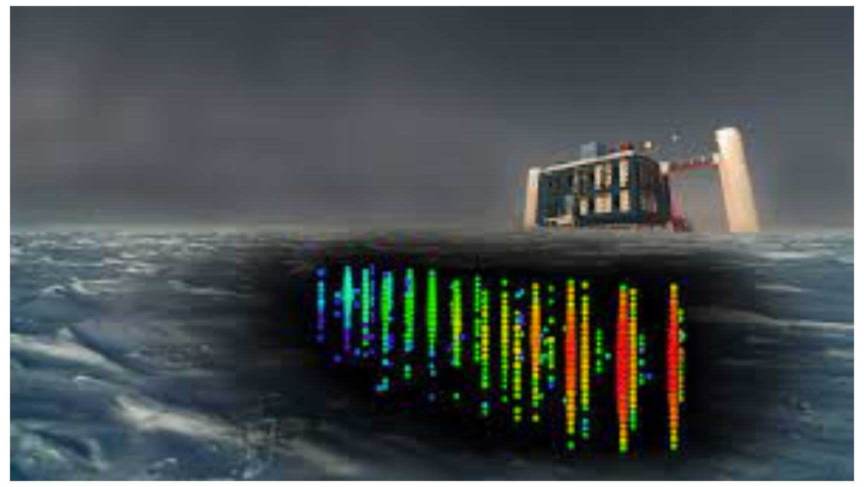


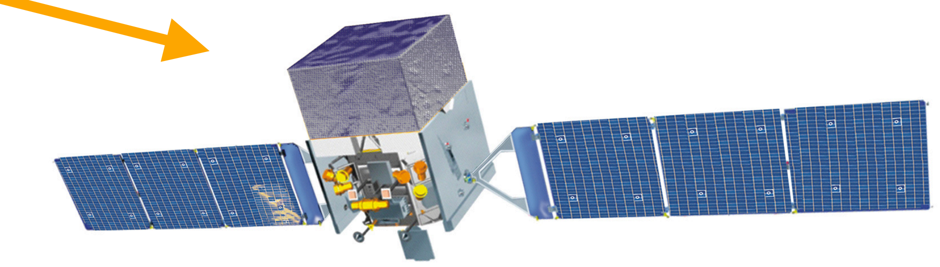
Photo-hadronic cascade



Spectral Energy Distribution (SED)

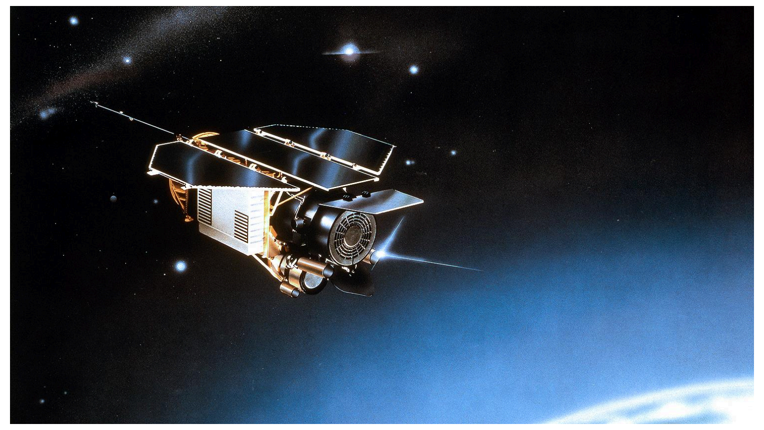


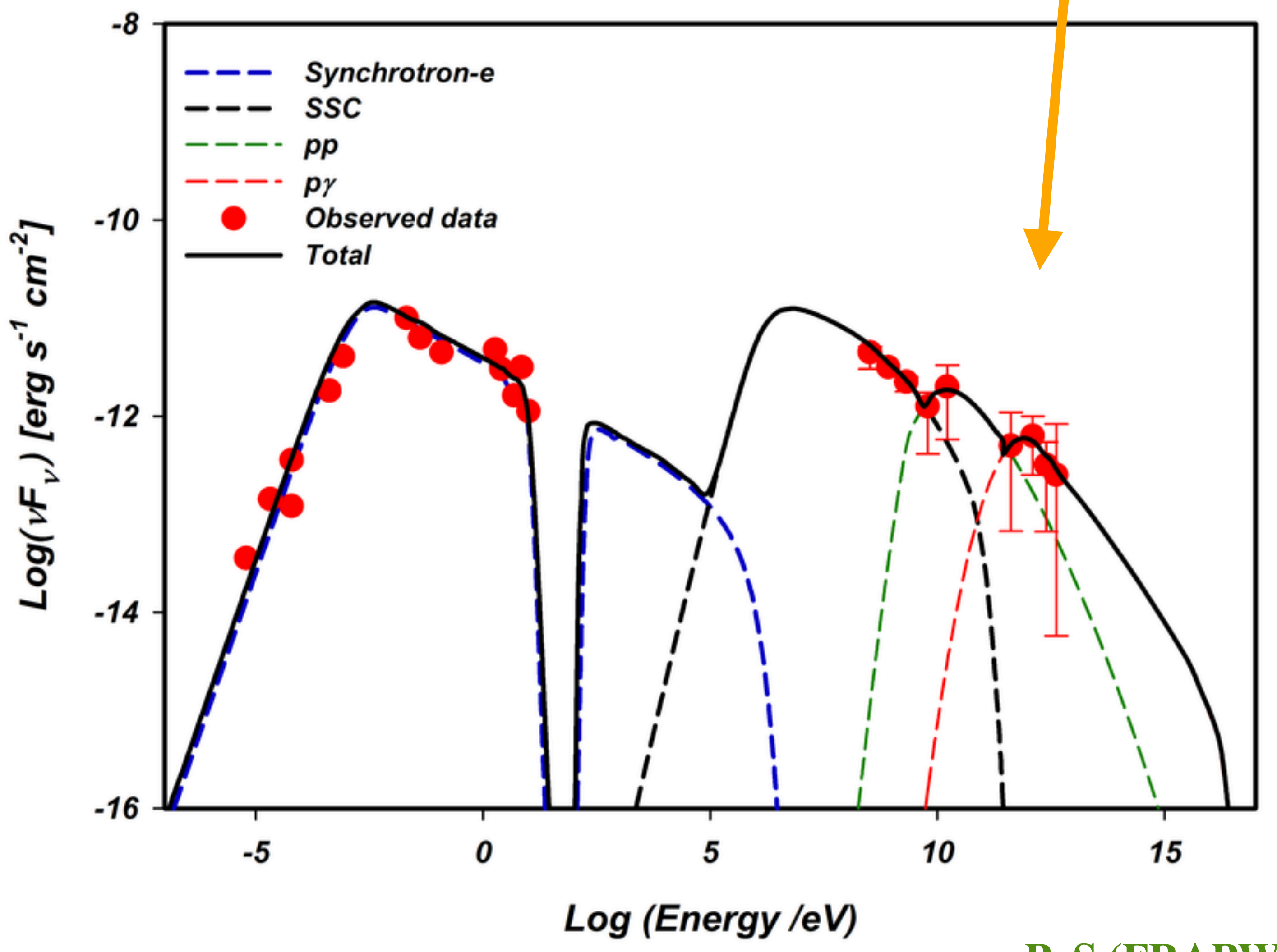
IceCube (neutrinos)



Fermi (γ-rays)

ROSAT (X-rays)

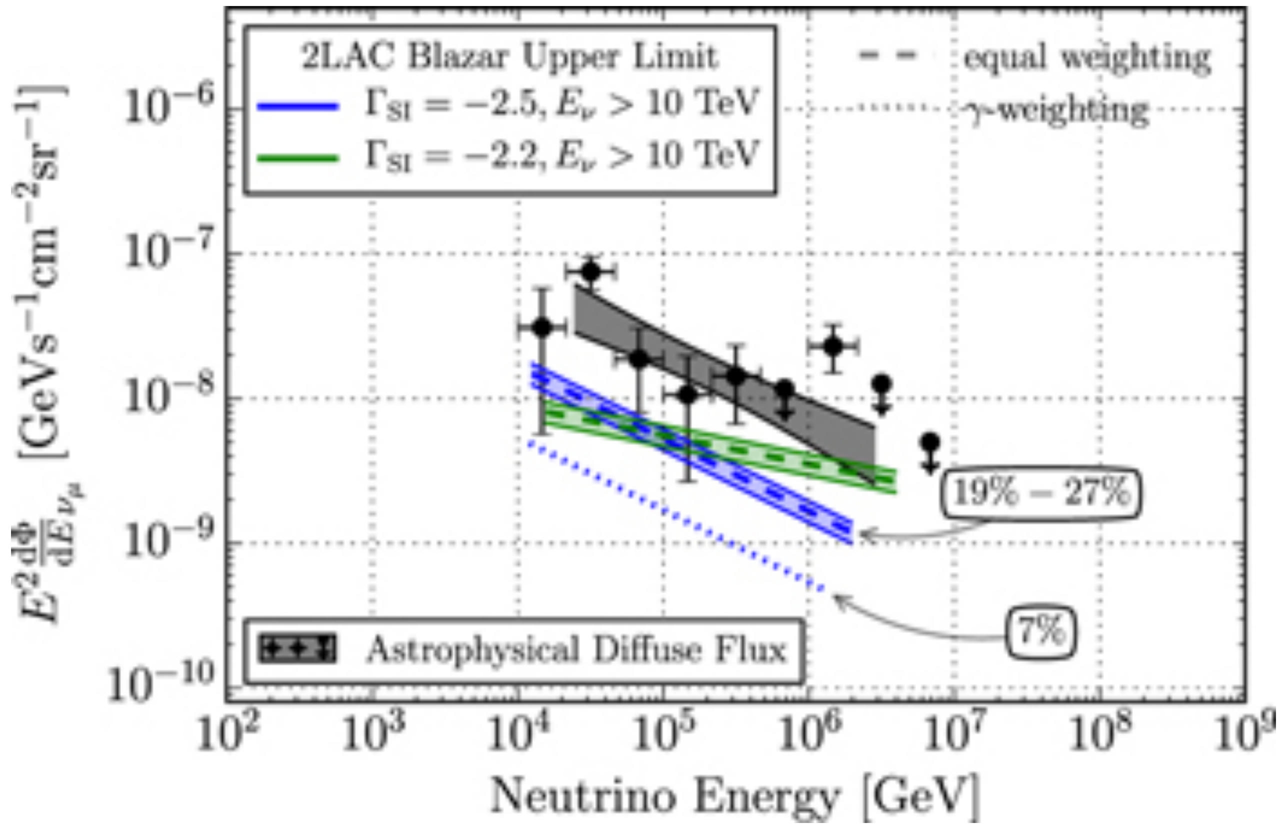




PoS (FRAPWS2016) 056

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

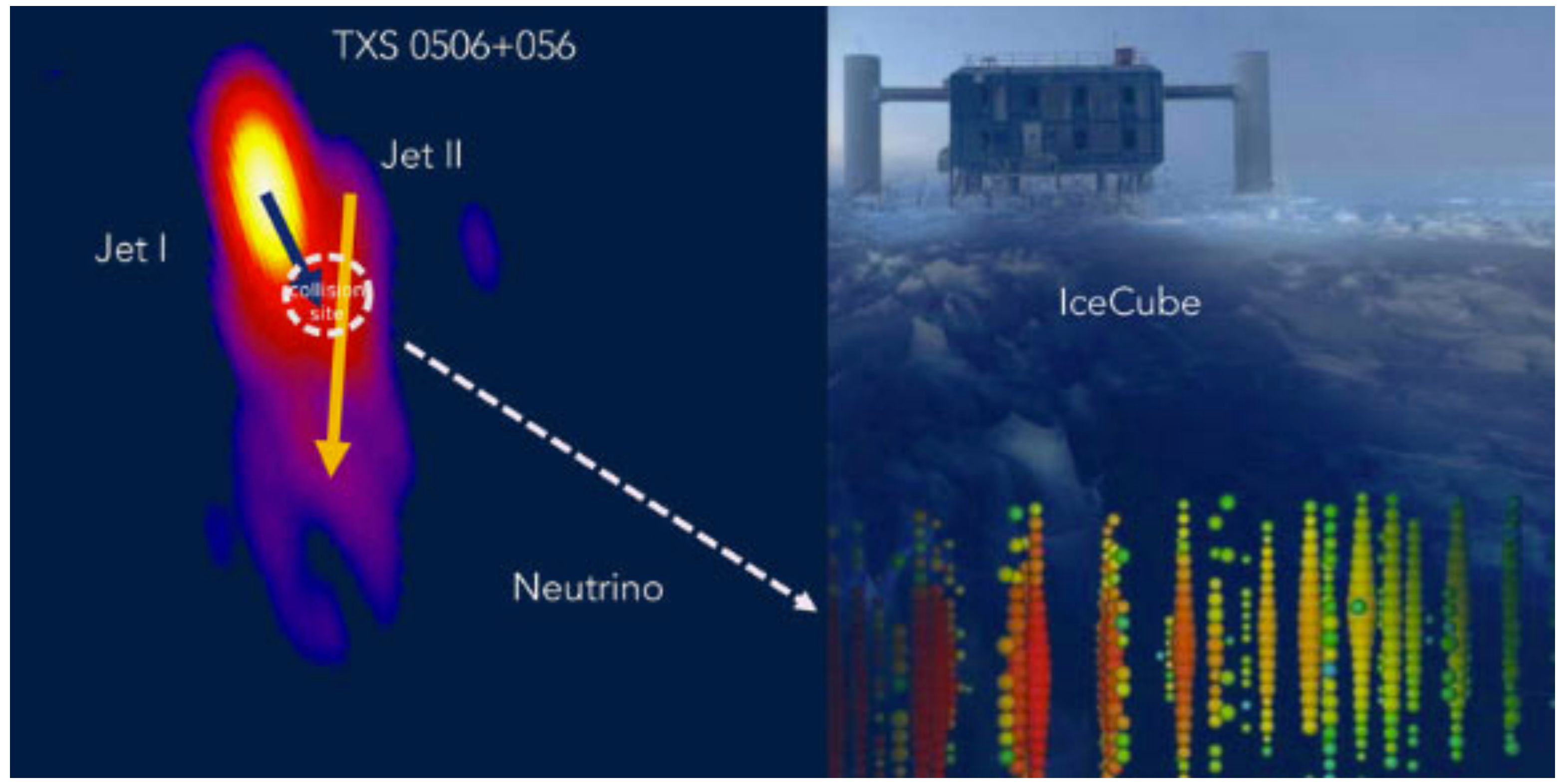
Active Galactic Nuclei [> 15%]

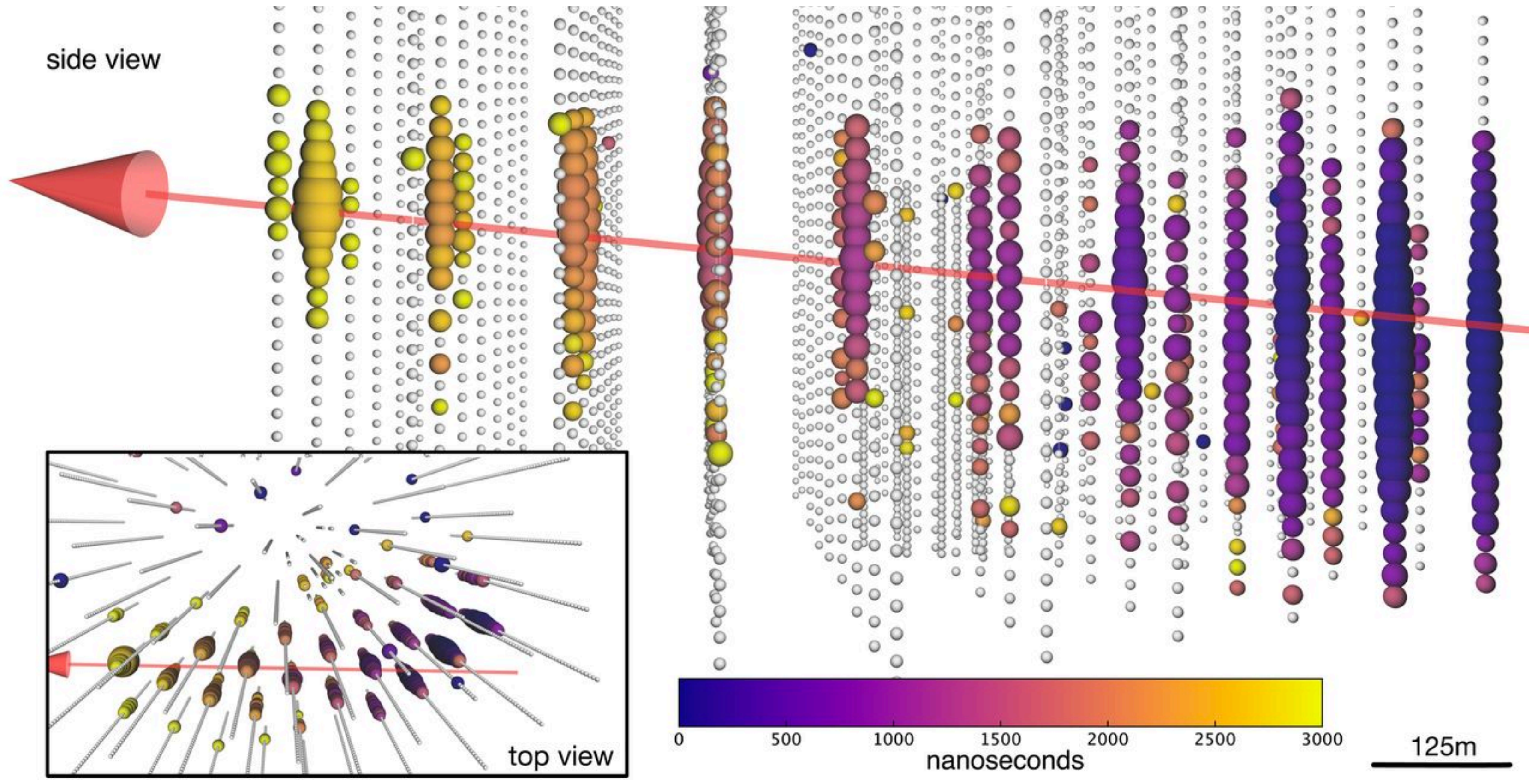


Blazar AGNs can contribute only upto 30% of the observed IceCube diffuse flux

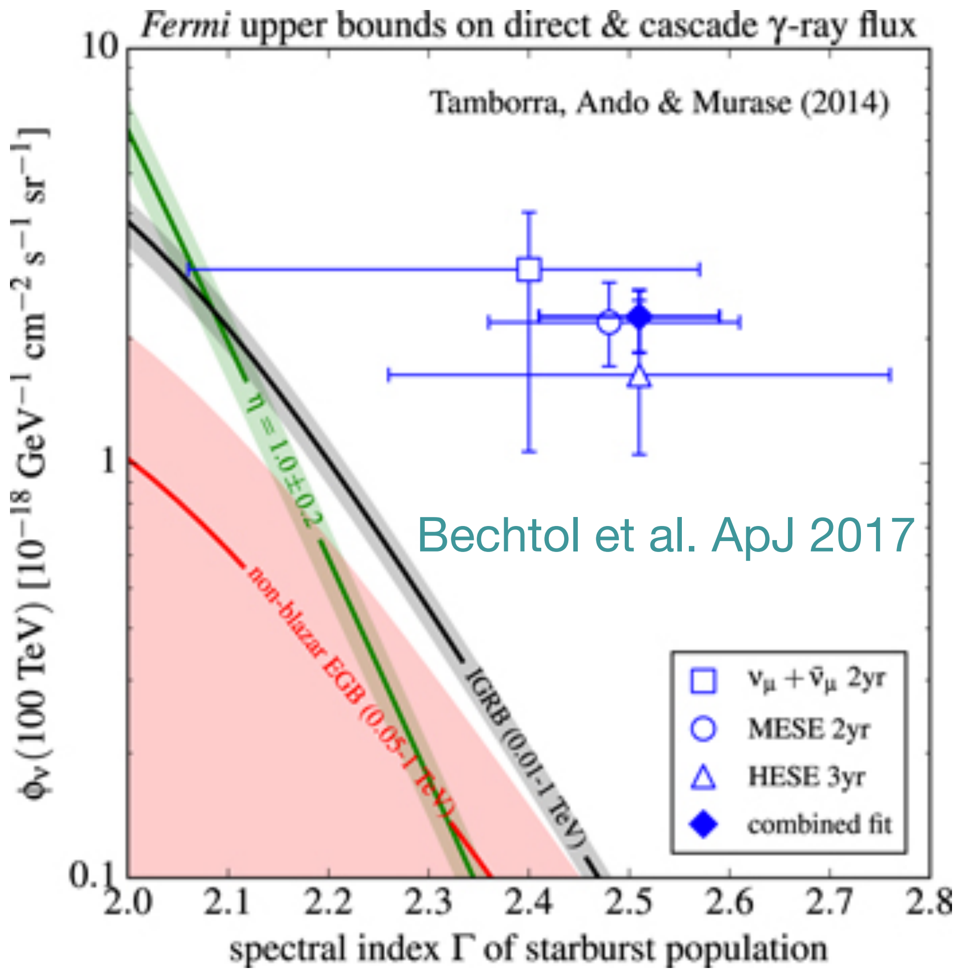
IceCube's first candidate source of high energy neutrinos was a blazar!

TXS 0506+056 (z = 0.336)



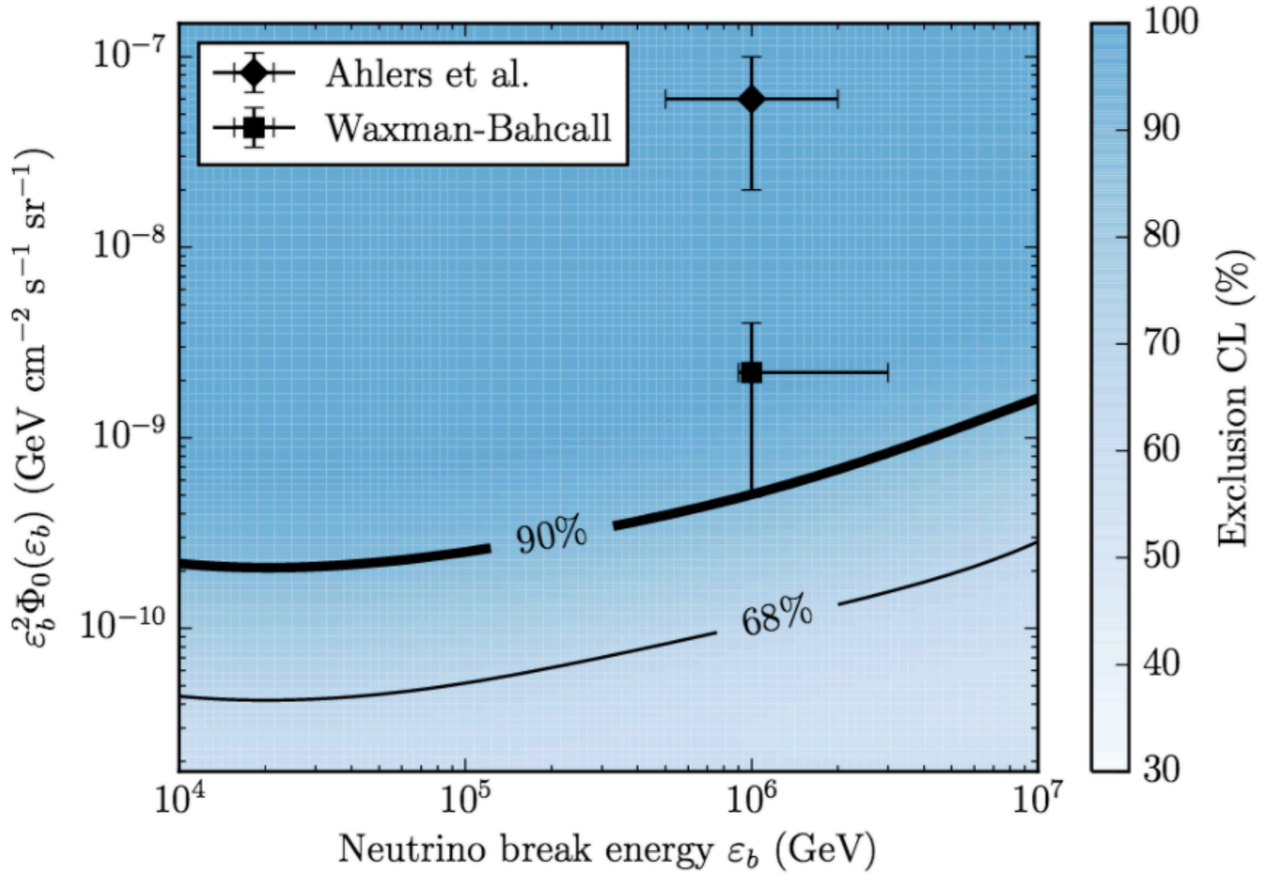


Gamma-Ray Bursts (transients) [< 1%]



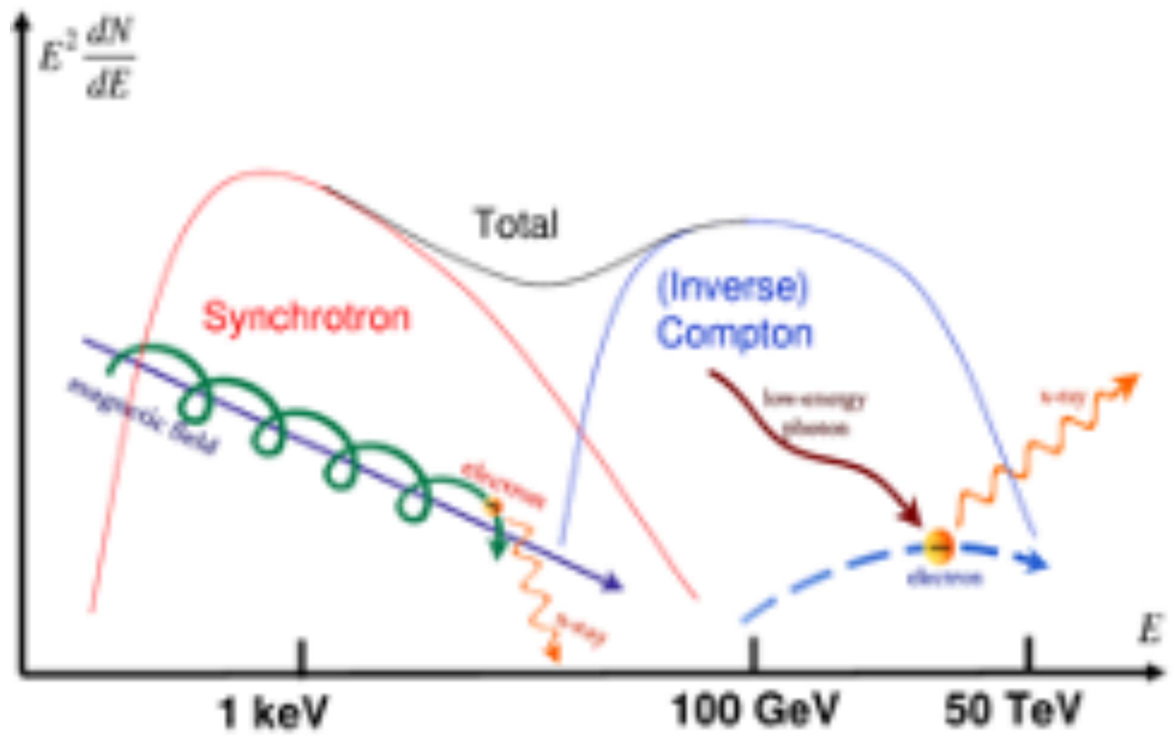
(Prompt phase only)

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



Aartsen et al. ApJ 2016

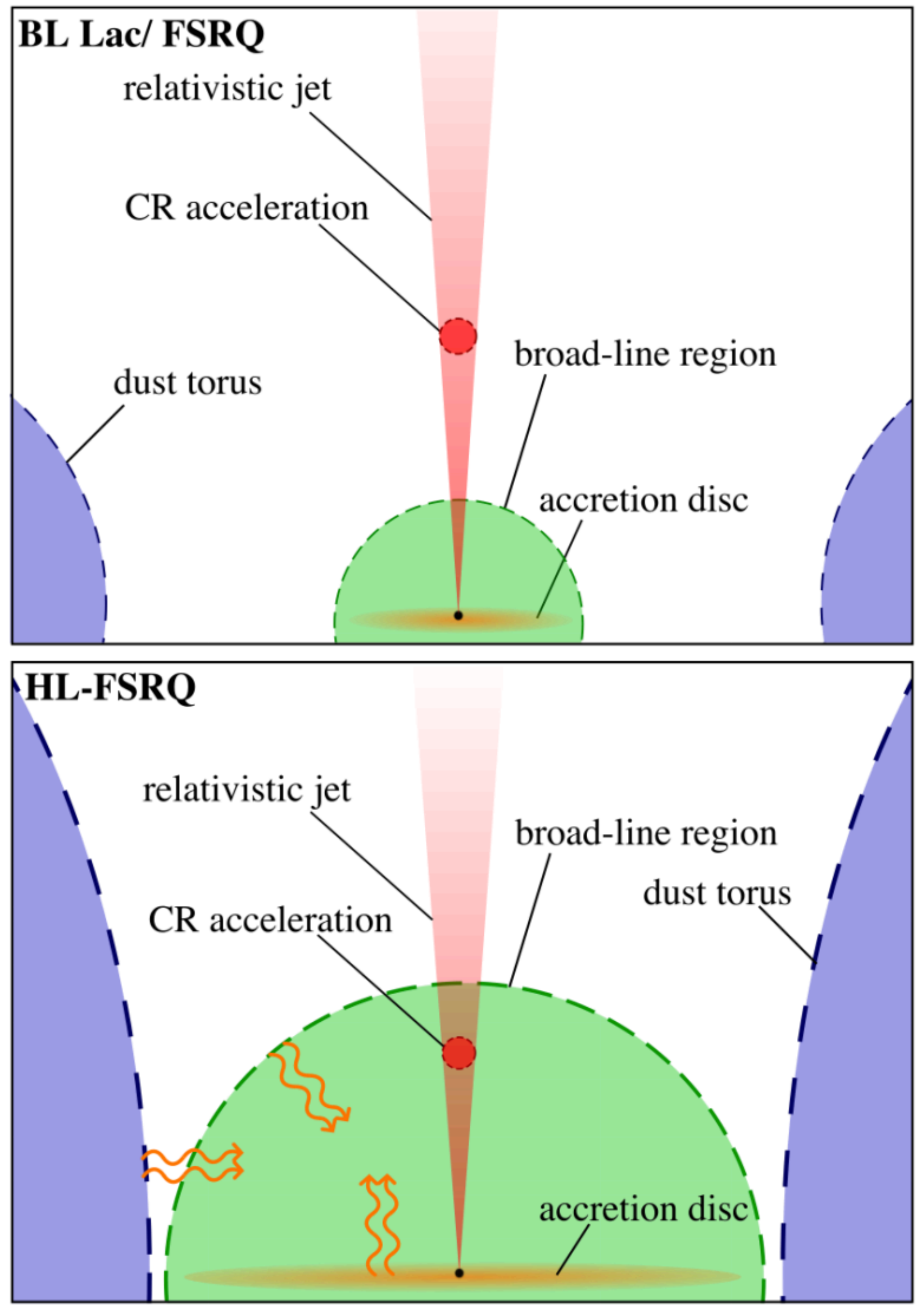
- A class of jetted AGN; jets point in our direction
- Intrinsically variable; can show episodes of increased activity (flares)



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



Rodrigues et al. ApJ 2018

BL Lacs -- High optical polarisation
weak emission lines

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

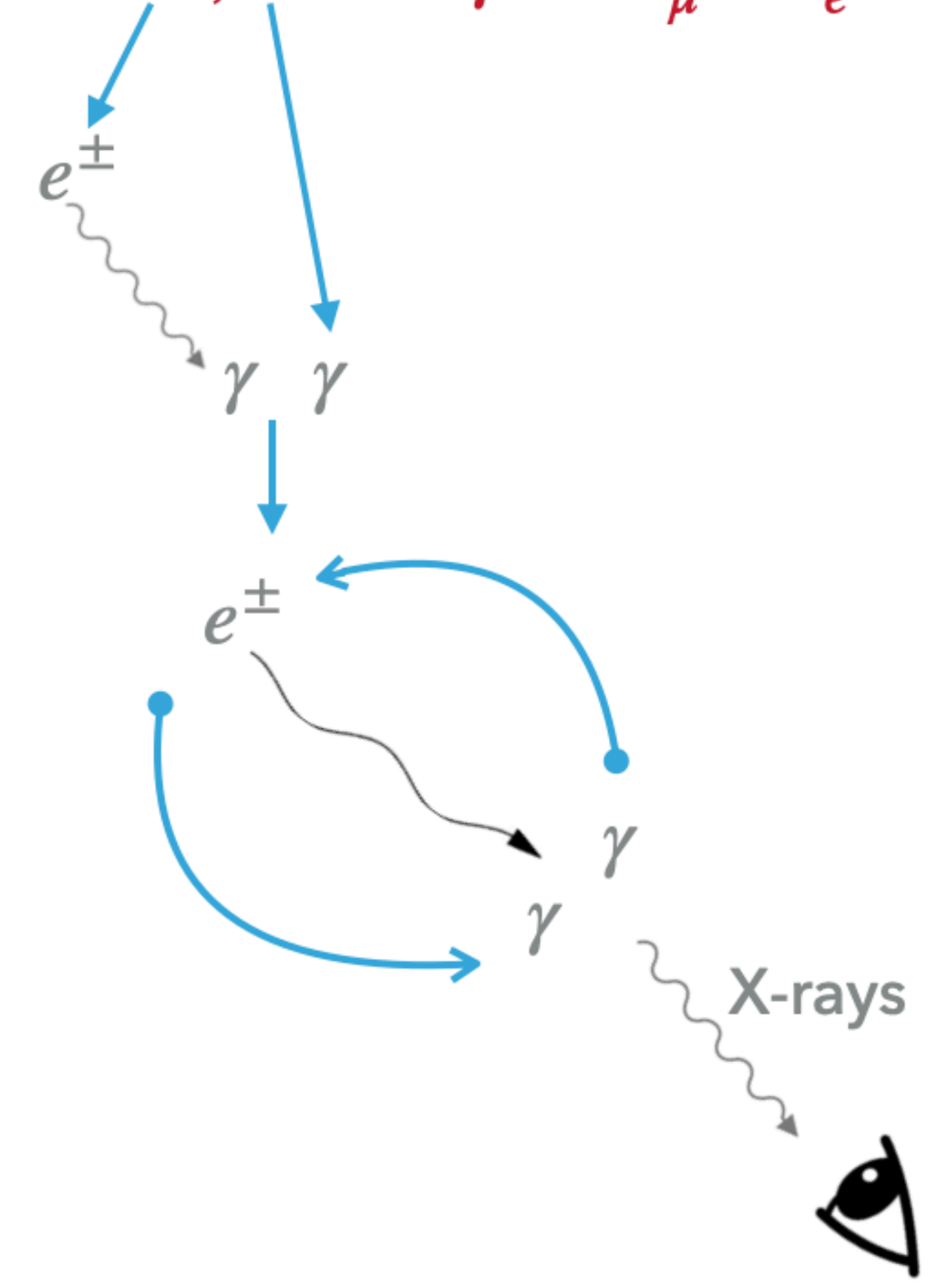
Difference between the two sub-classes possibly based on jet-power and mass of central engine

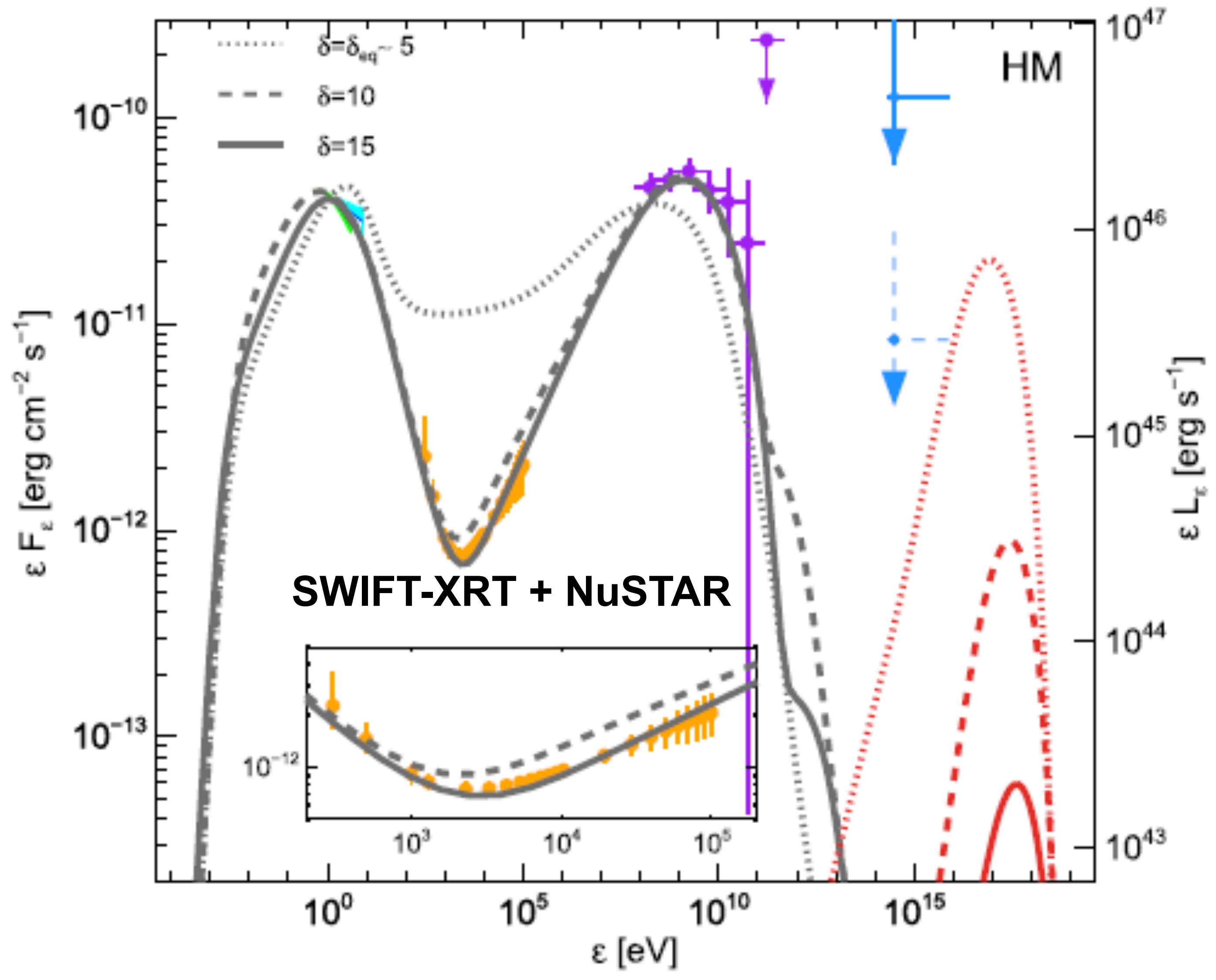
Tight correlations b/w radio core and soft-X-ray observations from radio-loud AGN suggest soft- X-rays produced in the jet

Proton Induced Cascades (PIC) :

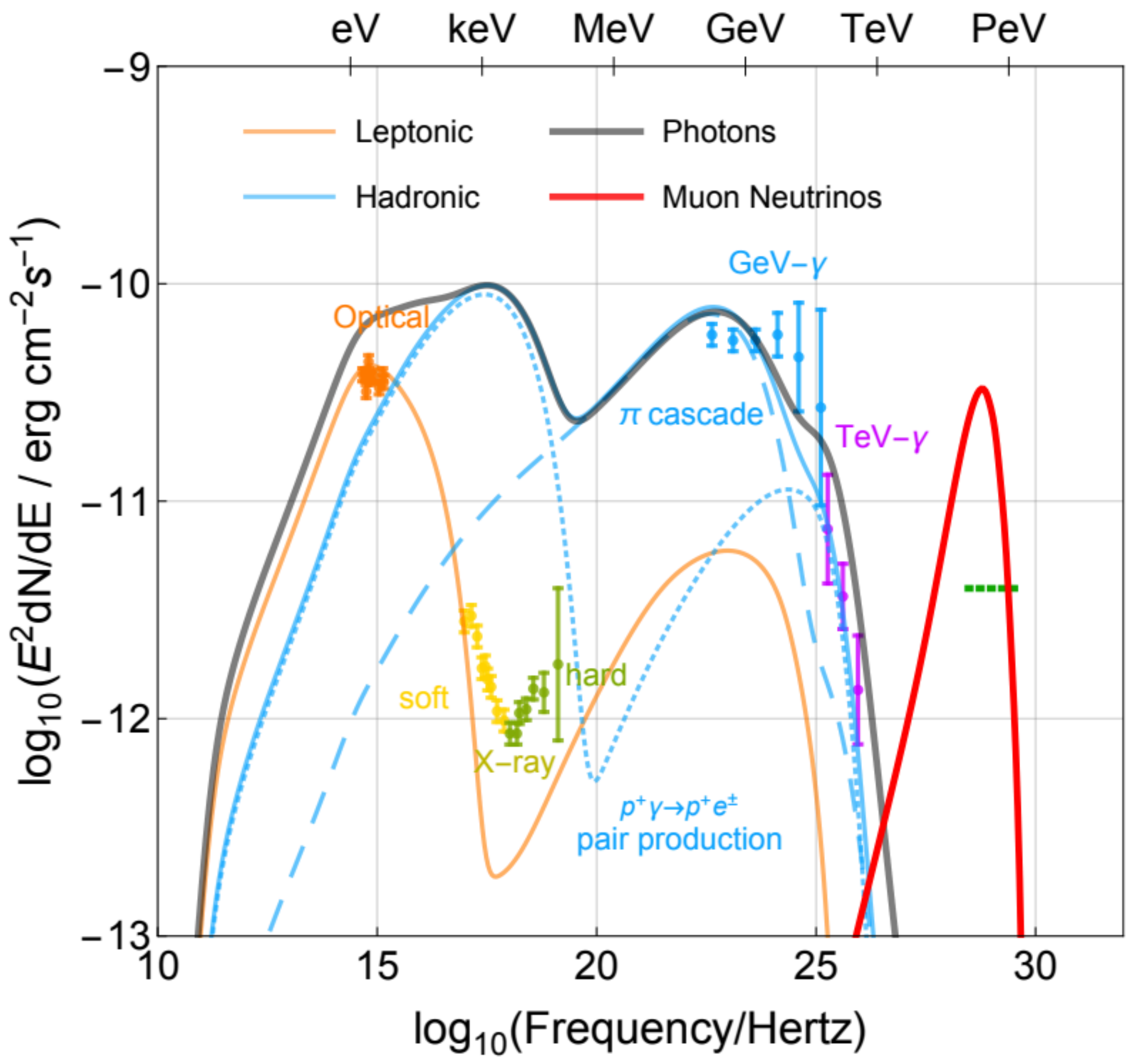
- Secondary $e^{\pm}$ pairs generated by pion decay shift the extreme proton energies down to the X-ray band

$$p + \gamma \rightarrow p/n + \pi^{\pm}, \pi^{0} \rightarrow 2\gamma + 2\nu_{\mu} + \nu_{e}$$





Keivani et al. 2018



Gao et al. 2018

Objective: **Search for correlation between soft 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:

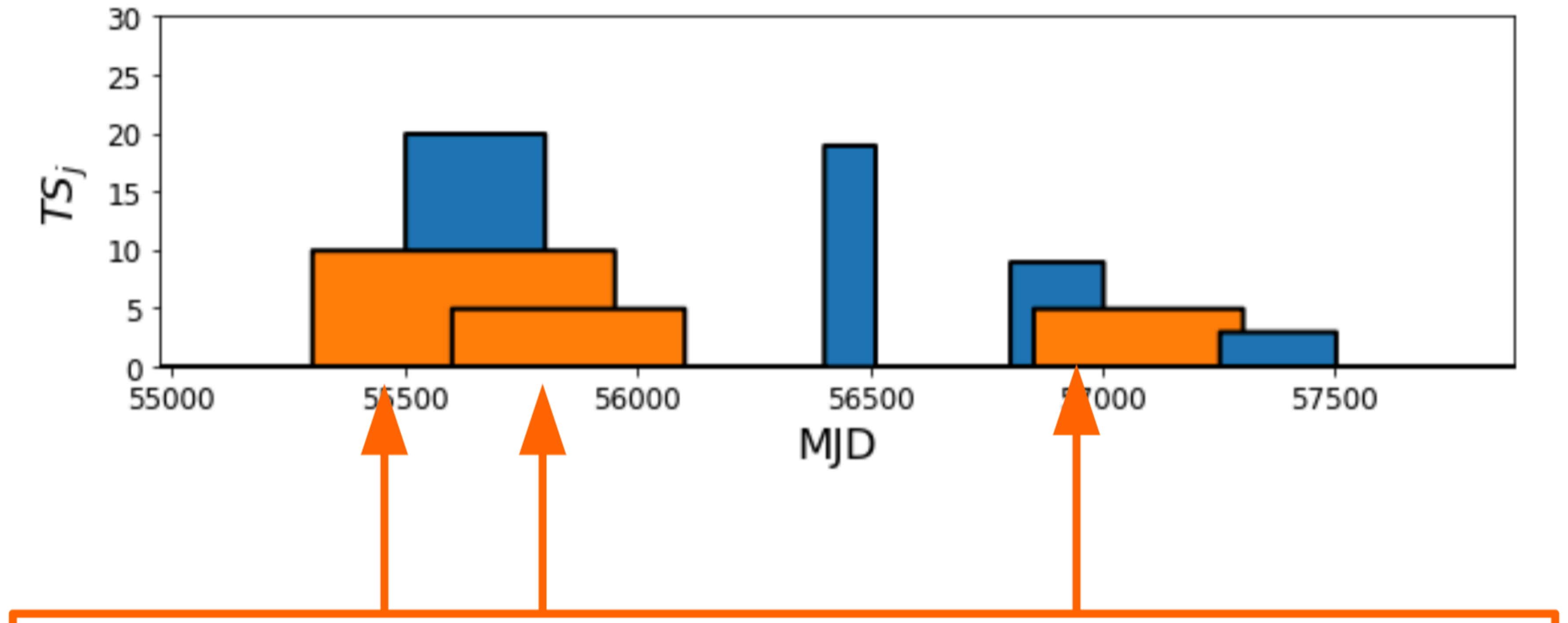
- ➡ search for neutrino flares in 10 years of IceCube data from each source in a catalog of blazars curated based on X-ray flux
- ➡ obtain a p-value for each source using the **multi-flare Test Statistic**
- ➡ perform a population test using the binomial test statistic to determine the sub-population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

Dataset	LLH	Catalog
Track-like events (6th April 2008 - 8th July 2018)	Un-binned (csky)	RomaBZCat (1k northern sky blazars)

- Blazars are variable sources. If neutrino flares behave like EM flares, **can expect > 2 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**

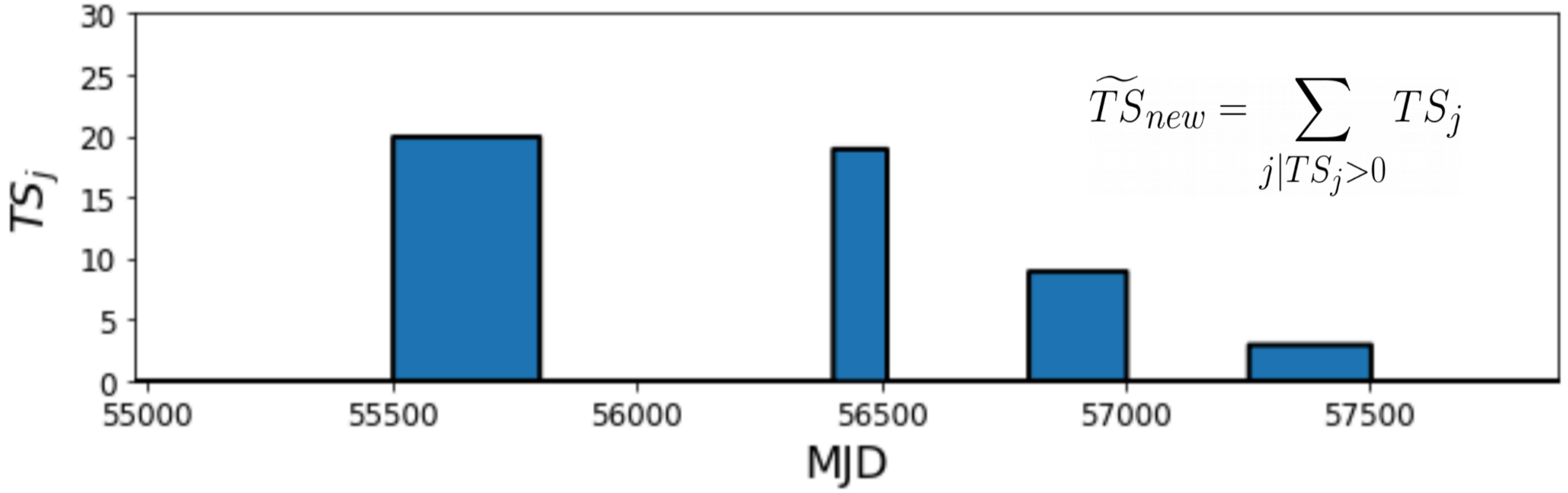
$$\mathcal{L}(n_s, \gamma, \Delta t_j) = \prod_{i=1}^{N} \frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i$$

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



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

Credit: Will Luszczak



$$\widetilde{TS}_{new} = \sum_{j|TS_j>0} TS_j$$

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

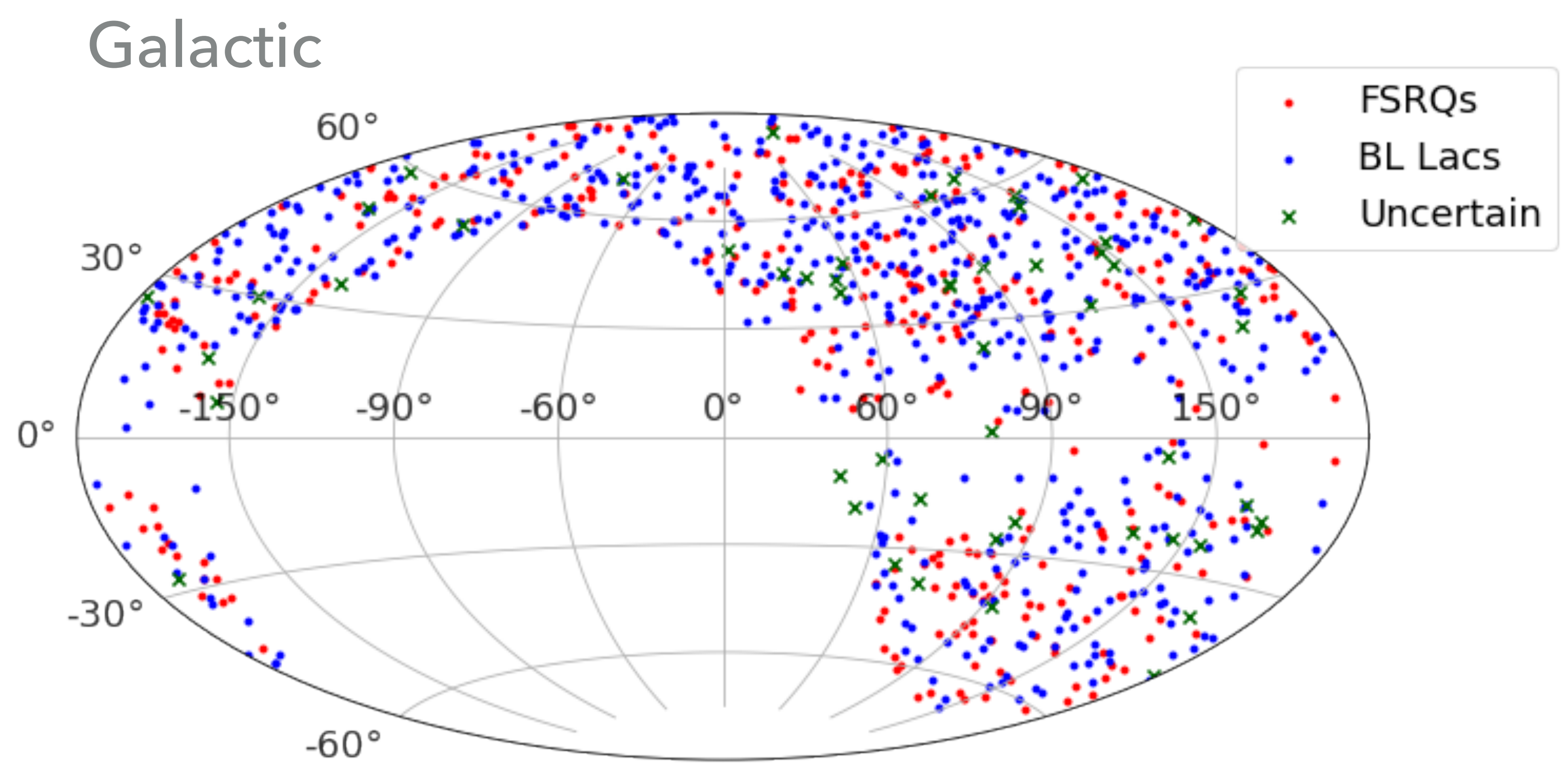
Good initial guess at the sub-population => better results

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

ROMABZCAT 5TH EDITION

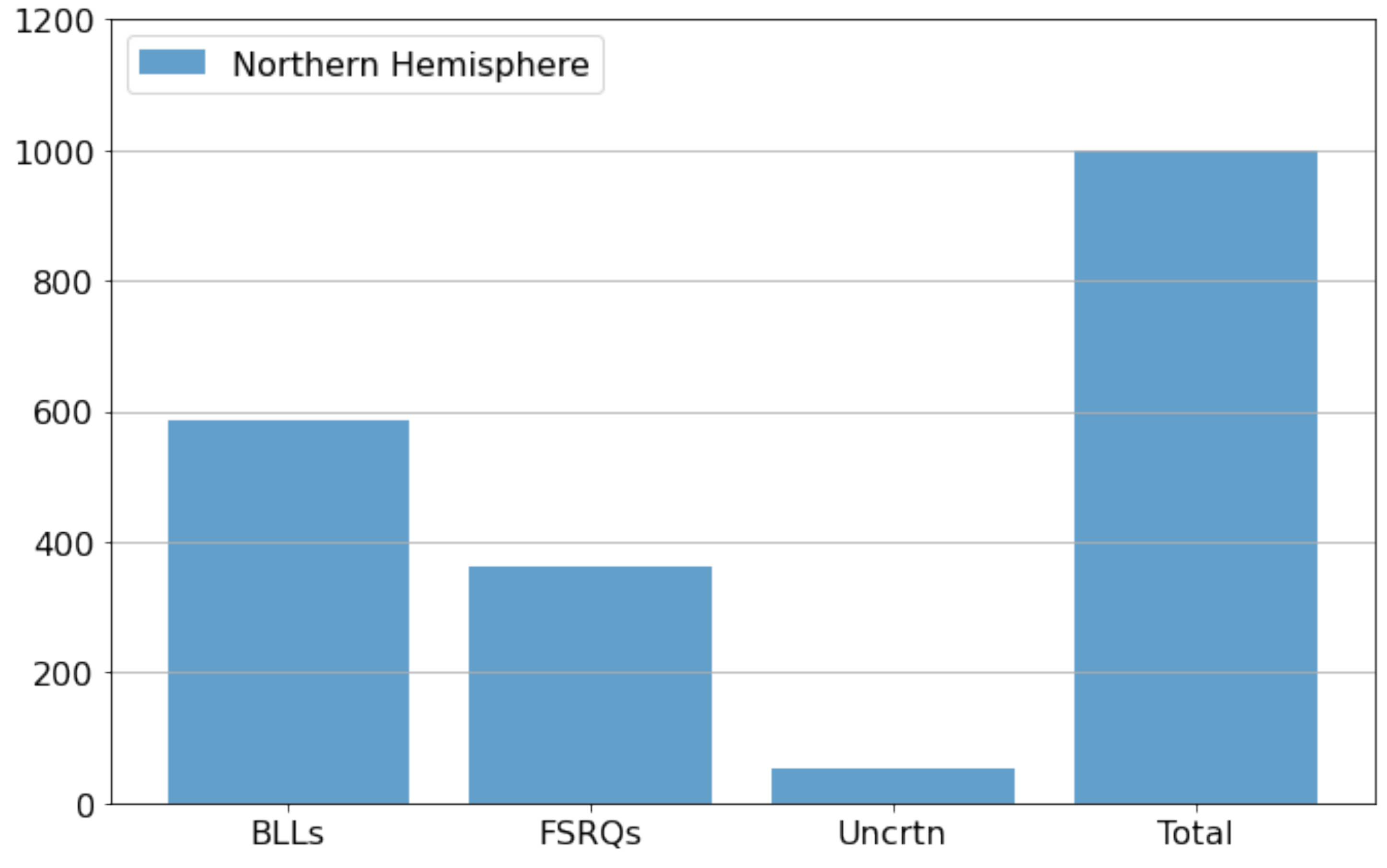
CATALOG DOWN-SELECTION

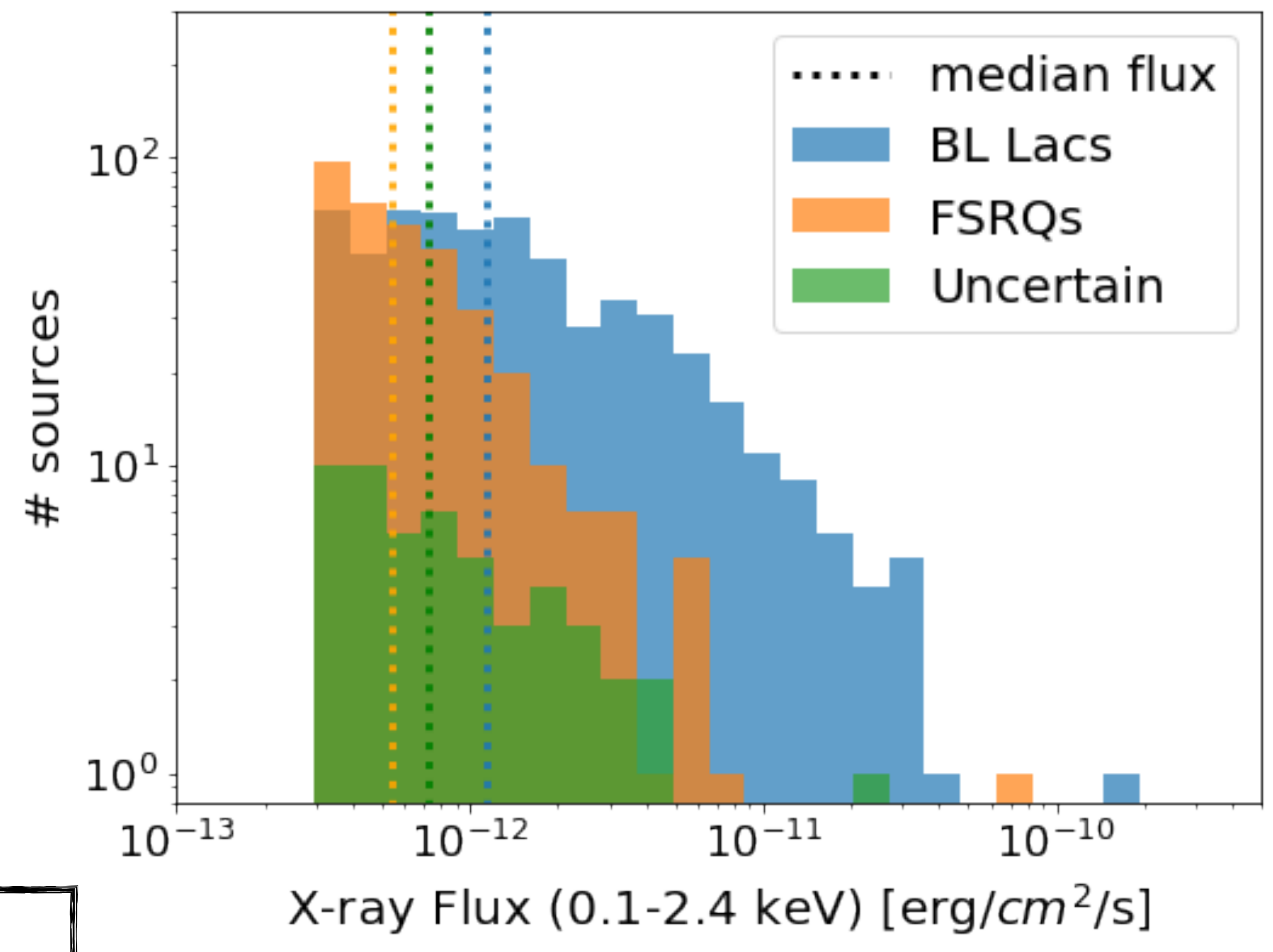
✓ We select 1000 blazars from the Northern hemisphere (-5, +85) with the highest (soft) X-ray fluxes in the catalog
[X-ray fluxes taken from **ROSAT (0.1 - 2.4 keV)**]



Northern Hemisphere

Before cuts: 2312 blazars
After cuts: 1000 blazars

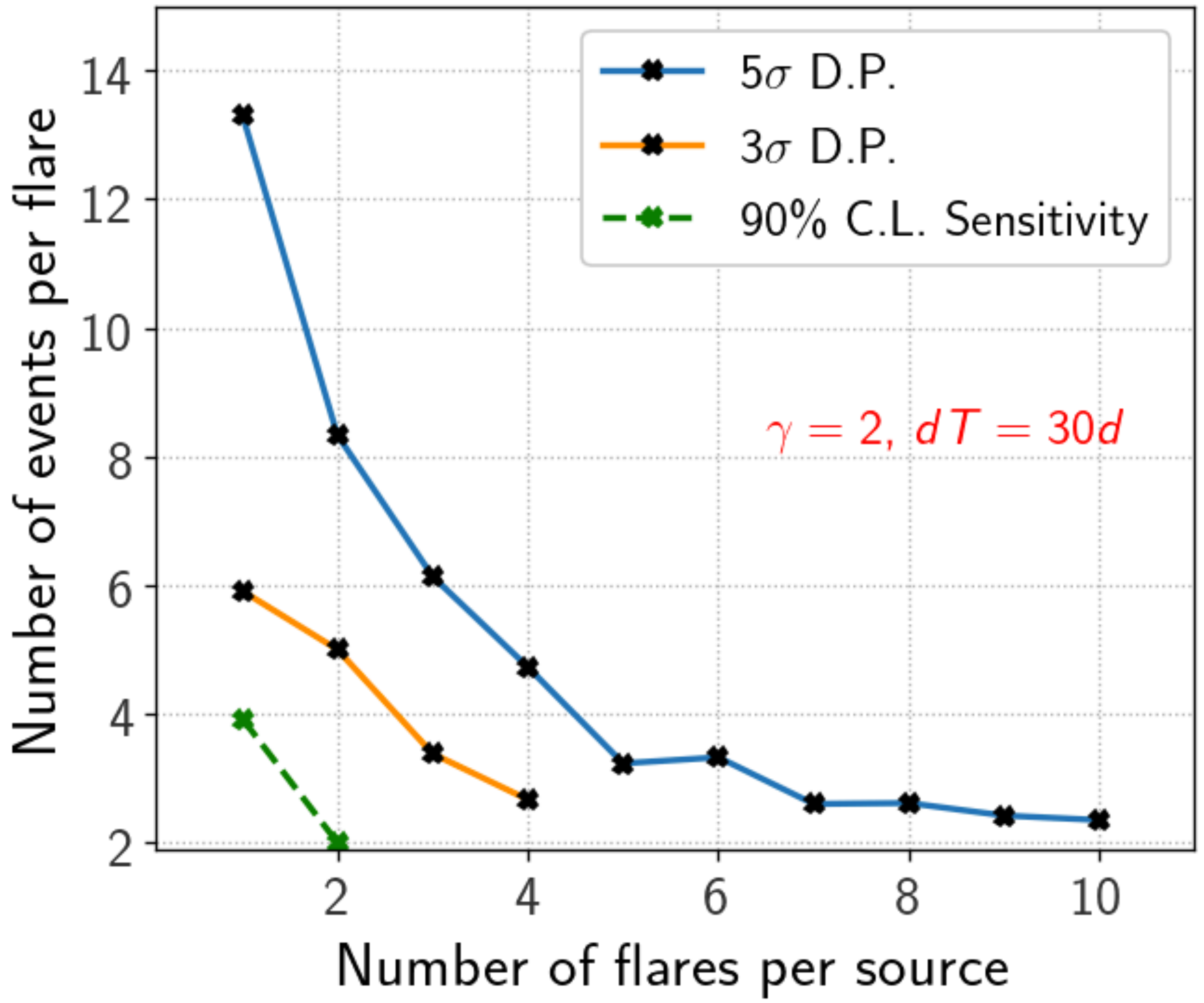




After selection cuts:

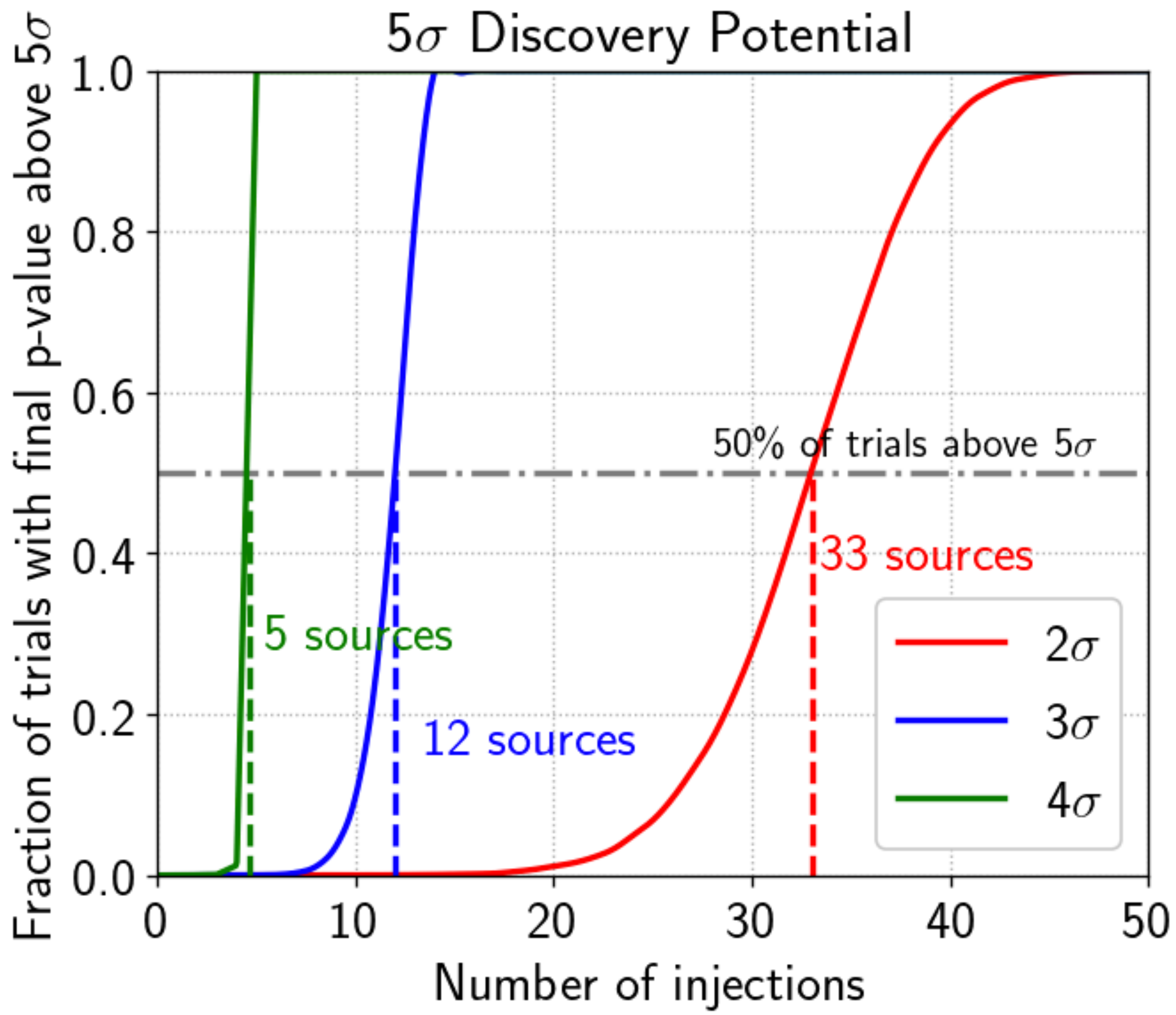
- **BL Lacs: 586, FSRQs: 361, Uncertain type: 53**
- **X-ray fluxes between: 3.1e-13 to 1.8e-10 erg/cm²/s**

PRE-TRIAL SENSITIVITY (FOR SOURCE AT DECL. OF TXS)



Multi-flare analyses can pick up individual sources with strong (but few) flares, or weak (but many) flares with an equal significance!

POST-TRIAL SENSITIVITY (BASED ON BINOMIAL TESTS)



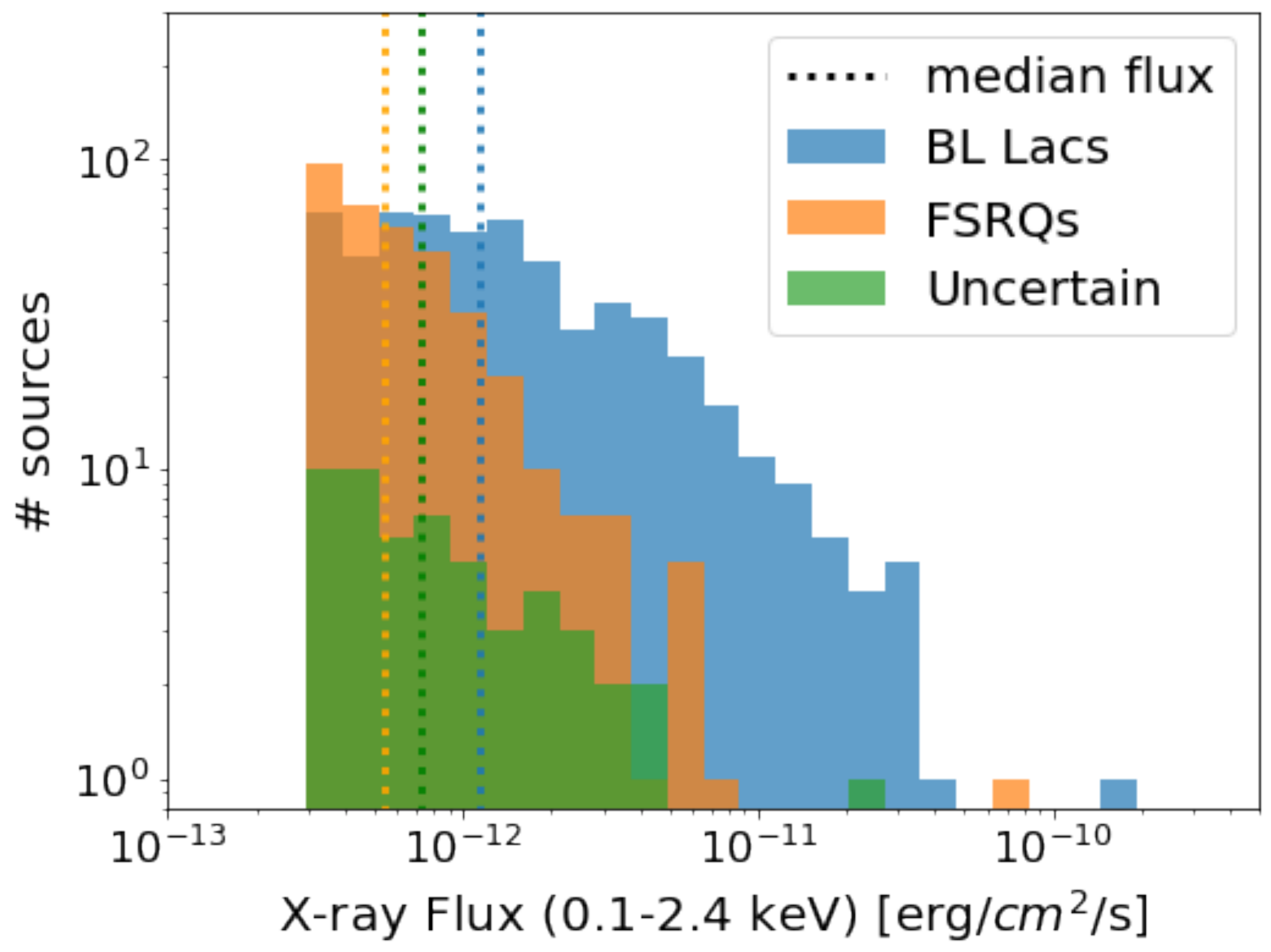
33 (12, 5) sources of 2σ (3σ, 4σ) individual (pre-trial) significance required to obtain a 5σ final significance from the analysis

- ✦ Multi-flare fit (*csky*) for all blazars in the catalog using parameters described above
  - ➡ S/B > 2000
  - ➡ Max. Flare duration = 1000 days
  - ➡ Spectral index from the fit

- ✦ Pre-trial p-value for the most significant blazar : 0.0003 (3.43 σ)

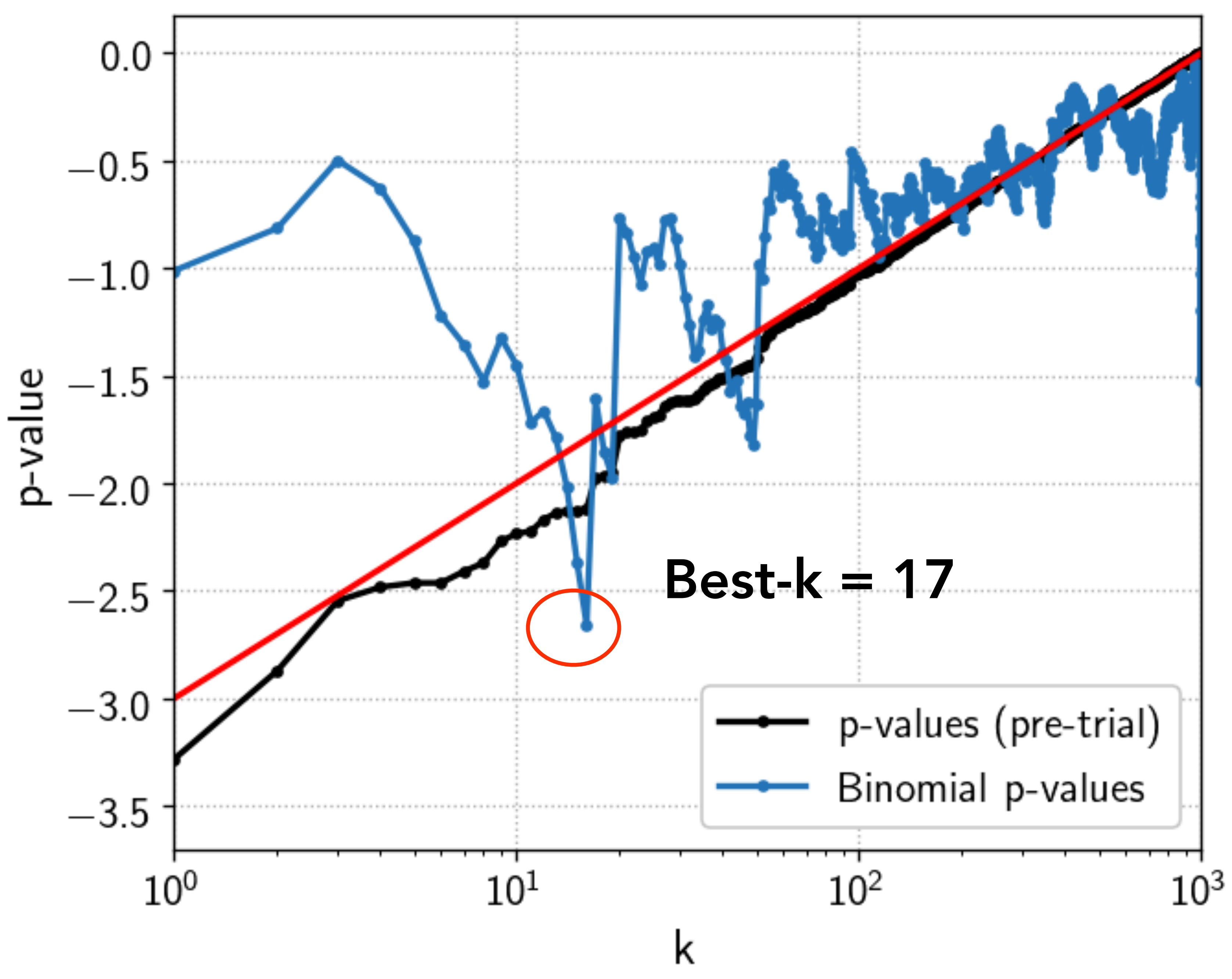
- ✦ **24 sources above 2σ, 3 sources above 3σ (1 BL Lac, 2 FSRQs). No 4σ sources!**

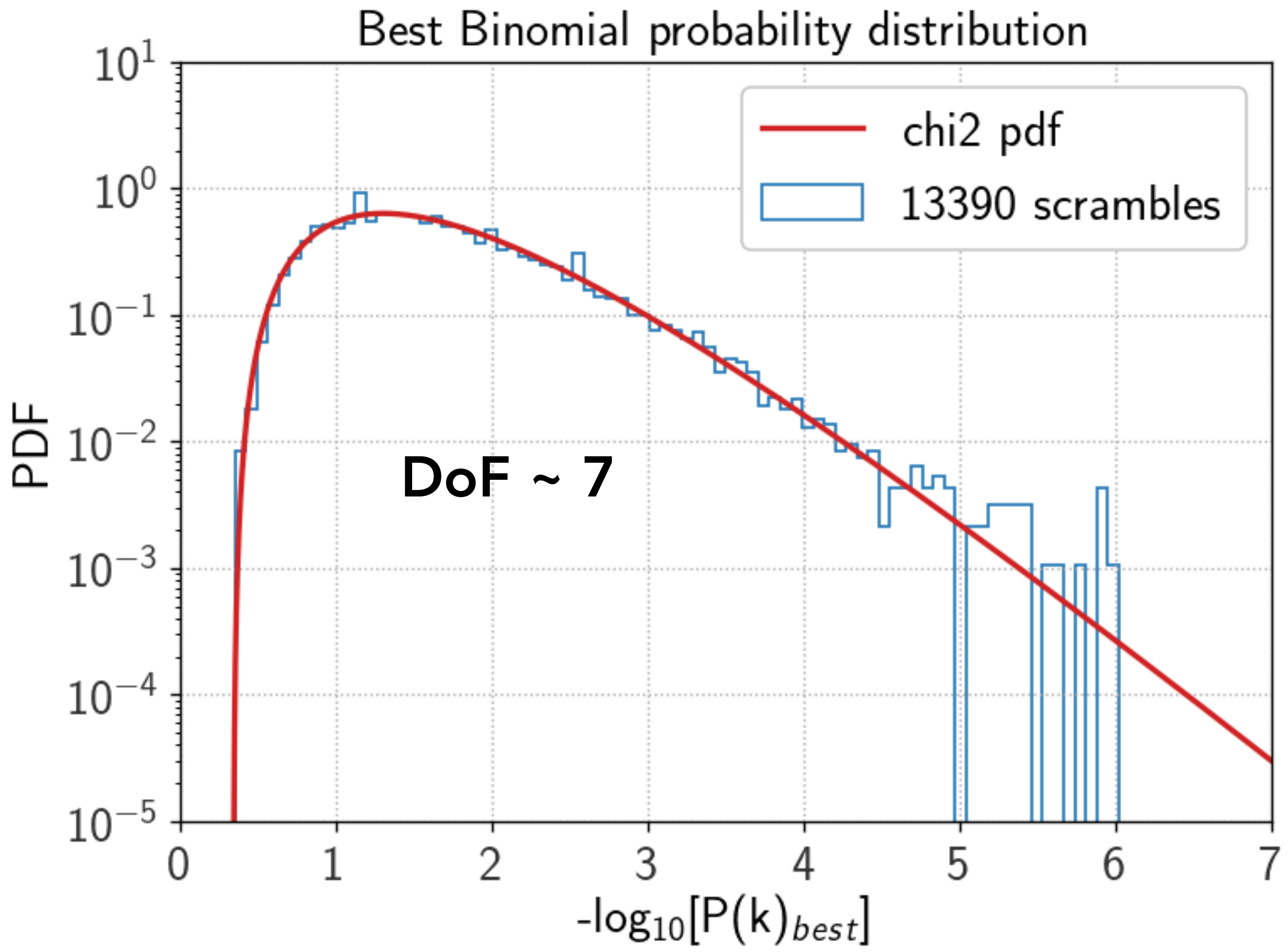
- ✦ TXS 0506+056 is at 2.51σ pre-trial

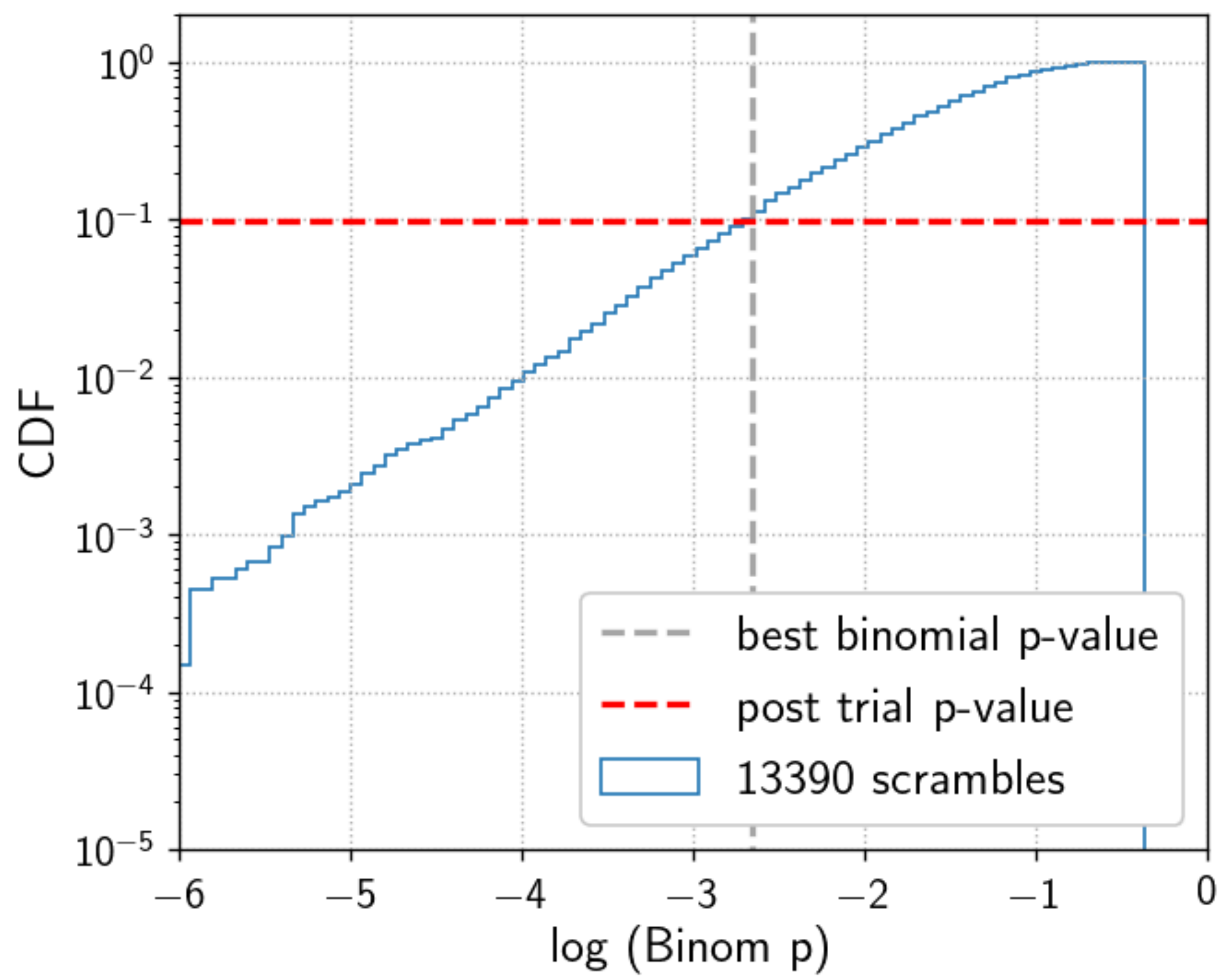


Name	RomaBZCat Name	RA	Dec	Redshift	Category	X-ray Flux (erg/cm2/s) [0.1-2.4 keV]	p-value (σ)
MS1207.9+3945	5BZBJ1210l+3929	182.61	39.48	0.617	BL Lac	2.47e-12	0.00029 (3.43)
GB6J0058+0620	5BZQJ0058+0620	14.64	6.33	0.592	FSRQ	3.1e-11	0.00052 (3.28)
4C13.14	5BZQJ0231+1322	37.94	13.38	2.065	FSRQ	3.5e-11	0.00134 (3.00)

Full sample: 1000 Northern sky blazars….



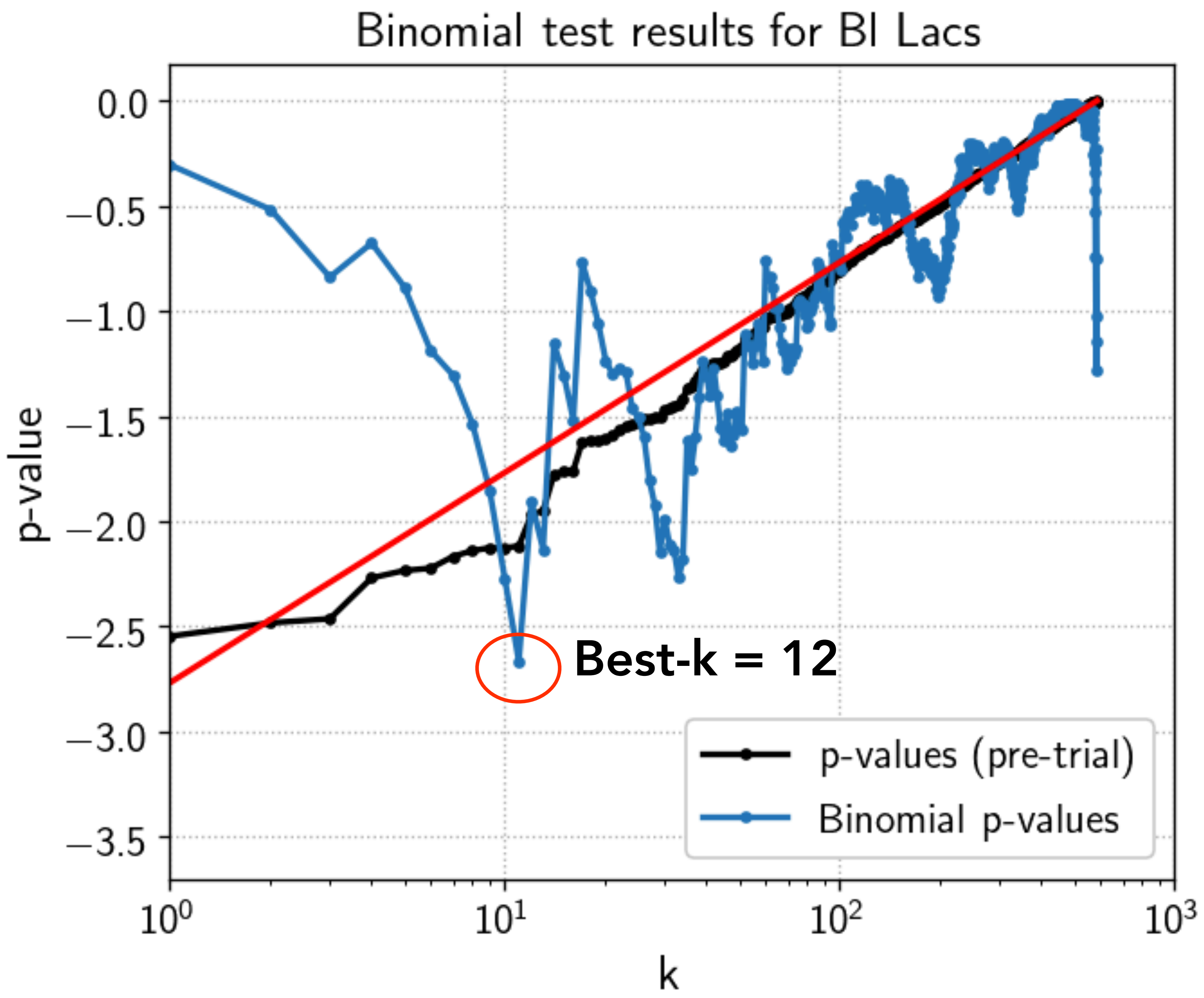




BEST CASE-K VALUE = 17
BEST BINOMIAL PROBABILITY = 0.0022
POST-TRIAL P-VALUE = 0.098 (1.29 SIGMA)

✦ None of the 17 significant sources lie within a degree of each other!

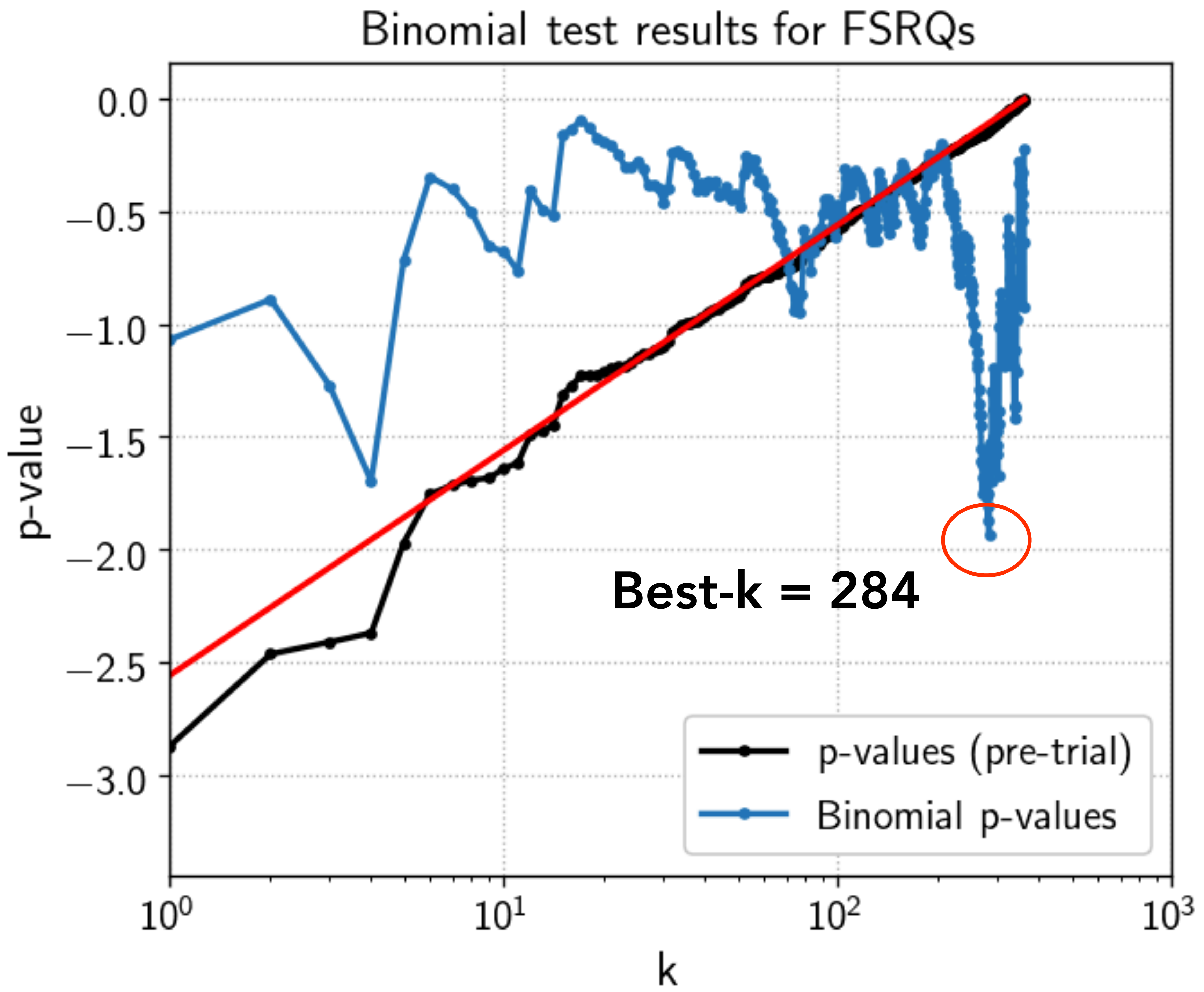
586 Northern sky BL Lacs....



BEST CASE-K VALUE = 12
BEST BINOMIAL PROBABILITY = 0.0021
POST-TRIAL P-VALUE = 0.082 (1.39 SIGMA)

- **No correlations among the 12 best case-k BL Lacs; including TXS 0506+056**

361 Northern sky FSRQs....



BEST CASE-K VALUE = 284
BEST BINOMIAL PROBABILITY = 0.117
POST-TRIAL P-VALUE = 0.239 (0.7 SIGMA)

- **26 out of 284 most significant sources lie within a degree of each other!**

SUMMARY & OUTLOOK

- Testing correlation b/w IceCube neutrinos and soft X-rays bright blazars; in a time-dependent and model-independent way

- No significant evidence for multi-flare neutrino emission from the Northern sky blazars

- Multi-flare fit reveals **three** 3σ sources, most significant blazar at a **pre-trial** significance of **3.43σ**

- Population tests on the full sample, as well as Bl Lacs find a small number of interesting sources

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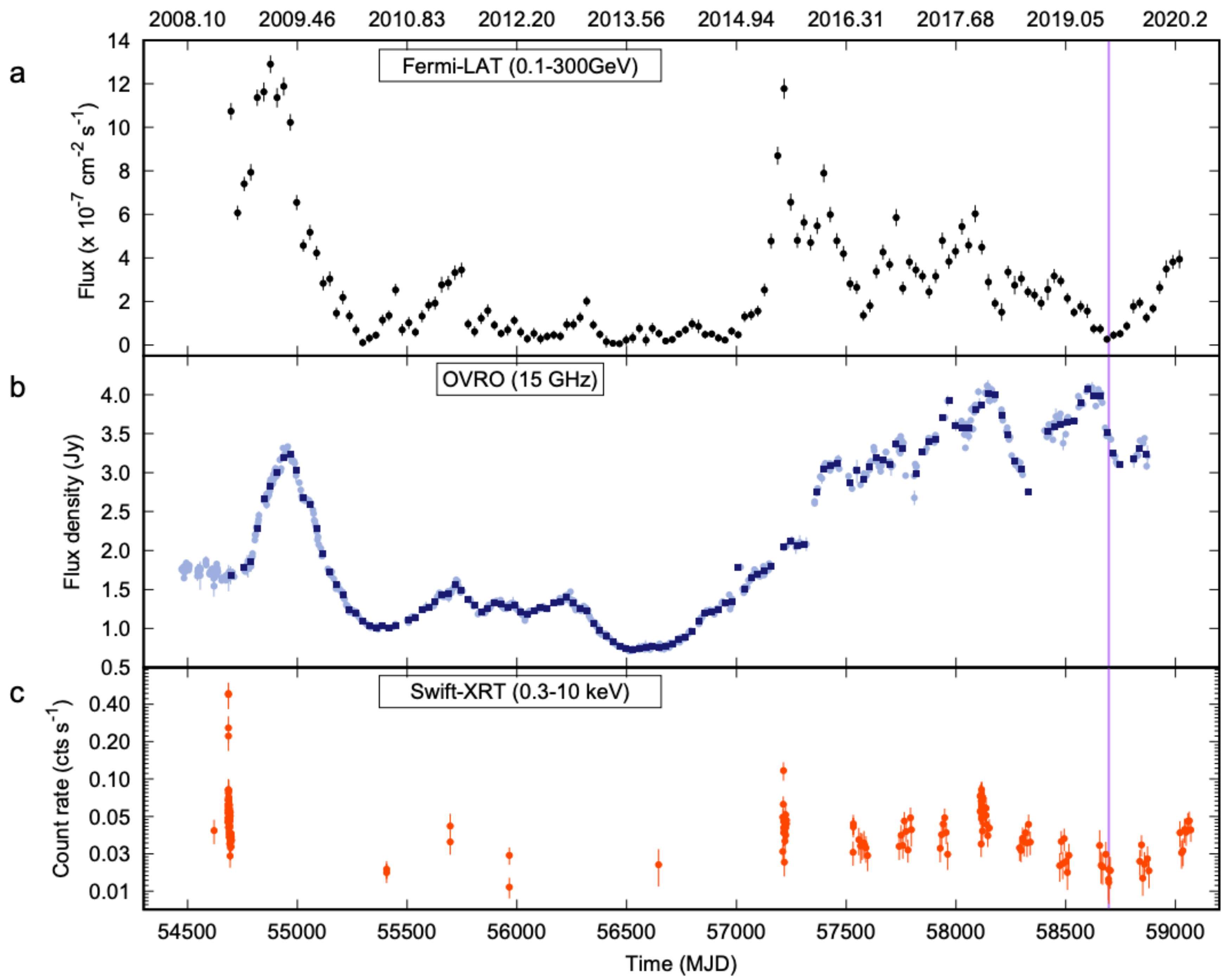
- Investigate further the top-k sources individually (neutrino light curves etc.)

- Preliminary investigation reveal no major correlations, but further examination required

BACKUP SLIDES

MOTIVATION



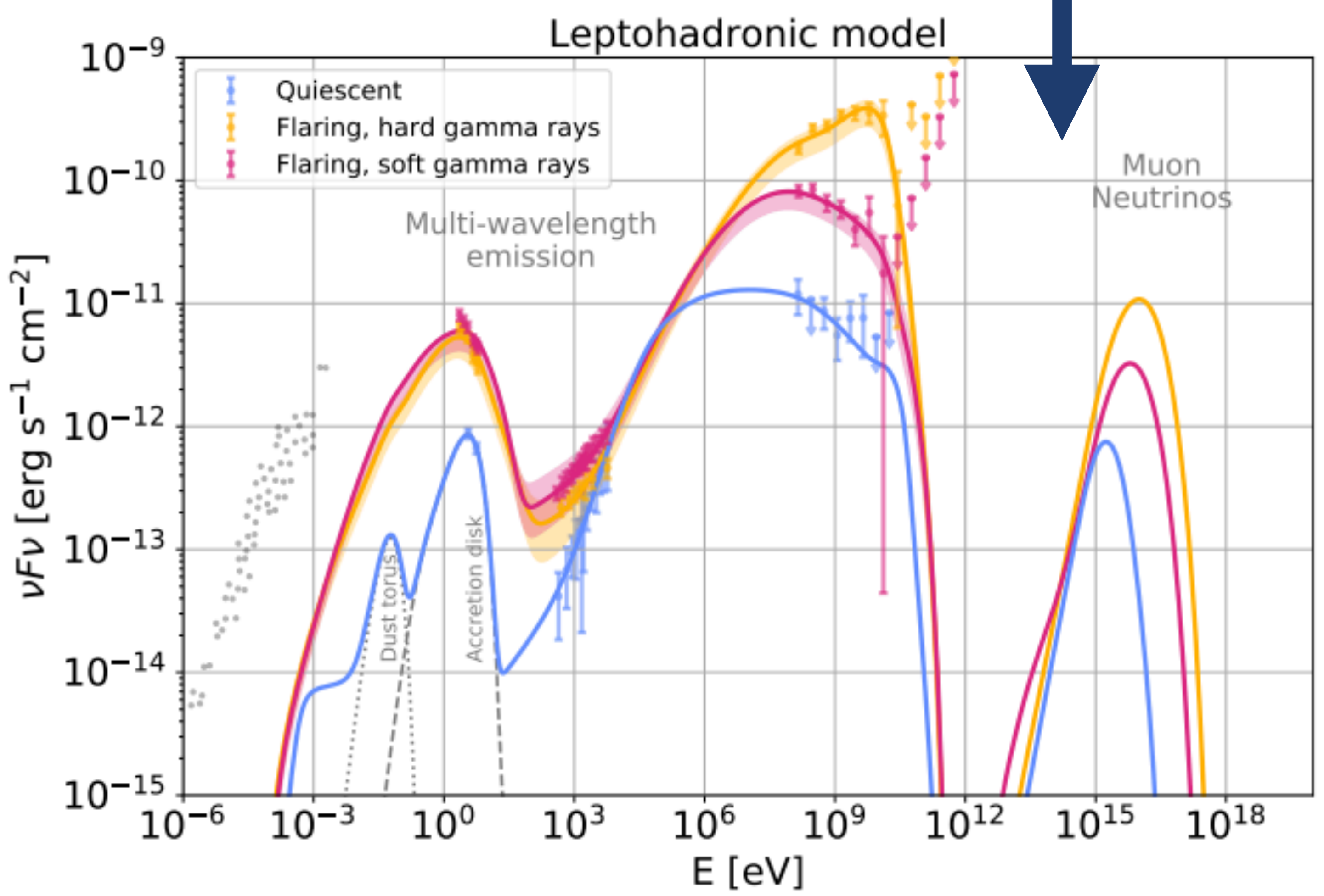
Kun et al. 2021

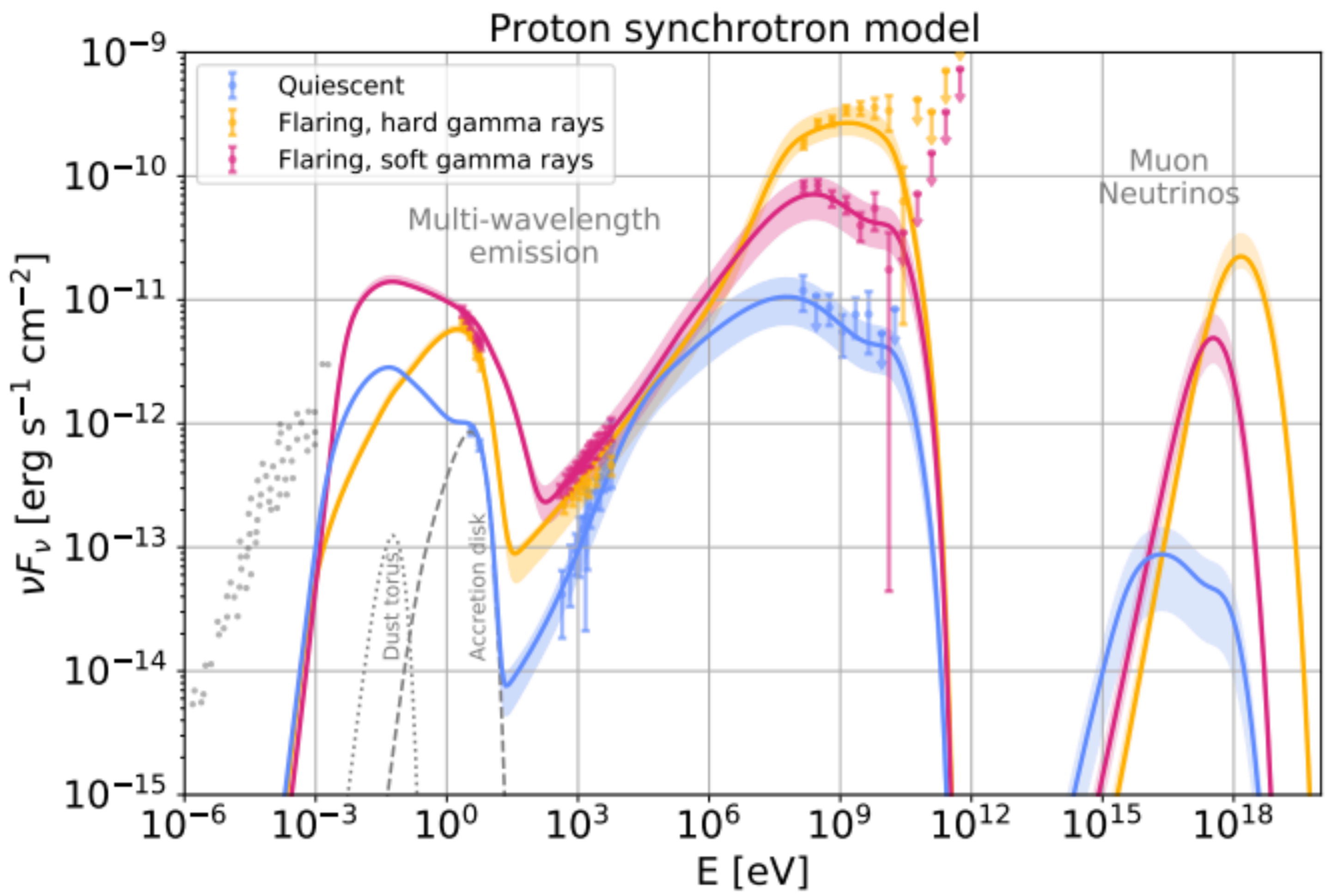
Gamma-rays temporarily subdued;
stronger association b/w radio, X-ray and neutrino data

Rodrigues et al. 2020

Multi-messenger SED disfavors a purely leptonic model due to incompatibility with X-ray flux

PKS 1502+106



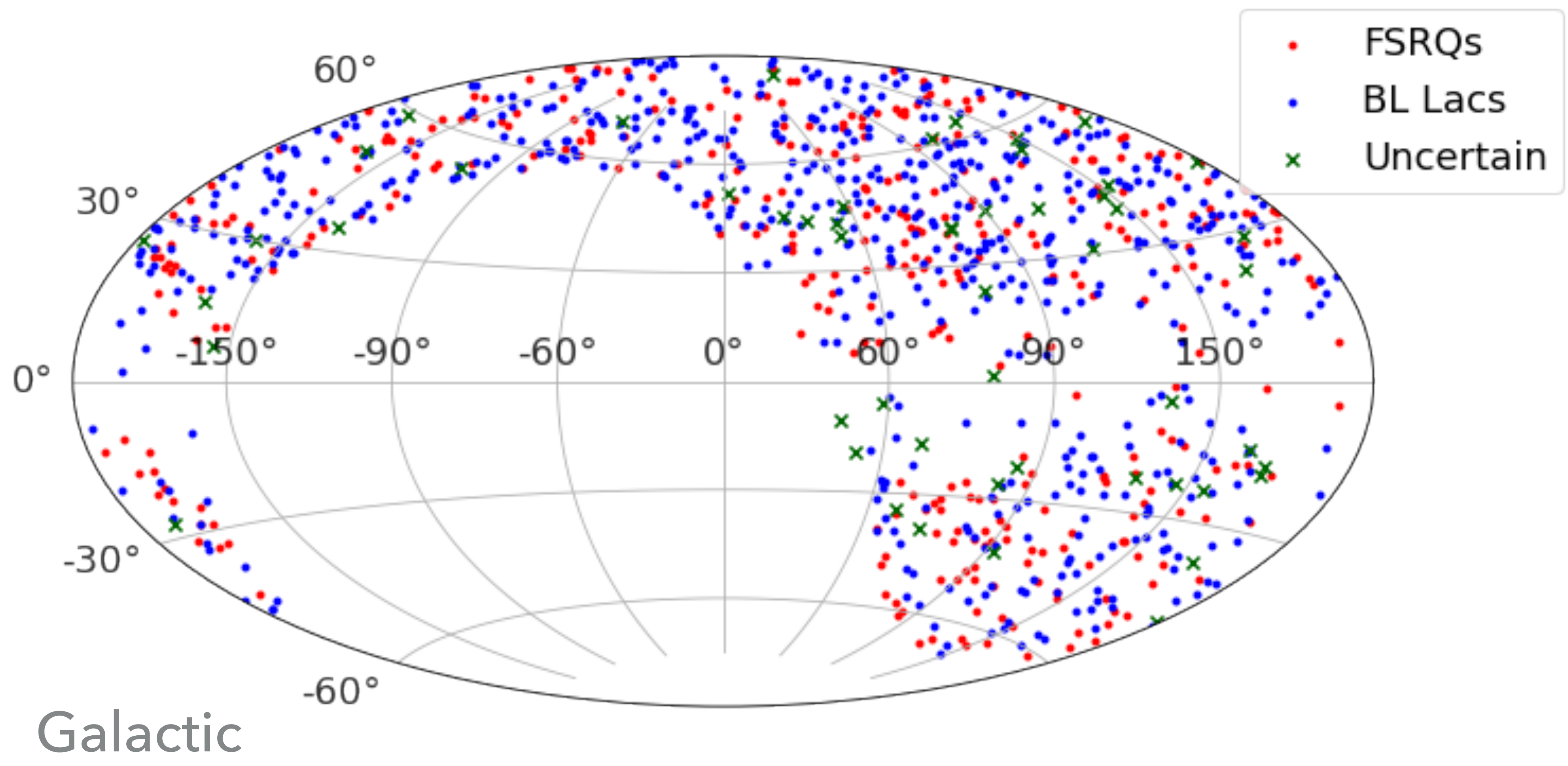


ROMABZCAT 5TH EDITION (2015)

- 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



Northern Hemisphere

Before cuts: 2312 blazars
After cuts: 1000 blazars

SIMILARLY MOTIVATED ANALYSES

- Stacking Analysis to search for neutrino emission from Hard X-ray AGN by S. Goswami
  - ✦ Stacking search vs. time-dependent search
  - ✦ Different weights vs. X-ray flux as weights for down-selection
  - ✦ All AGN (blazars included) vs. only blazars
  - ✦ Hard X-rays (14 -195 keV) vs. soft X-rays (0.1 -2.4 keV)
  - ✦ ~ 5% overlap between sources (SWIFT-BAT 70 month AGN catalog vs. RomaBZCat)

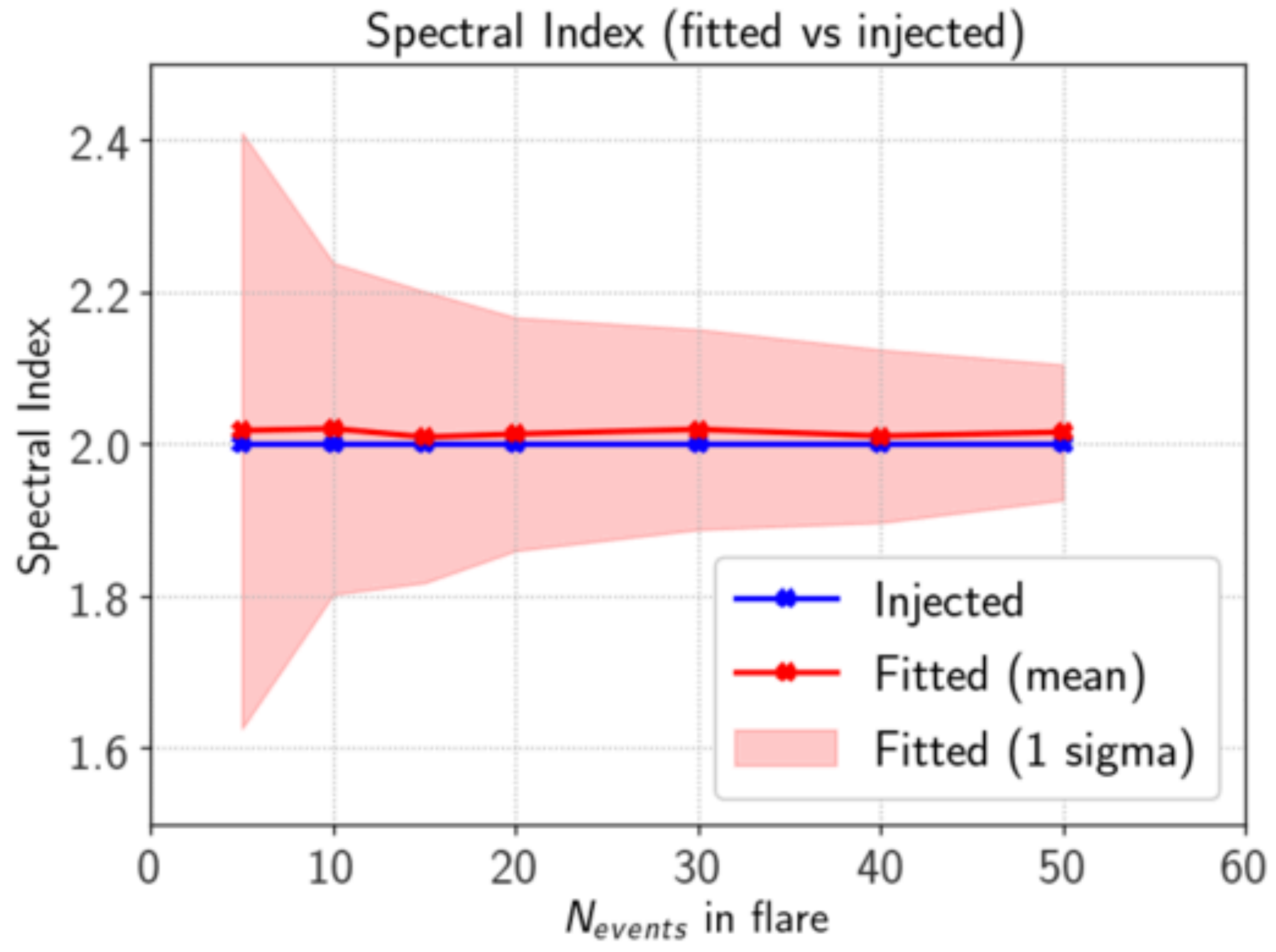
- Multi-flare stacking search from Fermi 3LAC blazars by W. Luszczak
  - ✦ Multi-flare stacking
  - ✦ Population test with binomial test statistic
  - ✦ Northern sky blazars: Fermi 3LAC vs. RomaBZCat
  - ✦ No weights vs. X-ray flux selection
  - ✦ Northern Tracks (8 yr) vs PS_Tracks (10 yr)
  - ✦ ~ 44% overlap between source lists

- 100 scrambles for 10 arbitrarily chosen sources
- Single flare injections, variable ***Nevts*** per flare
- Fixed spectral index and injected flare duration (**γ = 2, dT = 30 days**)
- S/B = 2000 & Max. Flare duration = 1000 days

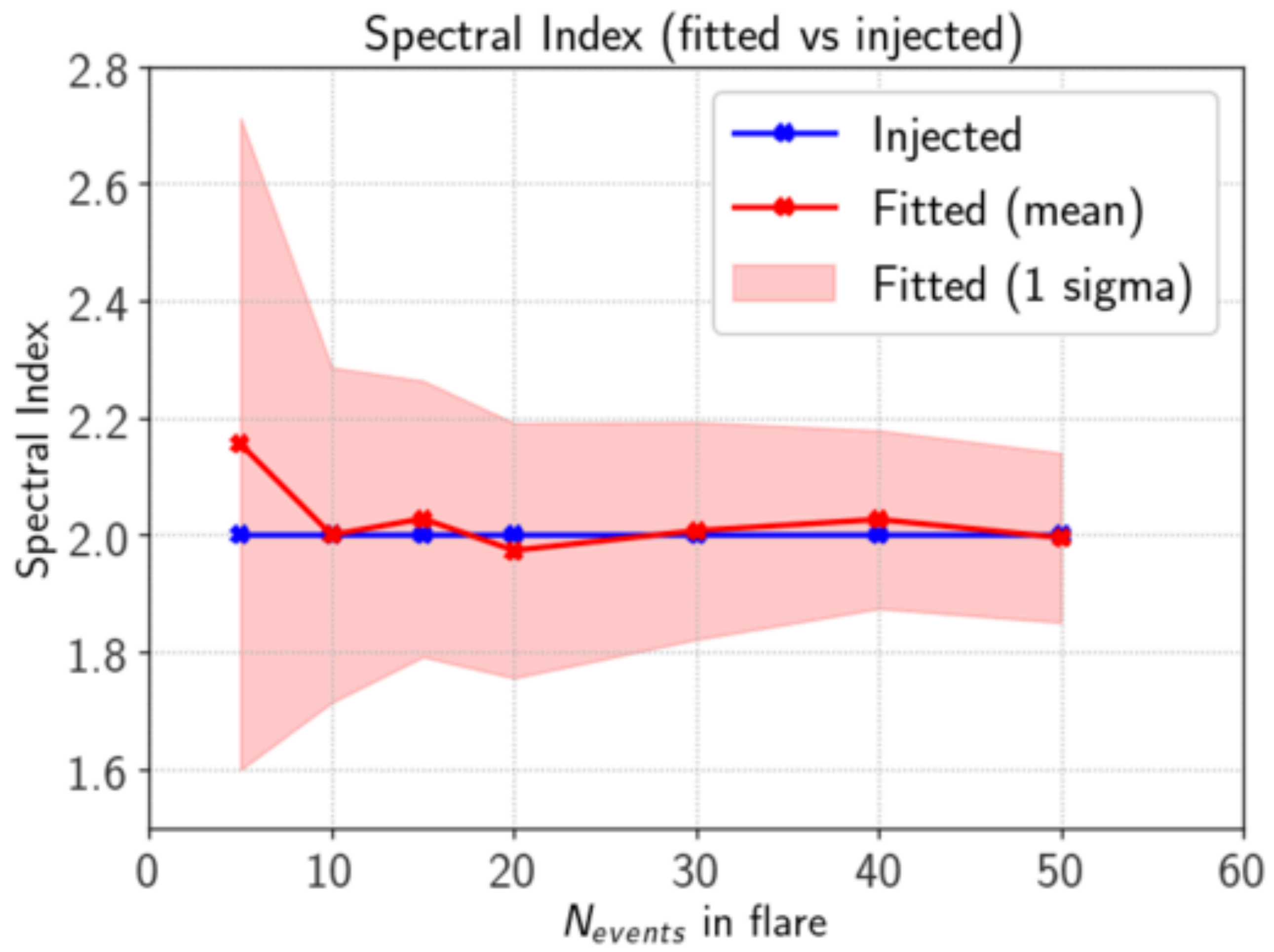
TEST OF FIT BIAS FOR ANALYSIS PARAMETERS WITH CSKY

{3/10 SOURCES}
DECLINATION = [5,50] DEG

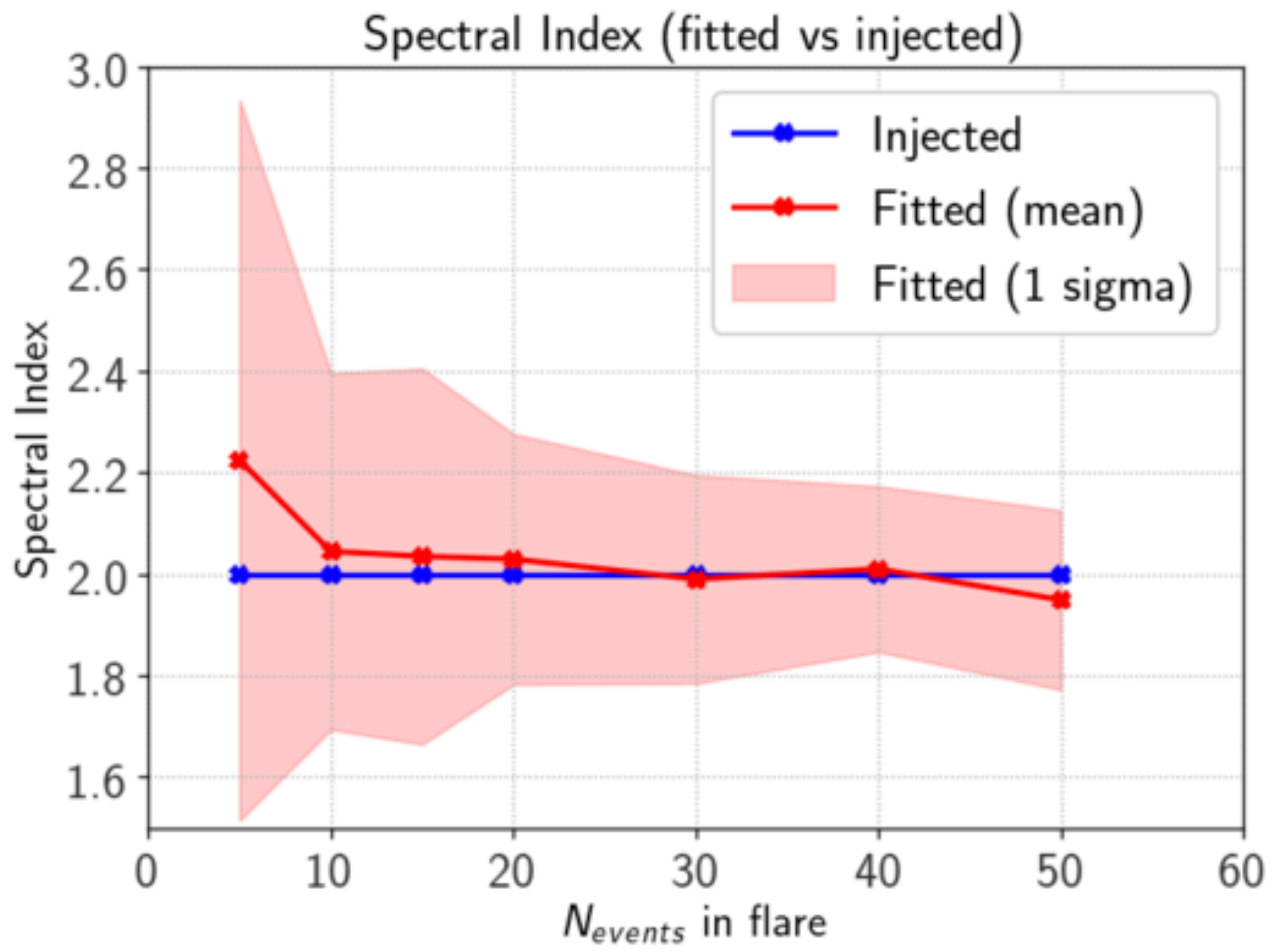
Dec. ~ 5 deg



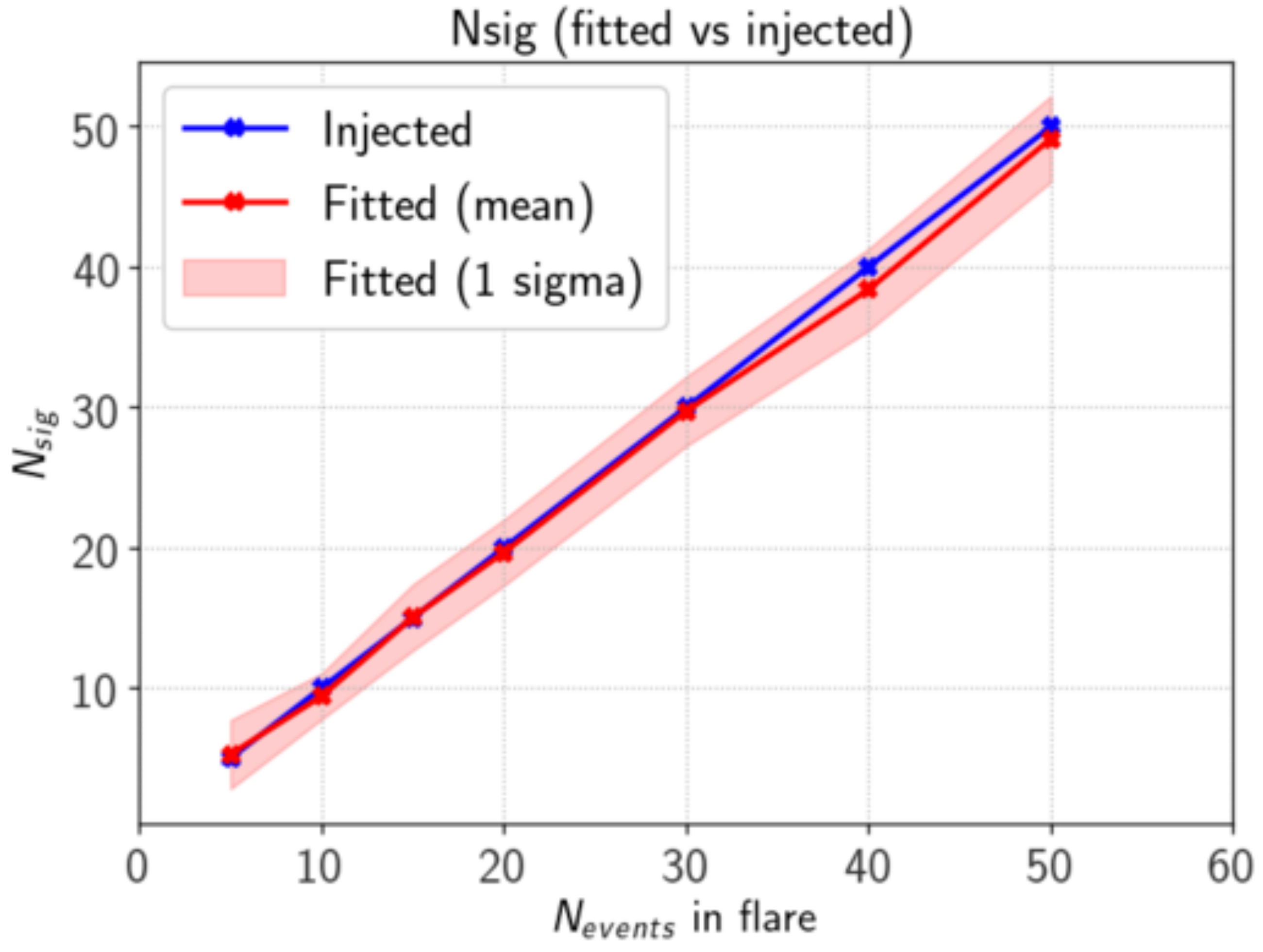
Dec. ~ 30 deg



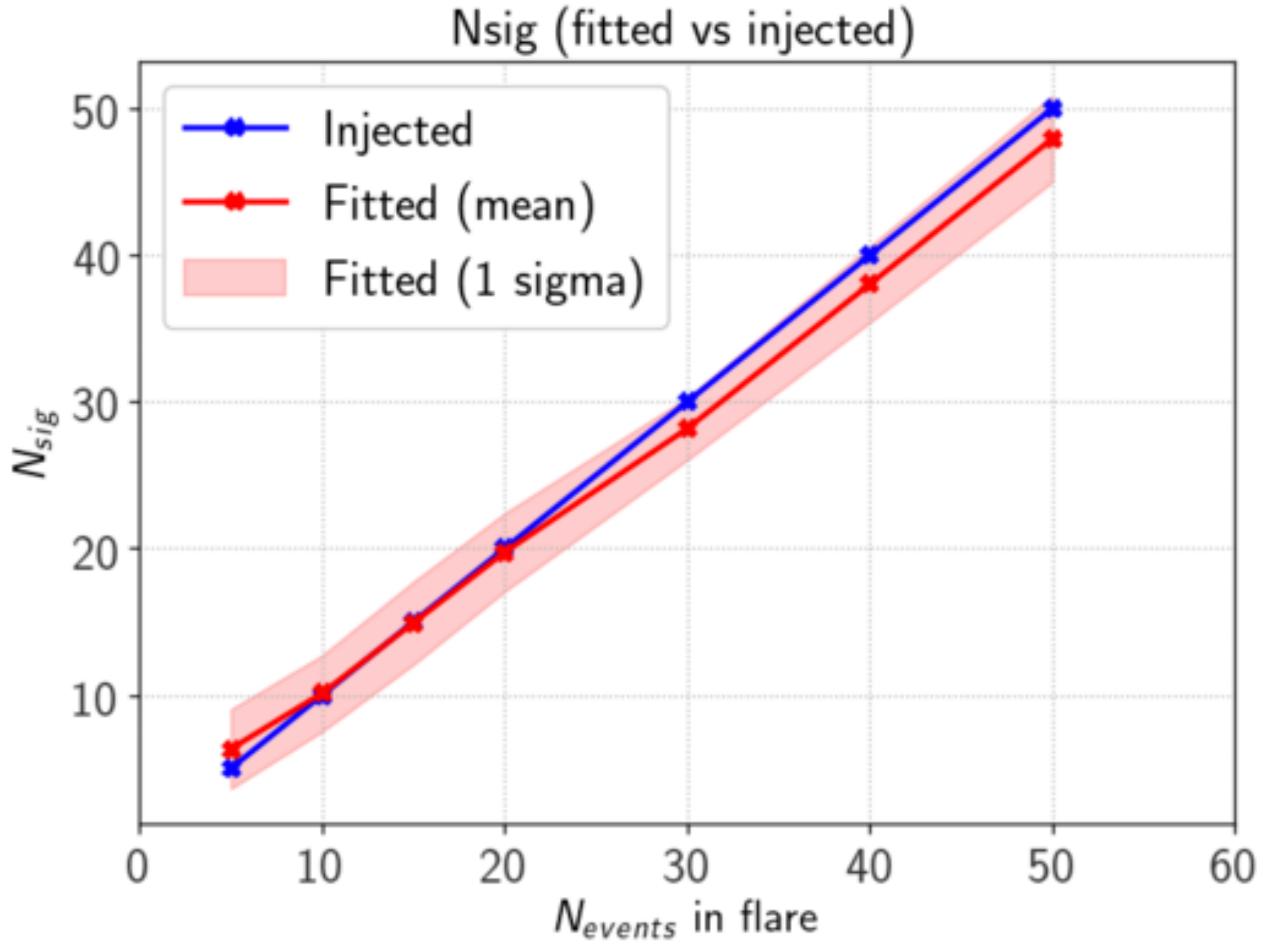
Dec. ~ 50 deg



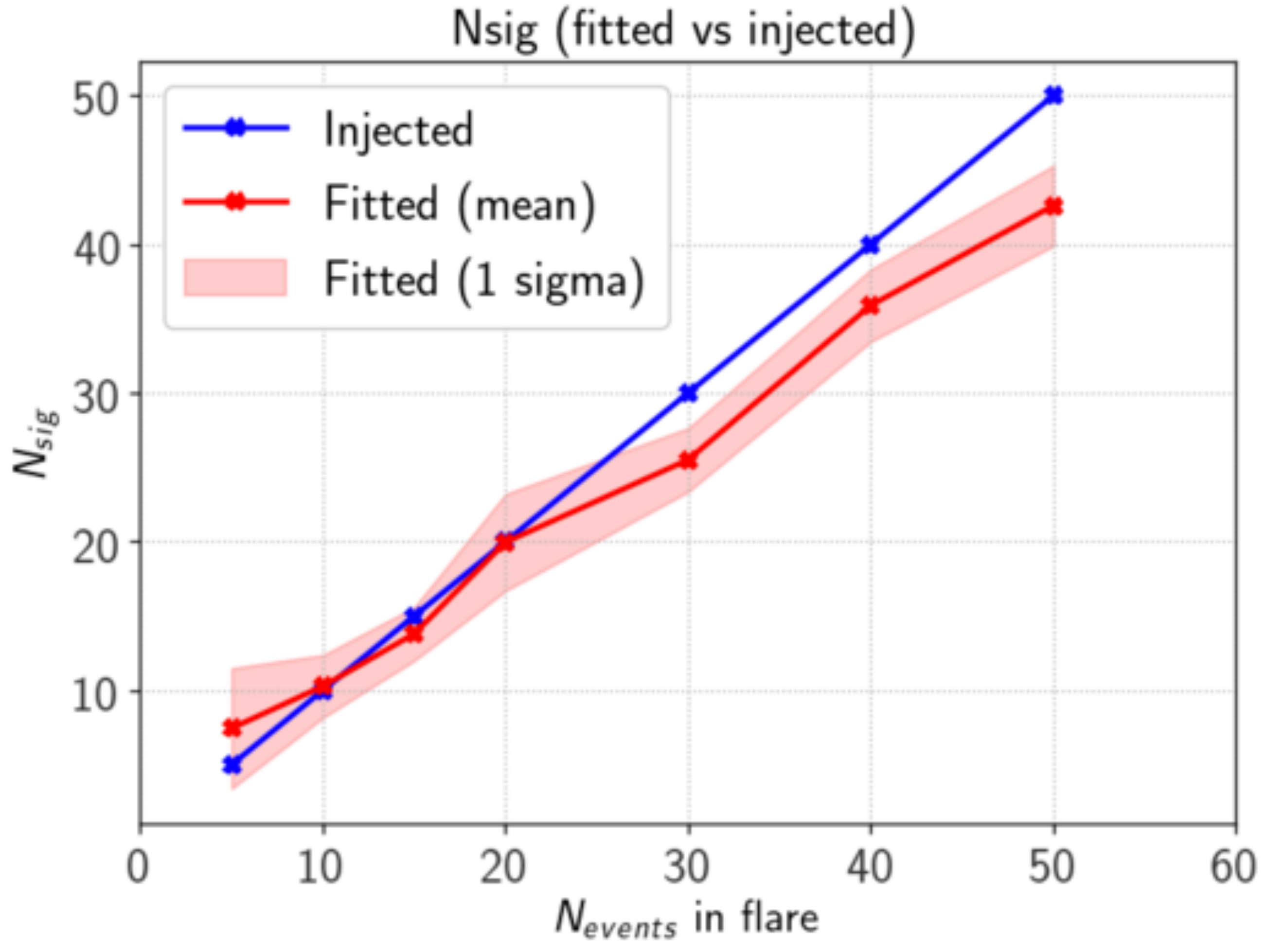
Dec. ~ 5 deg

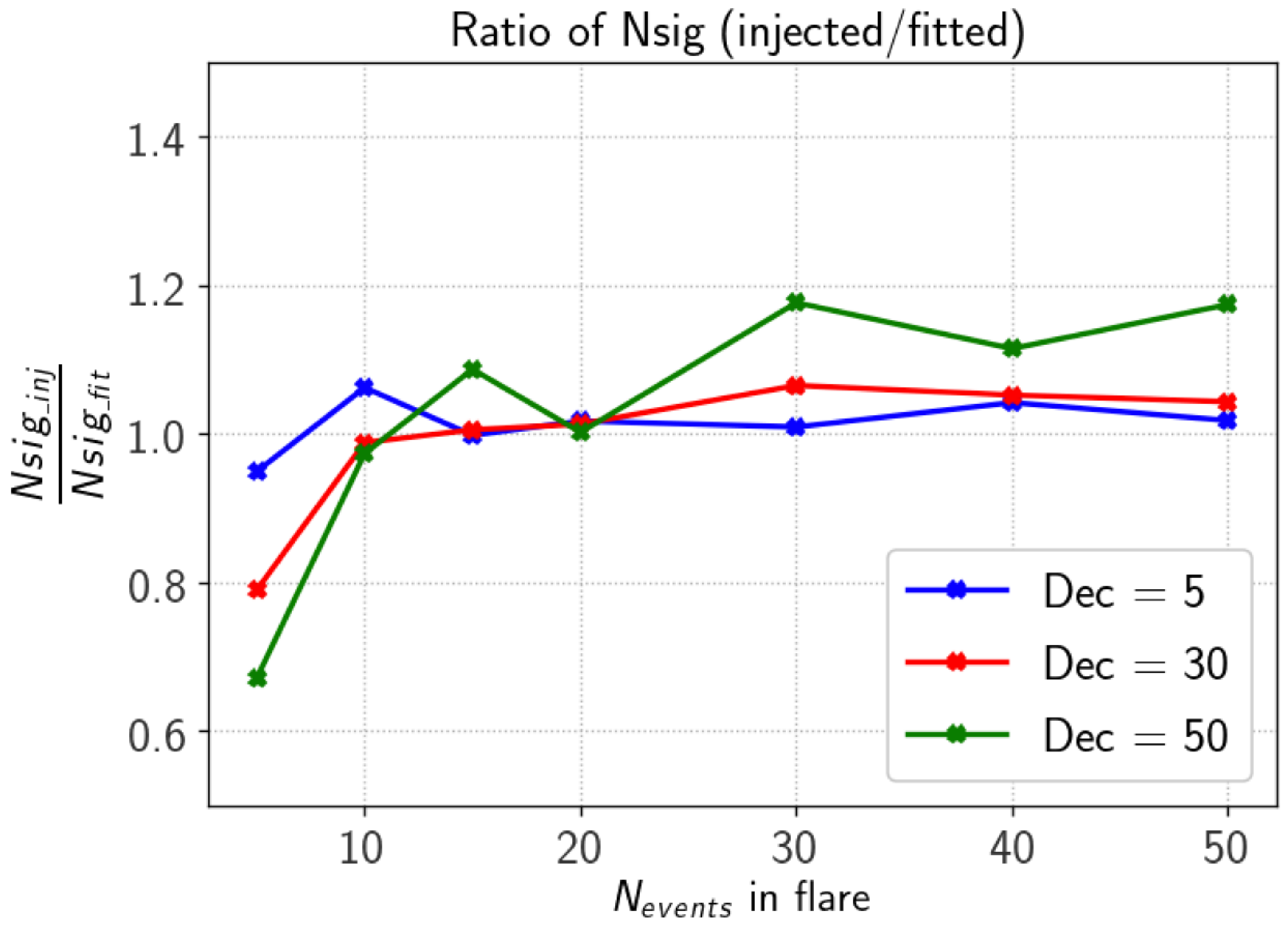


Dec. ~ 30 deg



Dec. ~ 50 deg

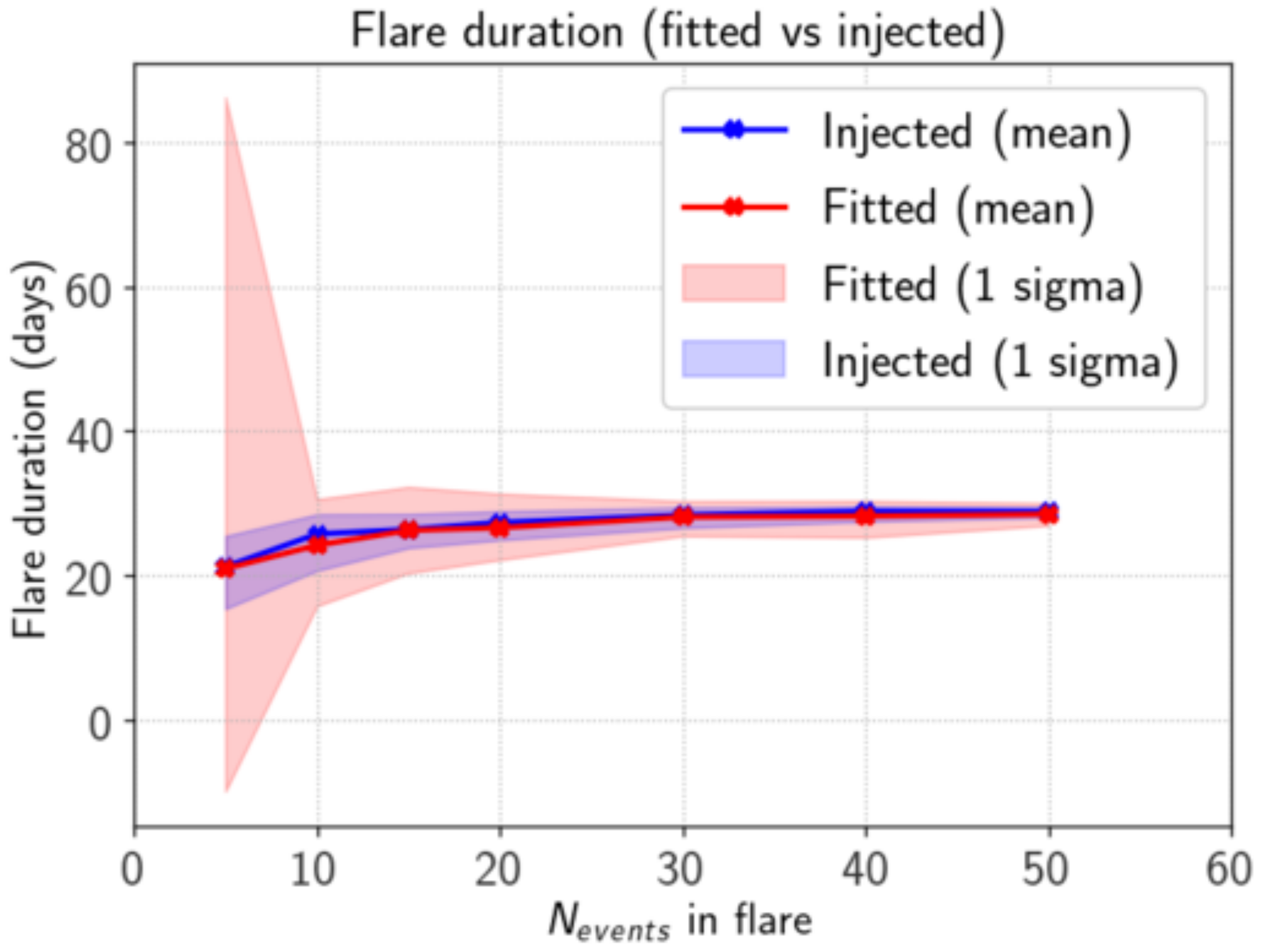


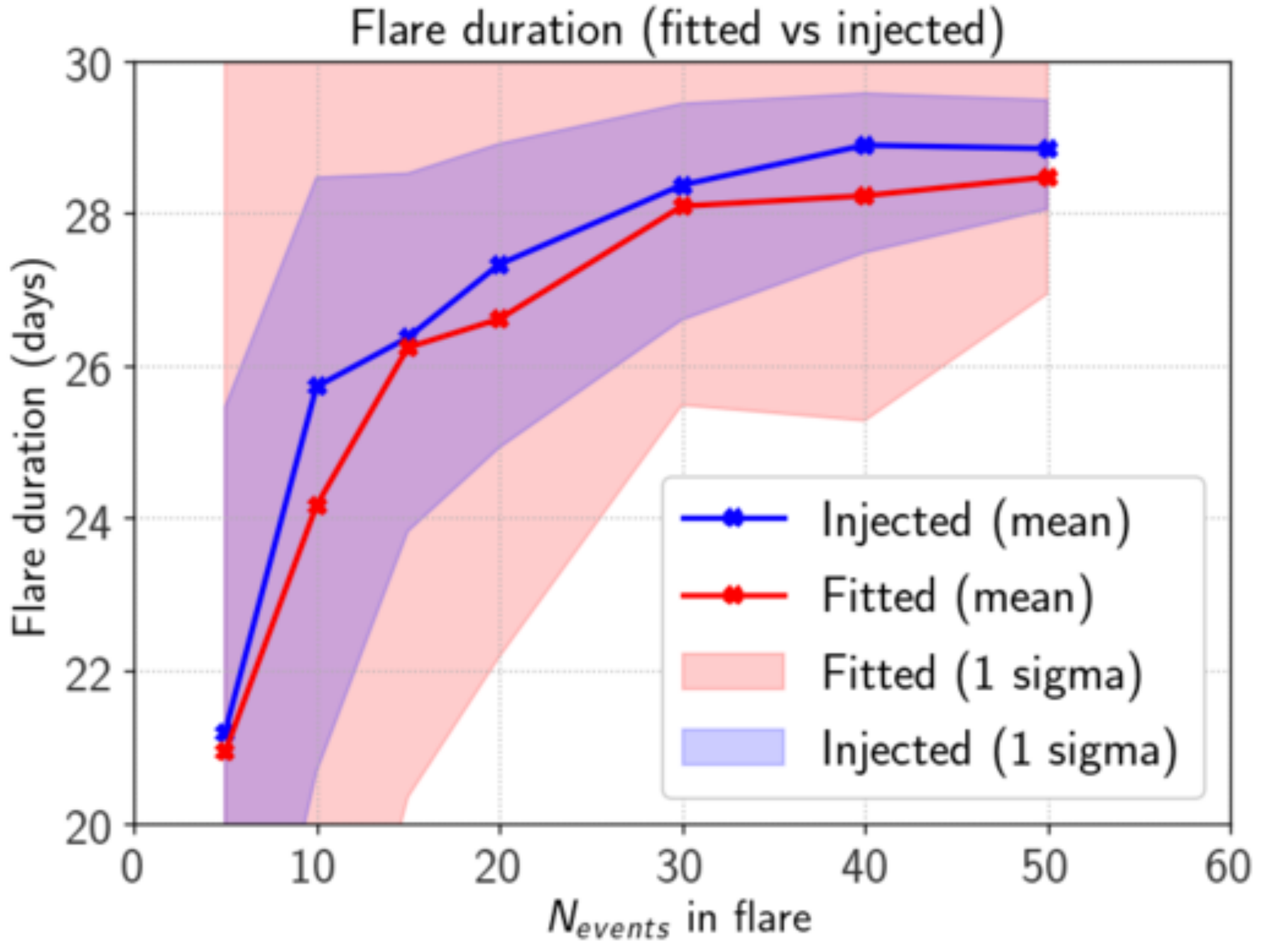


Ratio of Nsig (injected/fitted) < 1.2 for Nevt/flare > 5, with a slight underfit at higher declinations

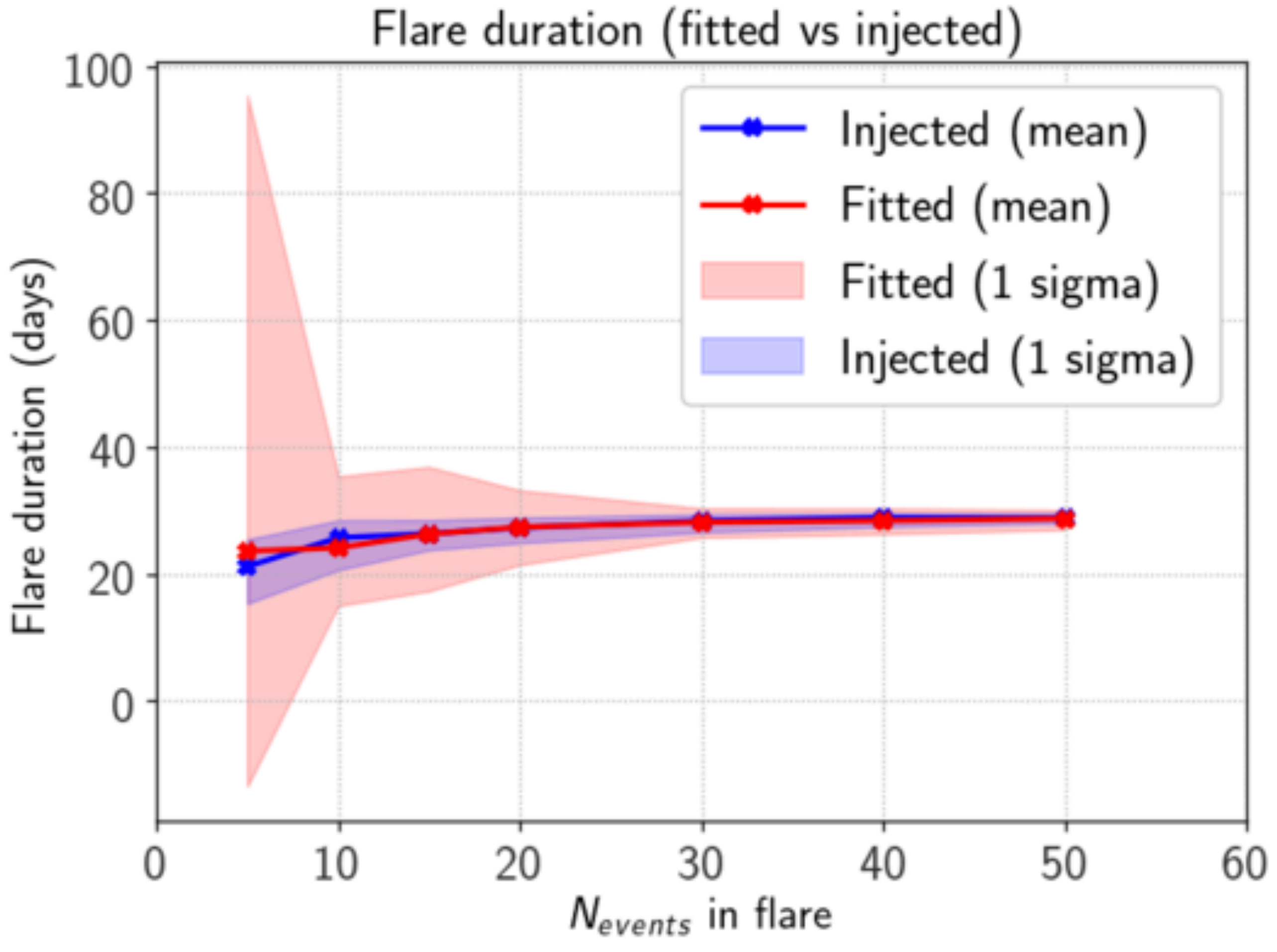
FIT BIAS - FLARE DURATION

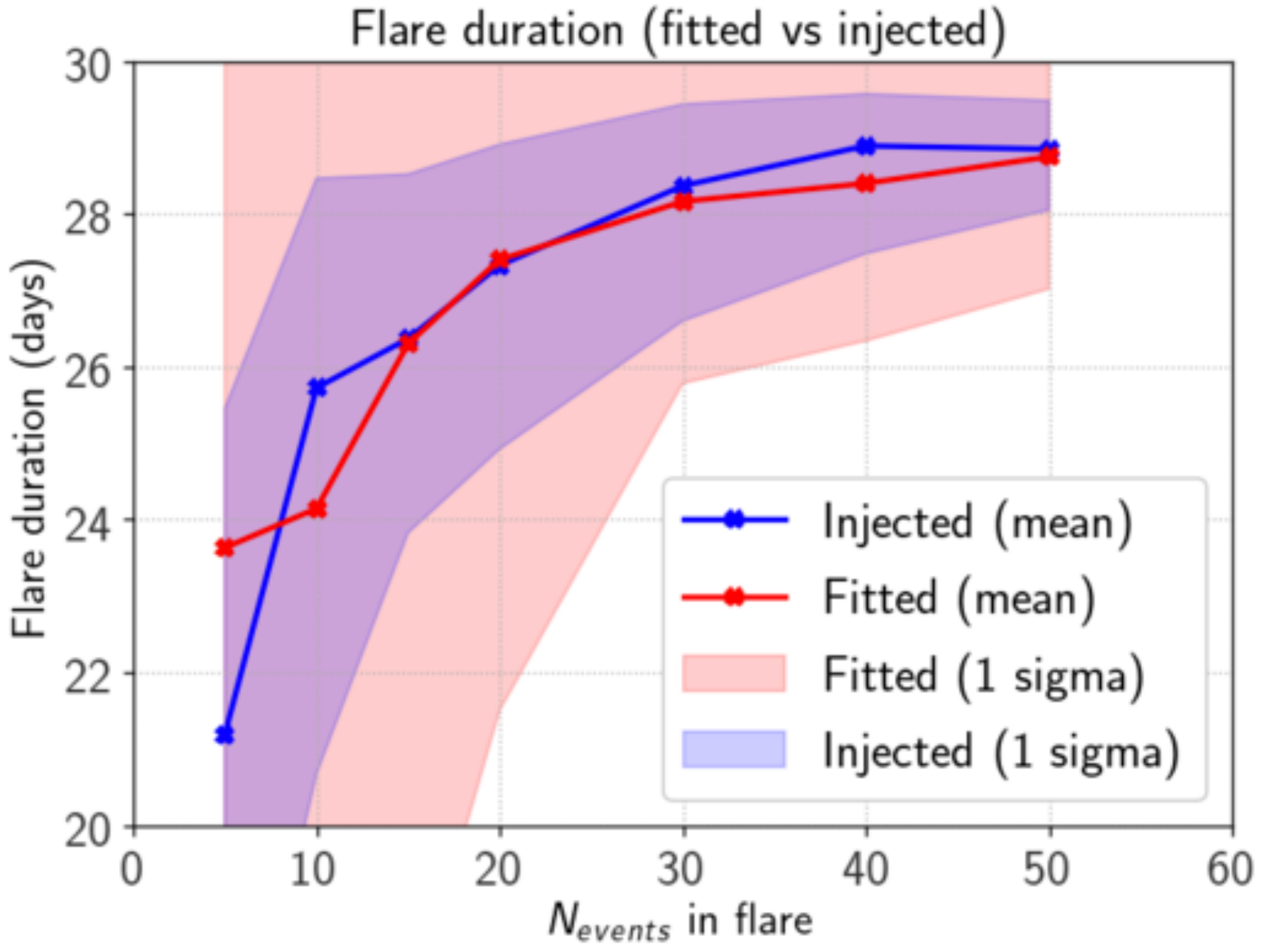
Dec. ~ 5 deg



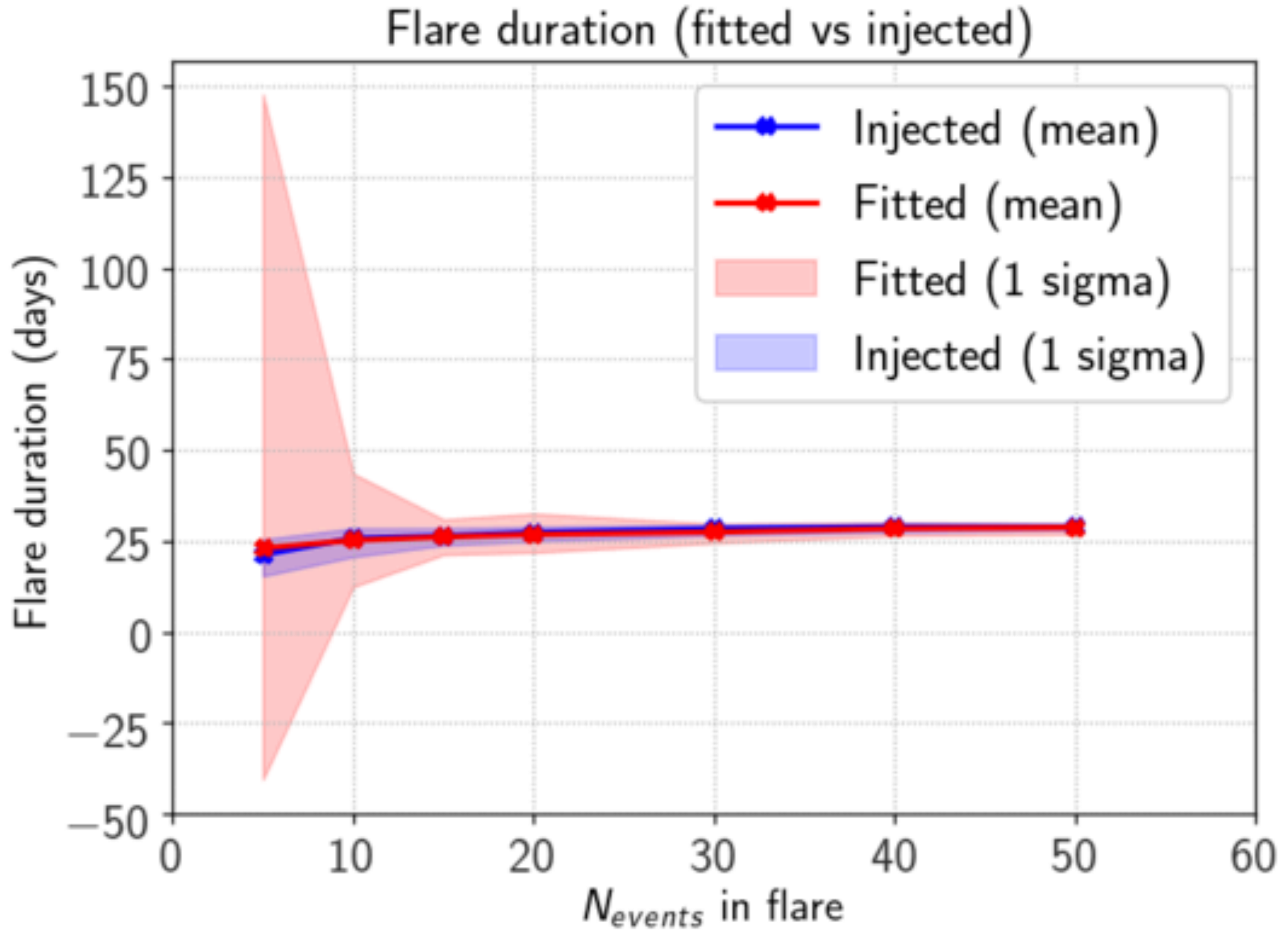


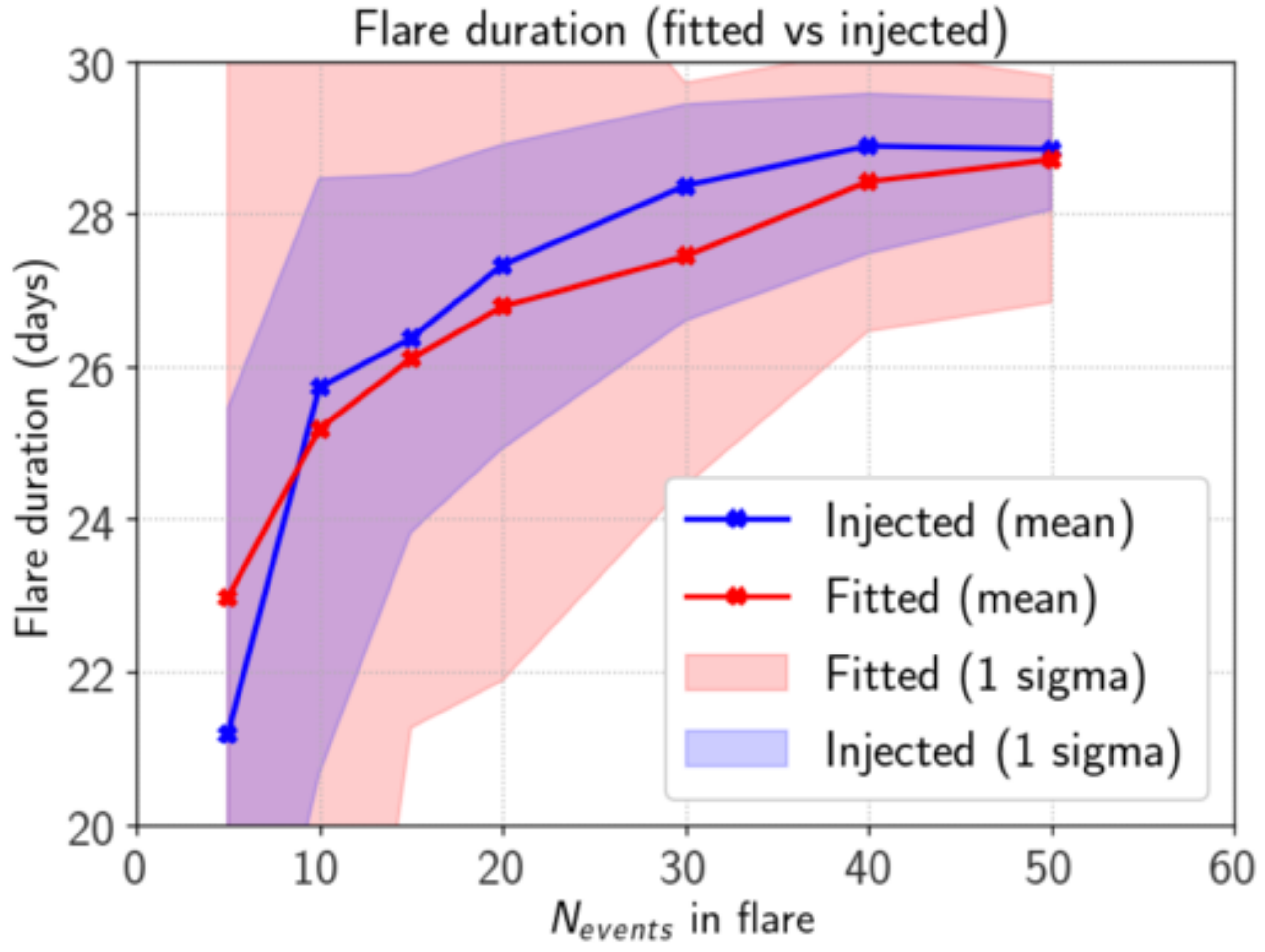
Dec. ~ 30 deg





Dec. ~ 50 deg



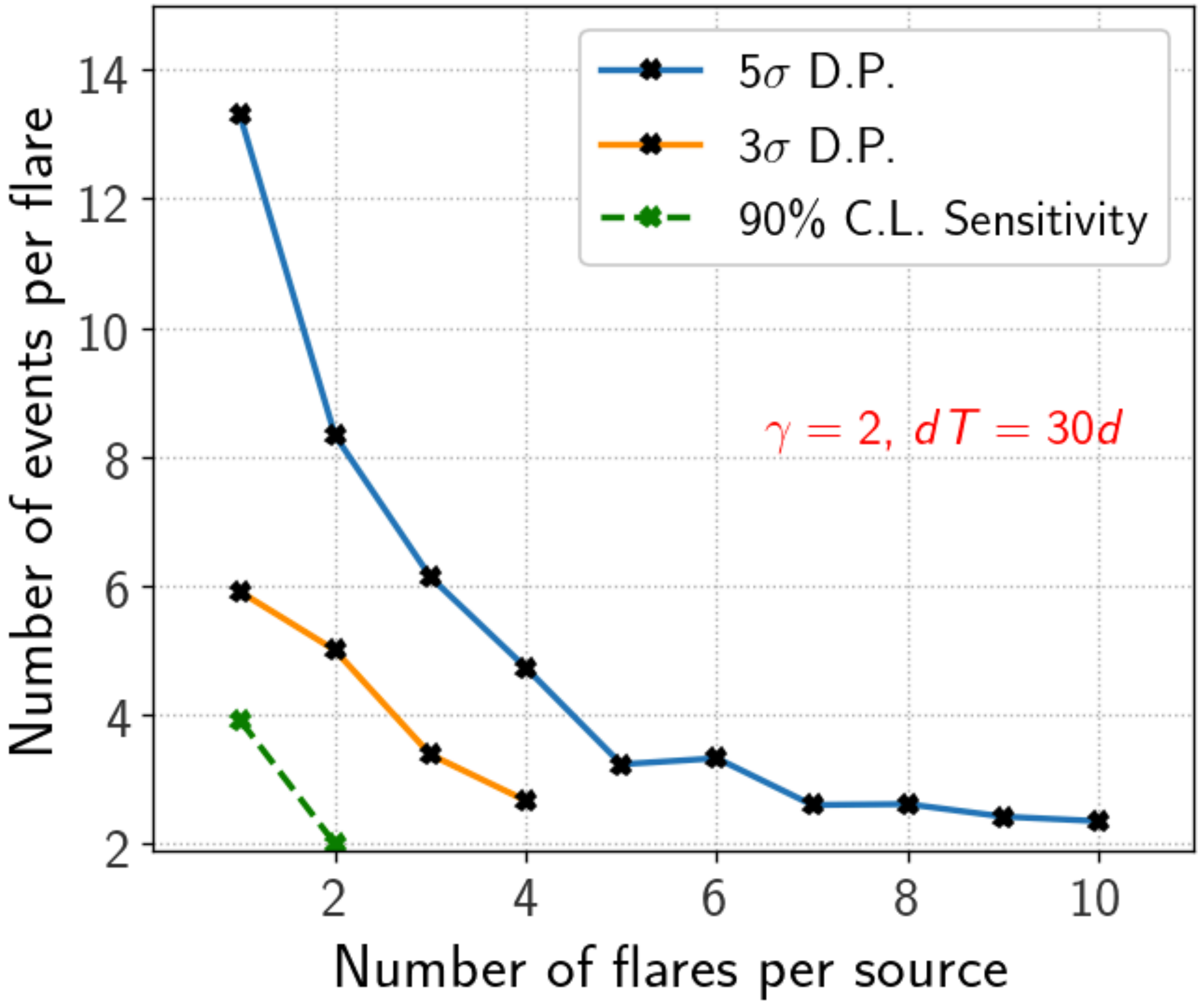


We want to obtain the following results post unblinding:

✦ **Multi-flare p-values (pre-trial)** of the **1000** individual blazars

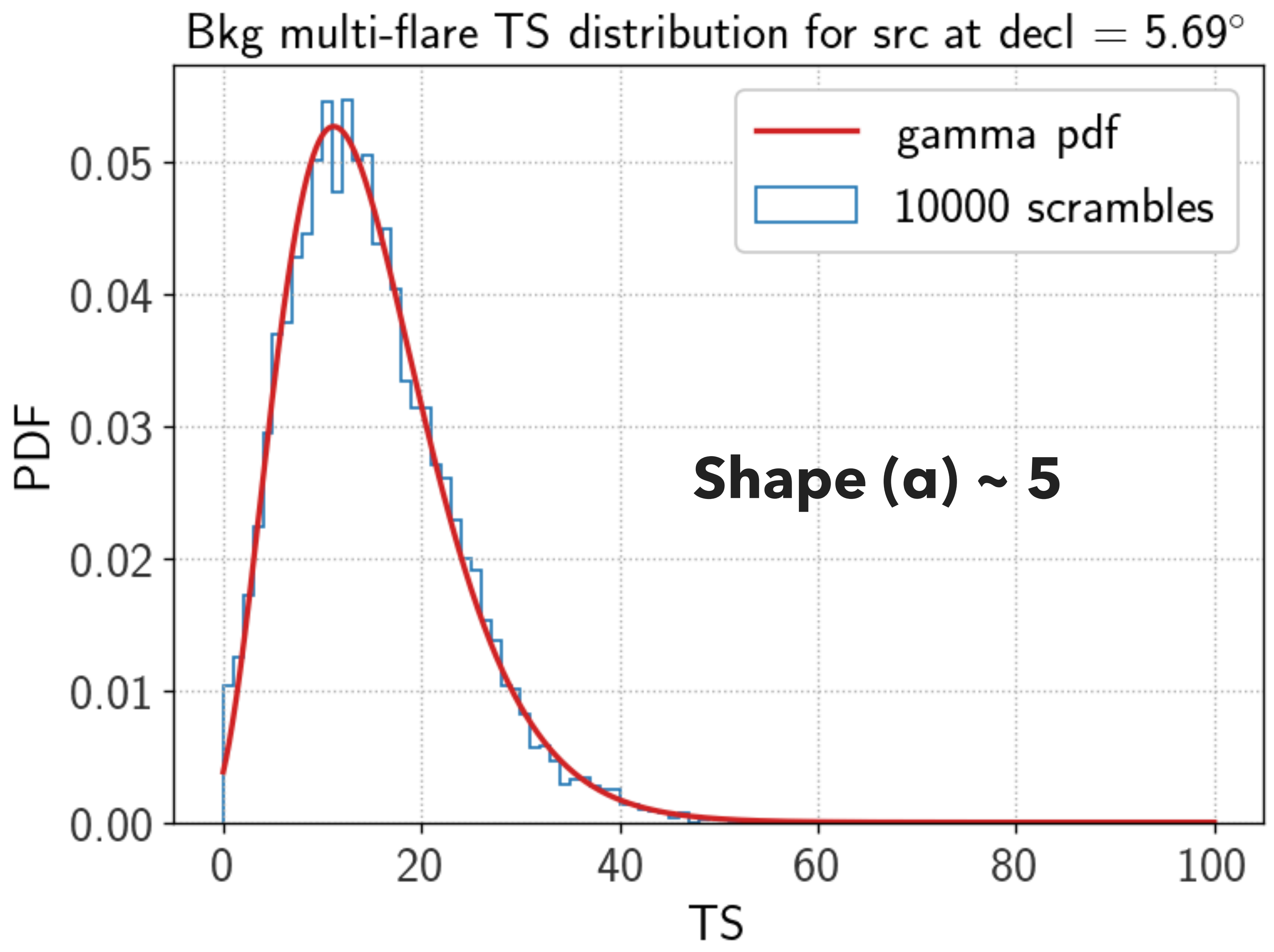
✦ **3 Binomial tests** [Northern BL Lacs, Northern FSRQs, all 1000 blazars] :

- ➡ Best binomial probability (post-trial p-value)
- ➡ Best-case *k* value (size of sub-population with significant emission)

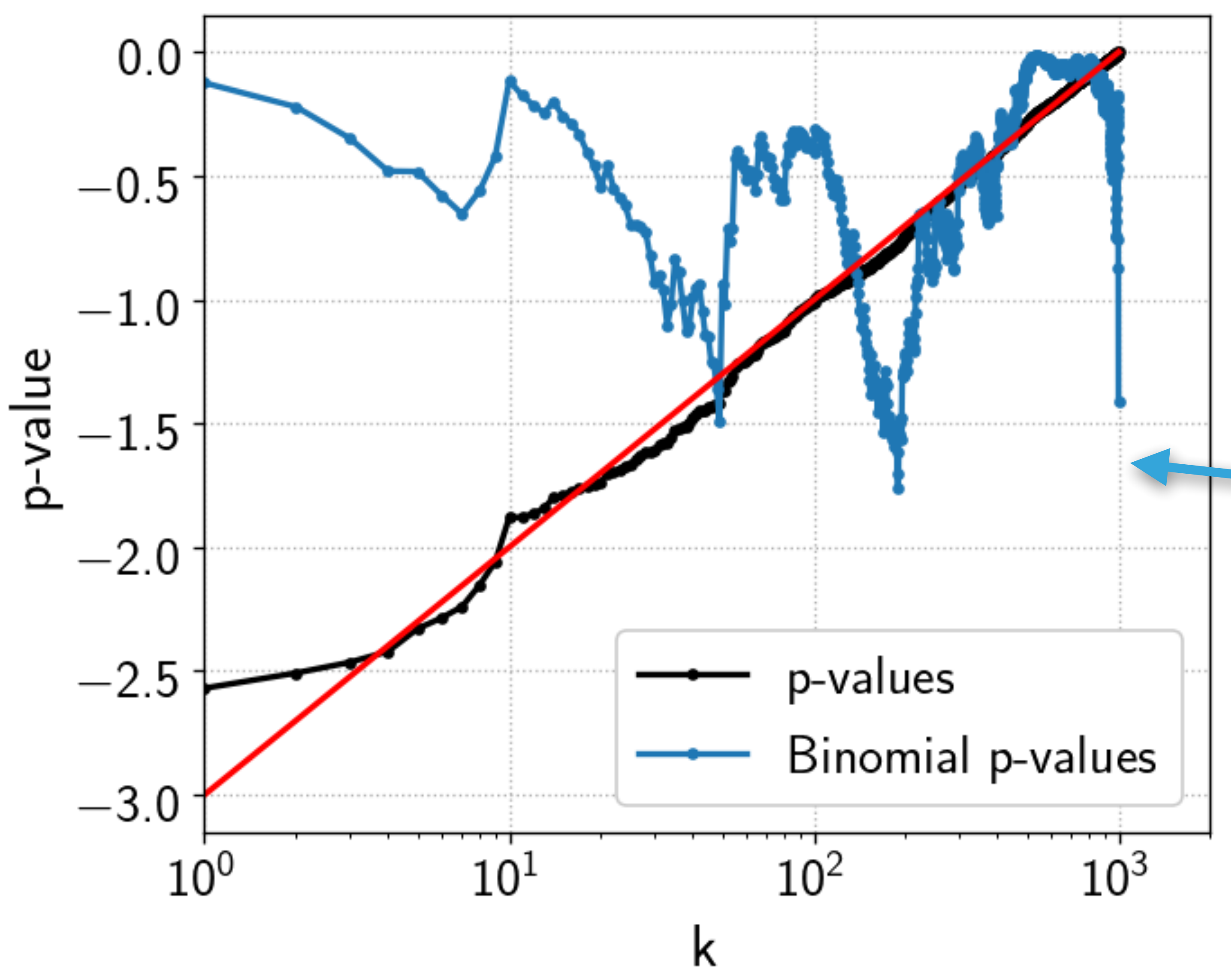


- 10k scrambles for a single source location (at the declination of TXS)
- With and without injections; Box profile flares
- Fixed spectral index and injected flare duration (**γ = 2, dT = 30 days**)
- S/B = 2000 & Max. Flare duration = 1000 days

Strength of individual flares from a single source required to obtain a final discovery potential (D.P.) of 5σ, 3σ and a 90% C.L. sensitivity



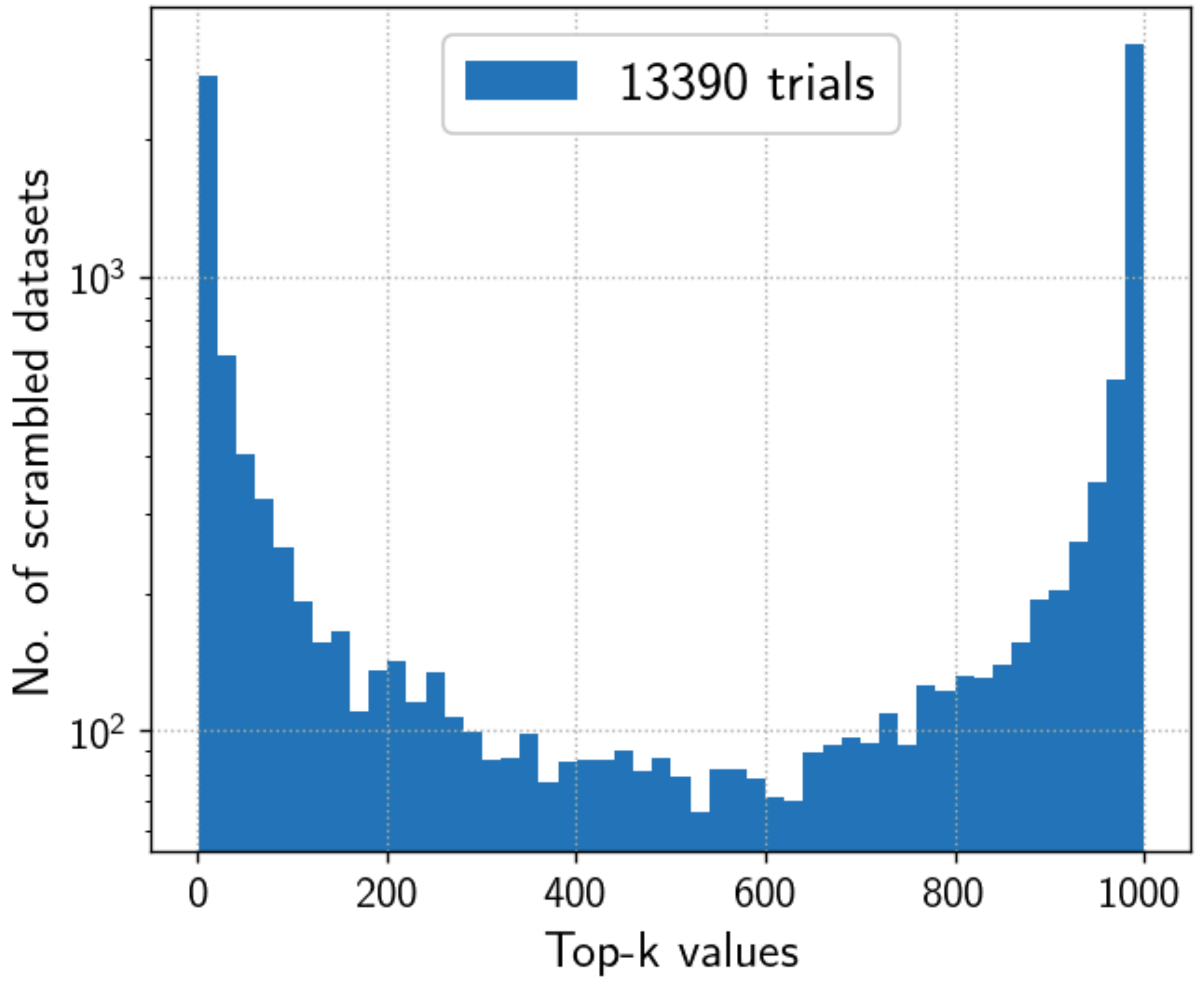
Background multi-flare TS distribution for the declination of TXS across 10k trials



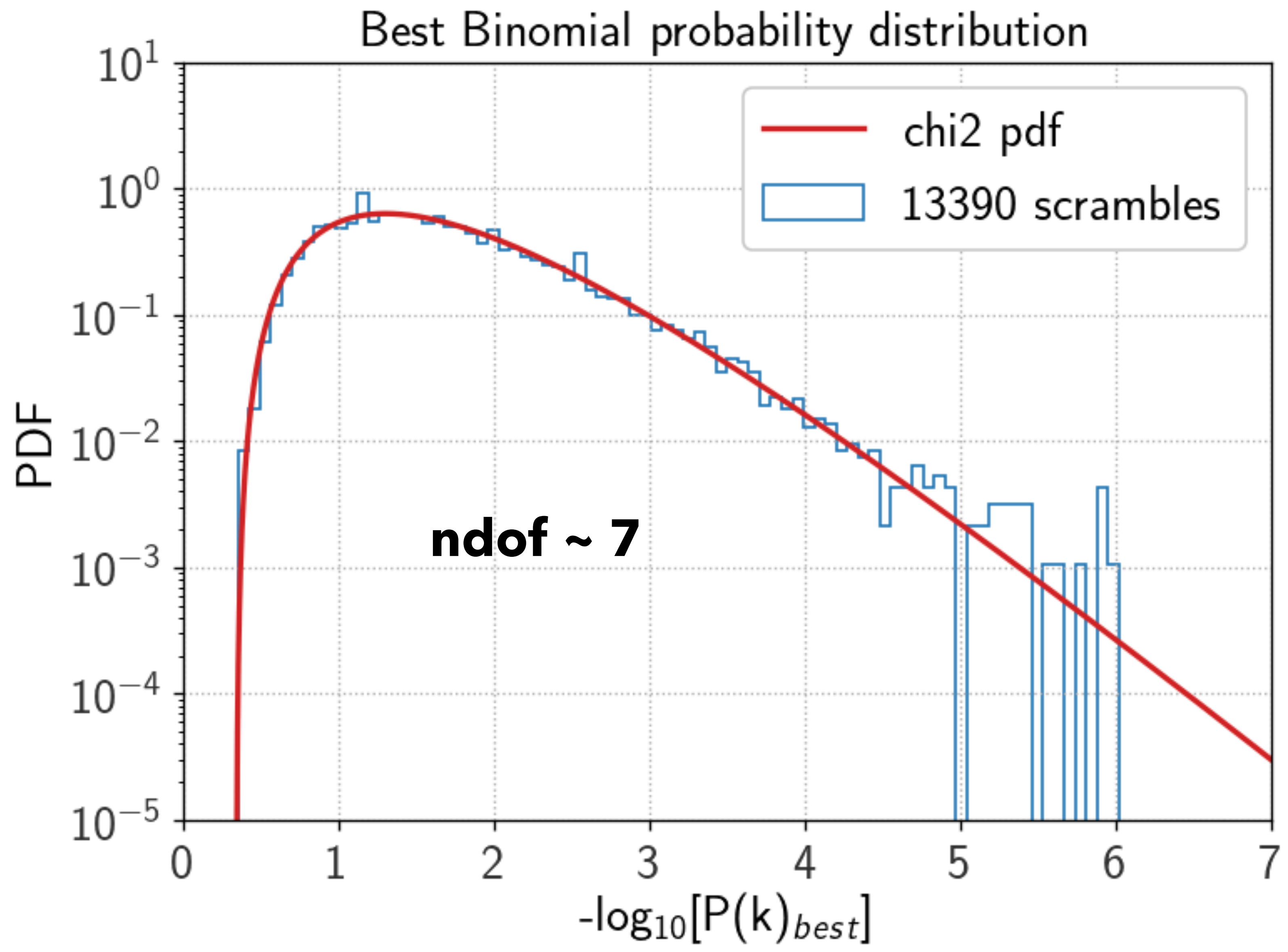
Binomial probability distribution (Binomial p-values) for a <u>single binomial test</u> on 1000 sources

Best case 'k' : 196

Best Binomial p-value: 0.016



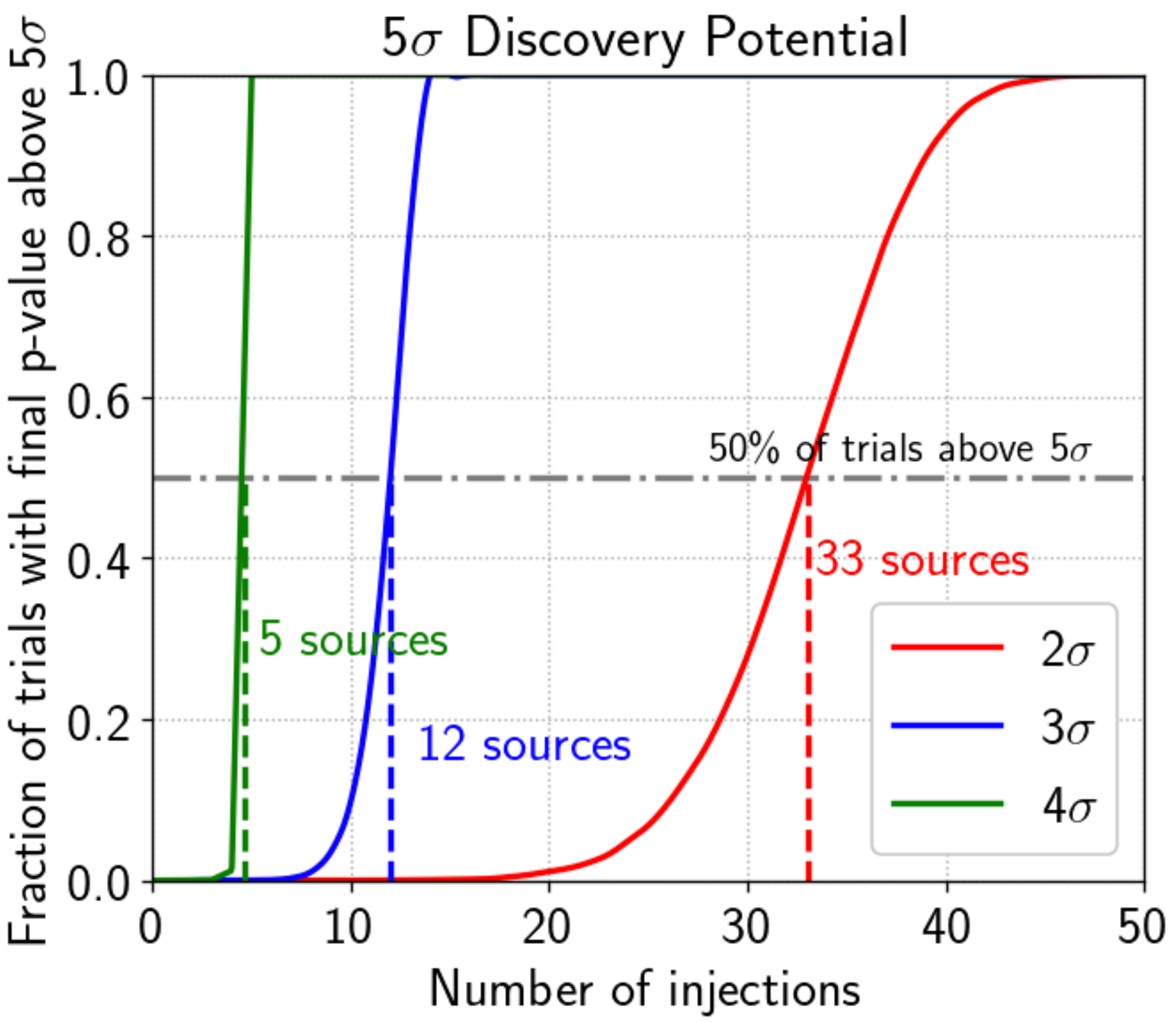
Top 'k' value distribution for 13.4k trials



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

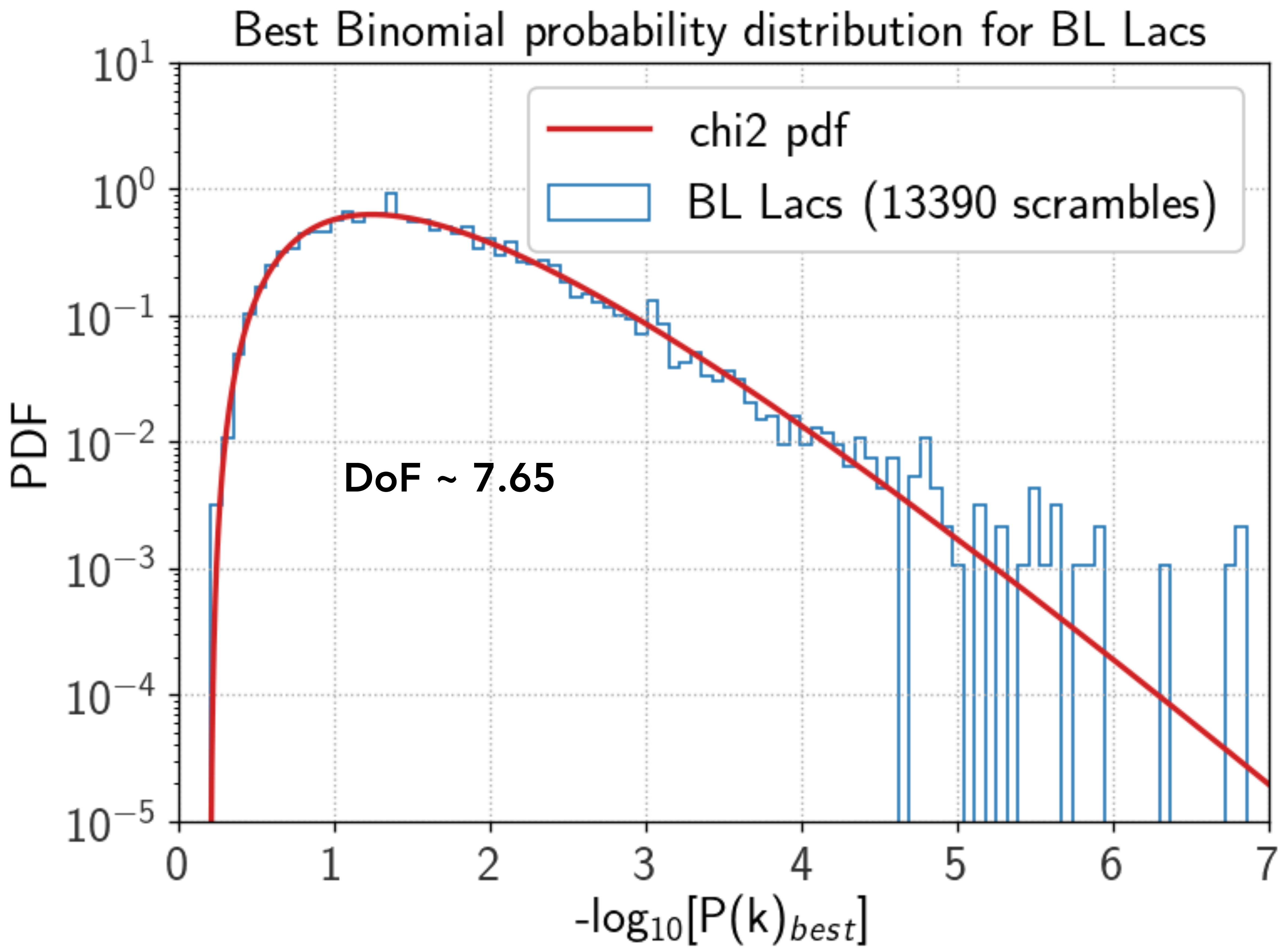
Binomial Test :

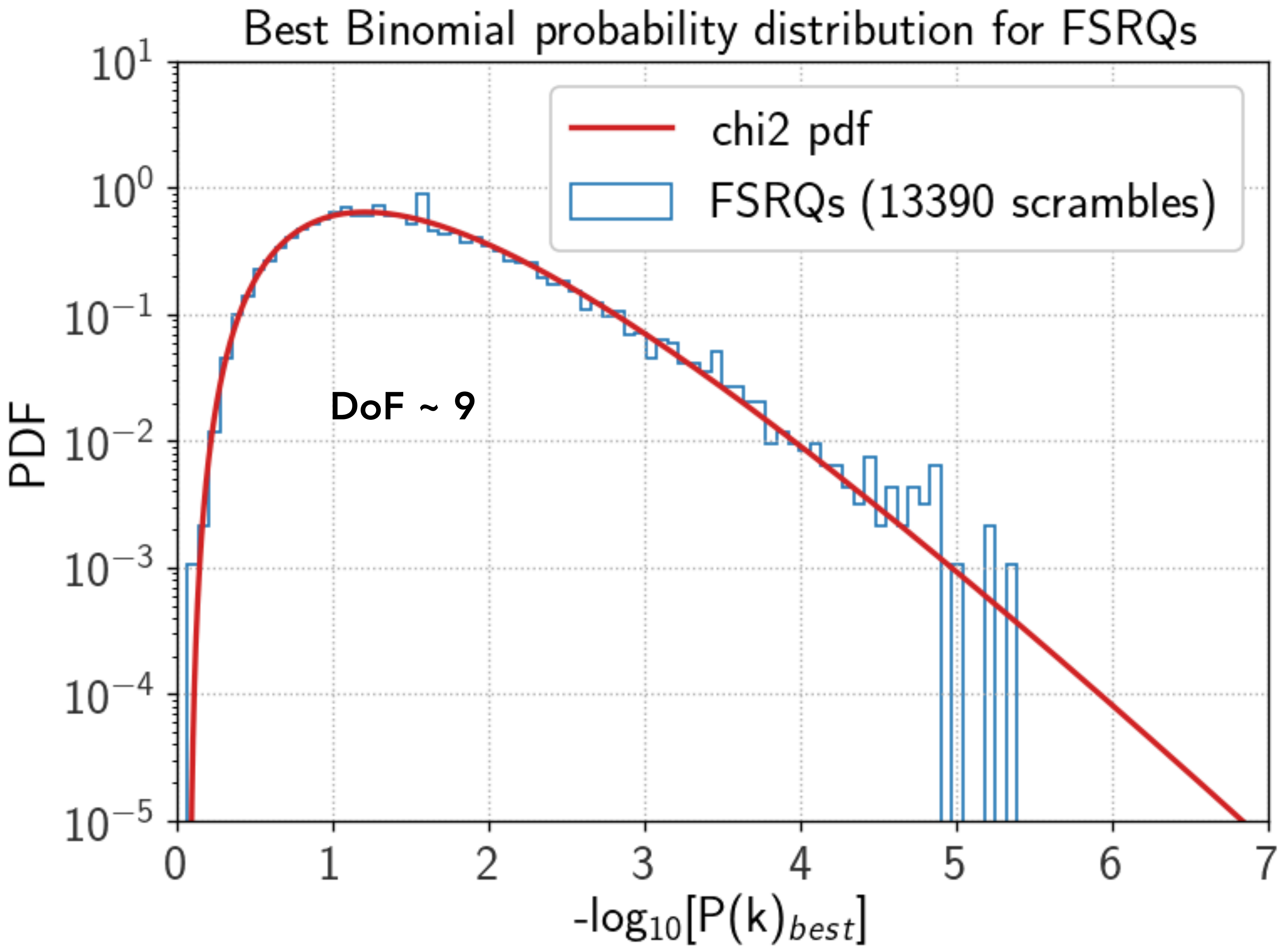
$$P(k) = \sum_{m=k}^{N} \binom{N}{m} p_k^m (1 - p_k)^{N-m}$$



- 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

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


Best Binomial probability distribution for BL Lacs
chi2 pdf
BL Lacs (13390 scrambles)
DoF ~ 7.65
PDF
-log10[P(k)best]
10^1
10^0
10^−1
10^−2
10^−3
10^−4
10^−5
0
1
2
3
4
5
6
7


Best Binomial probability distribution for FSRQs
chi2 pdf
FSRQs (13390 scrambles)
DoF ~ 9
PDF
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
1
2
3
4
5
6
7
$-\log_{10}[P(k)_{best}]$

Post-trial values for sources > 3σ (pre-trial) and TXS 0506+056

Name	RomaBZCat Name	Redshift	X-ray Flux (erg/cm2/s) [0.1-2.4 keV]	Pre-trial p-value (σ)	Post-trial p-val (σ)
MS1207.9+3945	5BZBJ1210l+3929	0.617	2.47e-12	0.00029 (3.43)	0.258 (0.64)
GB6J0058+0620	5BZQJ0058+0620	0.592	3.1e-11	0.00052 (3.28)	0.407
4C13.14	5BZQJ0231+1322	2.065	3.5e-11	0.00134 (3.00)	0.739
TXS 0506+056		0.33		0.005975 (2.51)	0.997

WG REVIEWER QUESTIONS I

1. **For Blazar Catalog section:** Why were only the top 1000 sources used? Is there a flux cut-off you are using for selecting the sample?

   - Multi-flare analysis is computationally very expensive, necessary to bring down the total of sources being tested. Northern hemisphere blazars selected considering the fact that IceCube has a higher sensitivity in this region of the sky

   - We tested both methods, but easier to justify selecting a 1000 sources than to justify a random cut on the X-ray flux

2. **Catalog completeness:**

   - Calculation not completed since it has proven difficult to find the X-ray luminosity function for blazars in the range of ROSAT sensitivity (0.1 - 2.4 keV)

   - The analysis can still move forward since there are no intentions to place any population limits with this time-dependent analysis

3. **Analysis Method:** Is there a reason for choosing 1000-day flare duration as maximum?

- Computational arguments: Increasing the flare duration substantially increases the computation time for each trial
- Tested max. flare durations of 2000 and 1500 days, and going down to a 1000 day flare window, we only lose 1.5% and 3.5% flares per source respectively. These were usually weak background flares of very long duration with a very low test statistic

4. **Fit Bias:** How is the source with dec = 5.3 chosen? Is it a random source, or is it bright in the X-ray regime?

- Fit bias studied for 10 (arbitrary) sources with declinations between ~ 5 - 60 degrees. Results presented here for just one of these sources, however similar results obtained for the others
- Source shown here chosen at random from the sample of 10, and has no special distinguishing characteristics (not bright in X-rays etc.)

1. **Source selection:** Have you made any other cuts except for declination cut before selecting the brightest 1000 X-ray sources? The numbers on wiki and slides not consistent with ~2312 sources in the north (dec. between -5, +85).

- Down-selection procedure: keep only sources with non-zero X-ray flux (2249 blazars), then cut on required declination range [-5 to +85], which has 1520 blazars, and finally select the first 1000 sources within this range ordered in a decreasing order of their X-ray fluxes

- Total number of sources in catalog within (-5, +85) was asked for by the WG reviewer to estimate how many more sources can be tested if we improved the computation time. 2312 is the number of sources in our declination range only if no cuts are placed on the X-ray flux. But this confusion will not have any effect on the code or the scrambles run so far

2. **Data sample and S/B cut:** Why the point source track v.3.2 was applied instead of v.4.0 or other datasets? Could you comment a bit about the S/B cut?

- Also tested performance of PS_Tracks (v4, v3.2) and Northern_Tracks (v5, 10 yrs). GFU offline wasn't considered since the beginning, because the initial plan was to run the analysis with more new data like PS_Tracks_v4 (12 yrs)
- Dominating factor in decision was the average computation time for a single source: PS_Tracks_v3.2 has 80% of the (all-sky) events of PS_Tracks_v4 but takes on average 66% of the time to fit a single source using similar parameters and seeding, with a similar number of fitted flares returned. NTv5 was the fastest among the three datasets (but returned fewer flares per source, the reason of which is unclear)
- Final decision to stick with PS_Tracks_v3.2 to be compatible with Multiflare Skymap study. By using the same dataset, same software (*csky*) and almost similar parameters, the need to repeat a lot of the already performed checks could be avoided
- Similar arguments for S/B cuts. Tested S/B = [100, 1000, 2000, 10k]. Lower values take a lot of computational time, while we lose signal flares for higher ones. S/B = 2000 returned a reasonable number of fitted flares in a reasonable time, and is compatible with above study

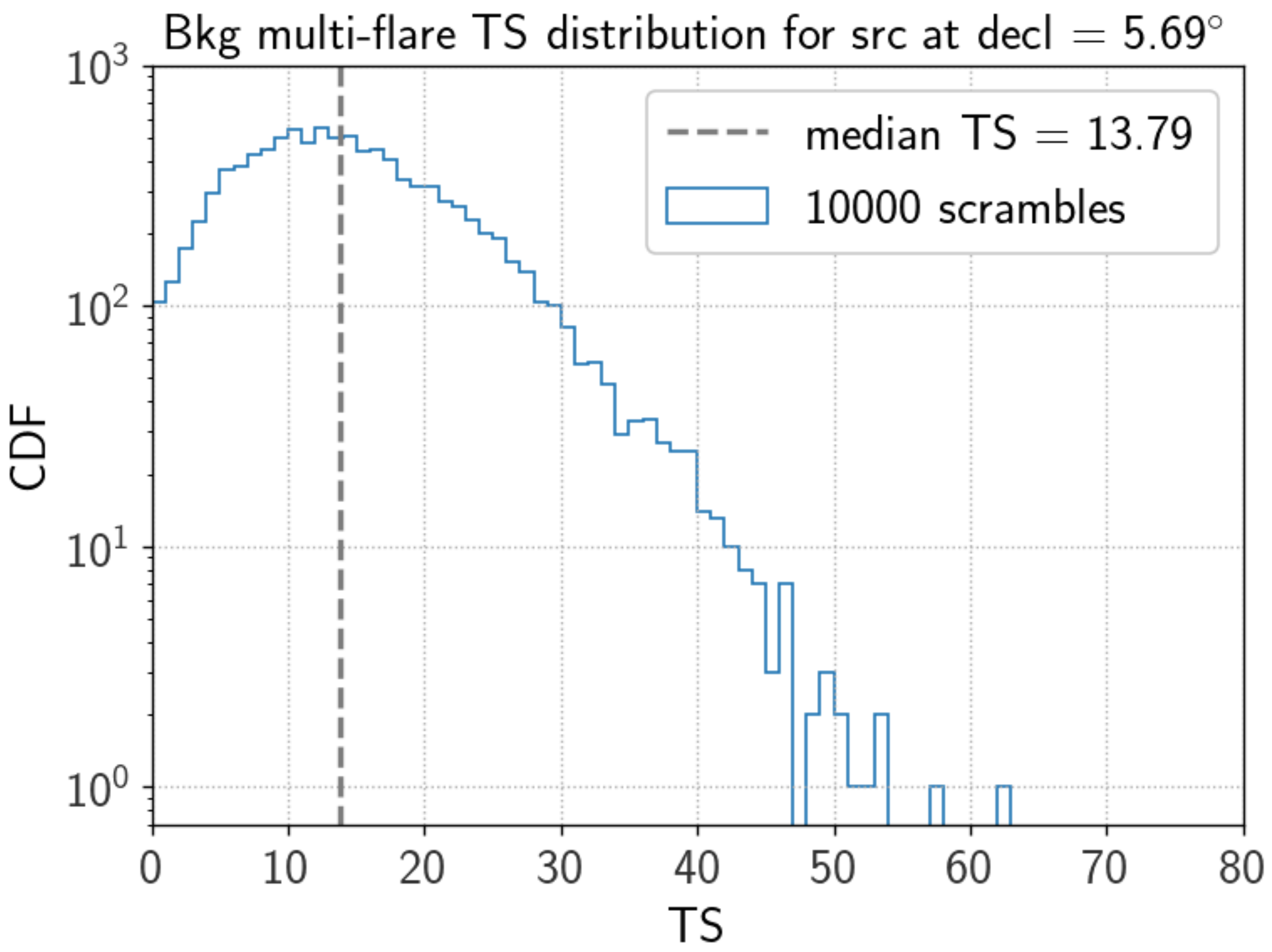
3. **Final Results:** You are planning to do the same test with sub-group of 1000 sources, BL Lacs and FSRQs as well. Then will you apply the same method to consider the trial factor and correlation among them? In the end, three final post-trial binomial p-values will be reported?

- Since the sub-catalogs are derived from the same set of 1000 sources, background scrambles are performed only for the entire 1000 source catalog and the correlations can be tested based on these background scrambles, without a need for testing the sub-populations separately

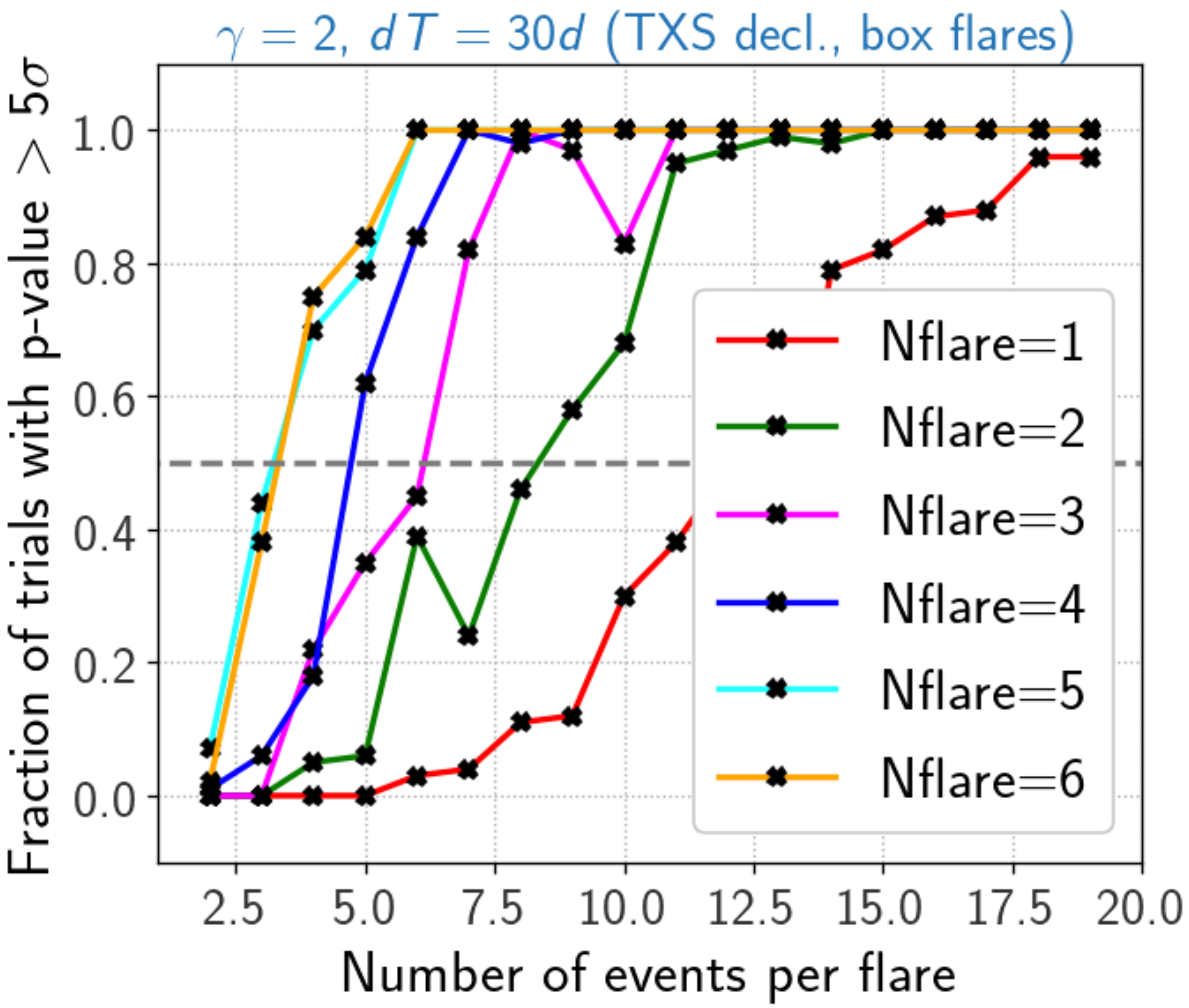
- However, the trial corrected (binomial) p-values will be calculated individually for each of the binomial tests planned, based on binomial scrambles of the sub-catalogs being evaluated. These are the p-values (or best case binomial probabilities) that we finally plan to report

- A background scramble is obtained by scrambling the RA of all the events in the data and fitting for flares. This has been done (13390 times) for all the 1000 sources of the catalog simultaneously.

- A binomial scramble is obtained by performing binomial tests on the multi-flare p-values (obtained after flare fitting in the background scrambles) to obtain a distribution of the best binomial probability (binomial p-value), with one binomial p-value coming from each binomial test. This background best binomial p-value distribution can be used to compare with the (pre-trial) p-values in the data (source-wise) and obtain trial corrected p-values. We plan to obtain background scrambles for each of the 3 population tests planned.



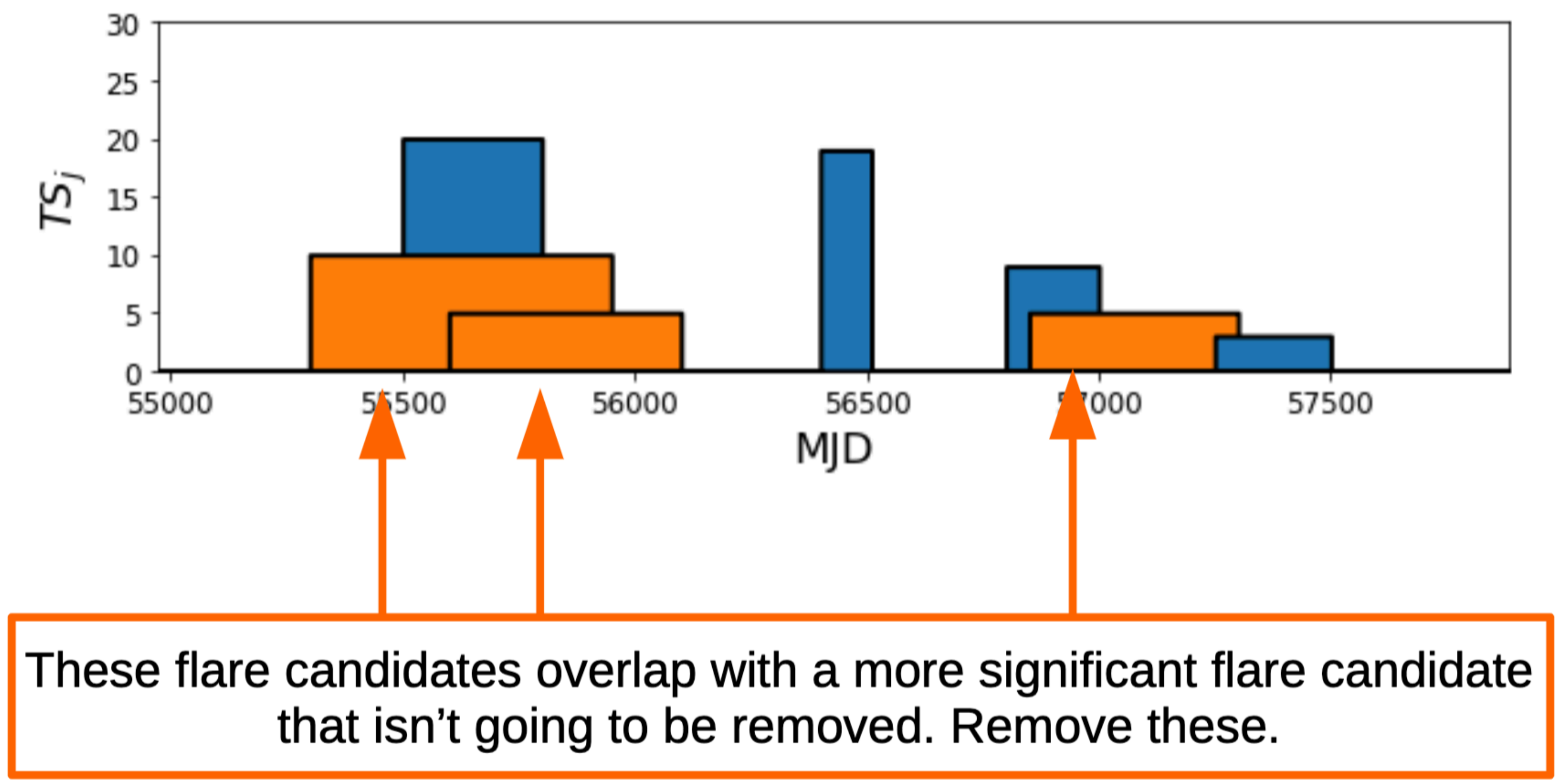
Background multi-flare TS distribution for a single source at the declination of TXS 0506+056



Number of events required for different values of NFlare to obtain 50% trials with p-value > 5σ

Correlation between flares from a single source:

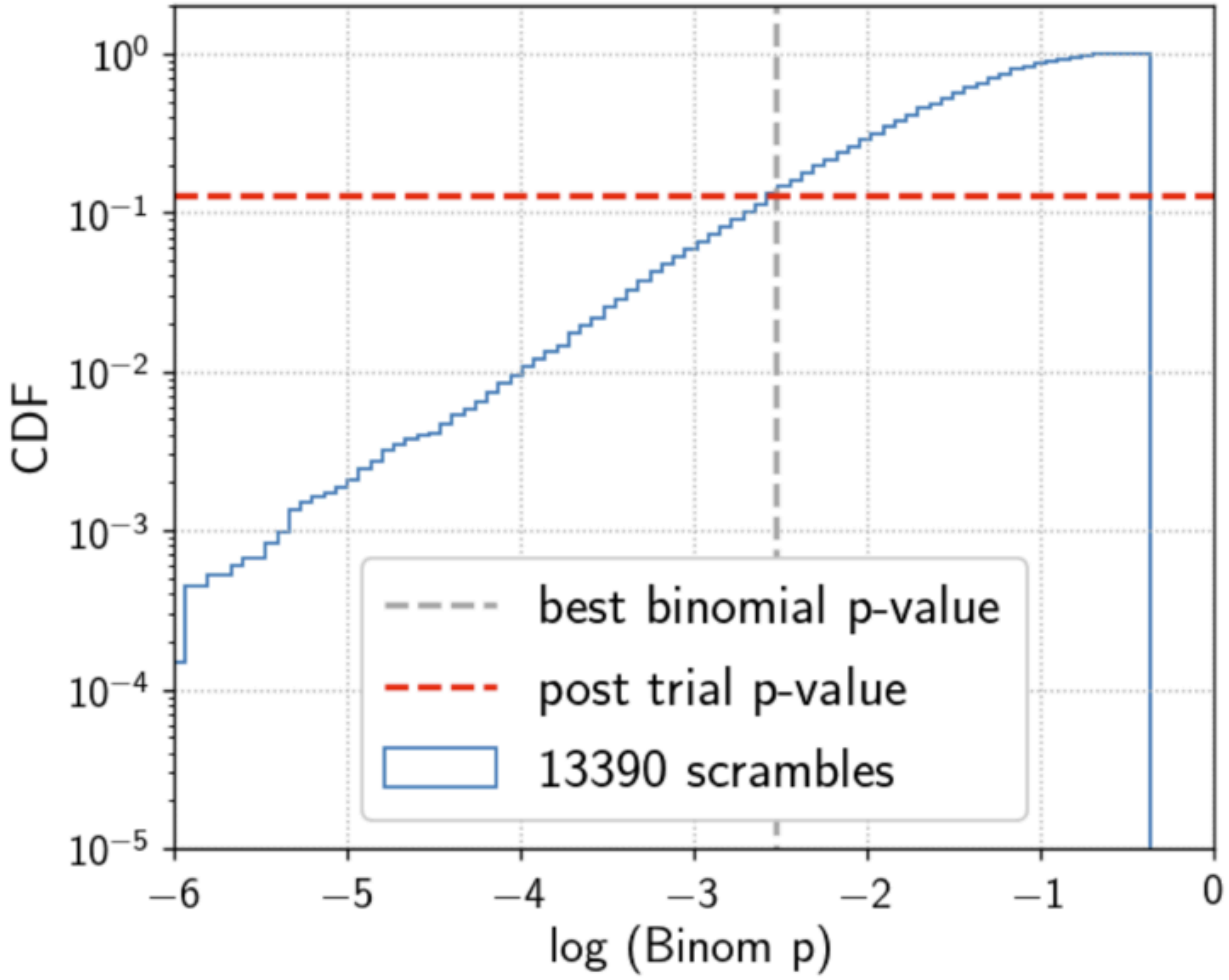
➡ remove all overlapping flares except the most significant one!



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**



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

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