Search for Neutrinos from Gamma-ray Bursts

Kunal Deoskar

1st August 2022

Supervisor: Chad Finley

Asst. Supervisor: Klas Hultqvist

Stockholm University

IceCube

Oskar Klein centre

Cosmic rays and neutrino connection

Cosmic rays can lead to production of neutrinos via the following channels:

- **p**γ interactions
- **pp** interactions (less efficient)
- Decay of pions and muons

$$p + \gamma \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

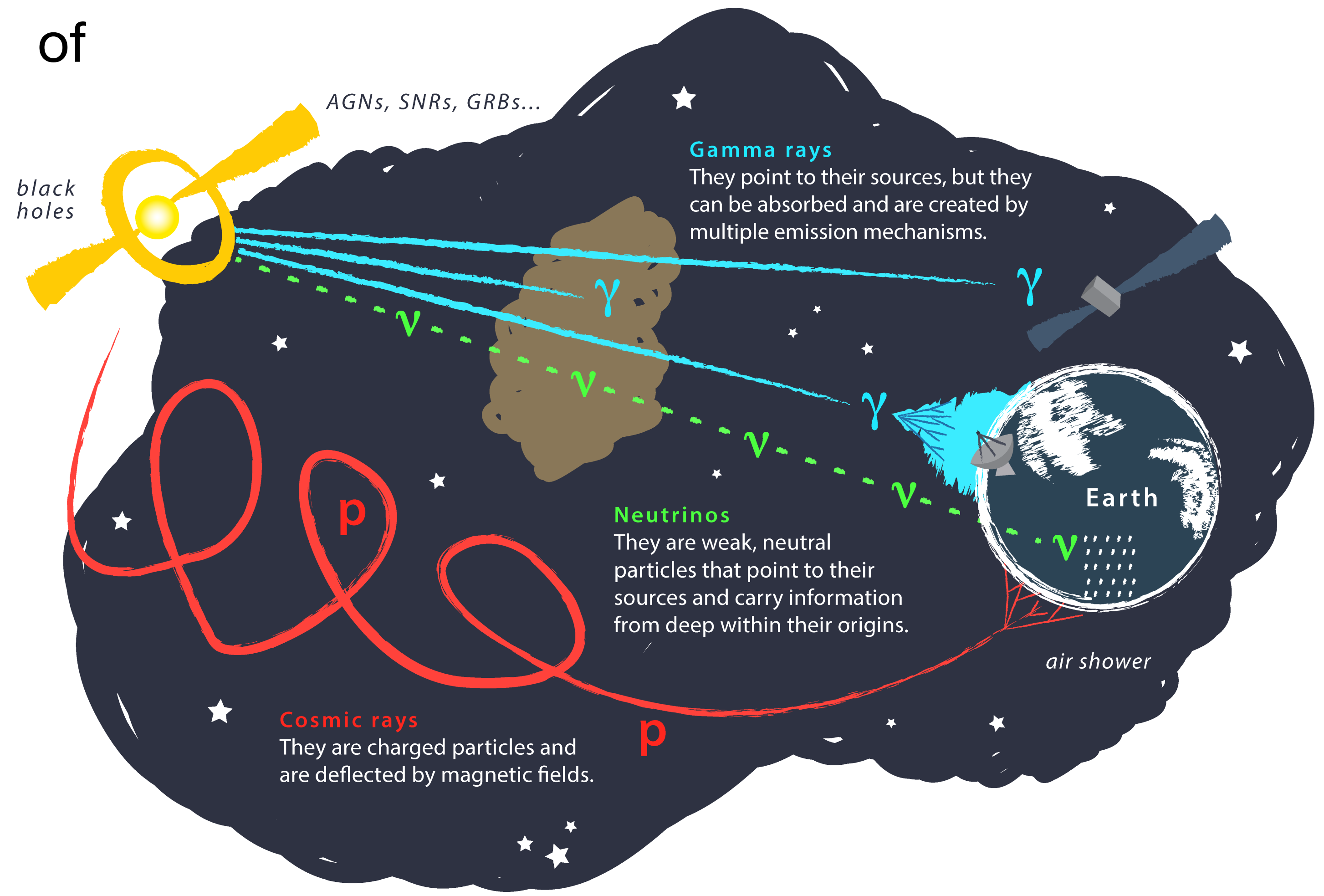
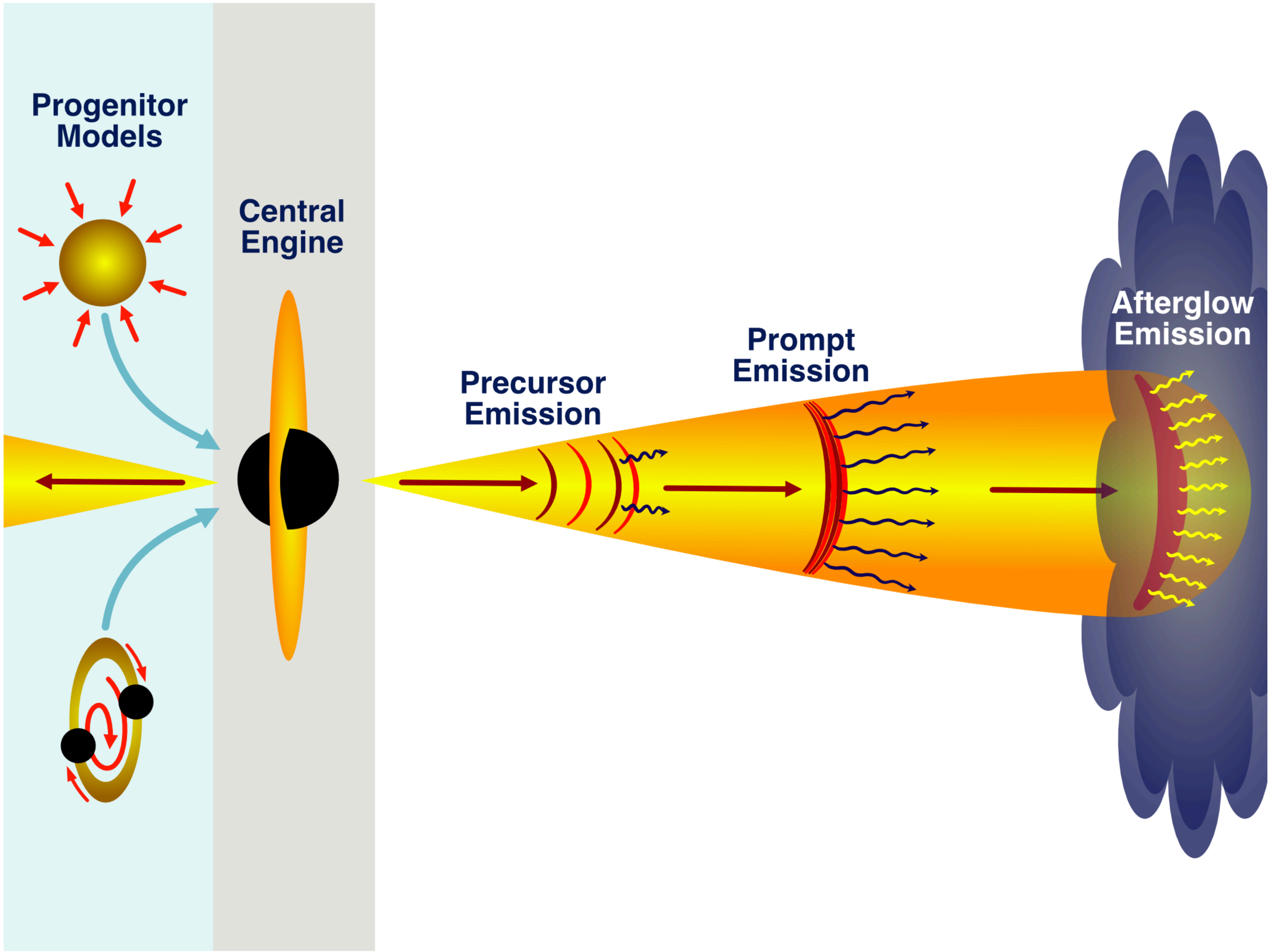


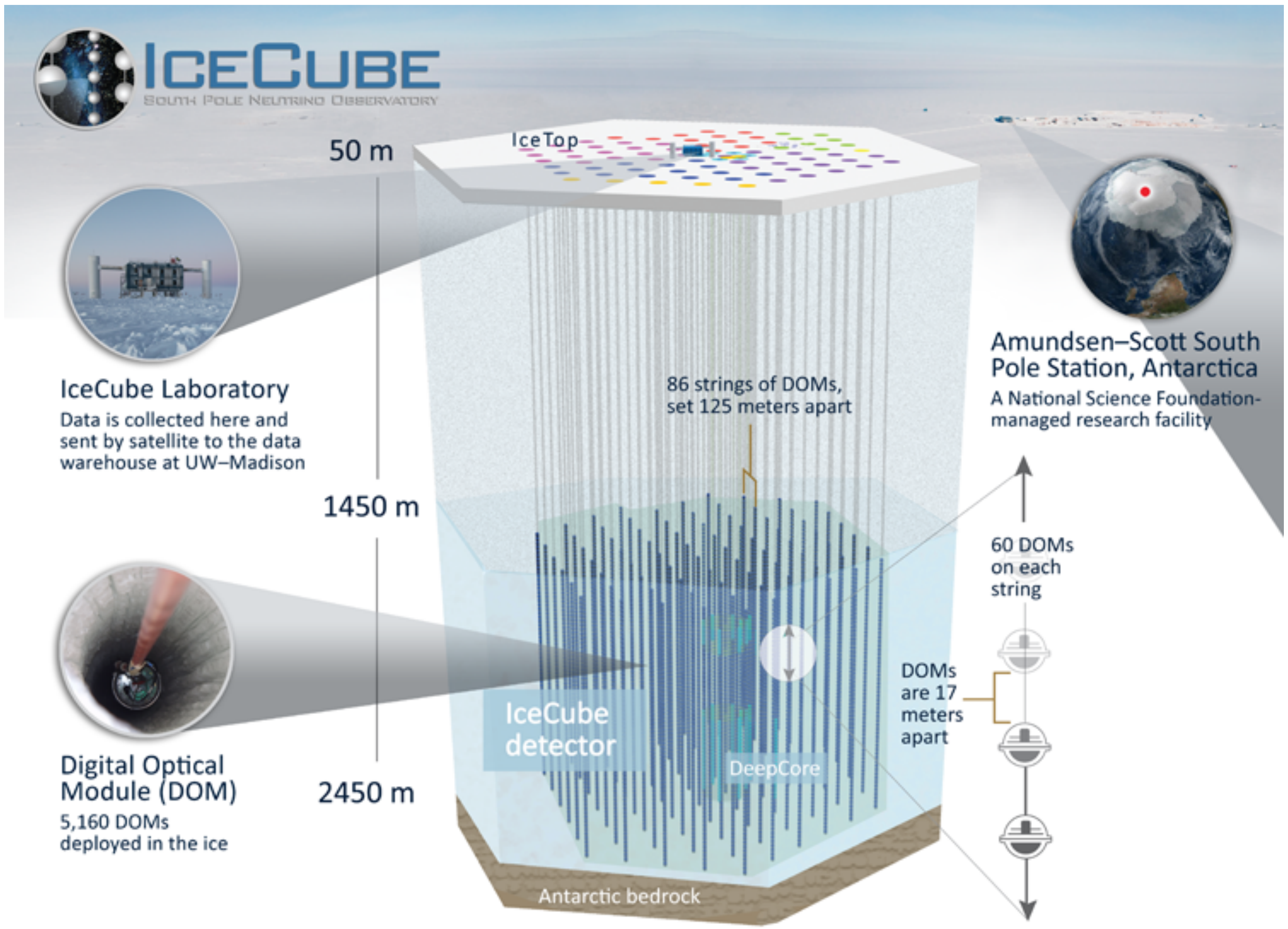
Image Credits: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Neutrinos are undeflected by magnetic fields, and they interact only weakly so they can escape from dense environments. This makes them possible to be used as messengers.

Gamma Ray Bursts as sources of high-energy neutrinos



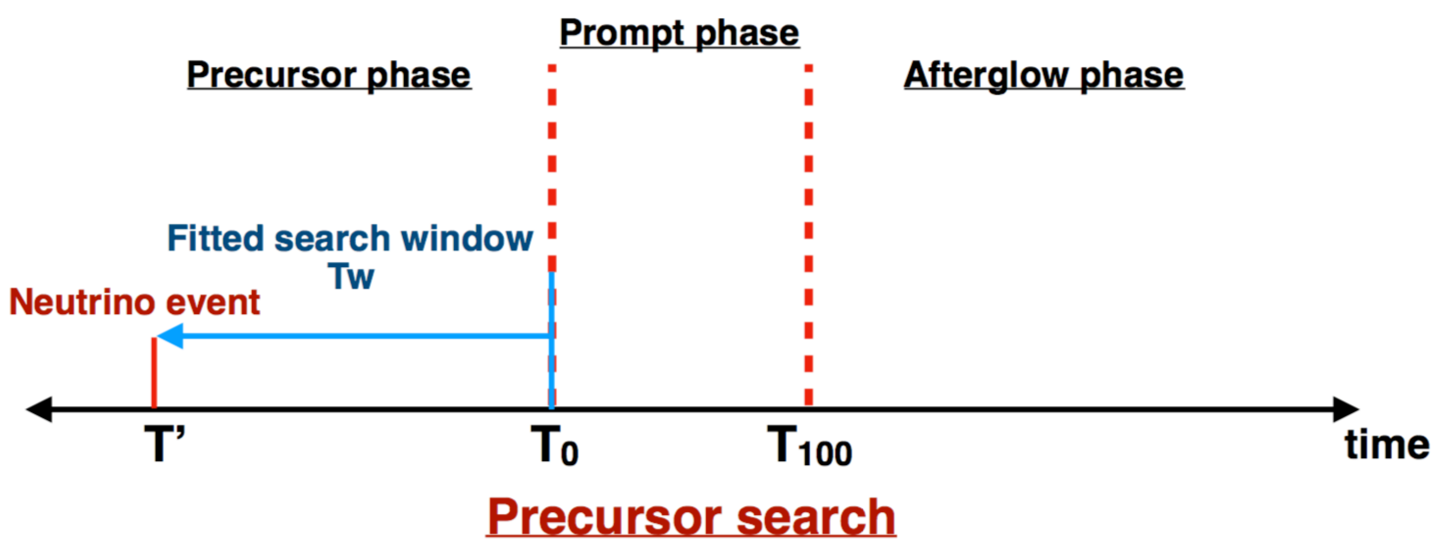
IceCube Neutrino Observatory



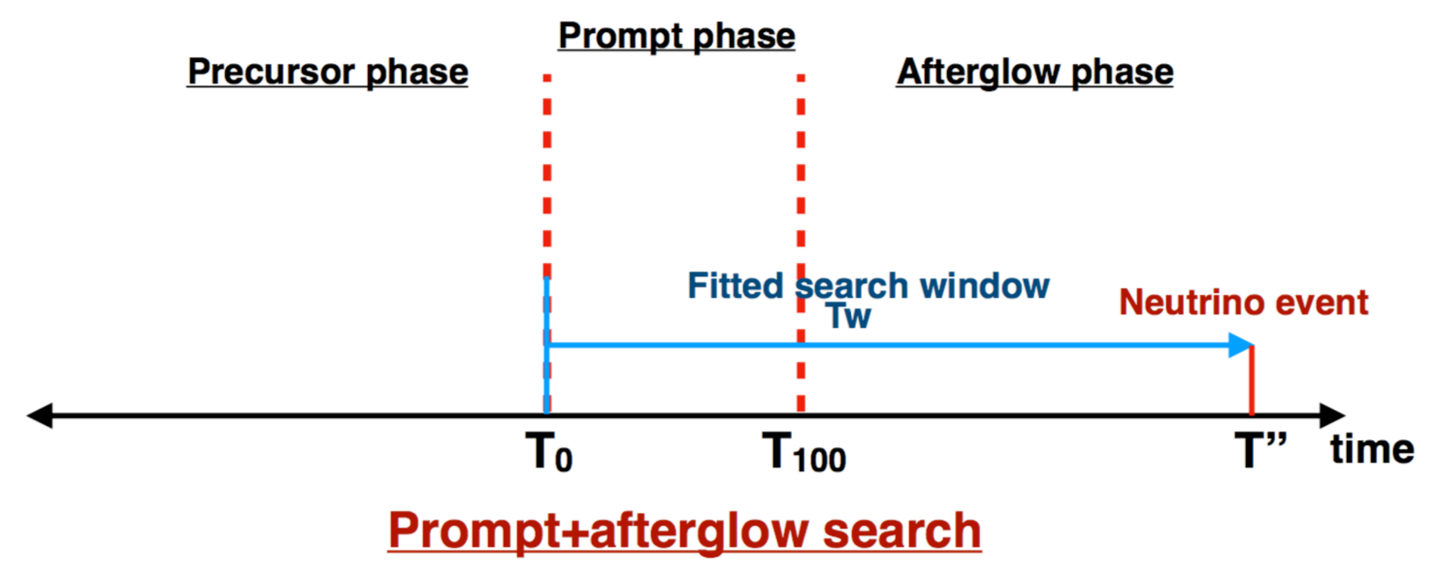
- A water Cherenkov detector at the South Pole making use of Antarctic ice as the medium.
- Total instrumented volume: 1 km^3.
- Total 5160 Digital Optical Modules deployed over 86 strings.

Analysis approach

- Previous IceCube analyses —> focused only on the prompt phase - reported no significant correlations.
- My analysis —> searches for neutrino correlations beyond the prompt phase.



- Two independent searches:
  - **Precursor search**: searching for neutrino correlations up to 14 days prior to start of prompt phase.
  - **Prompt+afterglow search:** searching for neutrino correlations up to 14 days after the start of prompt phase.



Results

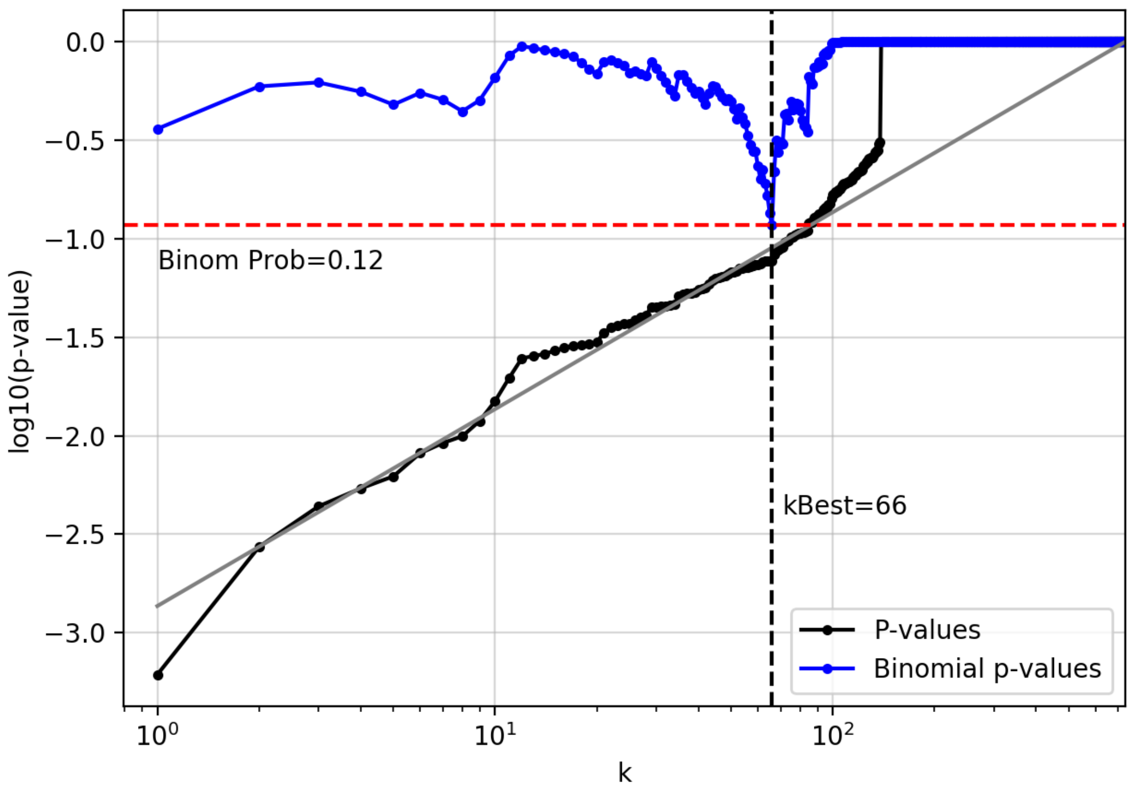
Precursor results (top 5):

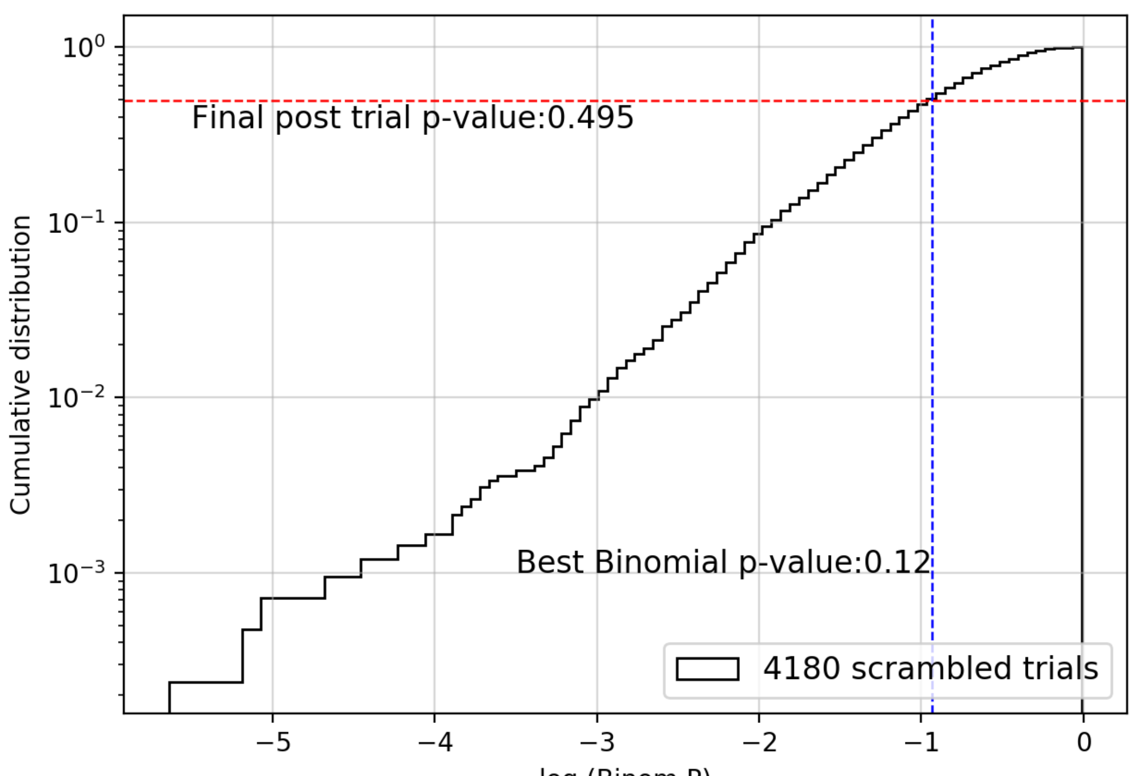
GRB information							Fit results					
GRB Name	α	δ	T_0	f_γ	z	T_{100}	$\hat{n}_s$	$\hat{\gamma}$	$\hat{T}_w$	TS	p-value	$\#\sigma$
GRB150202A	39.23	-33.15	57055.965301	–	–	25.70	1.00	4.00	3.367e+03	16.37	6.12e-04	3.23σ
GRB180721A	347.71	4.86	58320.463056	–	–	47.60	1.00	1.84	1.542e+04	12.46	2.73e-03	2.78σ
GRB140301A	69.56	-34.26	56717.642234	–	1.42	31.00	1.96	2.15	7.615e+05	11.51	4.38e-03	2.62σ
GRB141220A	195.07	32.15	57011.251986	5.34e-06	1.32	7.62	1.00	4.00	2.473e+02	11.19	5.39e-03	2.55σ
GRB111126A	276.06	51.46	55891.790069	–	–	0.80	1.84	4.00	3.556e+03	10.65	6.22e-03	2.50σ

Prompt+Afterglow results (top 5):

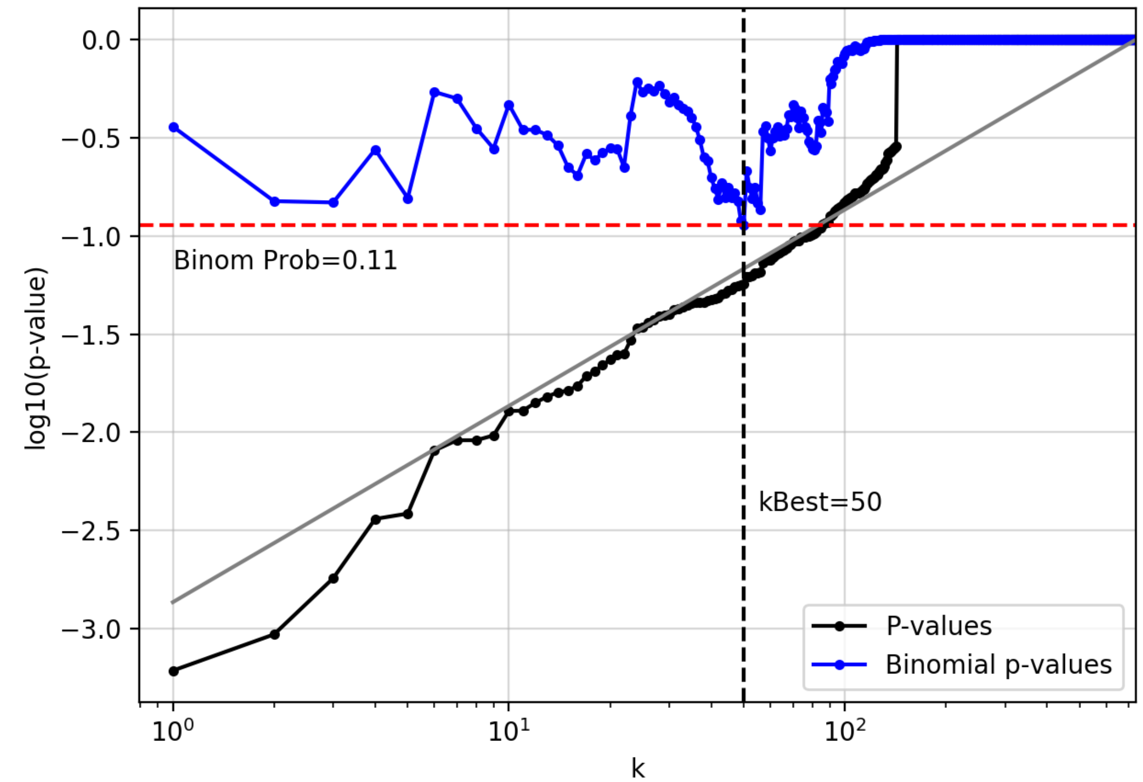
GRB information							Fit results					
GRB Name	α	δ	T_0	f_γ	z	T_{100}	$\hat{n}_s$	$\hat{\gamma}$	$\hat{T}_w$	TS	p-value	$\#\sigma$
GRB170318A	305.67	28.41	57830.508287	–	–	133.70	2.91	3.52	4.267e+04	16.13	6.11e-04	3.23σ
GRB140607A	86.37	18.90	56815.717720	–	–	109.90	1.00	1.53	2.602e+04	15.02	9.35e-04	3.11σ
GRB141121A	122.67	22.22	56982.160220	–	1.47	549.90	1.17	1.38	1.040e+06	13.28	1.81e-03	2.91σ
GRB140114A	188.52	27.95	56671.498380	–	3.00	139.70	1.00	1.14	8.478e+04	12.20	3.62e-03	2.69σ
GRB120911A	357.98	63.10	56181.297564	2.34e-06	–	22.02	1.00	2.49	1.219e+02	11.77	3.86e-03	2.66σ

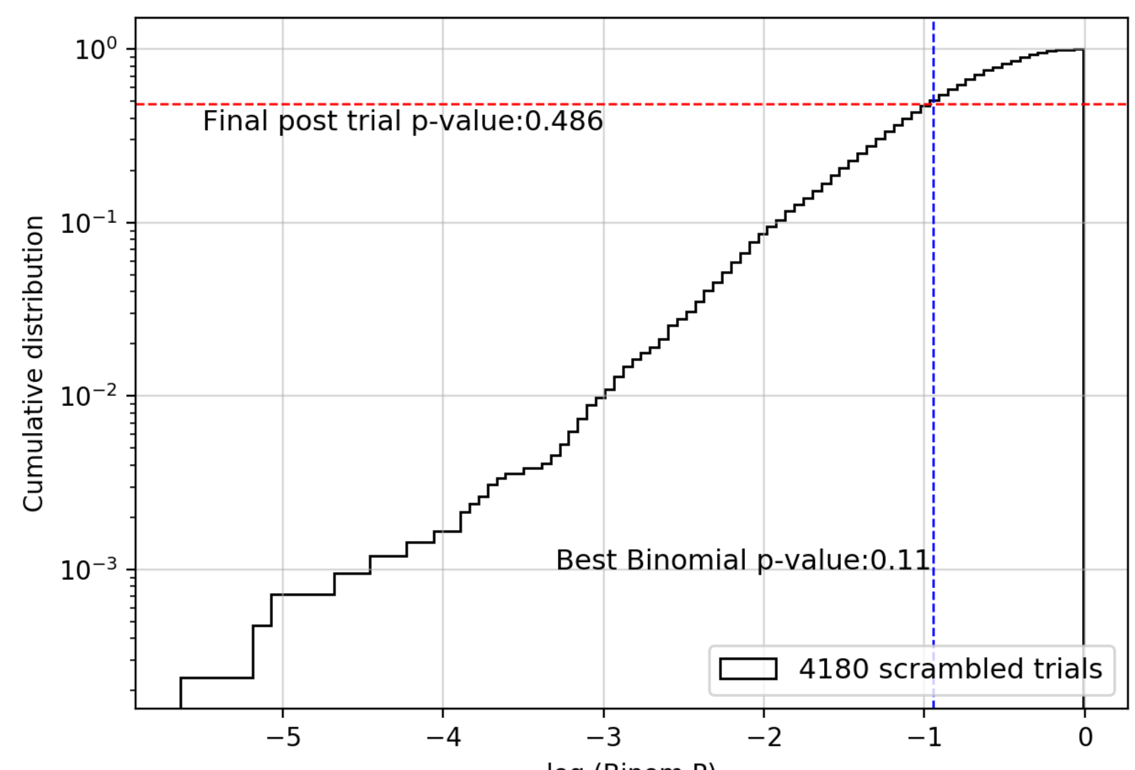
Precursor search results





Prompt+Afterglow results





(k is the index of each GRB when ranked by p-value)

Constraining GRB contribution to Diffuse Neutrino Flux

- The GRBs analysed were a subset of the total (cosmic) population of GRBs.
- The diffuse neutrino flux is the total high energy (>10 TeV) astrophysical neutrino flux observed by IceCube.
- We want to set a limit on the contribution of the total GRB source population to the diffuse flux (not just limit on the observed GRBs' contribution to the flux).

Setting population limits:

- For my analysis, I made selection of 733 GRBs from GRBWeb* which had good localisation (< 0.2°) and within the GFU data period.
- During this time period, Swift observed 556 long GRBs. All 556 of these GRBs are in my selection of 733 GRBs.
- We will use the Swift catalog for implementing a GRB population model.

*(https://user-web.icecube.wisc.edu/~grbweb_public/)

- Implementing a GRB model
  - '**Probing the Cosmic Gamma-Ray Burst Rate with Trigger Simulations of the Swift Burst Alert Telescope**' (arXiv:1311.4567) Amy Lien, Takanori Sakamoto, Neil Gehrels et.al. predicts ~4.5k long GRBs/year.
  - The above mentioned paper contains:
    - a cosmic population model
    - the detector selection effects which I can use to downsample from the total GRB population to the GRBs in my sample.

This paper allowed us to extrapolate the swift observation to a cosmic population of GRBs

Total population—> (simulated)Swift-detected sample

From Eq. 9 Lien et al. :

$$R_{Swift} = \mathcal{R}_{\rm GRB;dz} \times f_{\rm detect} \times {\rm FOV} \times {\rm t}_{\rm survey},$$

Swift observed GRBs (what we want)

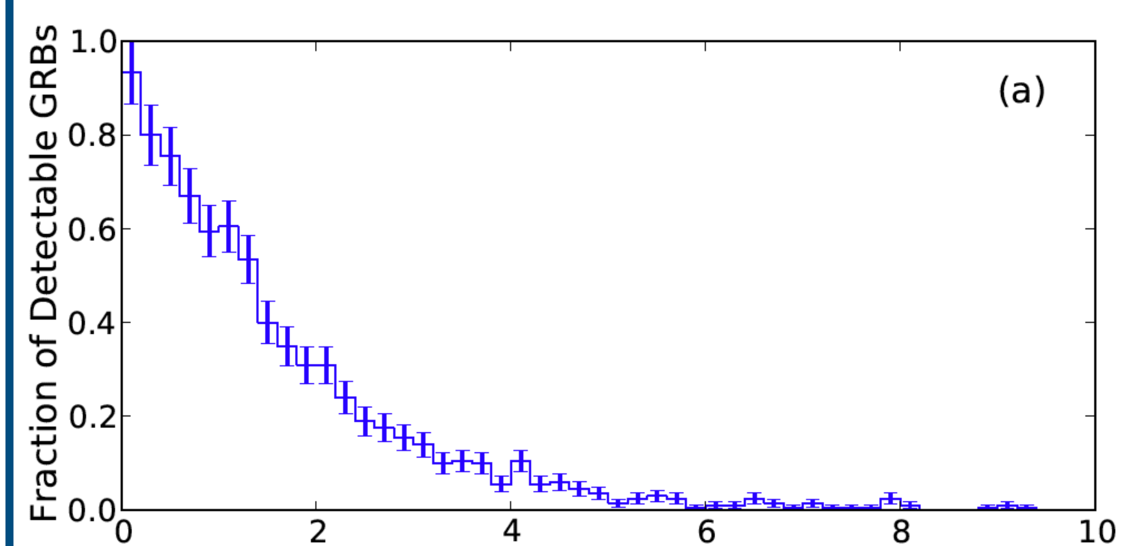
Actual redshift distribution (provided in the paper)

Swift detection efficiency as a function of z:

Fractional field-of-view of BAT (2 sr/4pi sr)

fraction of the time that BAT spends on searching for GRBs (~90%)

Figure 16 (a) from the paper:



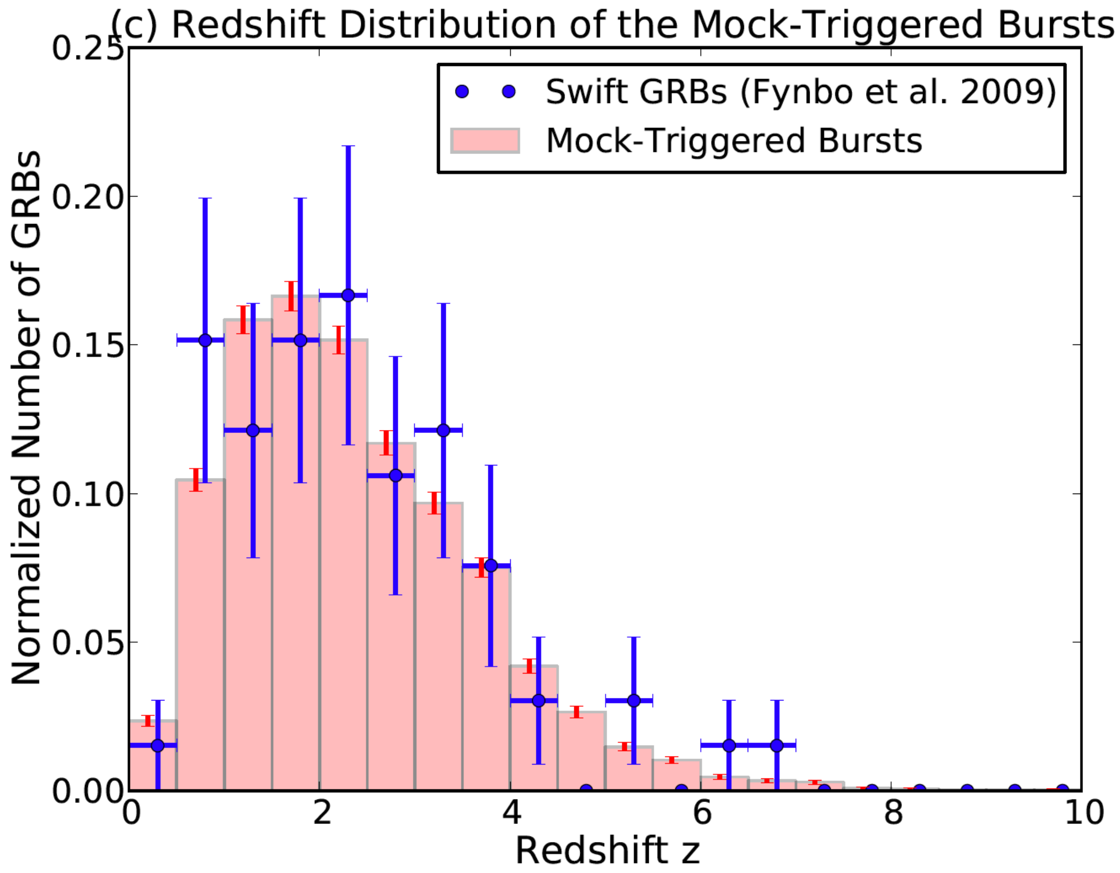
Implementing downselection

1. Use the software FIRESONG to simulate a population of GRBs.
2. From these simulations, randomly keep GRBs according to the detection efficiency based on z.
3. Downsample according to fraction of field of view that Swift has for the whole sky.

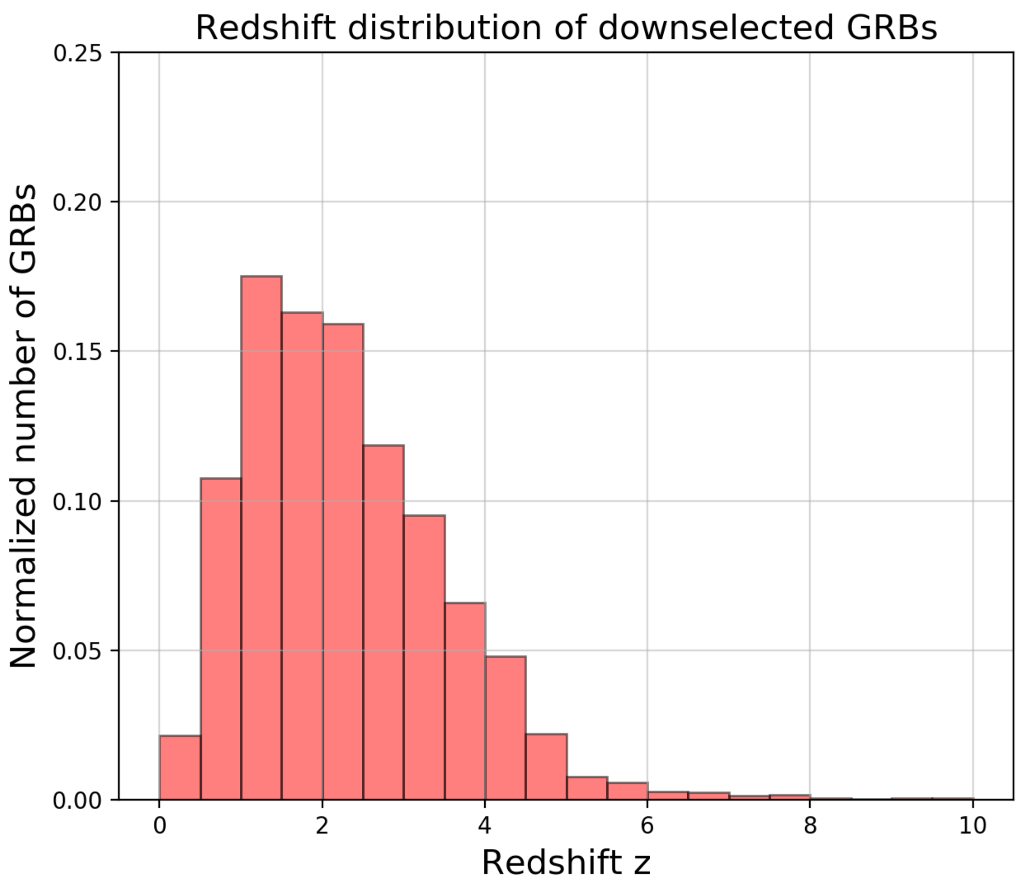
Final GRB sample:

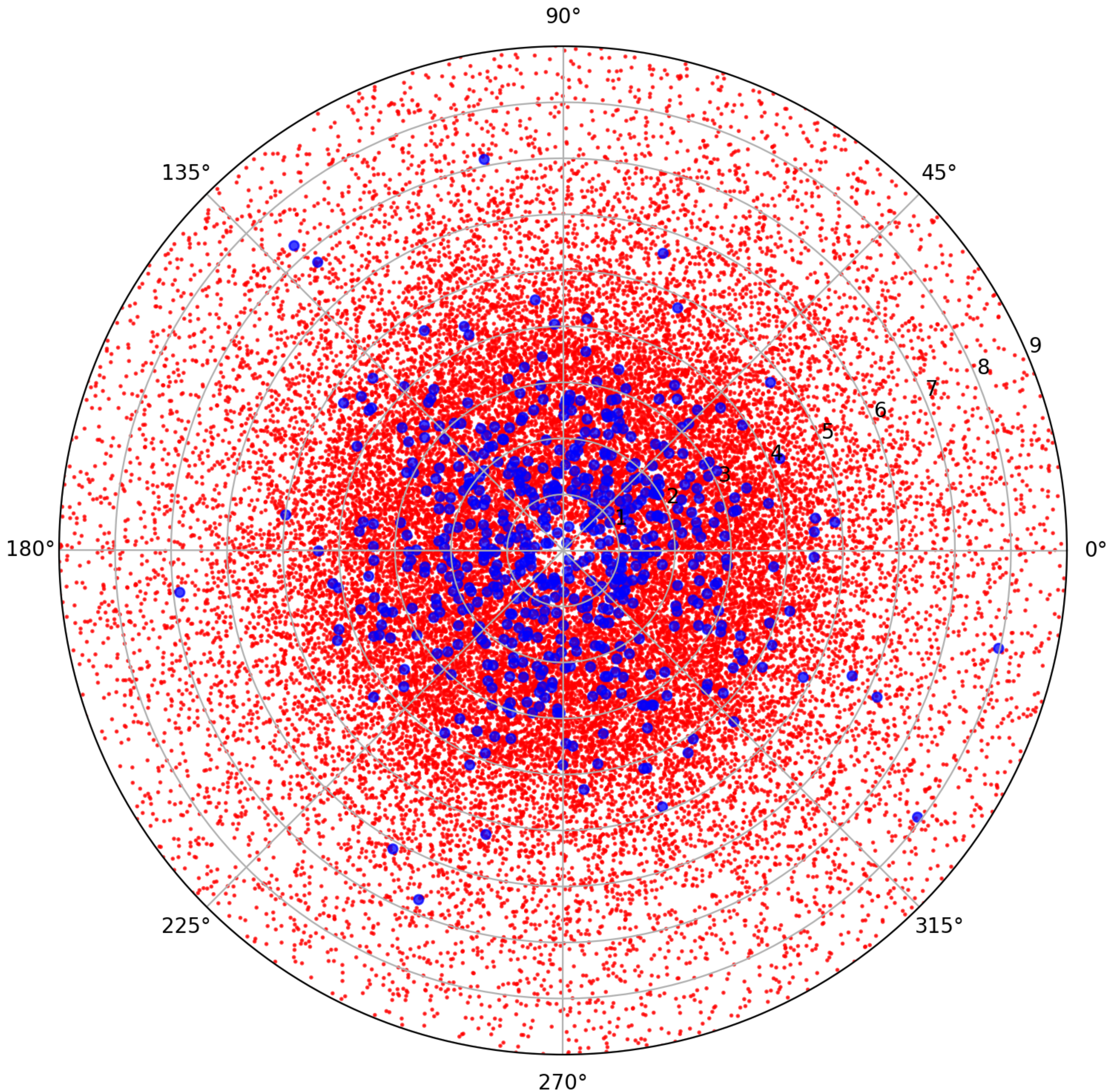
From Lien et al.

Figure 9(c) from the paper:



From my simulations




90°
135°
45°
180°
0°
225°
315°
270°
1
2
3
4
5
6
7
8
9

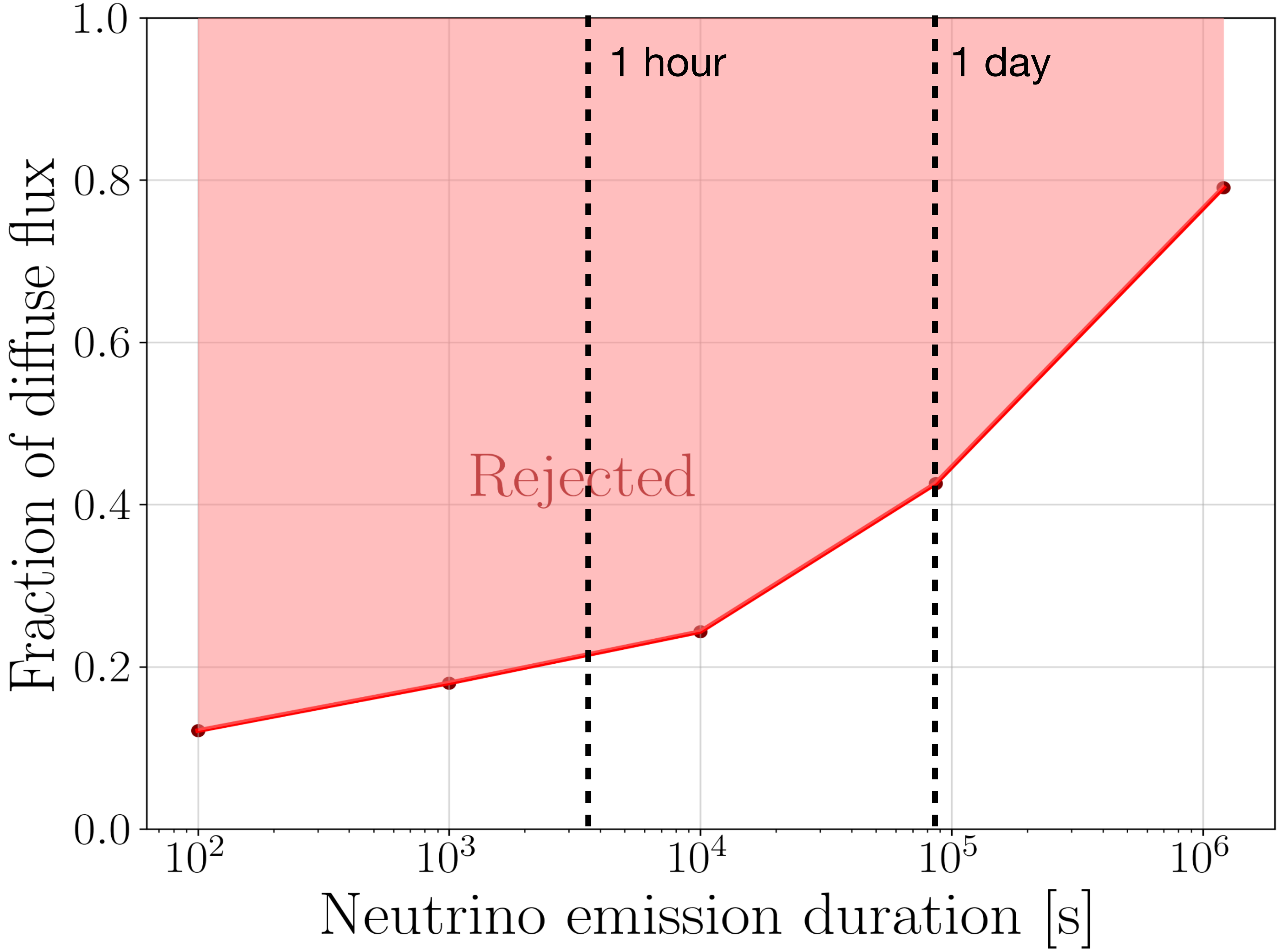
- Key takeaways
  - We can simulate a cosmic GRB sample, and can down-select to a sample of 556 GRBs **with a redshift distribution that matches the Swift-detected GRBs.**

- Next step
  - Use FIRESONG to scale the total neutrino flux from all GRBs (cosmic sample, not down-selected sample)

- Where the diffuse flux is simulated as a power law:

$$\frac{dN_{diffuse}}{dE} = 1.44 \times 10^{-8} (E/100 \ \mathbf{TeV})^{-2.28} [\mathbf{GeV}^{-1} \mathbf{cm}^{-2} \mathbf{s}^{-1} \mathbf{sr}^{-1}]$$

Limits on neutrino emission from cosmic GRB population



Since I have p~50% for both precursor and afterglow results, the upper limits are the same for both the precursor and afterglow analysis.

Summary of results

- Previous IceCube analyses did not find any evidence for emission from the prompt phase. We extend the search to include longer time windows.
- The analysis results are consistent with background expectation.
- For the first time, we constrain on extended timescales the contribution of the total long GRB population to the astrophysical neutrino flux. For emission on prompt timescales and up to a few hours after, the constraint is 10-25% of the total diffuse flux.
- The unblinded results were presented at the 37th International Cosmic Ray Conference 2021 (PoS(ICRC2021)1118).
- Recently submitted a paper summarising these results with two complementary IceCube analyses. (arXiv:2205.11410)

Thank you!

Backup slides

Parameter estimation: Method of unbinned maximum likelihood

Likelihood: $$\mathcal{L}(n_s,\theta) = \prod_{i=1}^{N}[(\frac{n_s}{N})S_i(\theta) + (1-\frac{n_s}{N})B_i]$$

$\theta : (T_w\ ,\ \gamma)$

Fit parameters: n_s, T_w and γ

n_s: subset of events attributed to the signal PDF
T_w: size of the time window
γ : spectral index of the neutrino energy distribution

$$S_i(T_w,\gamma) = \frac{1}{2\pi\sigma_i^2}e^{\frac{-(|\vec{x_s}-\vec{x_i}|)^2}{2\sigma_i^2}} \times \frac{1}{T_w} \times \int_{E_\nu} P(E_i|E_\nu)P(E_\nu|\gamma)dE_\nu$$

and

$$B_i = \frac{1}{\Omega T_L}\mathcal{E}(E_i|atm_\nu)$$

Log likelihood ratio: $$\Lambda(n_s,\theta) = 2\times\ln\left(\frac{\mathcal{L}(n_s,\theta)}{\mathcal{L}(n_s=0)}\right)$$

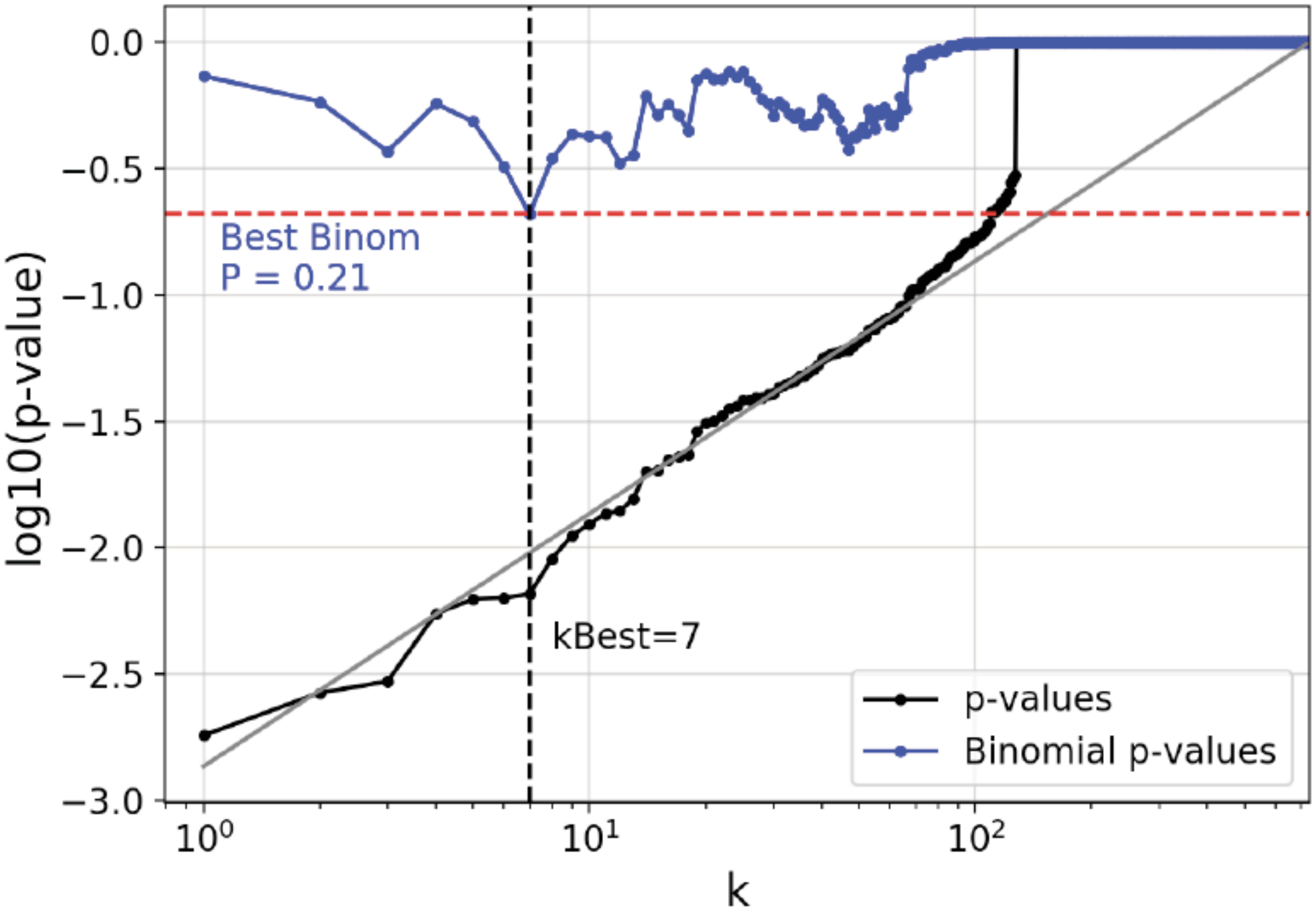
The maximum value of Λ is the Test Statistic (TS) for the search for the respective GRB.

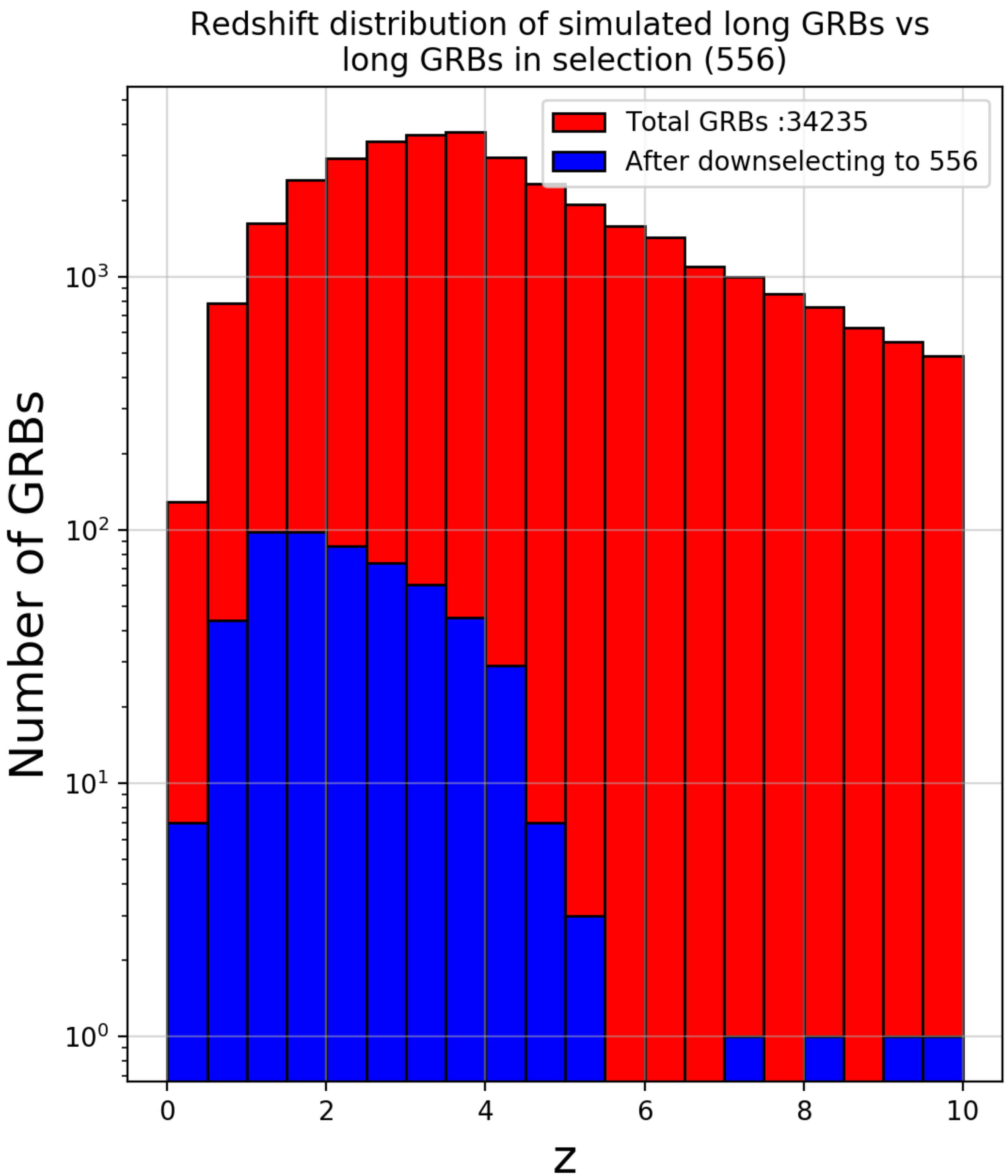
Binomial test

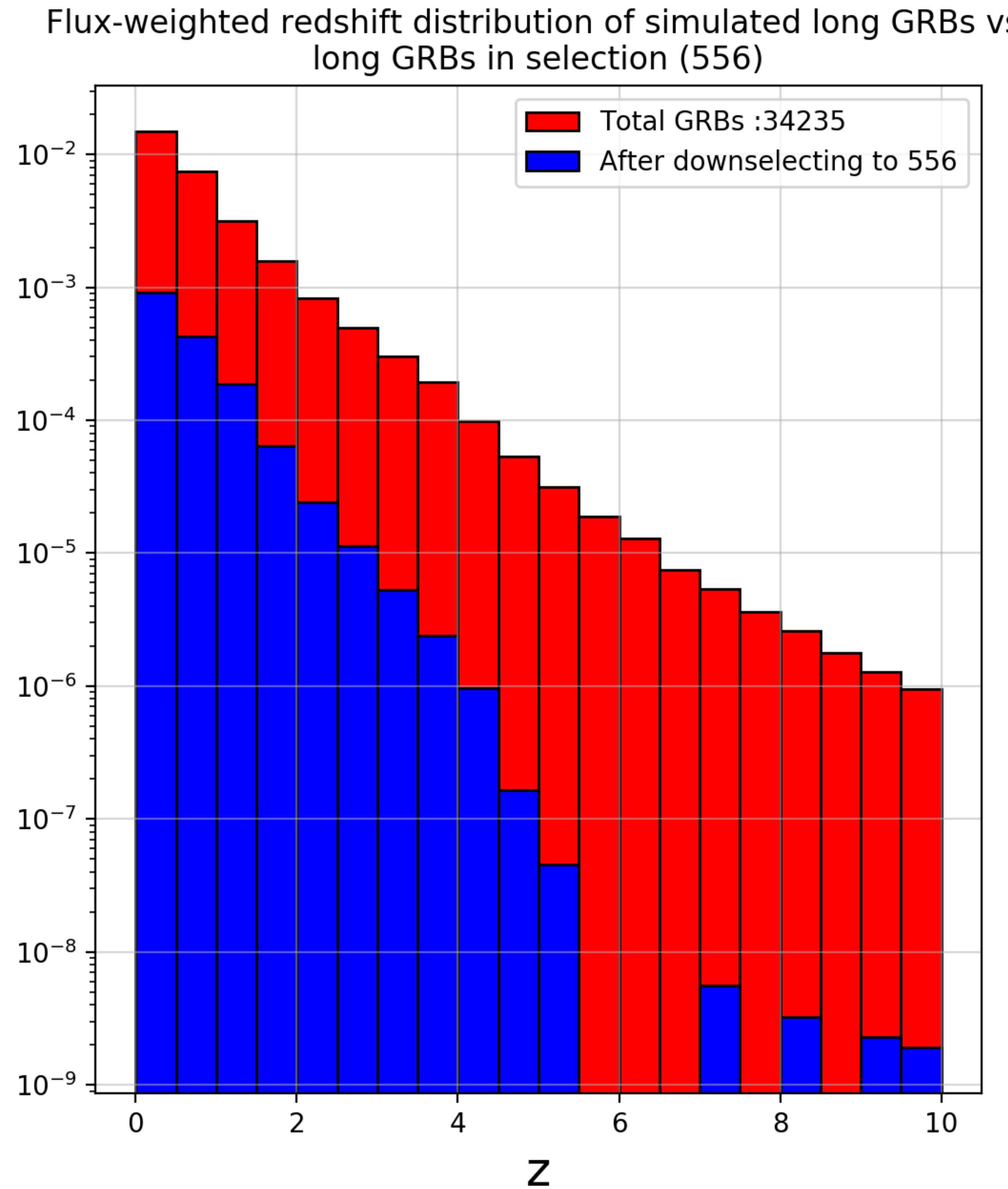
The a priori probability $P^b(k, p_k)$ of getting k or more p-values at or lower than the value of p_k.

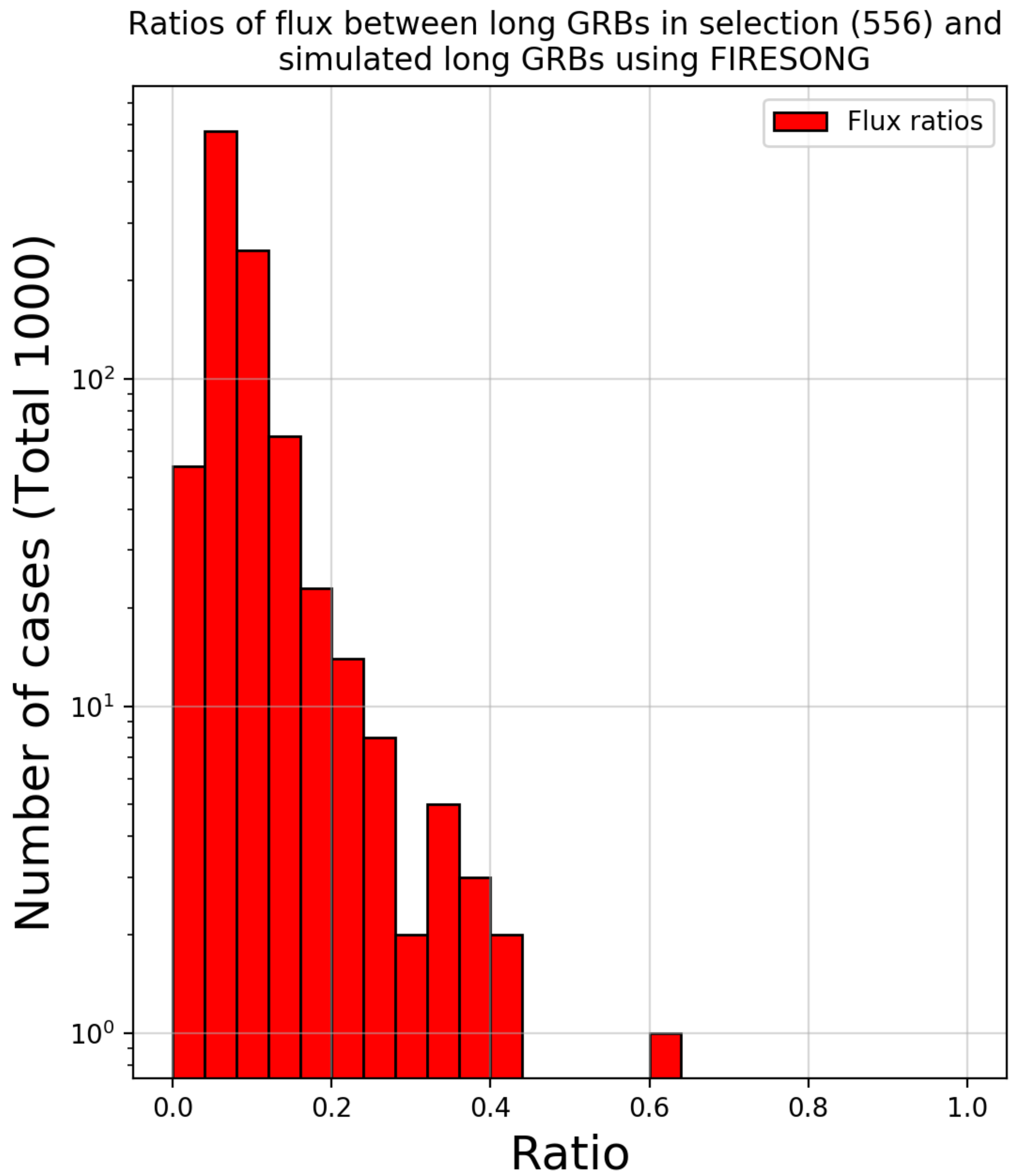
$$P^b(k, p_k) = \sum_{m=k}^{N} \frac{N!}{(N-m)!m!} {p_k}^m (1-p_k)^{N-m}$$

The Binomial test essentially tells us if there is a smaller population of p-values in our list which is better than what can be expected from a uniform random distribution of p-values for similar population sizes



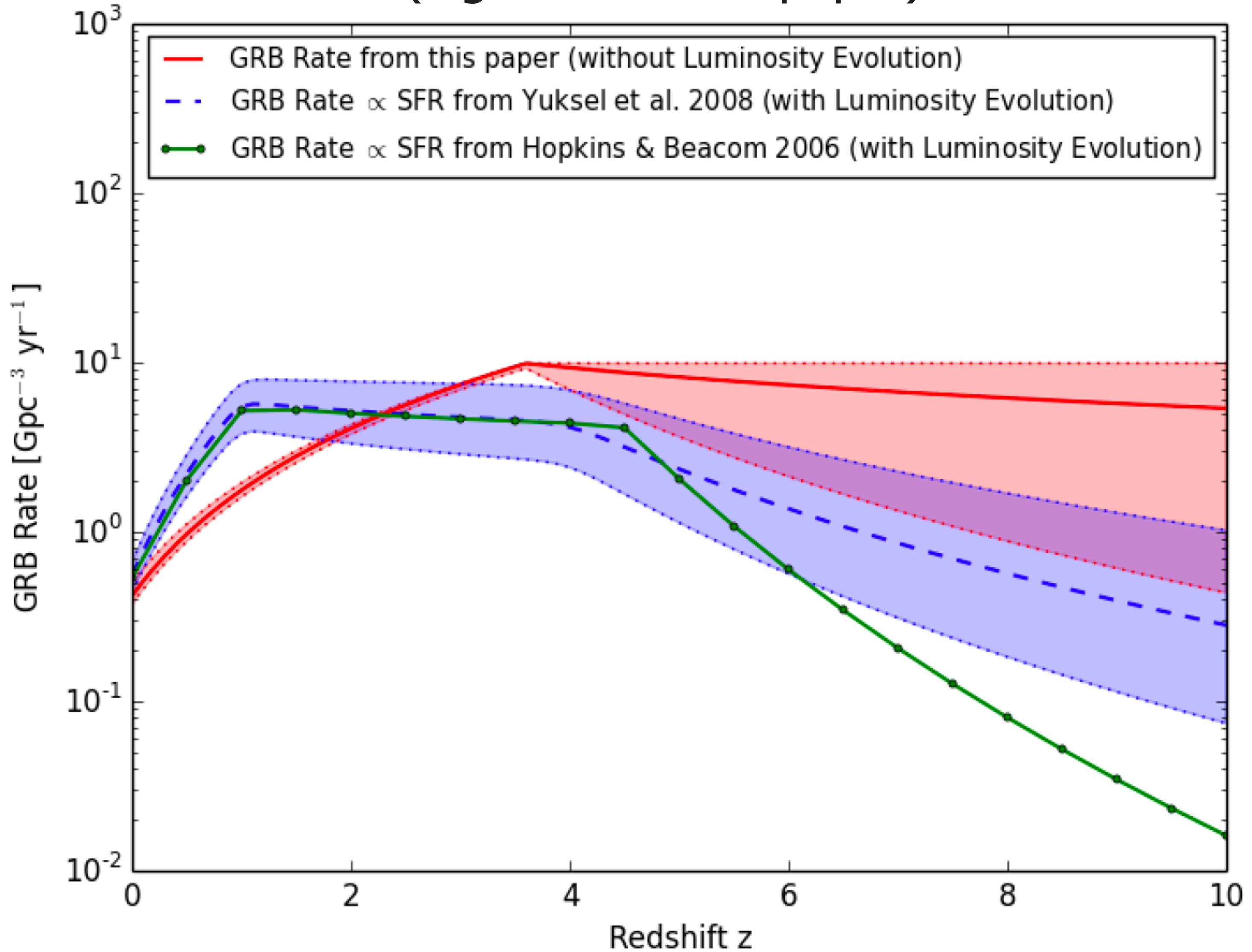

Redshift distribution of simulated long GRBs vs
long GRBs in selection (556)
Total GRBs :34235
After downselecting to 556
Number of GRBs
z


Flux-weighted redshift distribution of simulated long GRBs vs
long GRBs in selection (556)
Total GRBs :34235
After downselecting to 556
z



Ratios of flux between long GRBs in selection (556) and
simulated long GRBs using FIRESONG
Flux ratios
Number of cases (Total 1000)
10^2
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0
Ratio

The Lien et. al. model of GRB rate vs redshift
(Fig.17 from the paper)



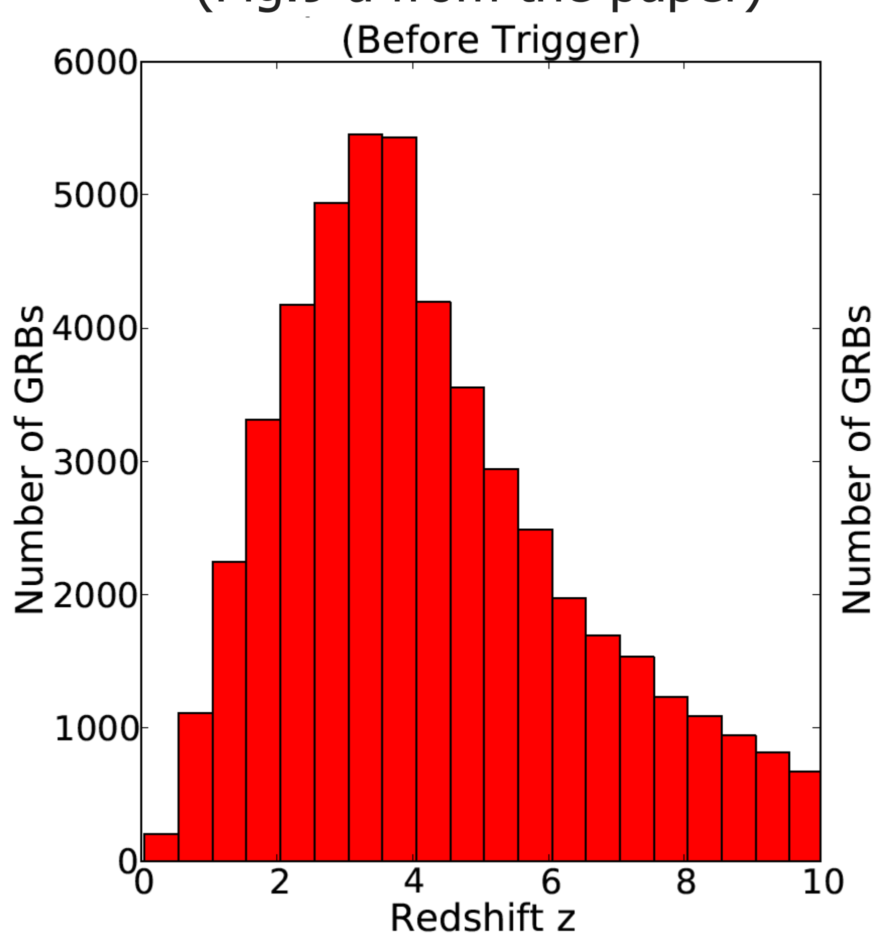
- If GRB rate follows SFR (blue curve), then the authors find that the GRB properties (luminosity distribution) needs to evolve with redshift.
- On the other hand, if GRB properties remain the same (don't evolve), the authors fit the GRB population rate with the red curve.

We will use the model produced by the authors, with no luminosity evolution (red curve). For making population limits, we will assume the GRBs are standard candle neutrino sources.

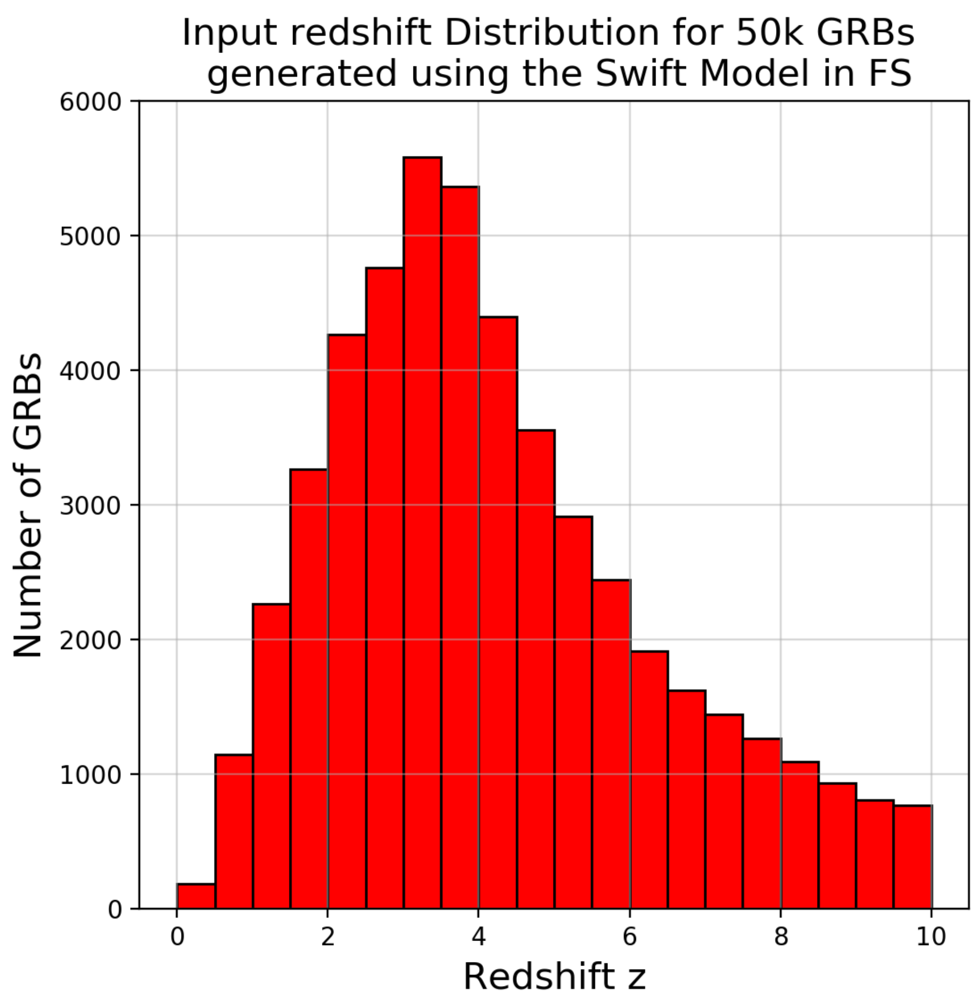
Implementing Lien et al. GRB population model

From Lien et al.

Input redshift Distribution
(Fig.9 a from the paper)

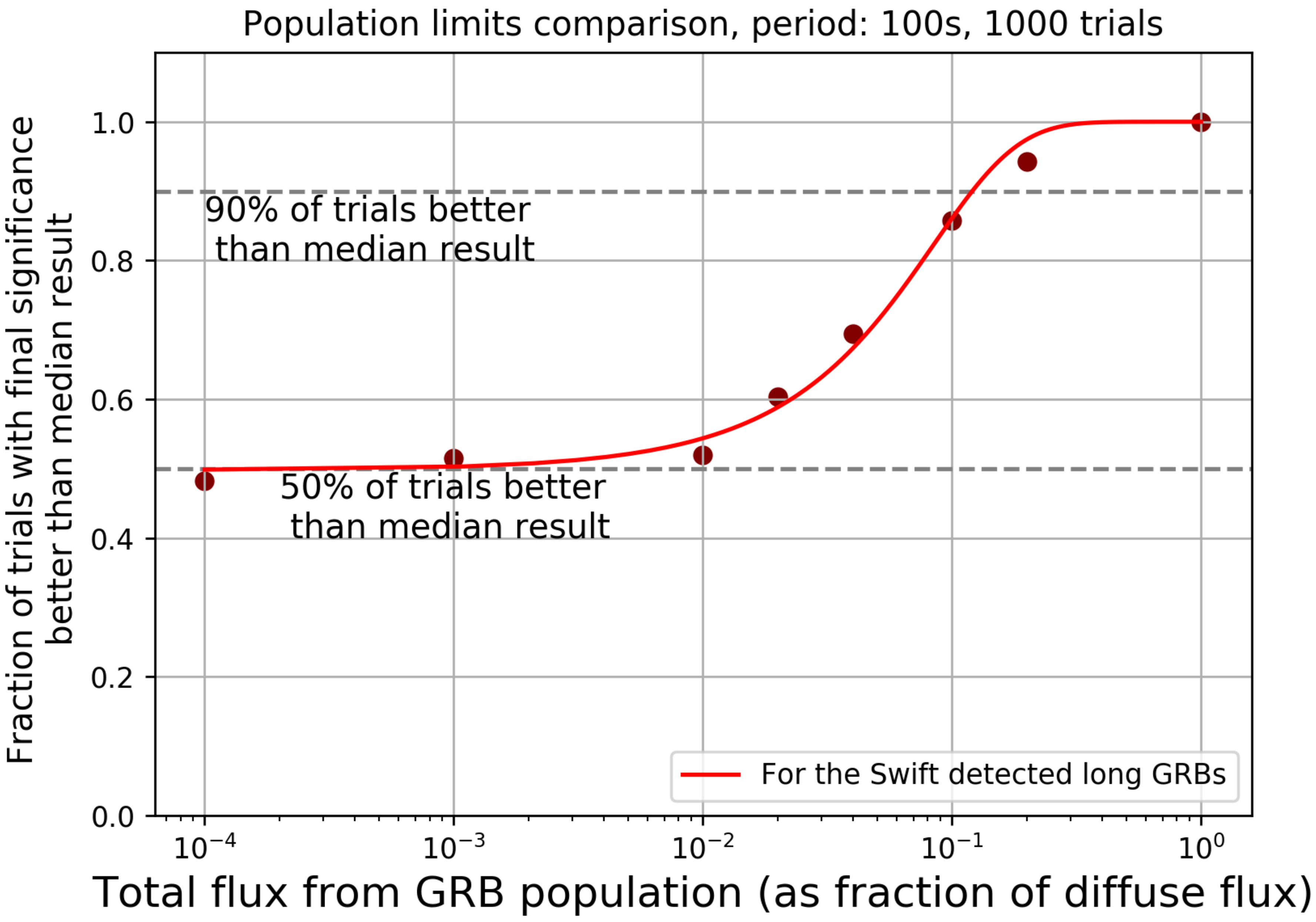


From my simulations
(using FIRESONG software)

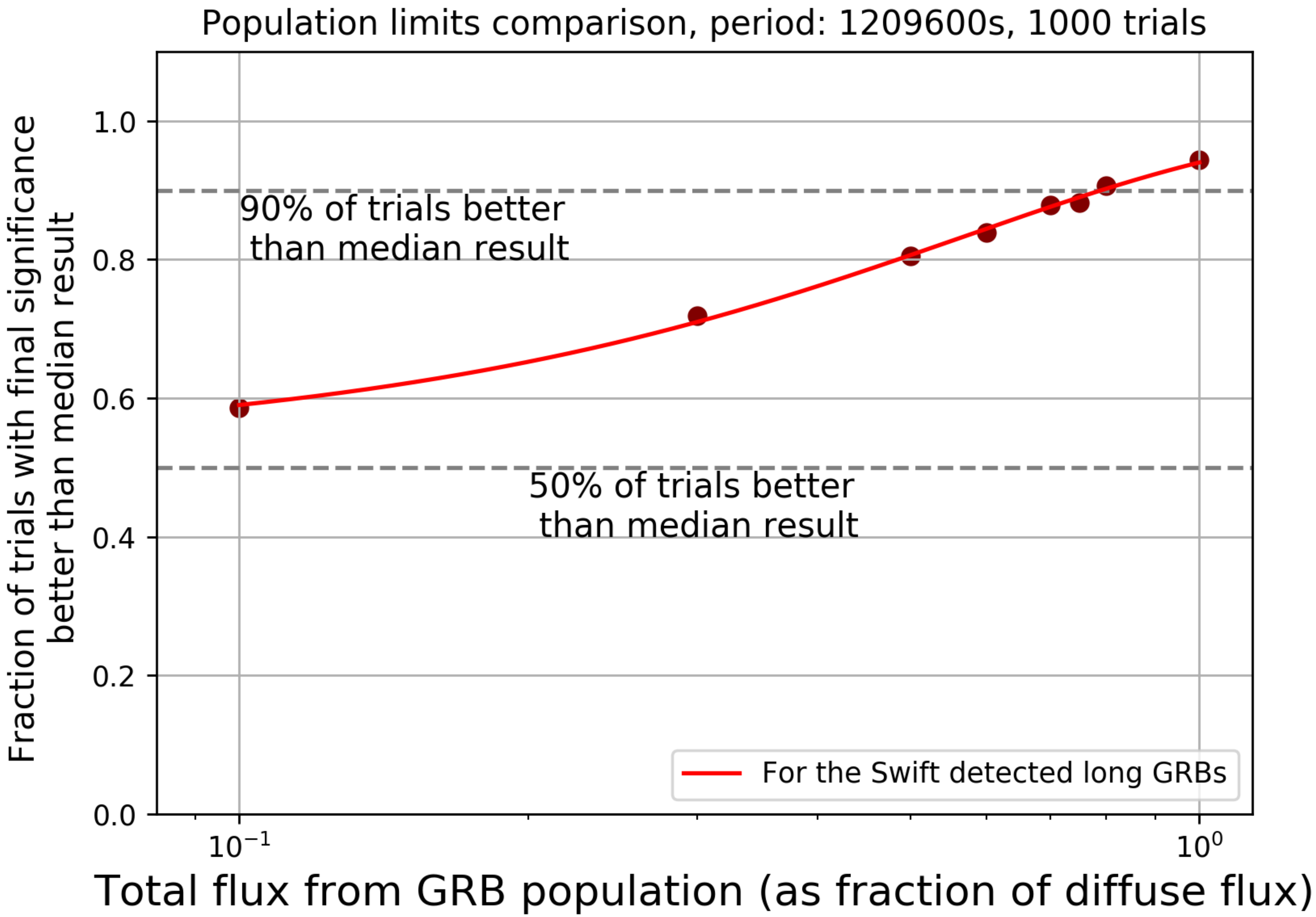


- The plots above are for the same arbitrary number of simulated sources (50k) for comparison.
- For the rest of the calculations I will be using the actual estimated rate normalization by Lien et. al. so that it matches the total cosmological number of GRBs during the ~7.5-year analysis period.

For simulations with Lien et al. GRB population model, neutrino emission duration: 100s

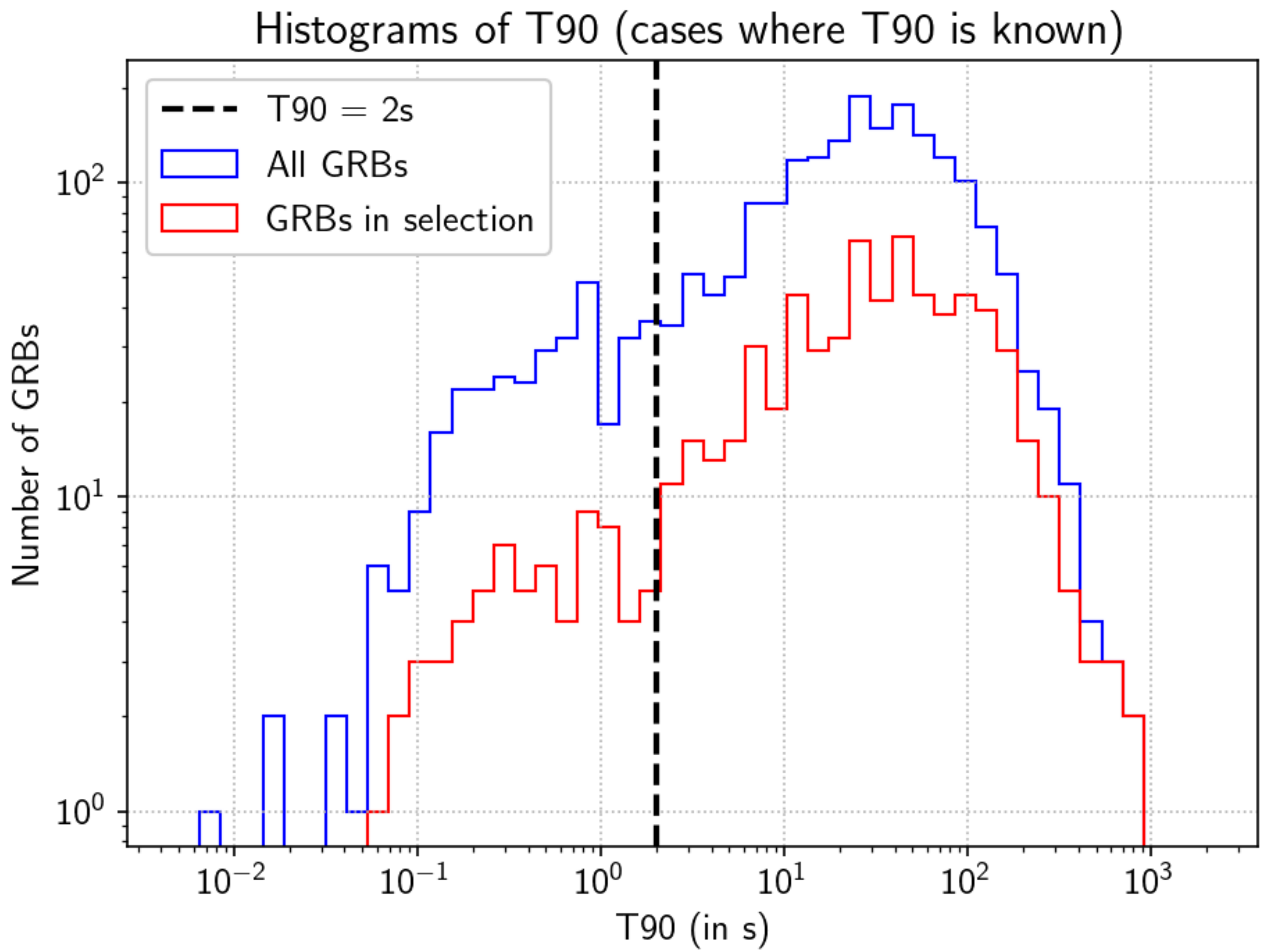


For simulations with Lien et al. GRB population model, neutrino emission duration: 2 weeks

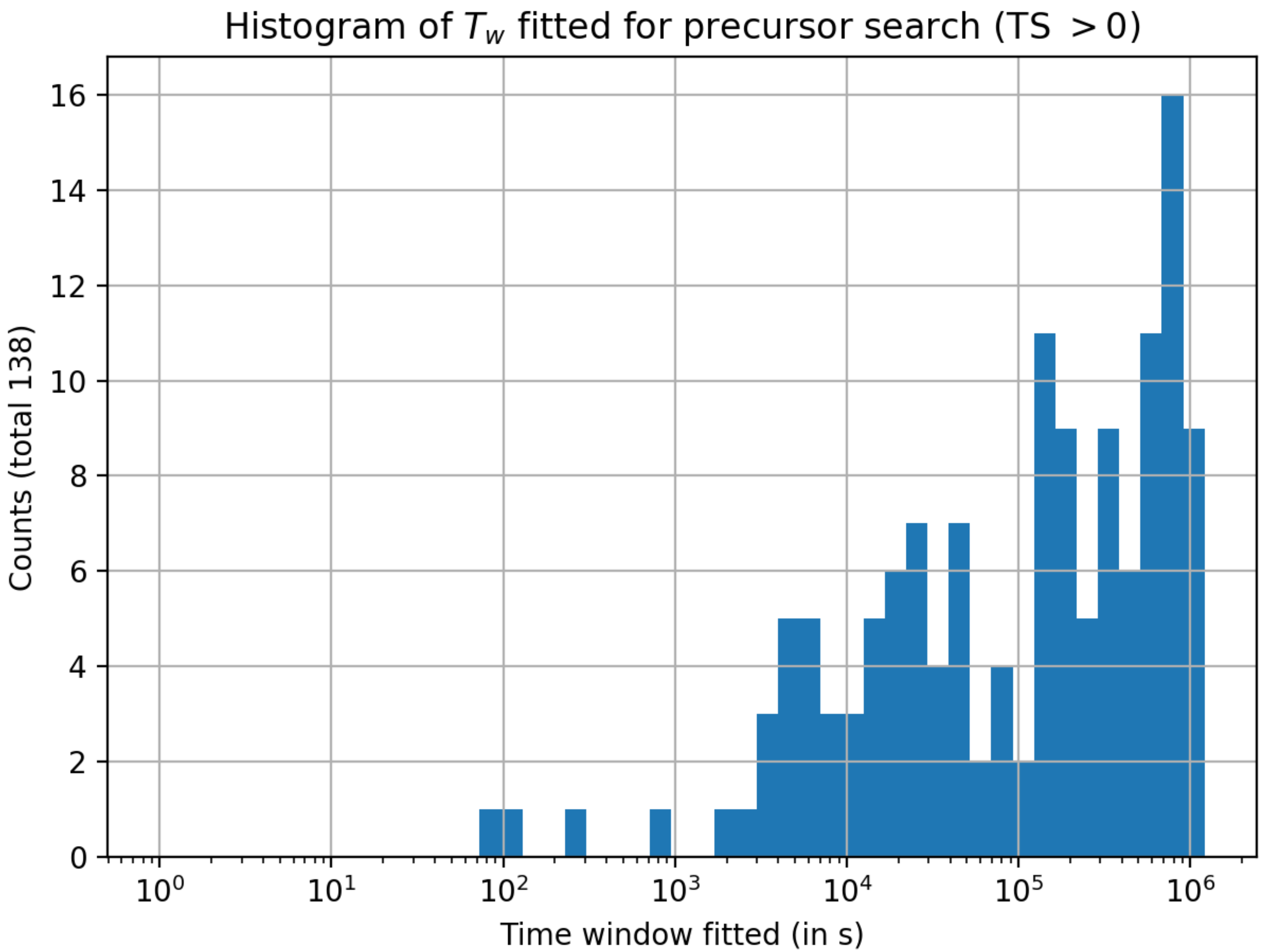


Total GRBs in selection: 733

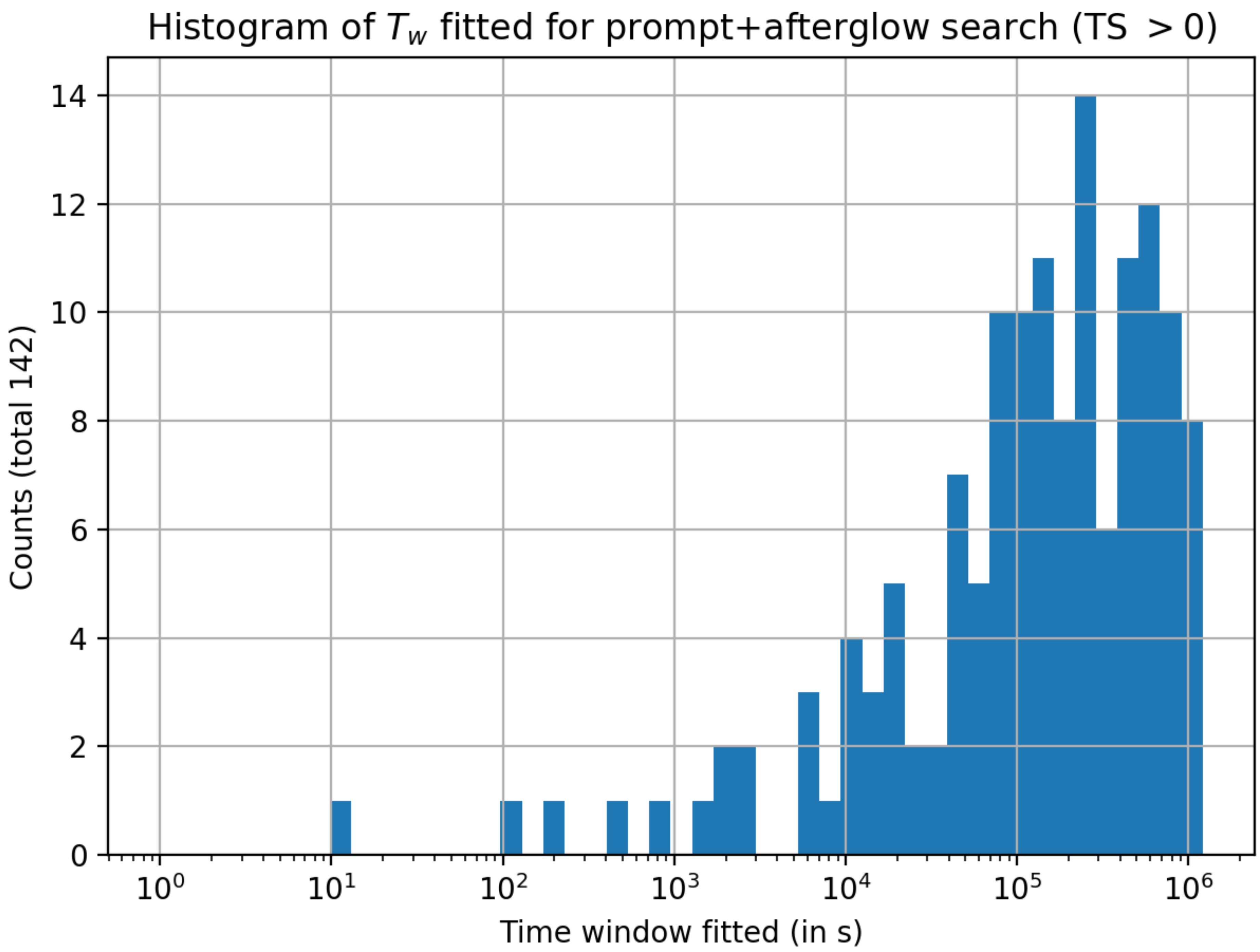
	Known fluence	Known T90	Short GRBs	Long GRBs
GRBs in selection	690	680	66	614
Swift	614	620	64	556
Fermi GBM	289	289	32	257
Fermi GBM only	60	60	2	58
Swift+Fermi GBM	229	229	30	199


Histograms of T90 (cases where T90 is known)
T90 = 2s
All GRBs
GRBs in selection
Number of GRBs
T90 (in s)
10^0
10^1
10^2
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3

Distribution of Tw fitted for the Precursor result



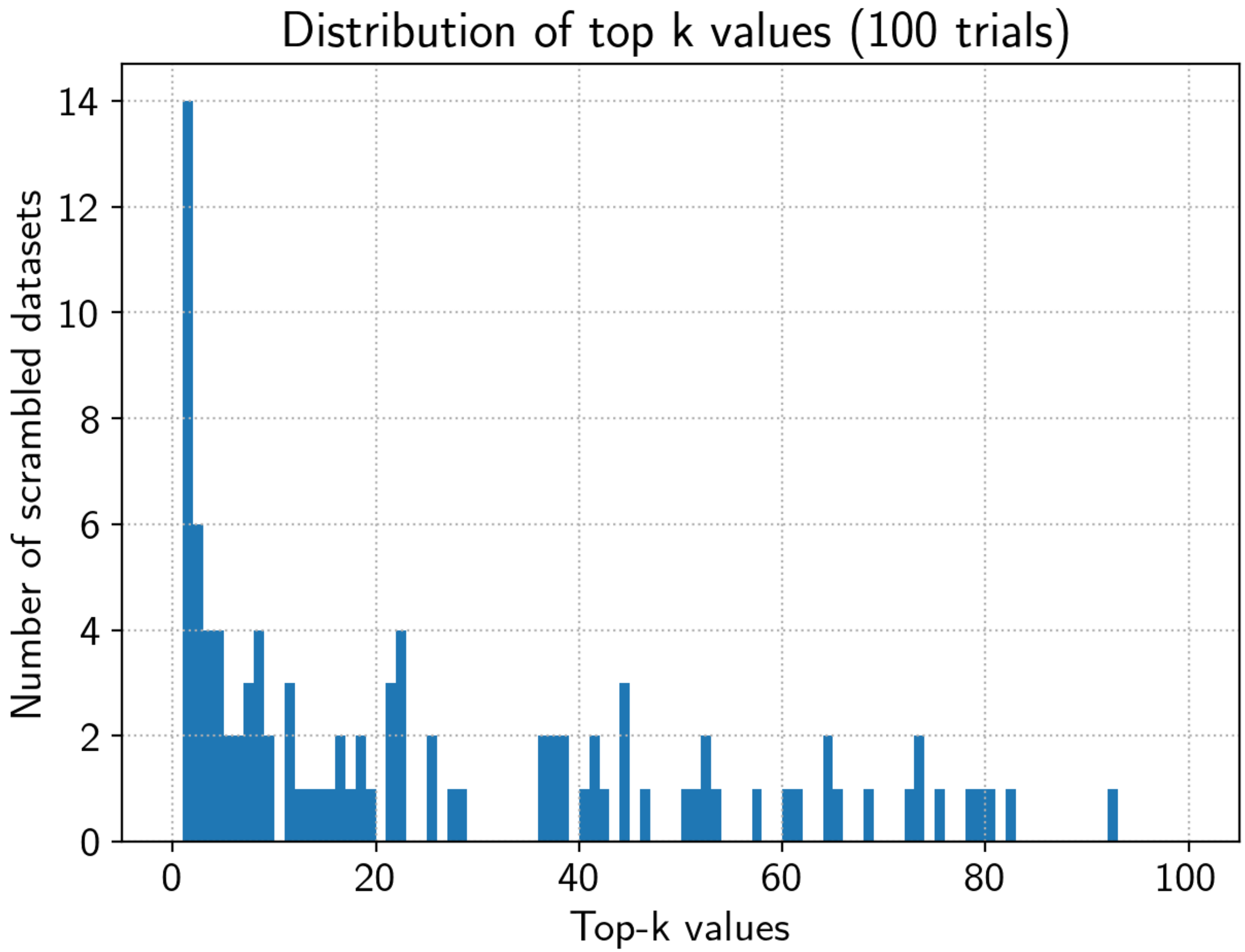
Distribution of Tw fitted for the Prompt+Afterglow result

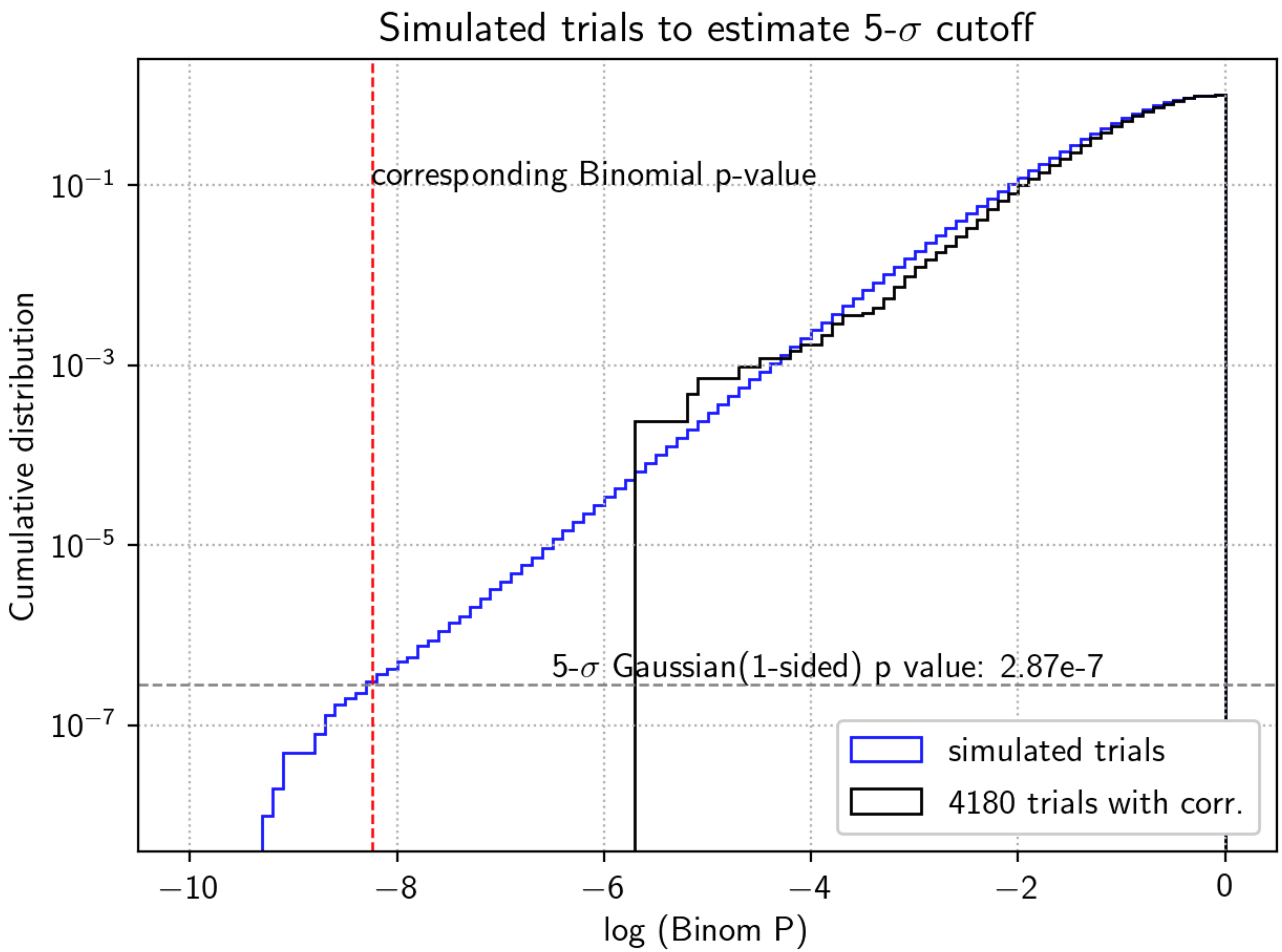


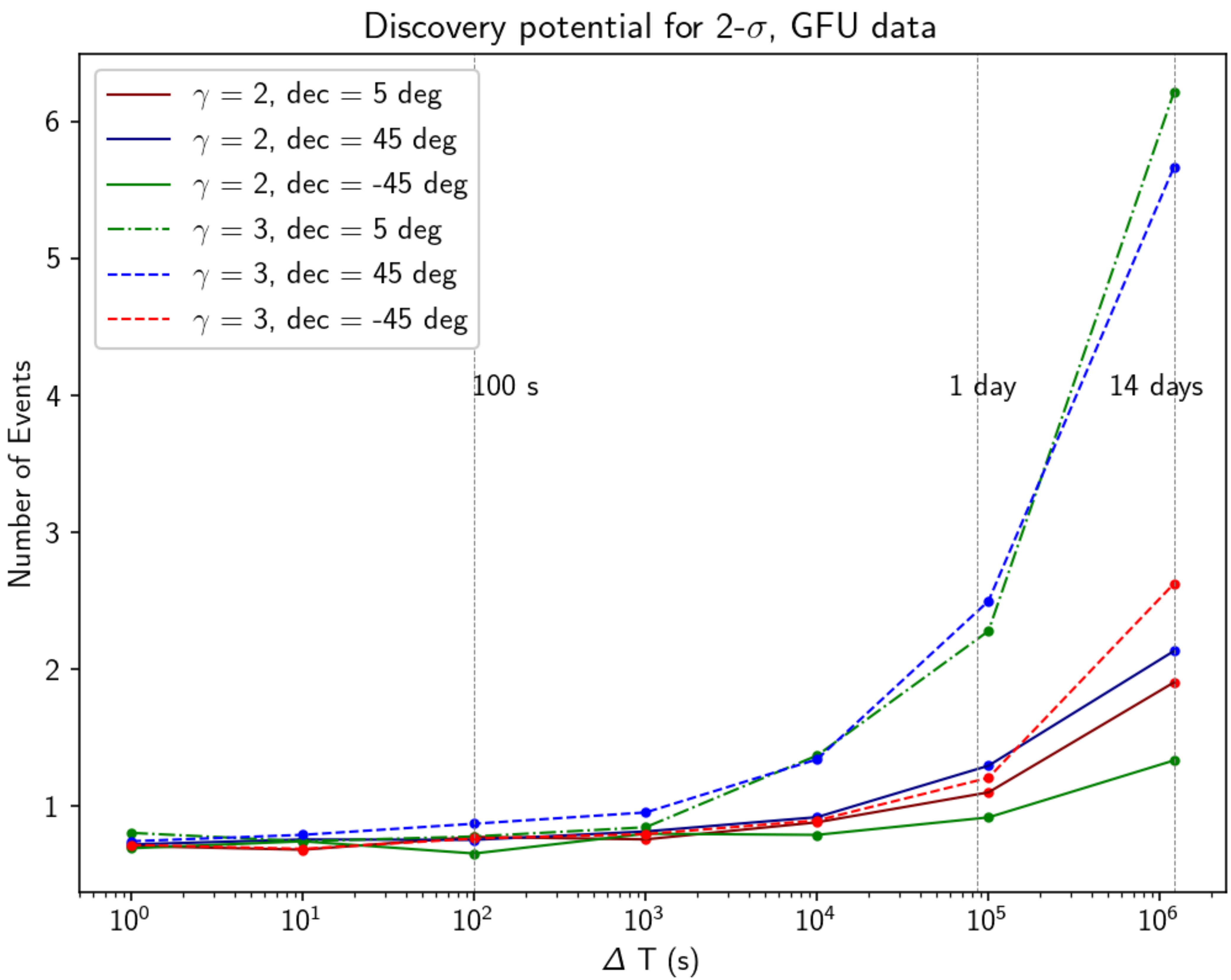
Kunal Deoskar

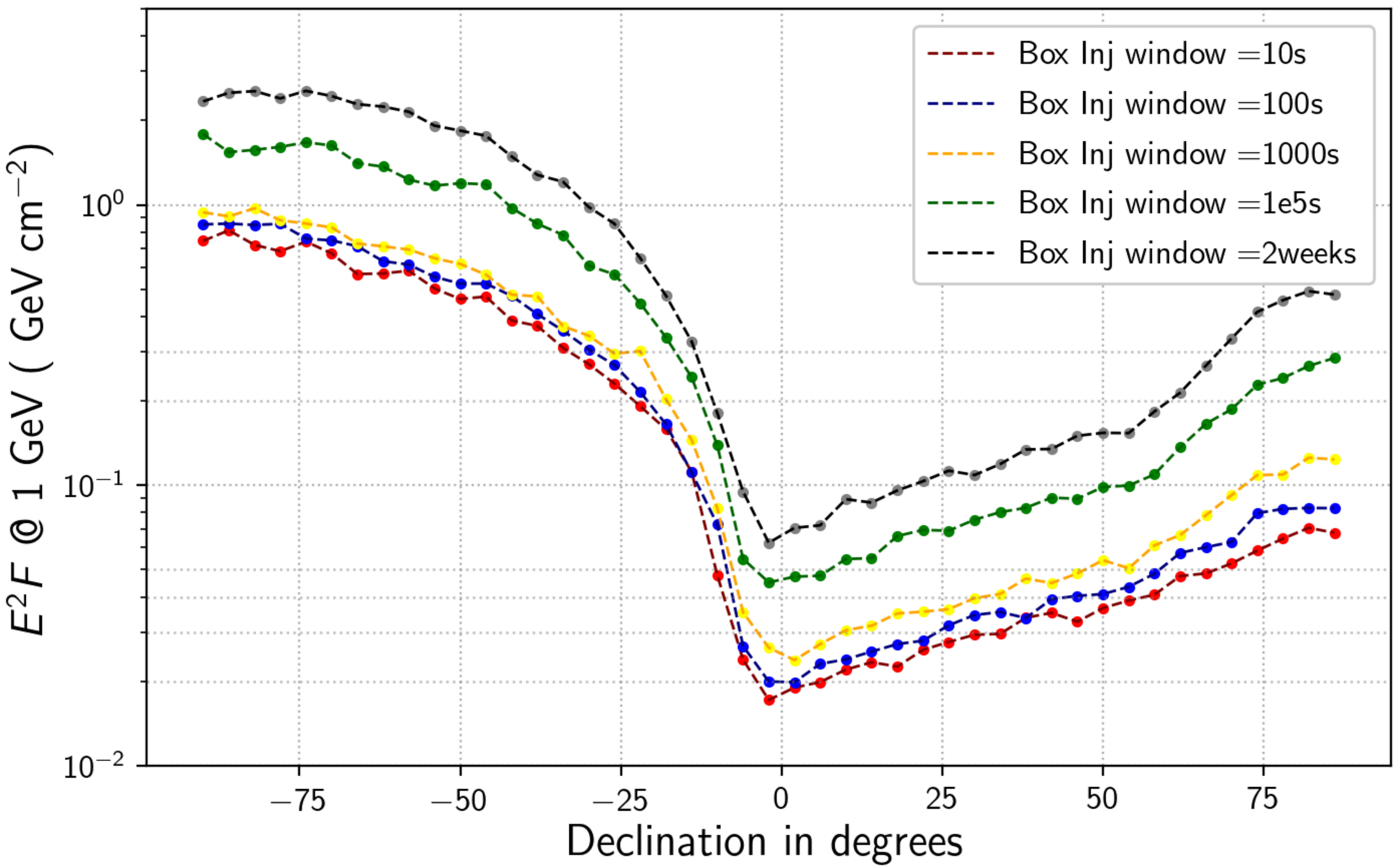
OKC / Stockholm University

Distribution of top k values obtained from 100 scrambled datasets

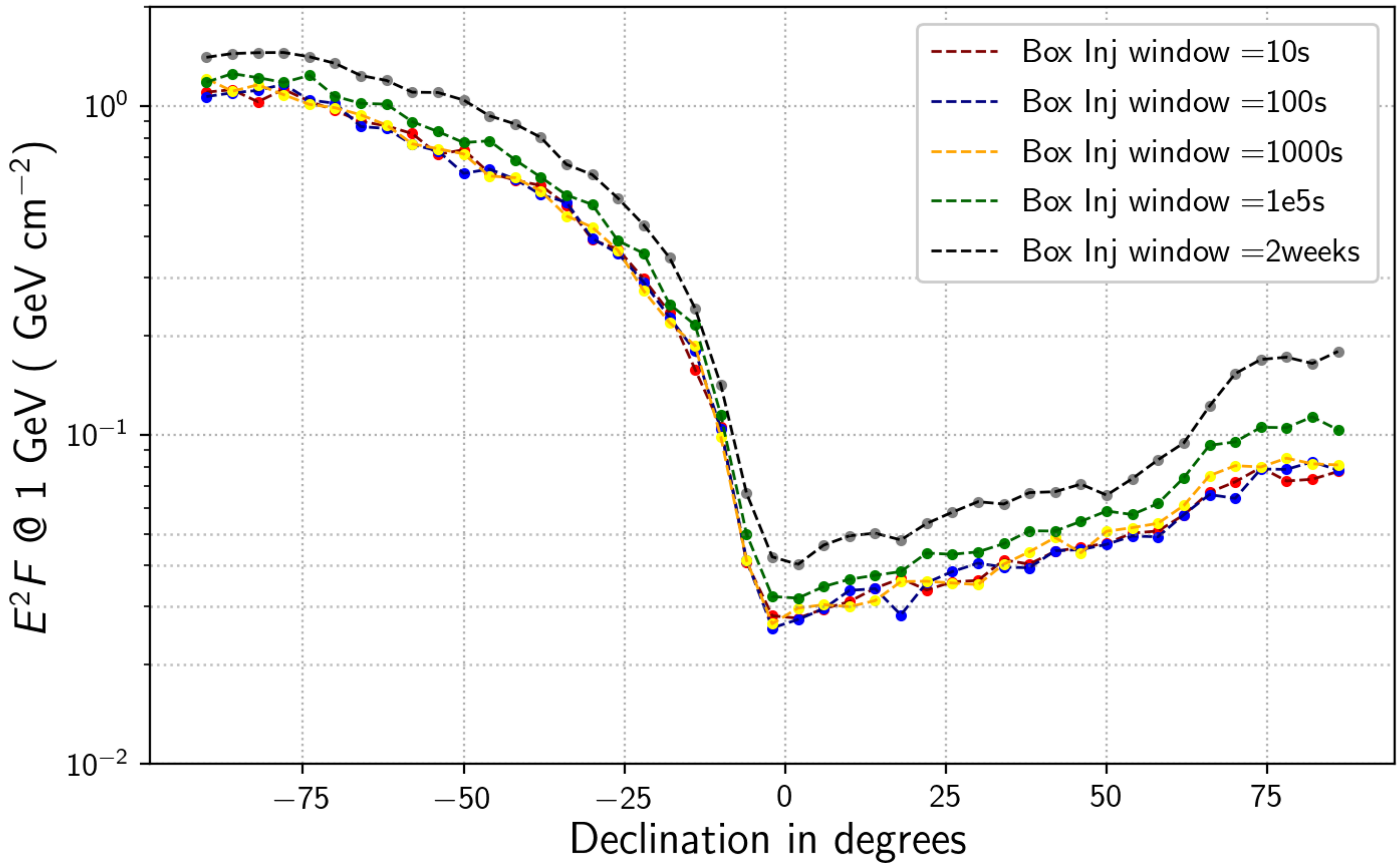



Simulated trials to estimate 5-σ cutoff
corresponding Binomial p-value
5-σ Gaussian(1-sided) p value: 2.87e-7
simulated trials
4180 trials with corr.
Cumulative distribution
log (Binom P)
10^−1
10^−3
10^−5
10^−7
−10
−8
−6
−4
−2
0


Discovery potential for 2-σ, GFU data
γ = 2, dec = 5 deg
γ = 2, dec = 45 deg
γ = 2, dec = -45 deg
γ = 3, dec = 5 deg
γ = 3, dec = 45 deg
γ = 3, dec = -45 deg
100 s
1 day
14 days
Number of Events
Δ T (s)
1
2
3
4
5
6
10^0
10^1
10^2
10^3
10^4
10^5
10^6



Box Inj window =10s
Box Inj window =100s
Box Inj window =1000s
Box Inj window =1e5s
Box Inj window =2weeks
E^2F @ 1 GeV (GeV cm^{-2})
10^0
10^{-1}
10^{-2}
−75
−50
−25
0
25
50
75
Declination in degrees



Box Inj window =10s
Box Inj window =100s
Box Inj window =1000s
Box Inj window =1e5s
Box Inj window =2weeks
10^0
10^{-1}
10^{-2}
−75
−50
−25
0
25
50
75
Declination in degrees
E^2F @ 1 GeV (GeV cm^{-2})

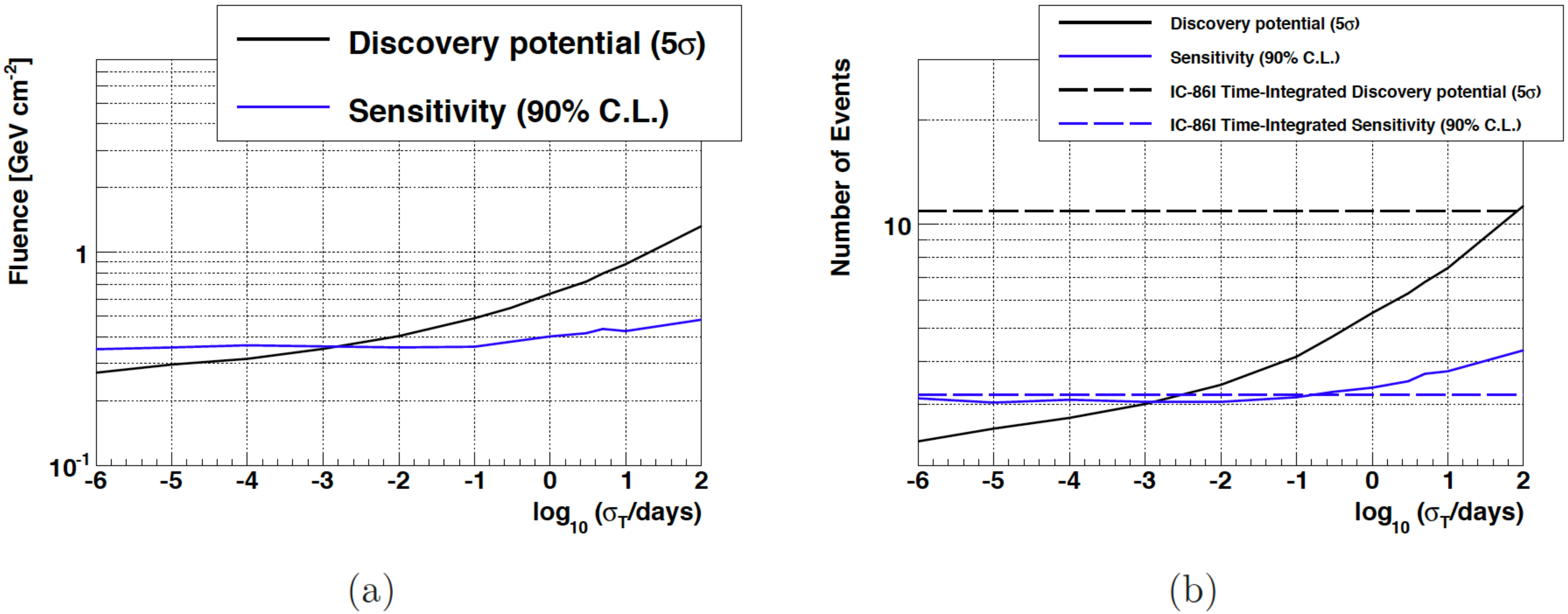
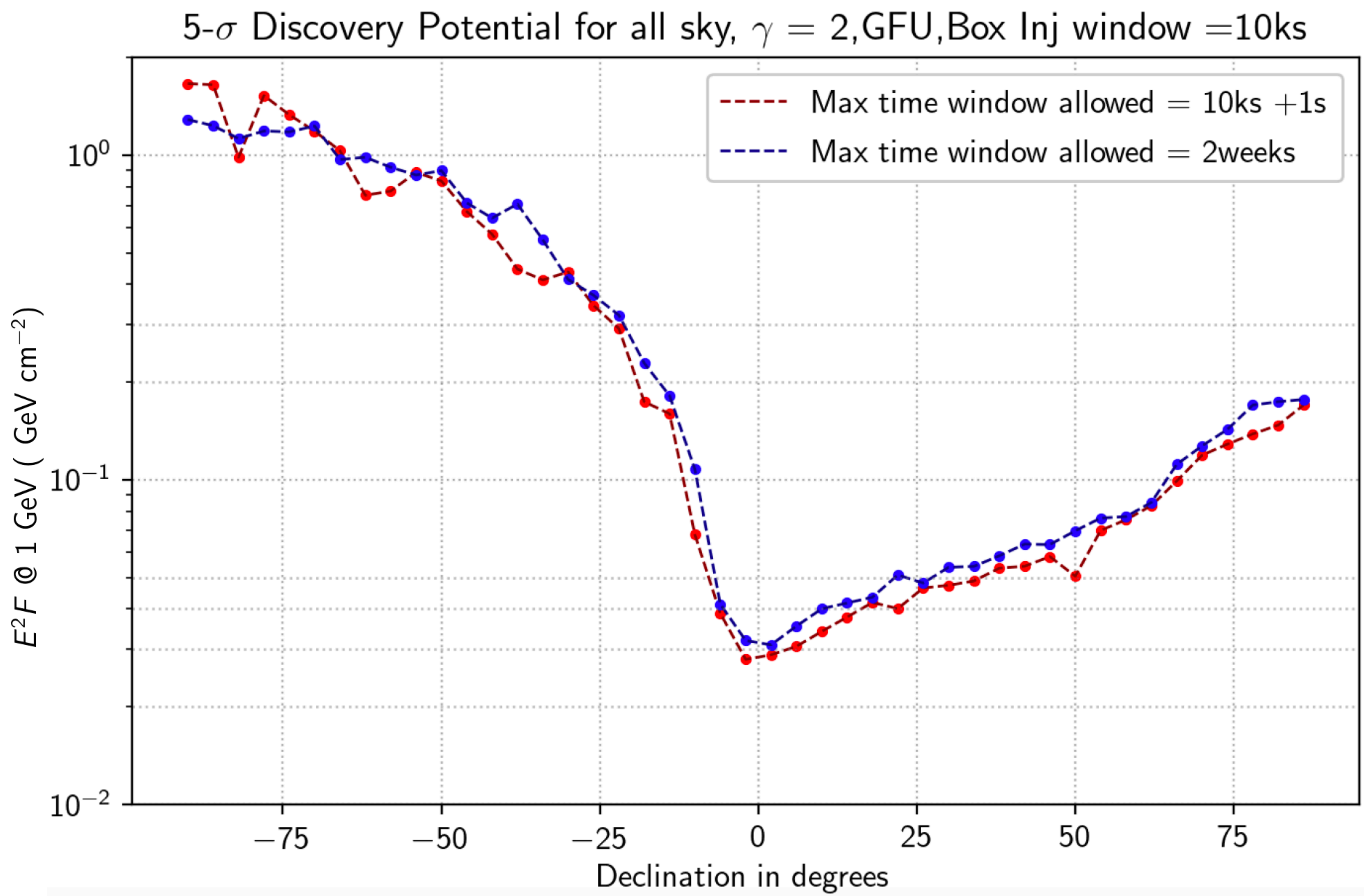
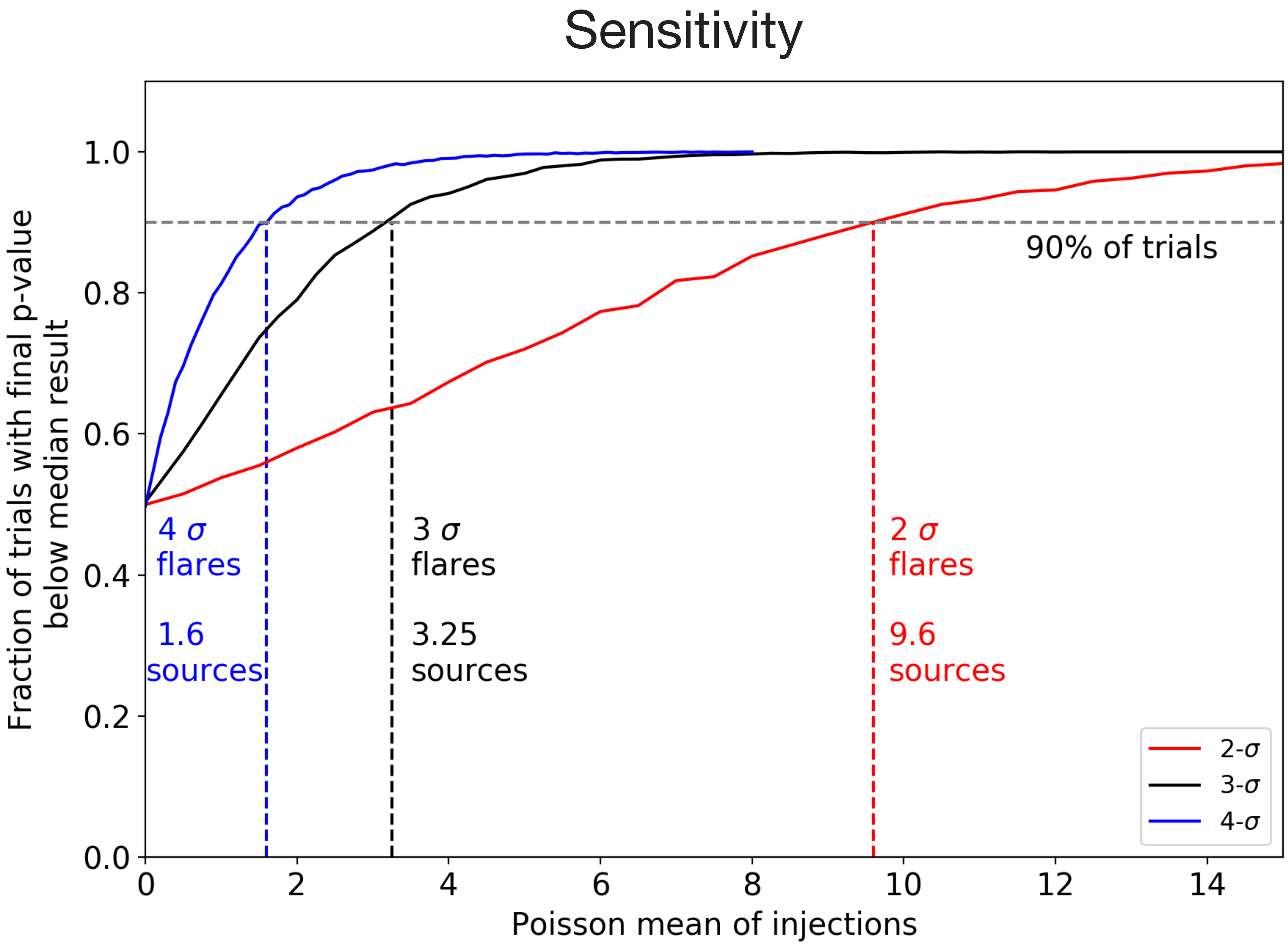


Figure 1: The 5σ discovery potential (signal required for 5σ detection in 50% of trials) and the sensitivity (90% CL median upper limit) for IC-86I shown in terms of the fluence (a) and the mean number of signal events (b) for a fixed source at $+16^o$ declination (solid lines) with an E^{-2} spectrum. The corresponding lines for the time integrated search are also shown. The time dependent search improves over the time integrated for flaring sources when solid lines become lower than dashed ones.

Ref: arXiv:1503.00598v2



5-σ Discovery Potential for all sky, γ = 2,GFU,Box Inj window =10ks
Max time window allowed = 10ks +1s
Max time window allowed = 2weeks
10^0
10^−1
10^−2
E^2F @ 1 GeV (GeV cm^−2)
−75
−50
−25
0
25
50
75
Declination in degrees



- Since my p-values are ~50%, this is approximately my upper limit as well.