Search for neutrinos from precursors and afterglows of Gamma-ray Bursts using the IceCube Neutrino Observatory

Kunal Deoskar

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Supervisor: Chad Finley

Asst. Supervisor: Klas Hultqvist

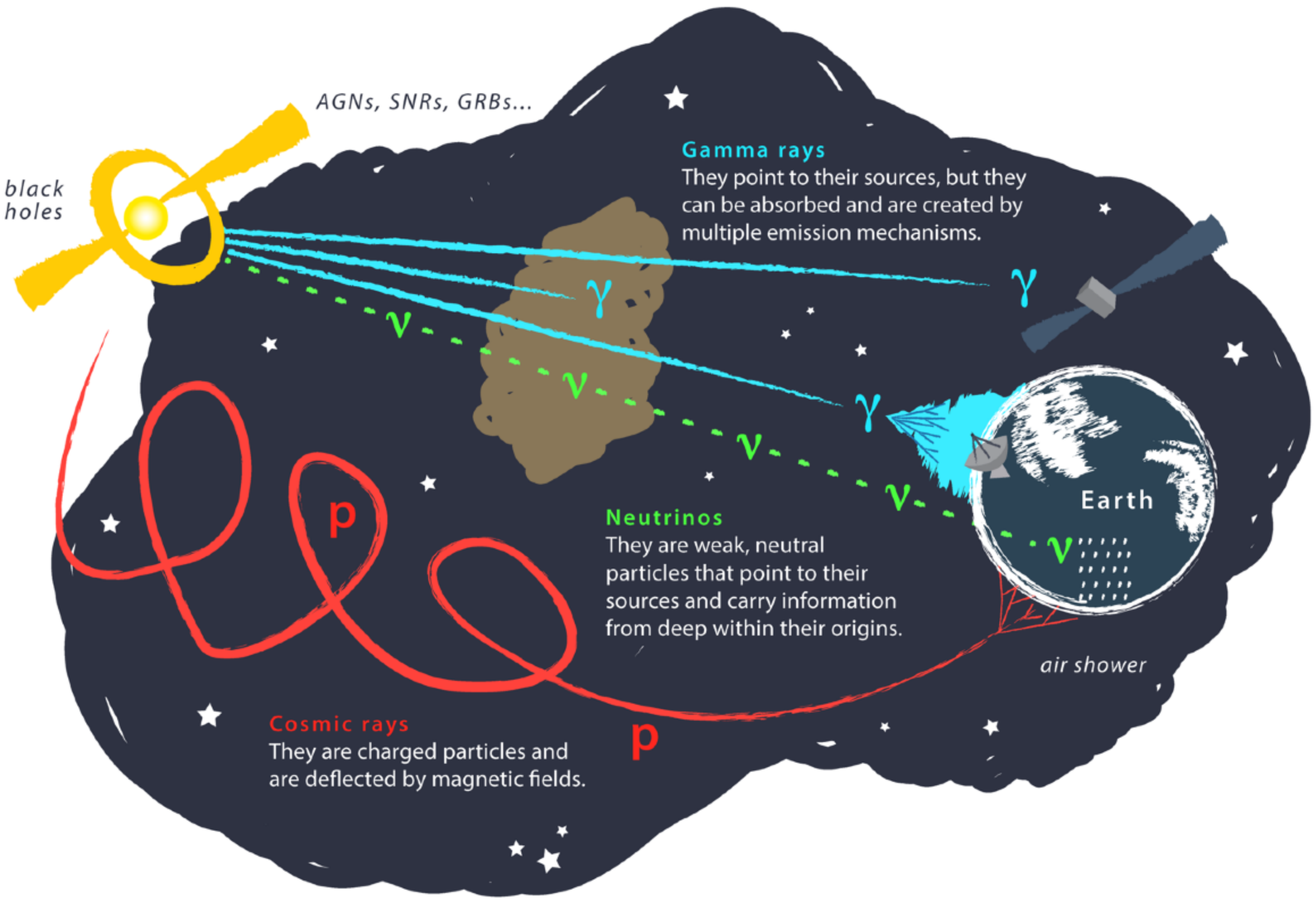
Stockholm University

ICECUBE

Oskar Klein centre

Cosmic rays and neutrino connection

- CRs are composed of relativistic particles coming to Earth from outer space.
- They can lead to production of neutrinos.
- Neutrinos can help identify the sources of CRs, and how they are produced.



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Gamma Ray Bursts as sources of high-energy neutrinos

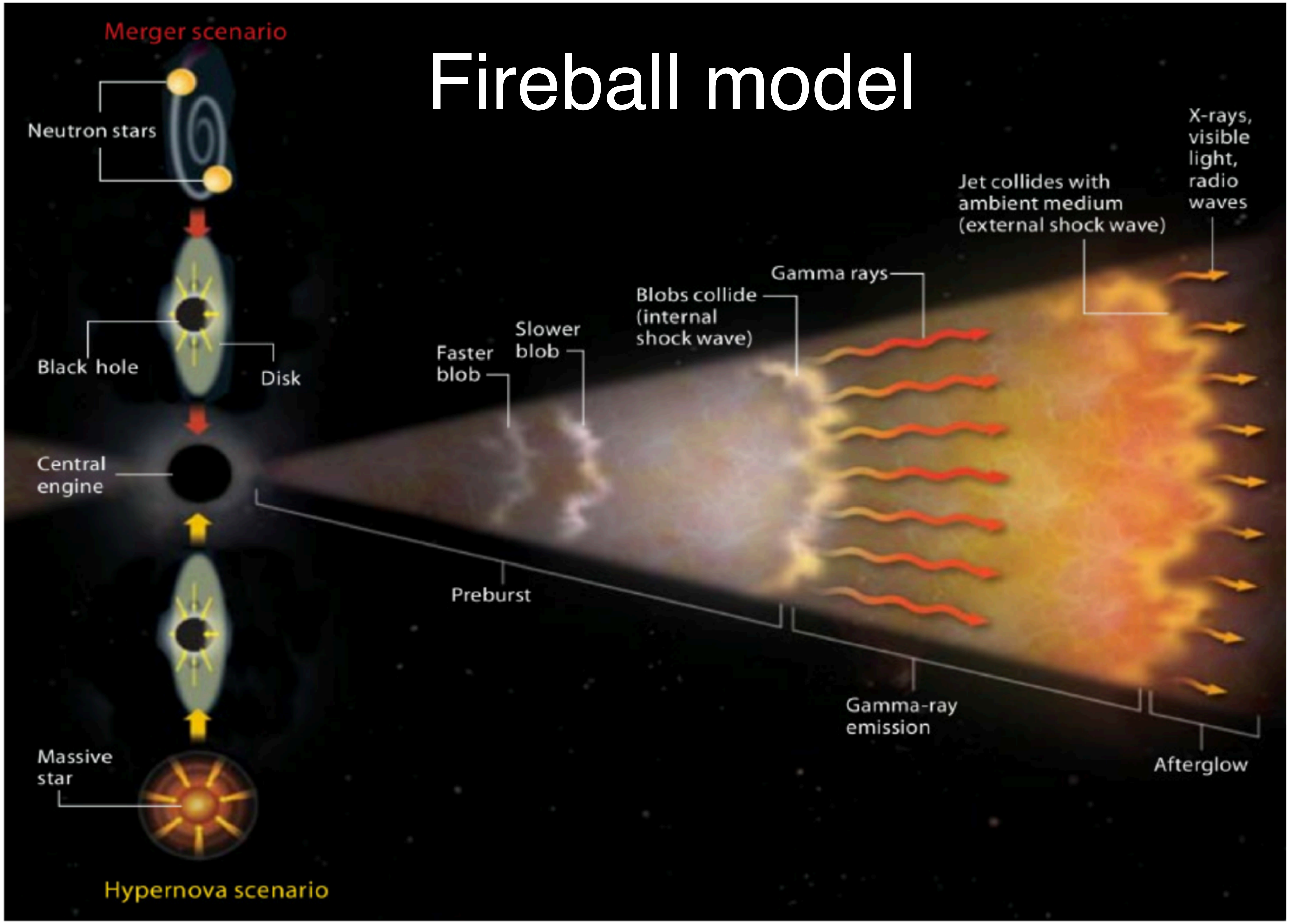
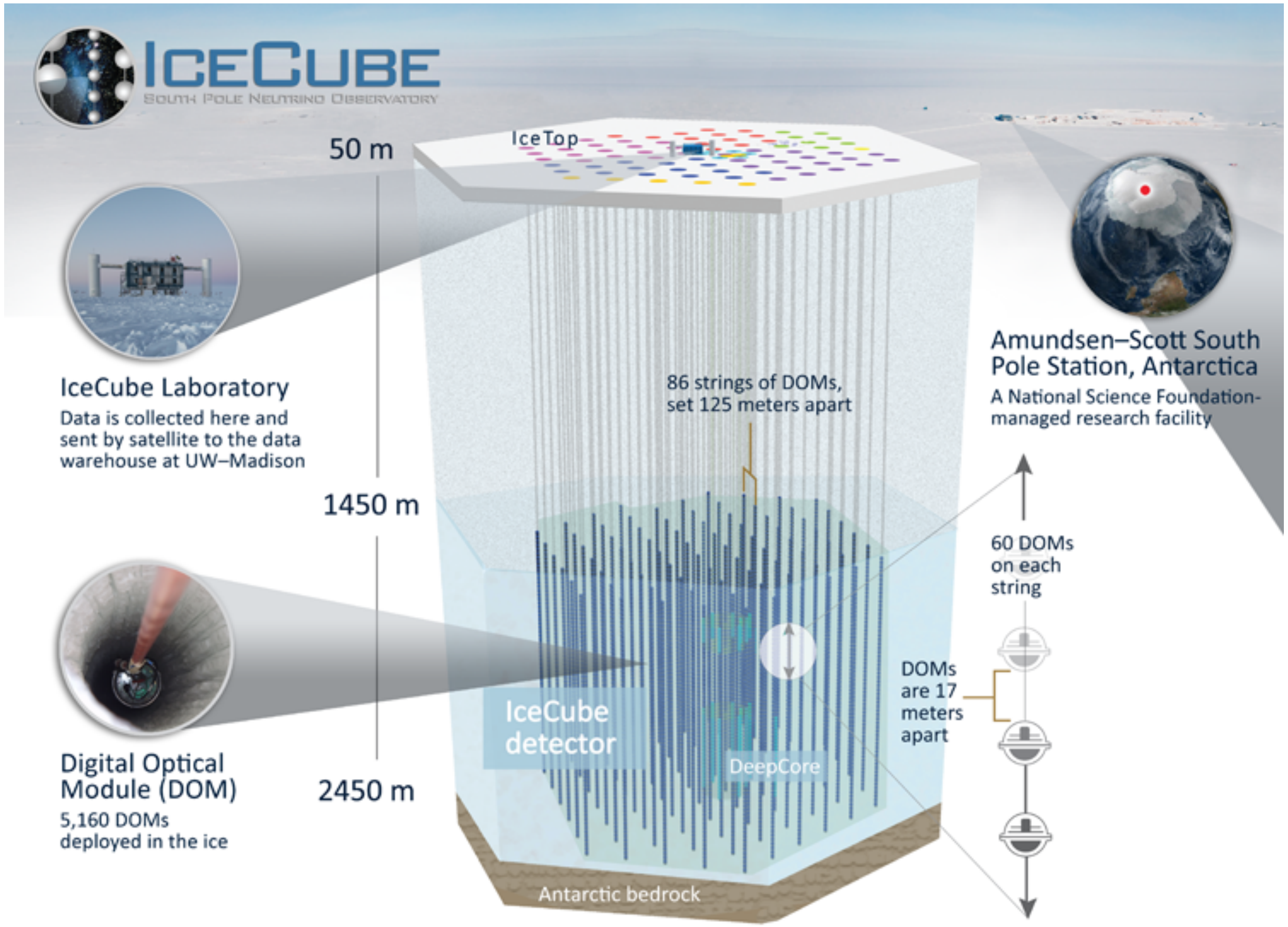


Image Credits: NASA

- Shocks in jet are likely place for CR acceleration.
- IceCube searches so far were only during the prompt phase, typically <100s, found no correlation.
- Recent observations of gammas by HESS long after prompt phase motivates us to look in a larger time window.

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.

Data for the analysis

Neutrino data:

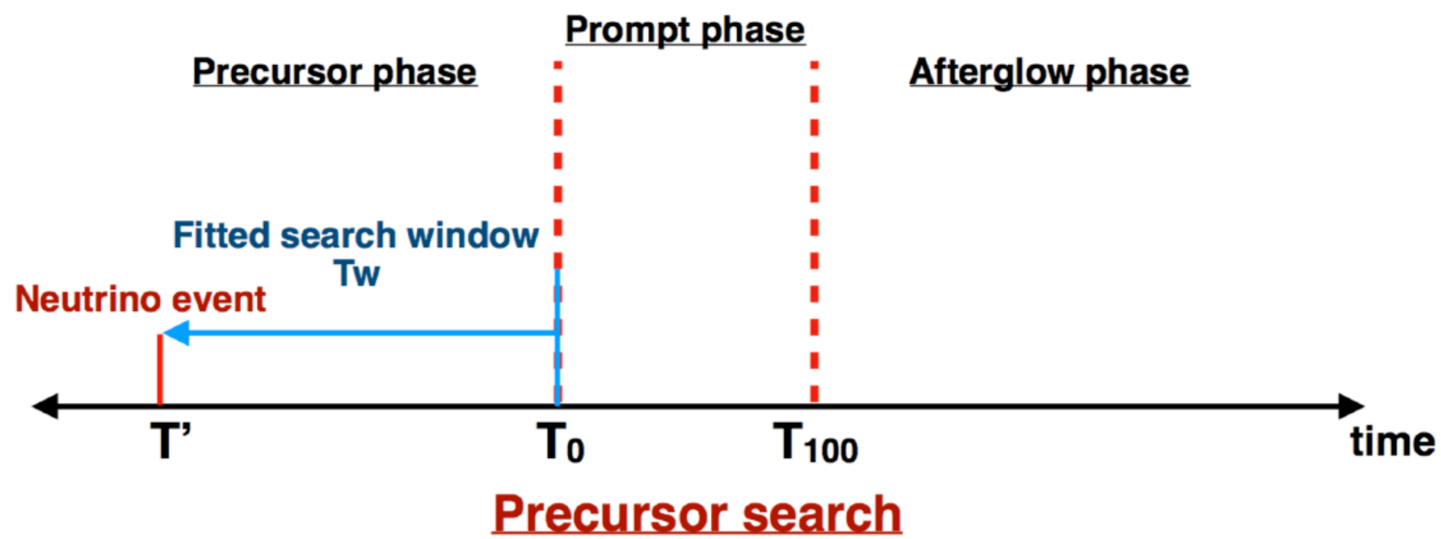
- I use 8 years of IceCube data - continuous observations of the sky between 2011-05-13 and 2018-10-14.
- The data sample had altogether ~1.5 million neutrino candidate events.

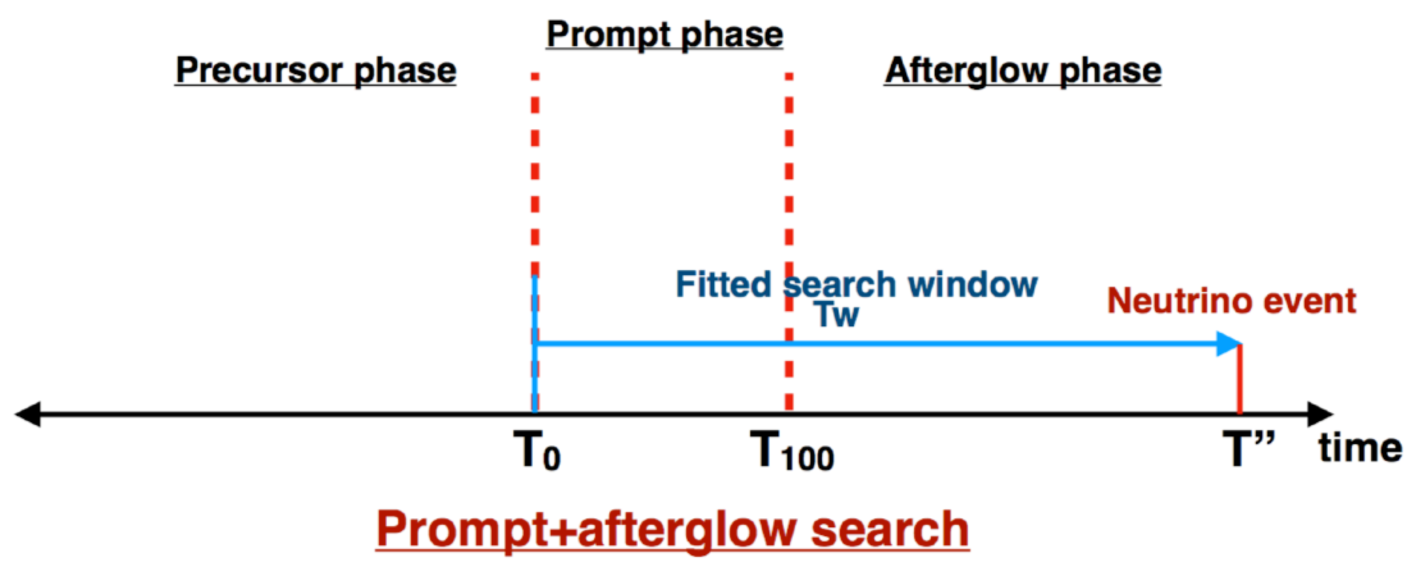
GRB data (source list):

Selection	Number of Objects
Total observed GRBs in GRBWeb	6399
and within the time period : 2011-05-27 - 2018-09-30	2270
and within the declination region: $[-85°,+85°]$	2260
and within estimated angular uncertainty: $< 0.2°$	**733**
and within estimated angular uncertainty: $<0.05°$	686

Analysis approach

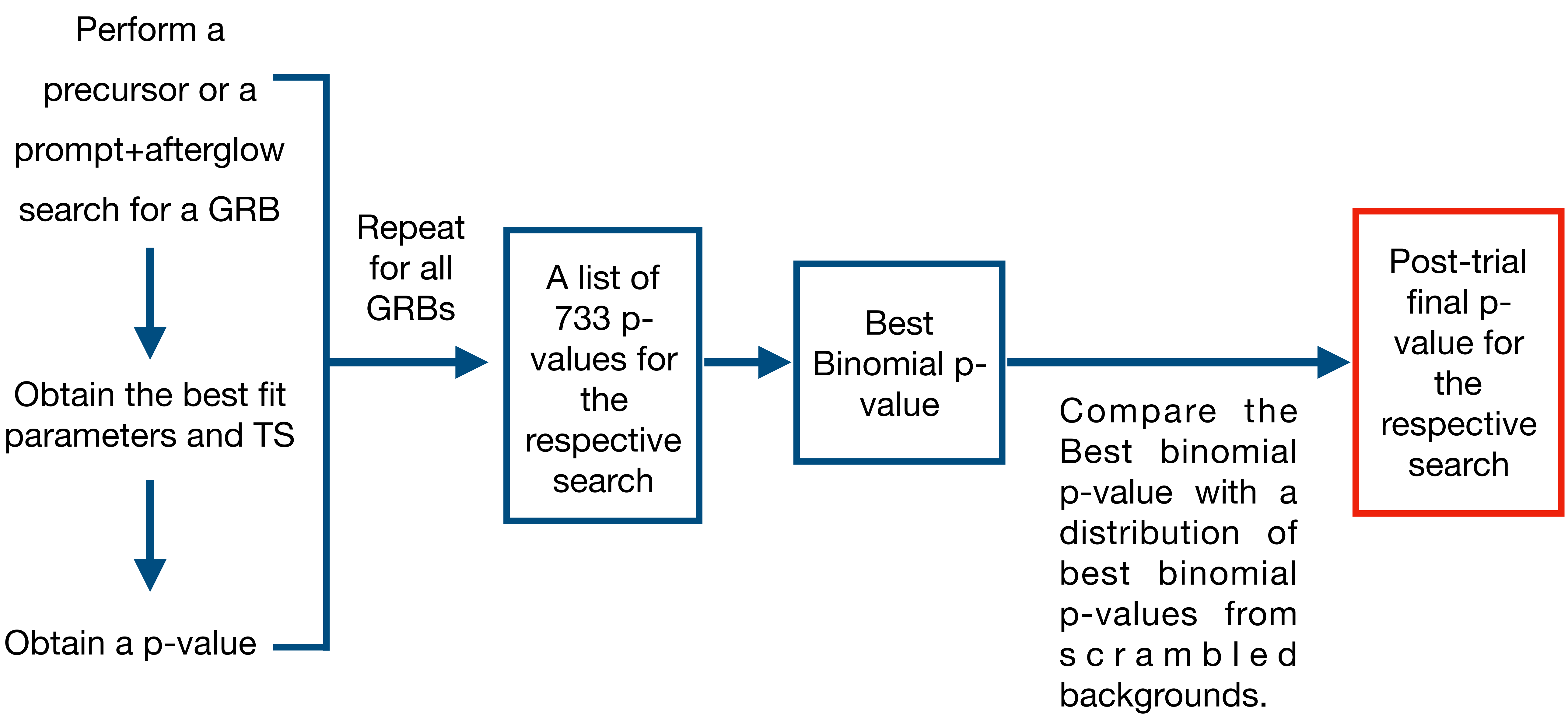
- My analysis searches for neutrino correlations beyond the prompt phase.
- Each GRB is fit separately.
- The use of the time window parameter differs to perform two independent searches:
  - **Precursor search**: searching for neutrino correlations **up to 14 days prior** to start of prompt phase.
  - **Prompt+afterglow search:** searching for neutrino correlations **up to 14 days after** the start of prompt phase.





We expect to find a small number of neutrinos correlated with GRBs, just due to chance alignment of background neutrinos. We take this into account in the final step of the analysis.

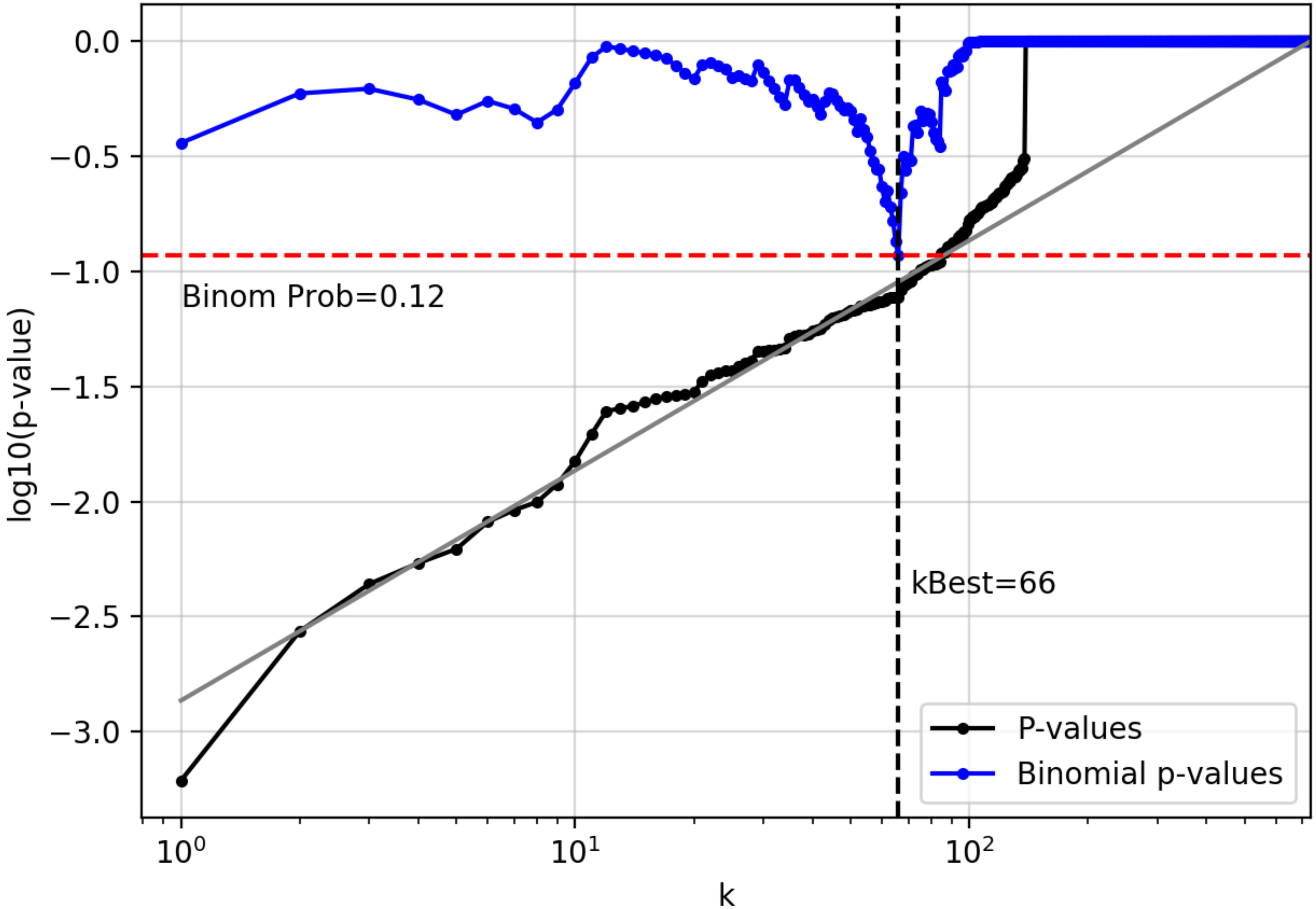
Steps of the analysis



Result table for precursor search (top 20 GRBs)

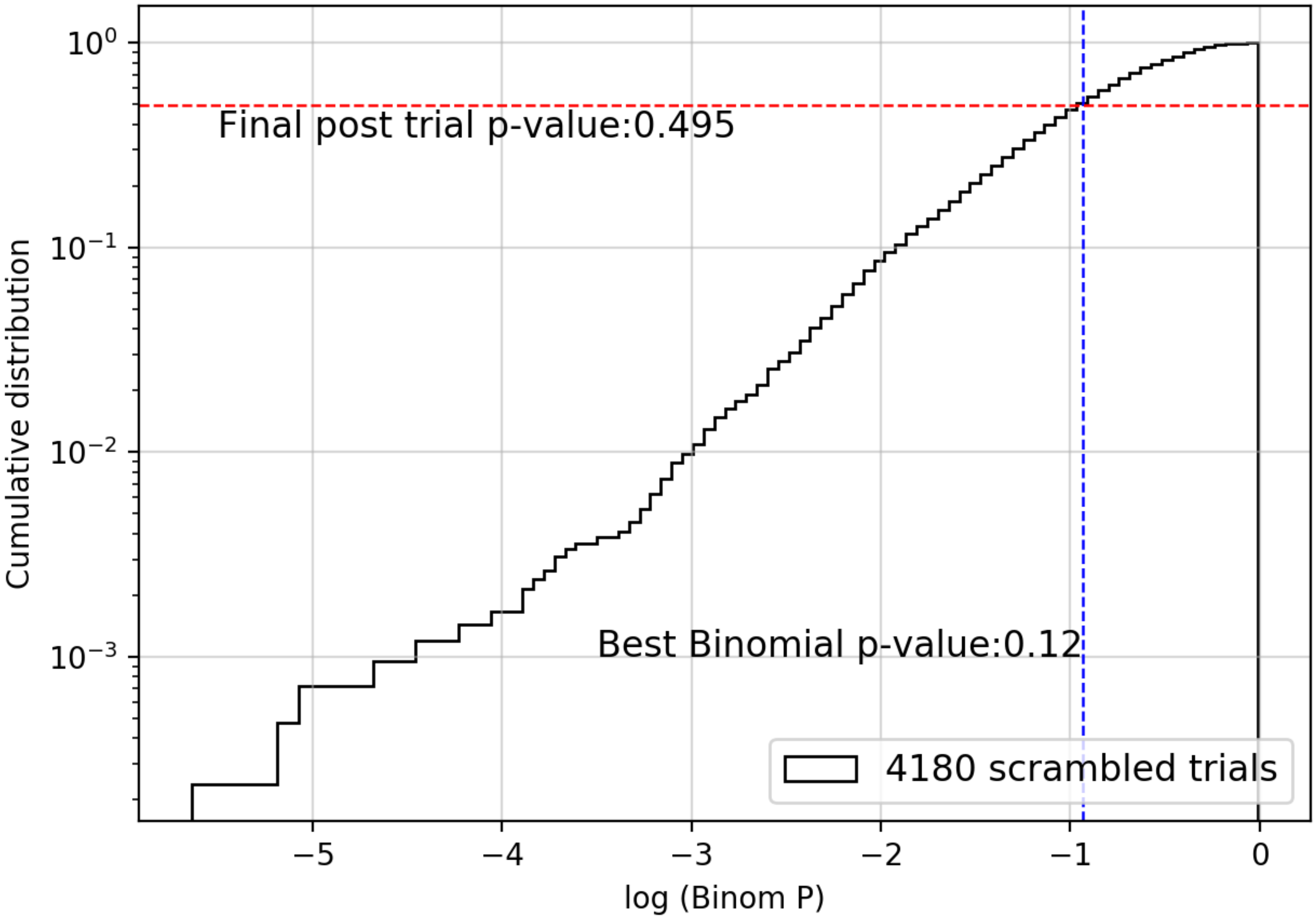
GRB information							Fit results				
GRB Name	RA [°]	Dec[°]	T_0[MJD]	Fluence[erg/cm^2]	redshift	T_{100}[s]	$\hat{n_s}$	$\hat{\gamma}$	$\hat{T_w}$[s]	TS	p-value
GRB150202A	39.23	-33.15	57055.965301	–	–	25.70	1.00	4.00	3.367e+03	16.37	6.12e-04
GRB180721A	347.71	4.86	58320.463056	–	–	47.60	1.00	1.84	1.542e+04	12.46	2.73e-03
GRB140301A	69.56	-34.26	56717.642234	–	1.42	31.00	1.96	2.15	7.615e+05	11.51	4.38e-03
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
GRB111126A	276.06	51.46	55891.790069	–	–	0.80	1.84	4.00	3.556e+03	10.65	6.22e-03
GRB151205A	229.29	35.74	57361.656944	1.84e-06	–	62.80	1.00	3.80	6.390e+03	10.10	8.15e-03
GRB170531B	286.88	-16.42	57904.918160	–	2.37	164.13	2.70	2.59	5.077e+05	9.35	9.17e-03
GRB171007A	135.60	42.82	58033.498356	3.03e-07	–	105.00	2.63	2.47	2.963e+04	9.72	9.94e-03
GRB160310A	98.82	-7.22	57457.015943	5.25e-06	–	26.60	0.99	1.83	4.455e+04	8.59	1.19e-02
GRB180720B	0.53	-2.92	58319.598368	2.99e-04	0.65	53.90	3.59	2.32	7.435e+05	8.89	1.50e-02
GRB160422A	42.09	-57.88	57500.499303	8.80e-05	–	14.12	0.99	2.12	4.246e+04	7.16	1.96e-02
GRB140619A	27.11	-39.26	56827.485127	–	–	233.90	0.98	2.54	8.499e+04	6.21	2.47e-02
GRB160629A	4.82	76.98	57568.930208	1.31e-05	3.33	76.38	3.17	3.40	3.327e+05	7.06	2.54e-02
GRB131014A	100.30	-19.10	56579.214583	1.98e-04	–	4.36	0.98	3.31	6.707e+03	6.38	2.60e-02
GRB151027A	272.49	61.35	57322.165556	1.41e-05	0.81	129.69	0.99	2.90	4.185e+03	7.59	2.70e-02
GRB131218A	113.80	-64.72	56644.878843	–	–	–	0.98	2.97	3.542e+05	5.84	2.79e-02
GRB120722A	230.50	13.25	56130.537106	–	0.96	42.40	2.42	2.51	3.223e+05	7.39	2.87e-02
GRB120711B	331.69	60.02	56119.132669	–	–	60.00	2.52	2.59	7.865e+04	7.31	2.88e-02
GRB150627A	117.47	-51.49	57200.182905	1.80e-04	–	70.57	0.98	1.73	8.081e+05	5.58	2.92e-02
GRB131030A	345.07	-5.37	56595.872428	–	1.29	41.29	0.99	3.81	3.250e+03	7.07	2.98e-02

Precursor search results



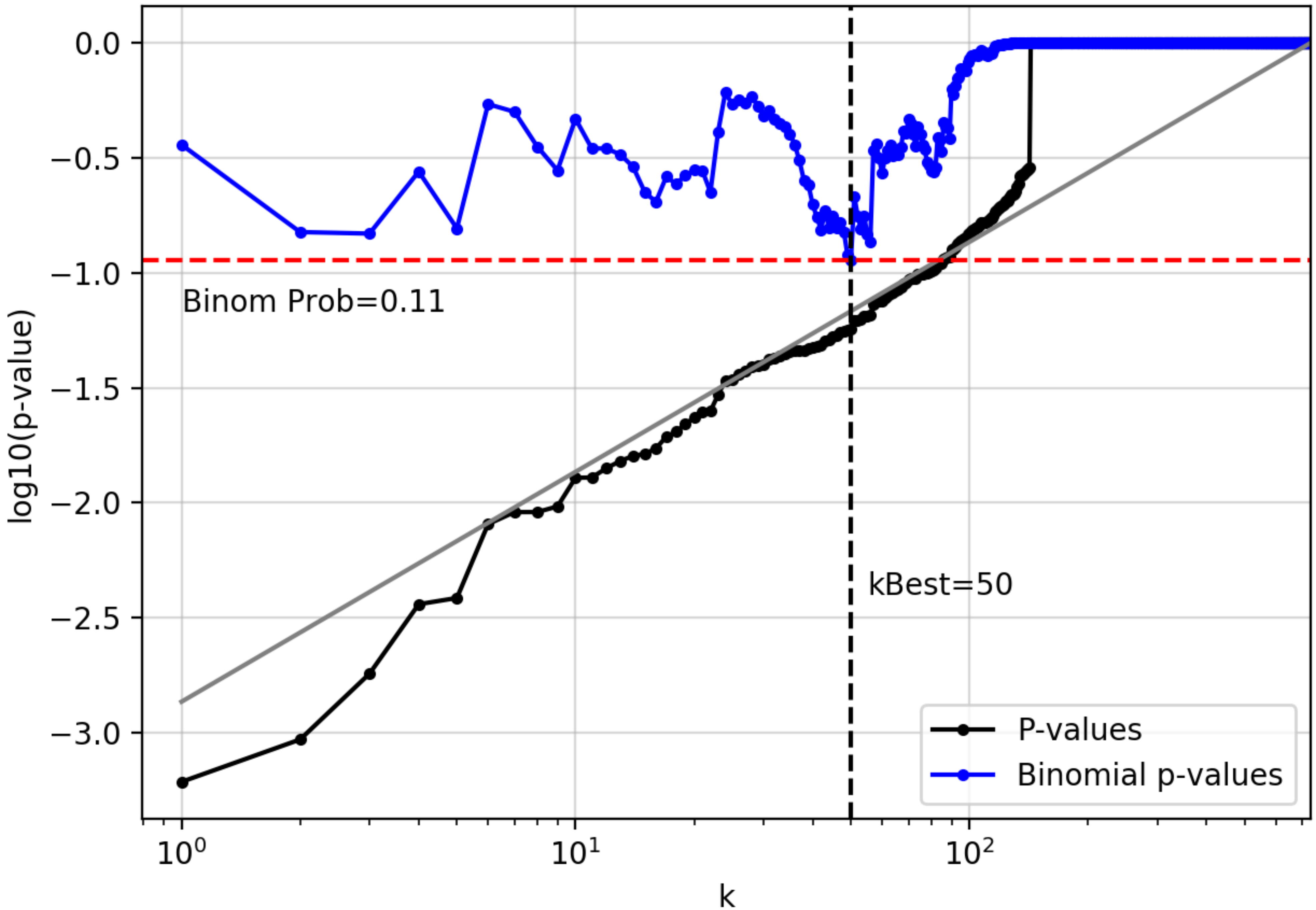
(k is the index of each GRB when ranked by p-value)

Final post trial significance



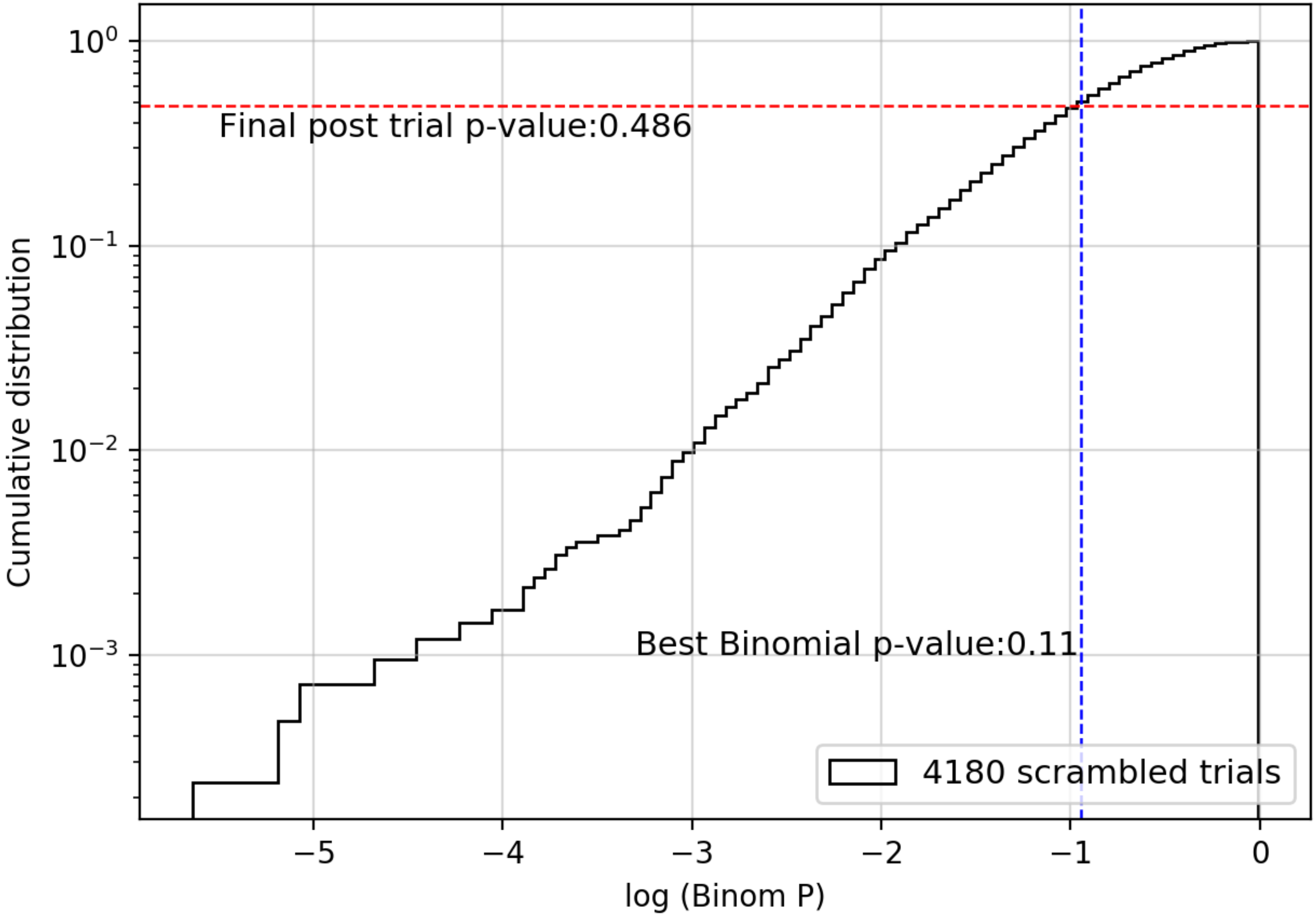
- Final post-trial p-value: ~50%.

Prompt+Afterglow results



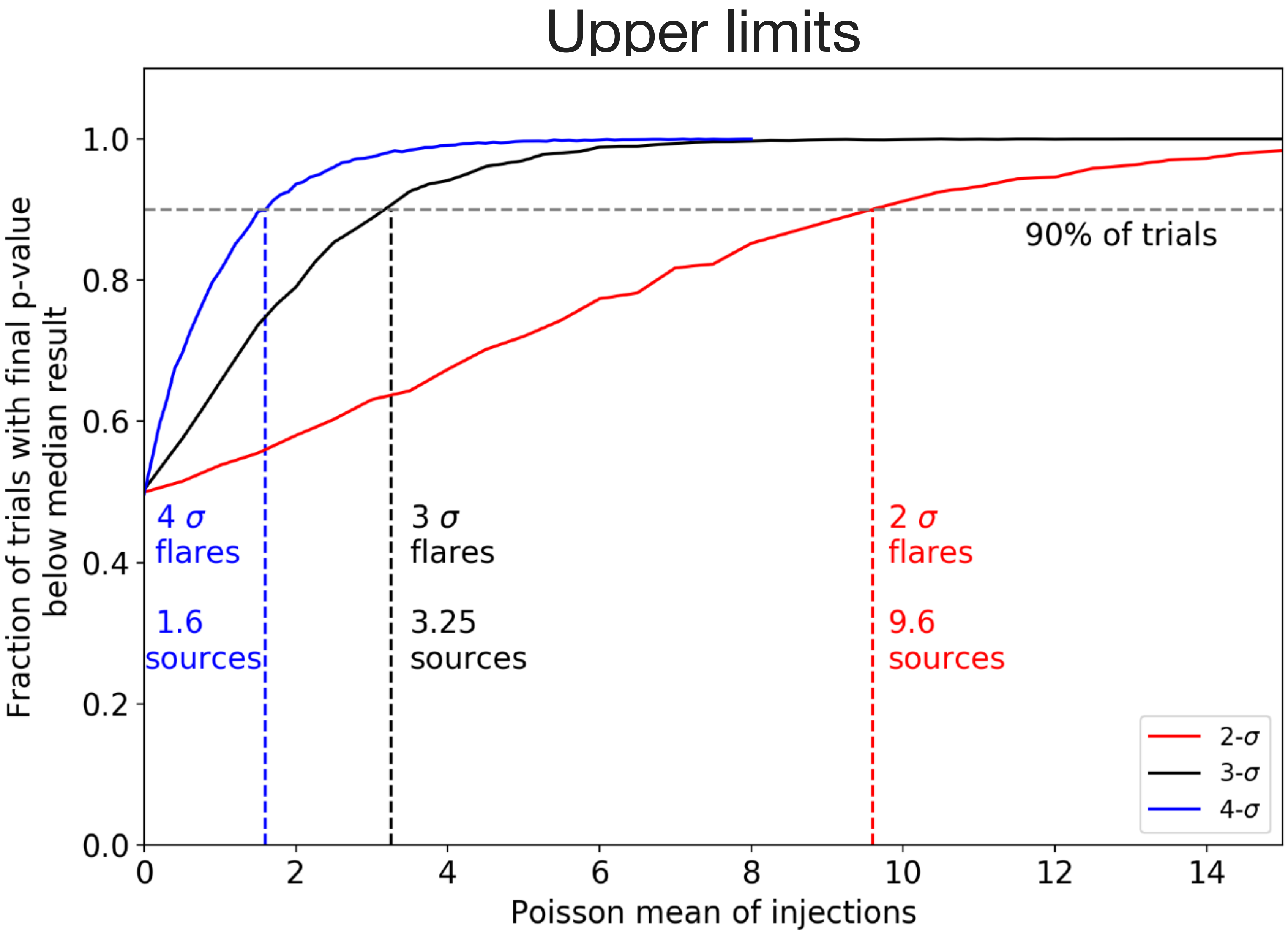
(k is the index of each GRB when ranked by p-value)

Final post trial significance



- Final post-trial p-value: ~50%.

Next step: Towards population limits



Different scenarios can be excluded at 90% CL. A scenario where you expect e.g.:

- ~ 2 neutrino-bright GRBs (each > 4-σ), or
- ~ 3 GRBs at > 3-σ, or
- ~ 10 GRBs at > 2-σ

Next step: relate physical models of source populations (neutrino luminosity, cosmological distribution of sources) to these scenarios to constrain the models.

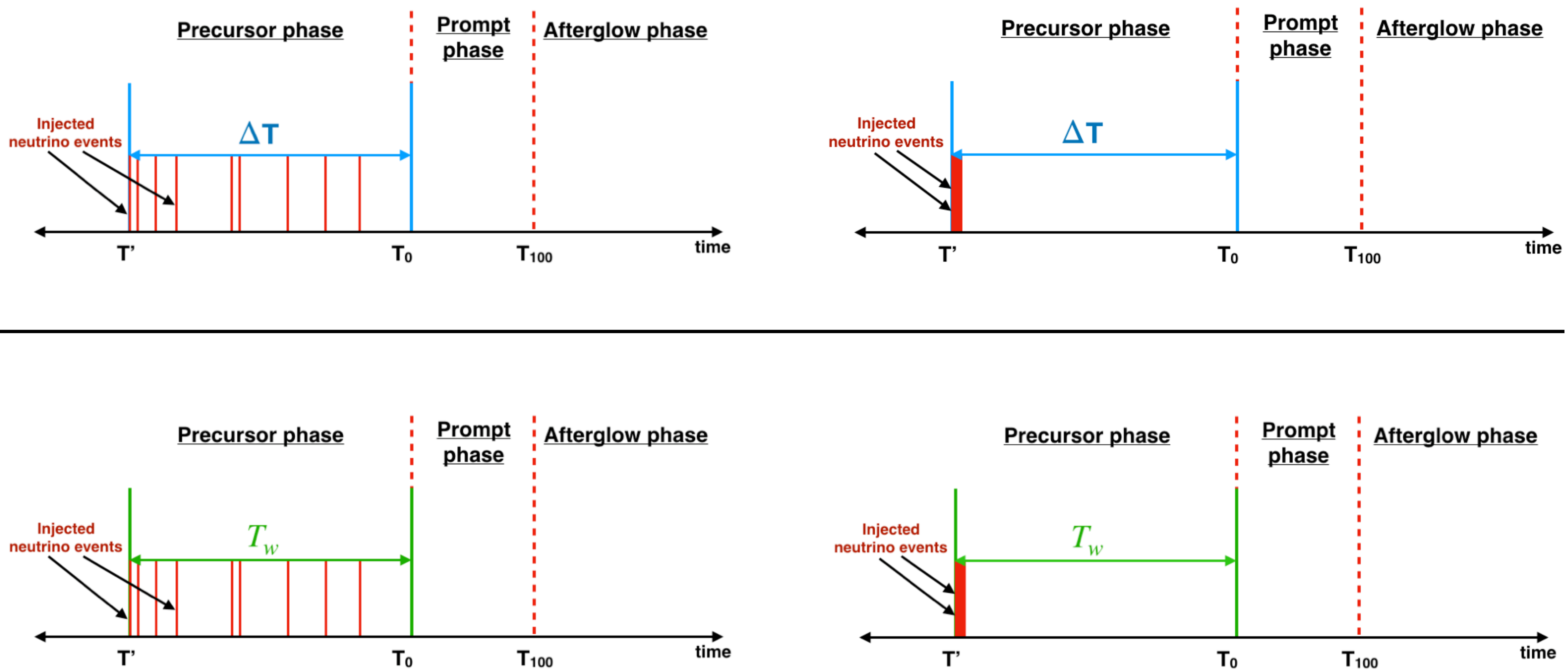
Thank you!

Backup slides

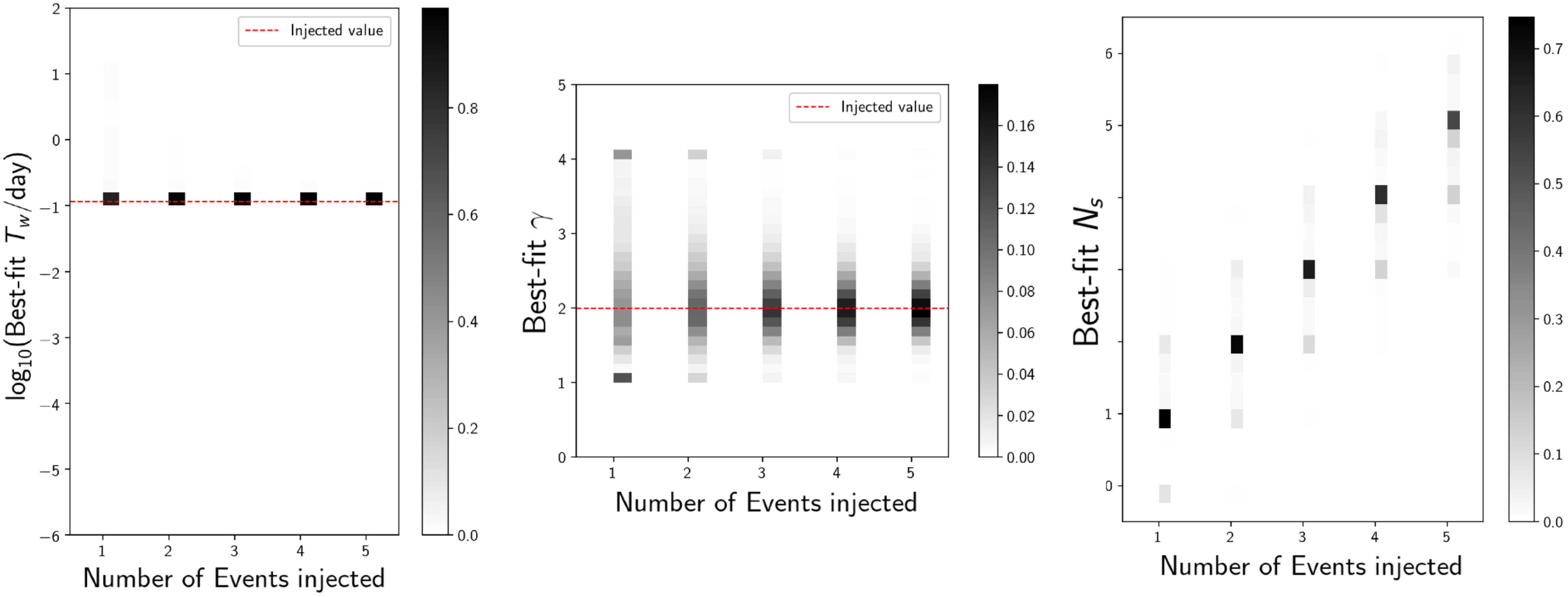
Performance testing

Box injection | **Pulse injection**

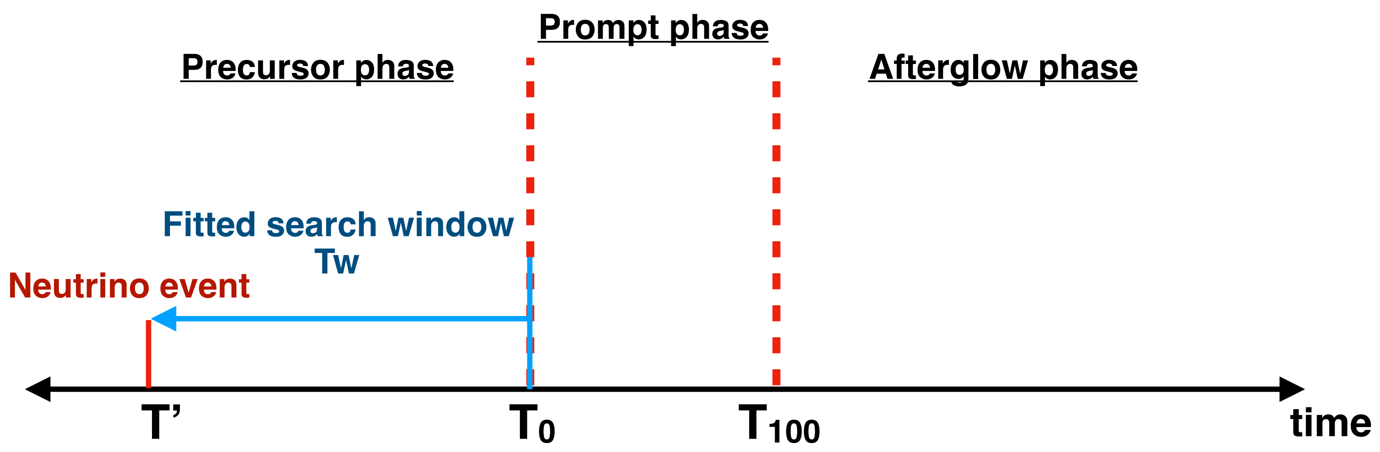
Signa injection / **Search**



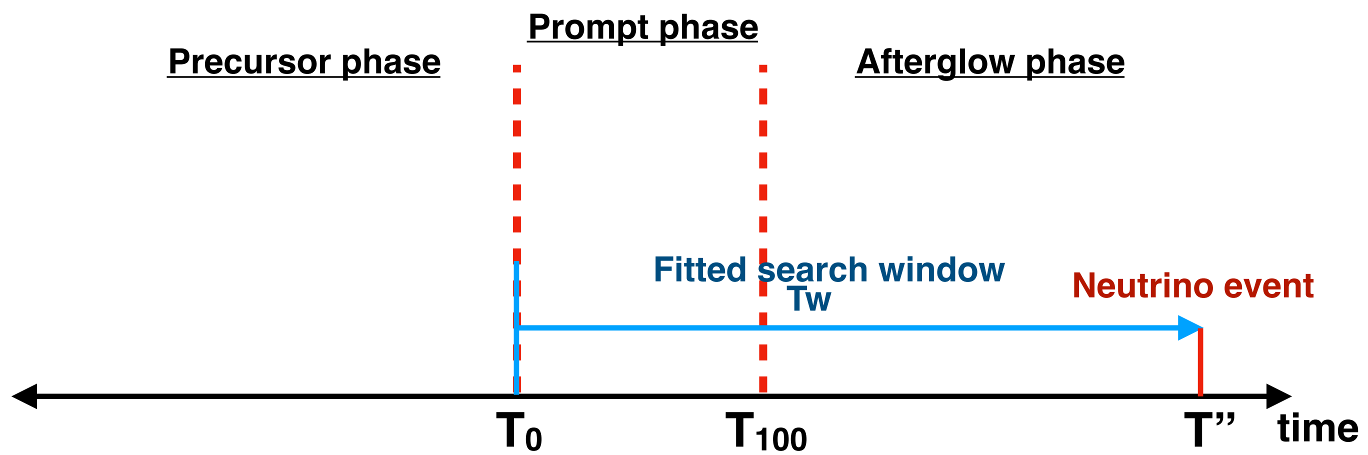
Performance testing: Pulse injection



Summary of analysis

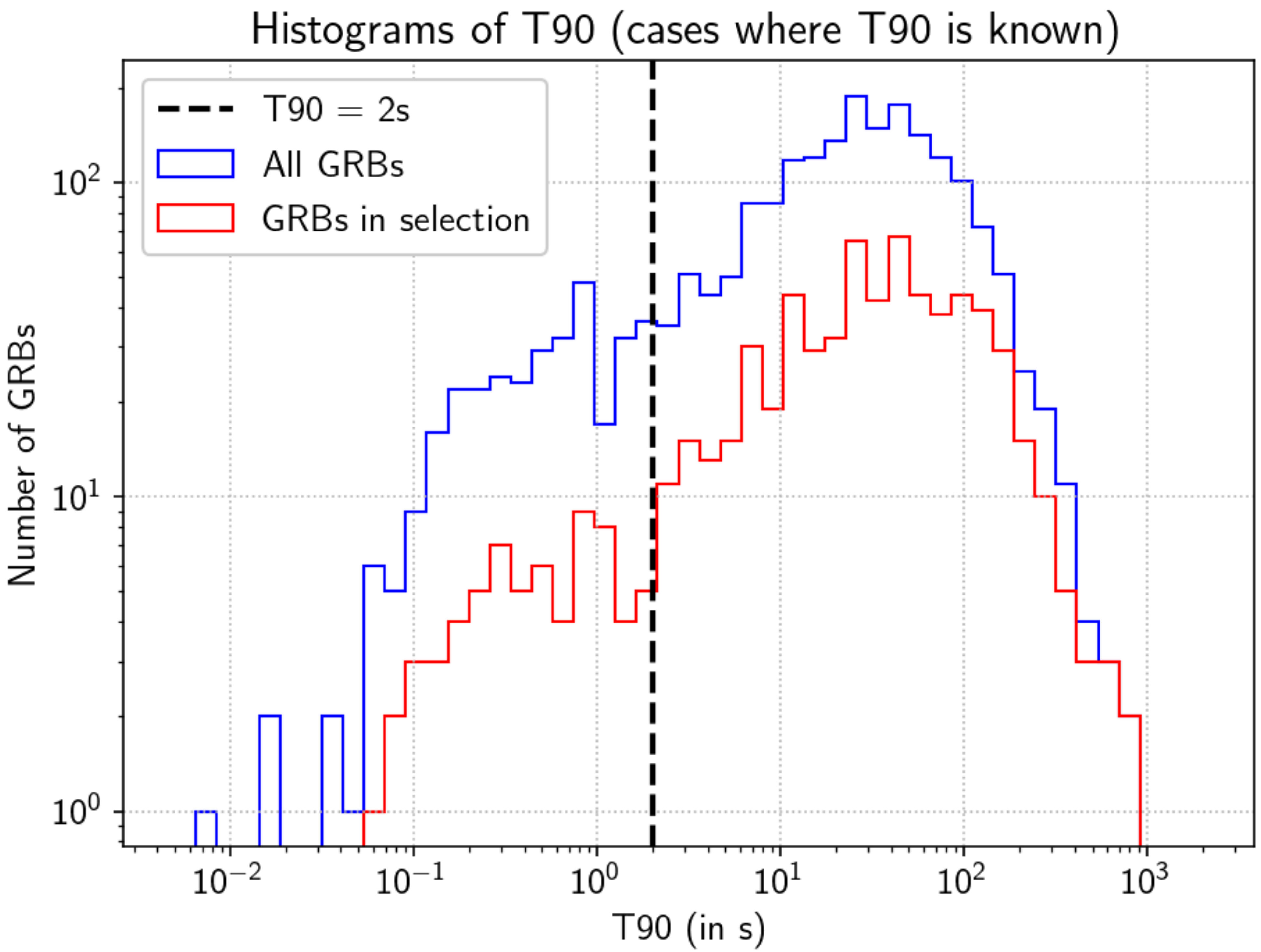


Precursor search



Prompt+afterglow search

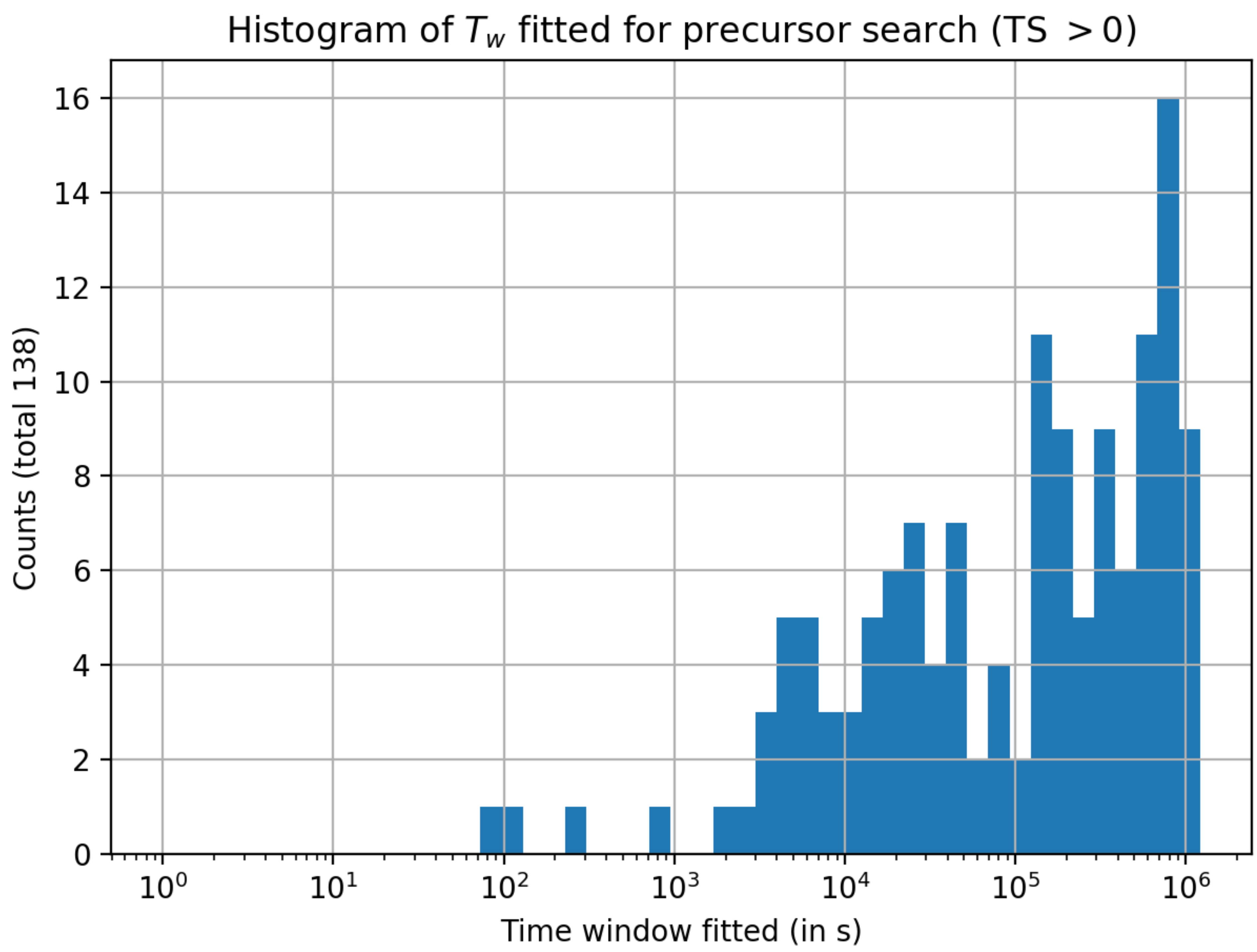
- Search for neutrino emissions from GRBs.
- General point source search using a flat time pdf (Box profile).
- Unbinned maximum likelihood method.
- For a given GRB in the sky, one end of the time window is fixed and other end of the time window 'Tw' is fitted according to the data, together with the parameters n_s and γ (spectral index in range $1< \gamma <4$).


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

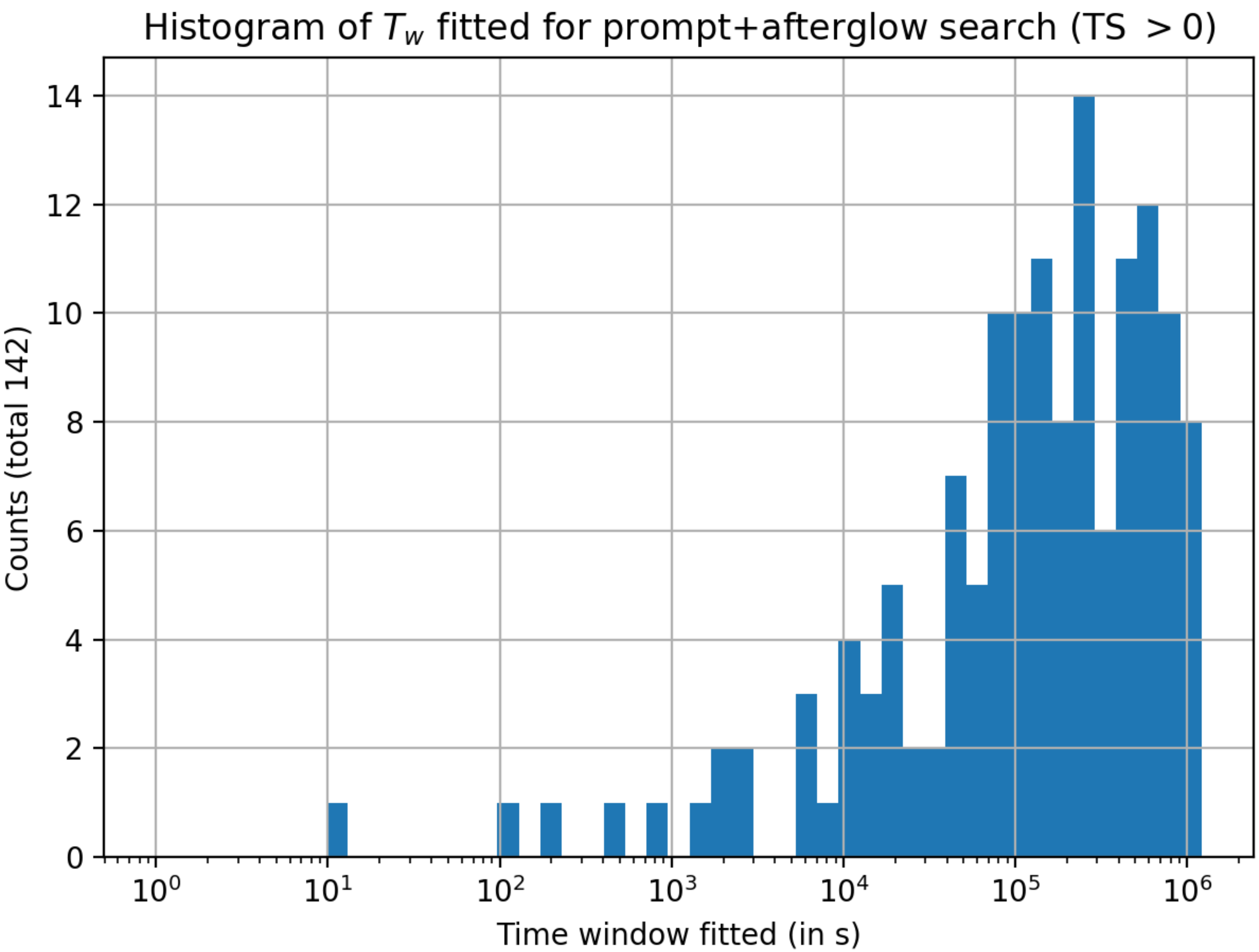
Some details regarding the selected GRBs for the analysis.

Selection	**Number of Objects**
Total observed GRBs in GRBWeb within the GFU data period	2270
GRBs selected for our analysis	733/2270
GRBs in selection with measured redshifts	201/733
GRBs in selection with measured fluence	289/733
GRBs in selection with measured T90,redshifts and fluence	86/733
GRBs in selection with measured T90	680/733
Short GRBs ($T_{90} < 2$s)	66/680
Long GRBs ($T_{90} > 2$s)	614/680

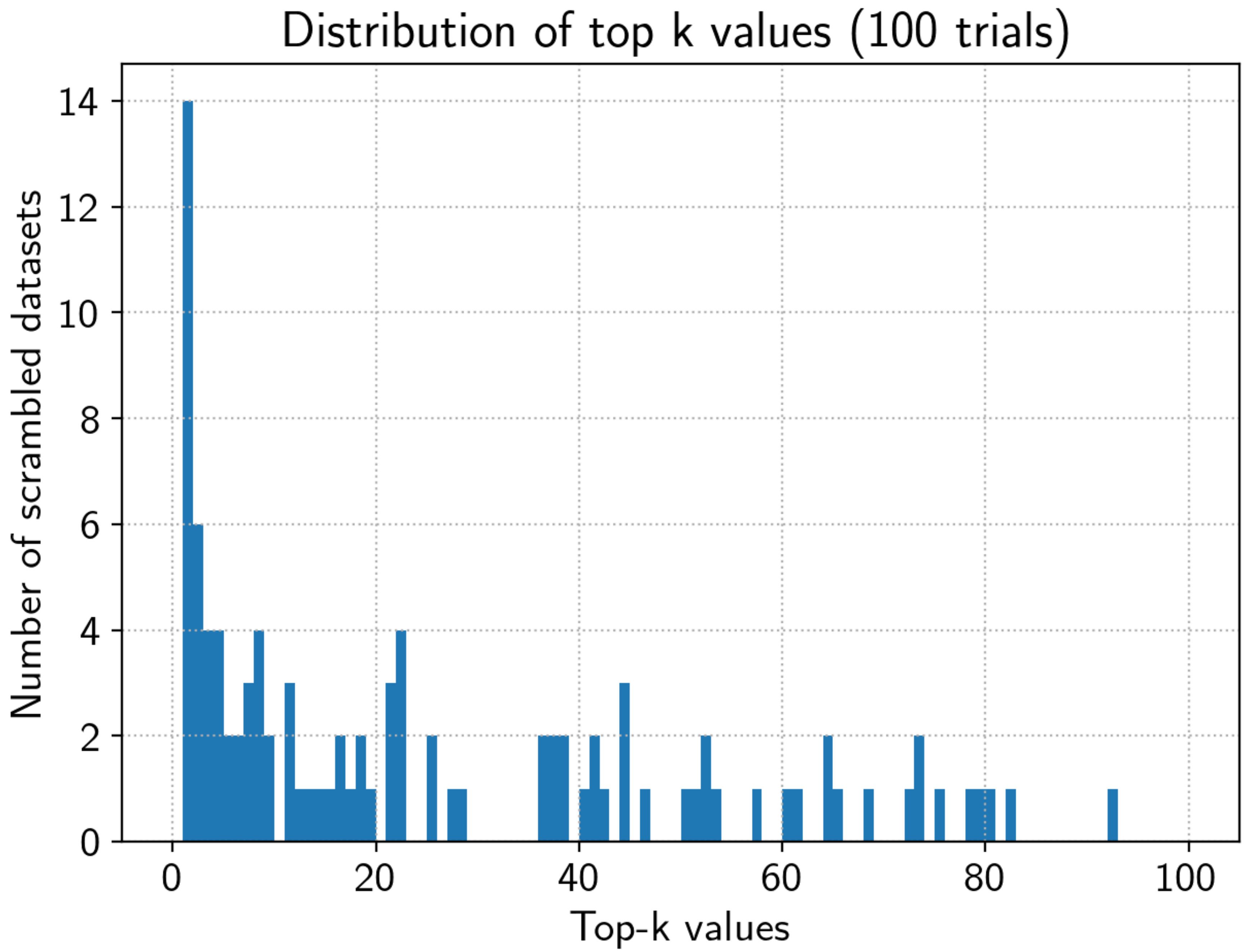
Distribution of Tw fitted for the Precursor result



Distribution of Tw fitted for the Prompt+Afterglow result



Distribution of top k values obtained from 100 scrambled datasets



Result table for prompt+afterglow search (top 20 GRBs)

GRB information							Fit results				
GRB Name	RA[°]	Dec[°]	T_0[MJD]	Fluence[erg/cm^2]	redshift	T_{100}[s]	$\hat{n}_s$	$\hat{\gamma}$	$\hat{T}_w$[s]	TS	p-value
GRB170318A	305.67	28.41	57830.508287	–	–	133.70	2.91	3.52	4.267e+04	16.13	6.11e-04
GRB140607A	86.37	18.90	56815.717720	–	–	109.90	1.00	1.53	2.602e+04	15.02	9.35e-04
GRB141121A	122.67	22.22	56982.160220	–	1.47	549.90	1.17	1.38	1.040e+06	13.28	1.81e-03
GRB140114A	188.52	27.95	56671.498380	–	3.00	139.70	1.00	1.14	8.478e+04	12.20	3.62e-03
GRB120911A	357.98	63.10	56181.297564	2.34e-06	–	22.02	1.00	2.49	1.219e+02	11.77	3.86e-03
GRB140930B	6.35	24.29	56930.820625	–	–	0.84	1.00	4.00	6.691e+03	10.34	8.08e-03
GRB150317A	138.98	55.47	57098.182431	–	–	23.29	2.76	4.00	6.264e+04	9.79	9.12e-03
GRB160827A	179.27	-29.18	57627.657465	–	–	13.30	1.00	4.00	1.426e+05	8.91	9.12e-03
GRB180418A	170.12	24.93	58226.280625	5.90e-07	–	2.78	1.81	1.78	9.165e+04	9.85	9.65e-03
GRB130313A	236.41	-0.37	56364.672350	–	–	0.26	2.81	1.96	4.446e+05	9.51	1.29e-02
GRB131202A	344.05	-21.66	56628.633409	8.17e-07	7.50	32.90	0.99	4.00	1.315e+05	8.01	1.29e-02
GRB170728B	237.98	70.12	57962.960630	4.02e-06	–	48.29	1.90	2.41	1.080e+04	8.63	1.42e-02
GRB170604A	342.66	-15.41	57908.797801	–	1.33	26.70	0.99	4.00	1.103e+05	7.80	1.52e-02
GRB140730A	56.40	-66.55	56868.822118	–	–	41.30	0.99	3.94	2.110e+04	7.68	1.60e-02
GRB160411A	349.36	-40.24	57489.061701	2.25e-07	–	1.26	0.99	2.79	4.832e+04	7.47	1.63e-02
GRB150725A	220.42	-2.42	57228.364056	–	–	–	1.00	4.00	7.339e+02	8.86	1.72e-02
GRB180823A	210.36	14.89	58353.794815	–	–	80.30	1.56	4.00	2.689e+04	8.42	1.94e-02
GRB150912A	248.43	-20.98	57277.442708	3.43e-06	–	34.82	0.99	3.48	1.423e+05	6.65	2.04e-02
GRB160221A	232.08	-28.45	57439.992847	1.75e-06	–	12.95	0.99	1.84	7.981e+04	6.47	2.20e-02
GRB160424A	319.49	-60.41	57502.492429	2.73e-06	–	7.46	1.82	1.95	6.239e+05	6.49	2.35e-02

Results for well-known / interesting GRBs

- GRB180720B: The GRB detected by HESS in July 2018.
- GRB130427A: Exceptionally bright GRB detected in 2013.

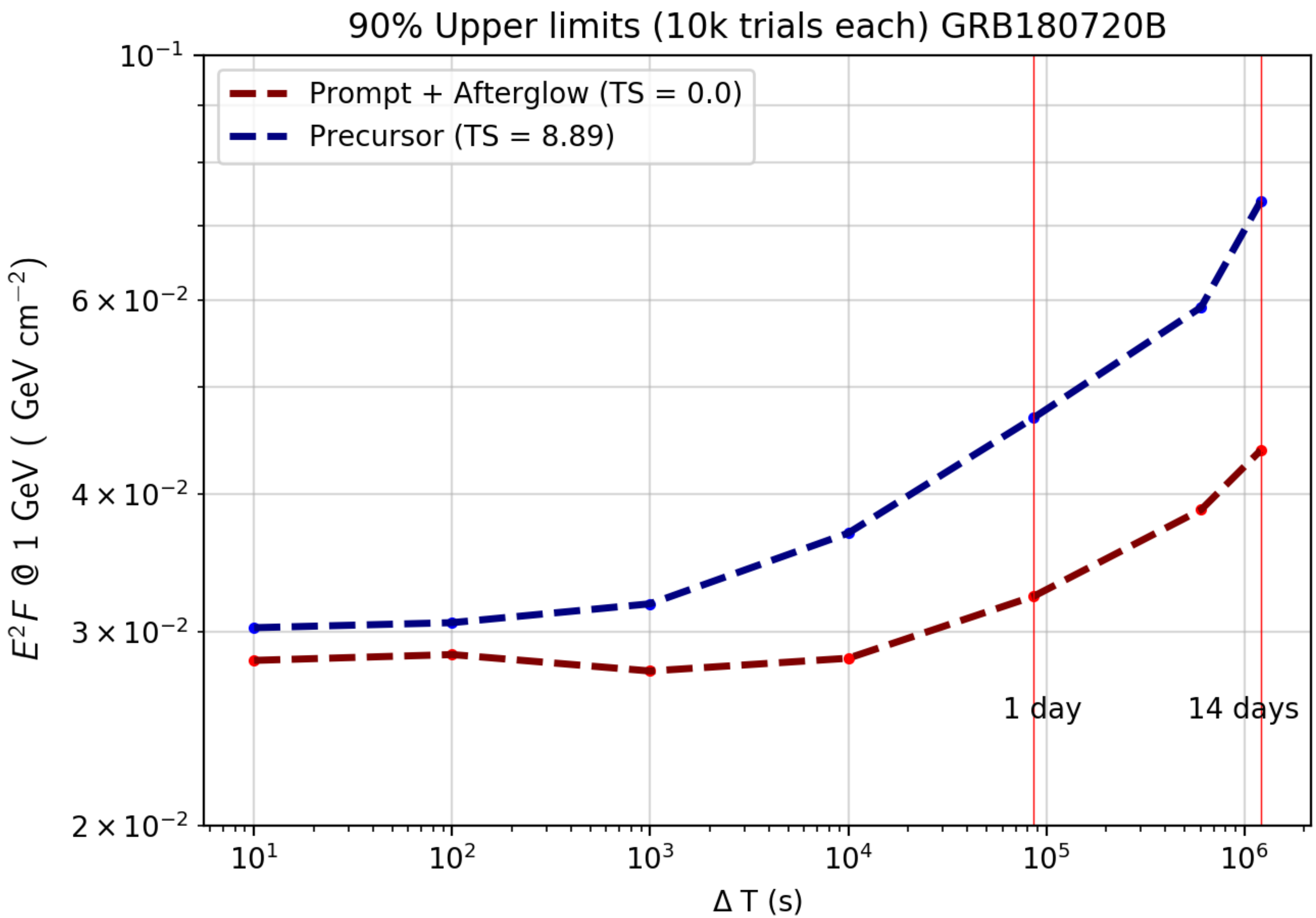
- **Precursor search results:**

GRB information							Fit results				
GRB Name	RA[°]	Dec[°]	T_0[MJD]	Fluence[erg/cm^2]	redshift	T_{100}[s]	$\hat{n_s}$	$\hat{\gamma}$	$\hat{T_w}$[s]	TS	p-value
GRB180720B	0.53	-2.92	58319.598368	2.99e-04	0.65	53.90	3.59	2.32	7.435e+05	8.89	1.50e-02
GRB130427A	173.14	27.70	56409.324375	2.46e-03	0.34	213.83	0.00	–	–	0.00	1.00e+00

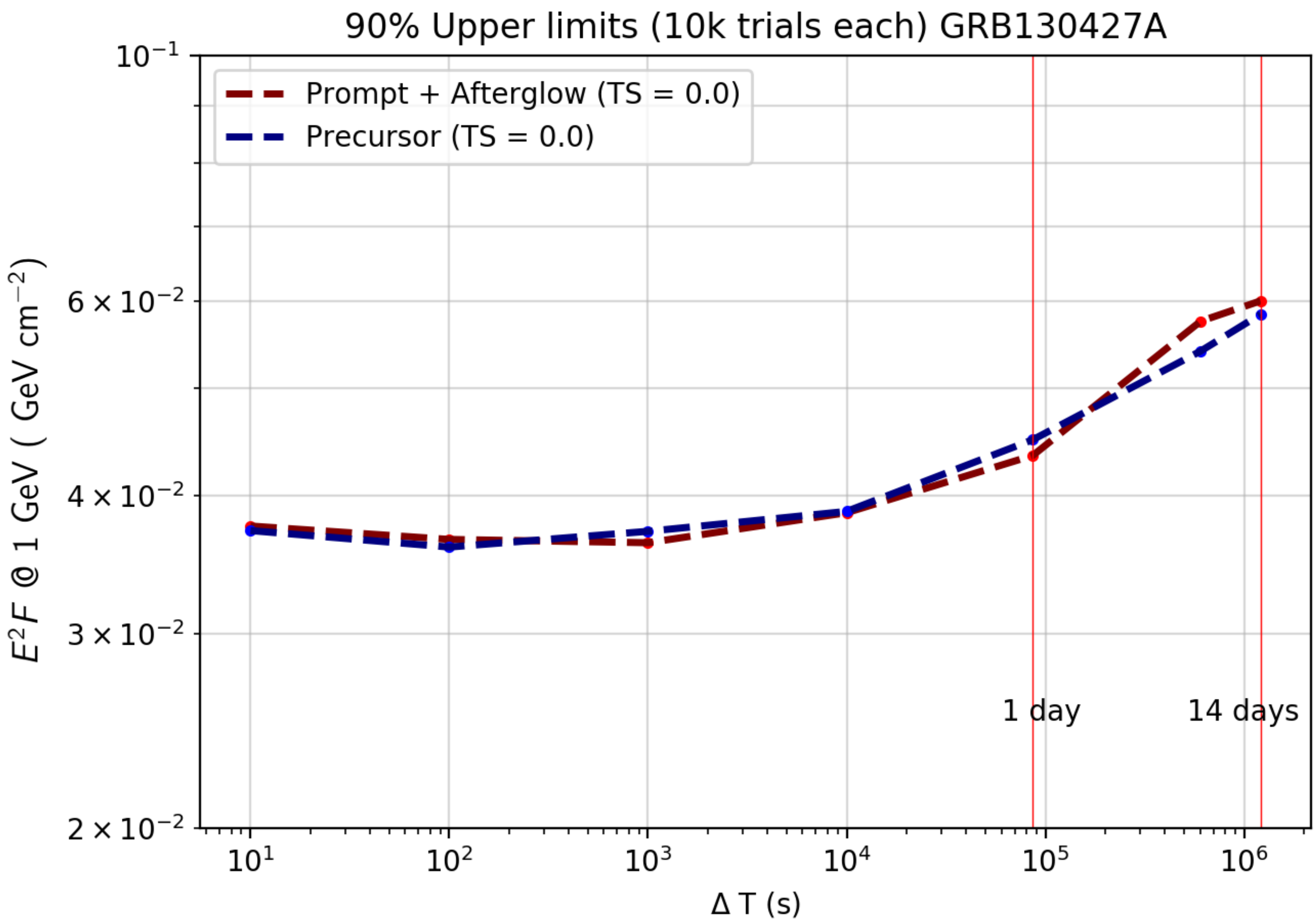
- **Prompt+afterglow search results:**

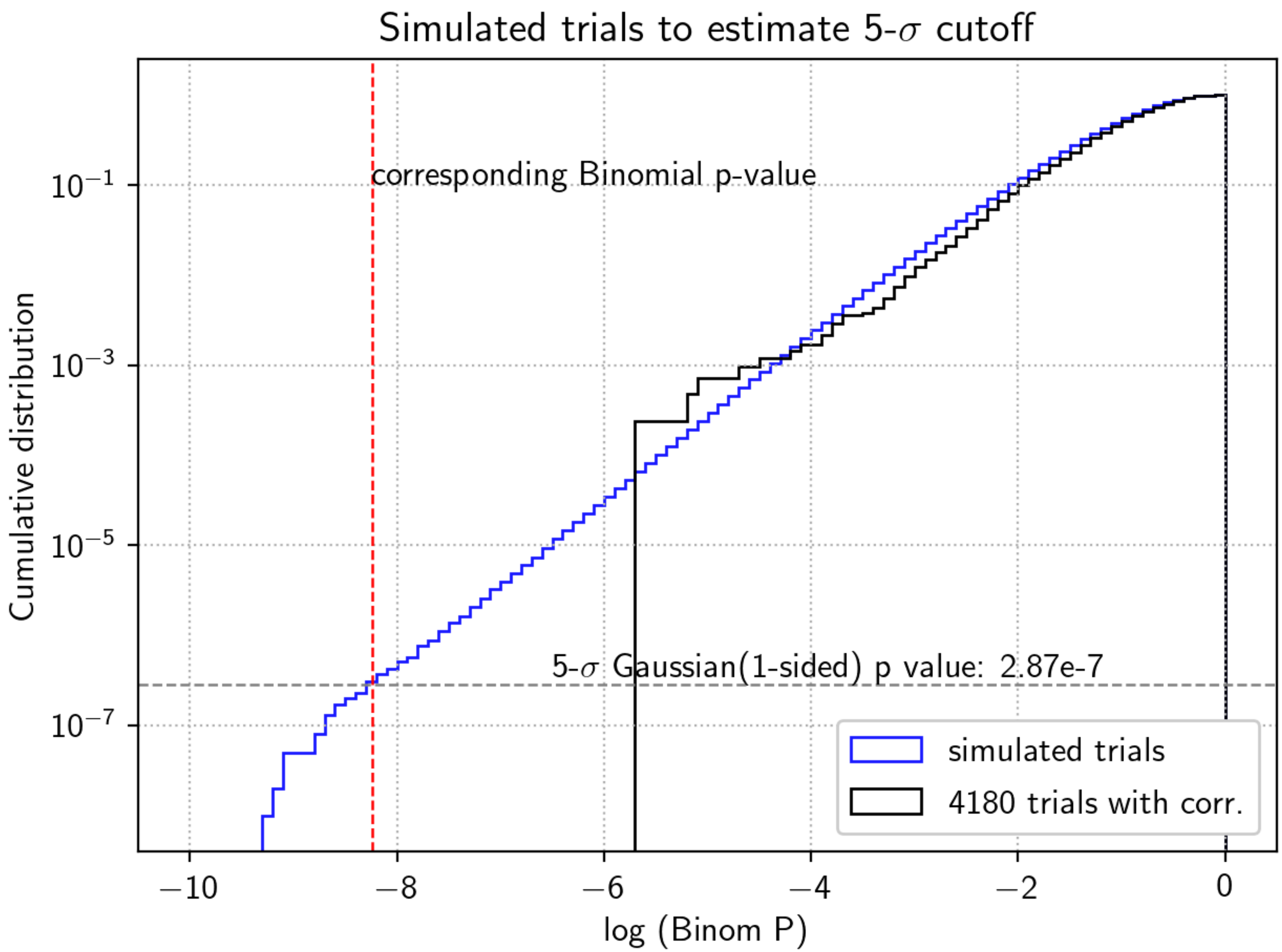
GRB information							Fit results				
GRB Name	RA[°]	Dec[°]	T_0[MJD]	Fluence[erg/cm^2]	redshift	T_{100}[s]	$\hat{n_s}$	$\hat{\gamma}$	$\hat{T_w}$[s]	TS	p-value
GRB180720B	0.53	-2.92	58319.598368	2.99e-04	0.65	53.90	0.00	–	–	0.00	1.00e+00
GRB130427A	173.14	27.70	56409.324375	2.46e-03	0.34	213.83	0.00	–	–	0.00	1.00e+00

Time integrated flux upper limits on interesting GRBs

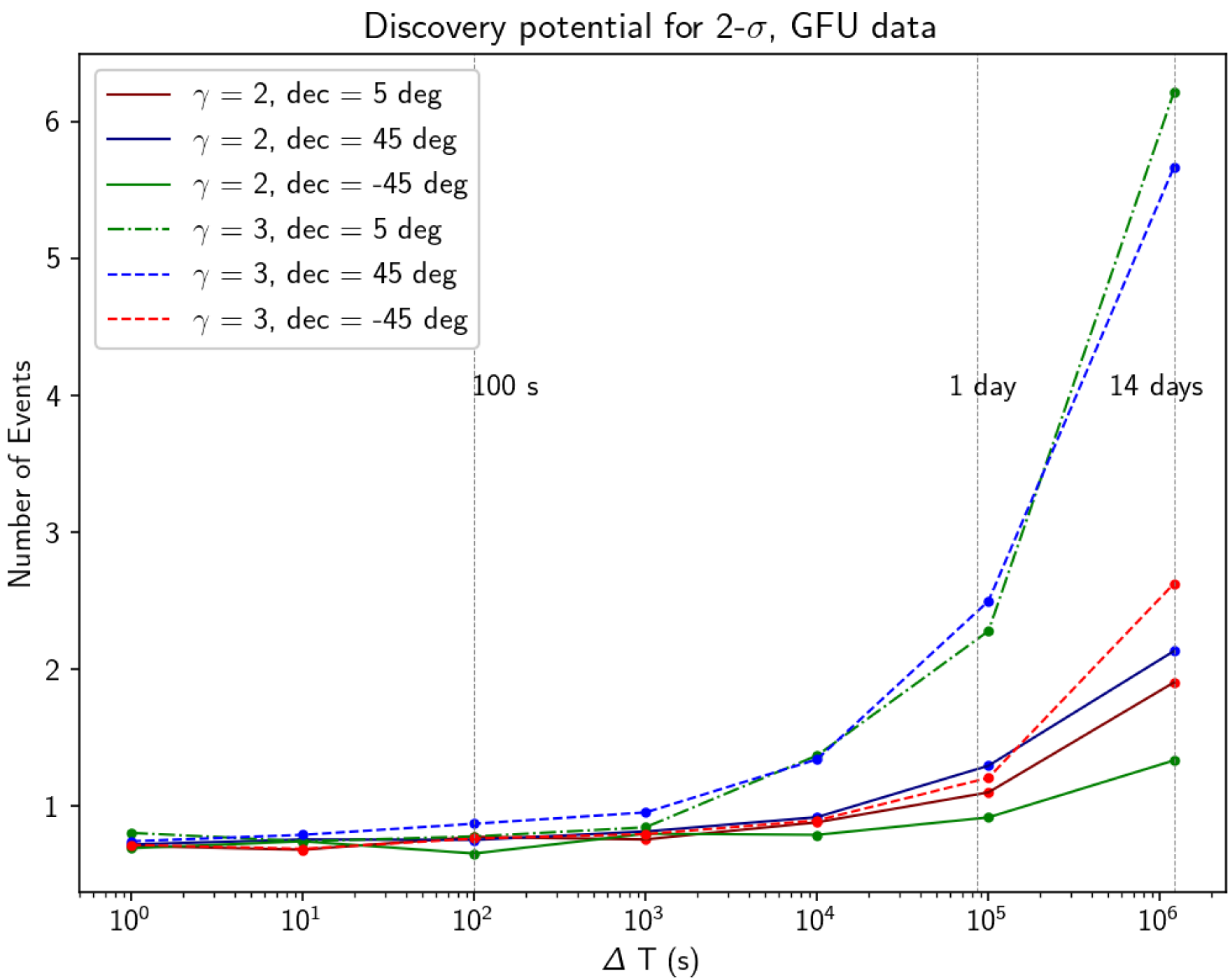


Time integrated flux upper limits on interesting GRBs



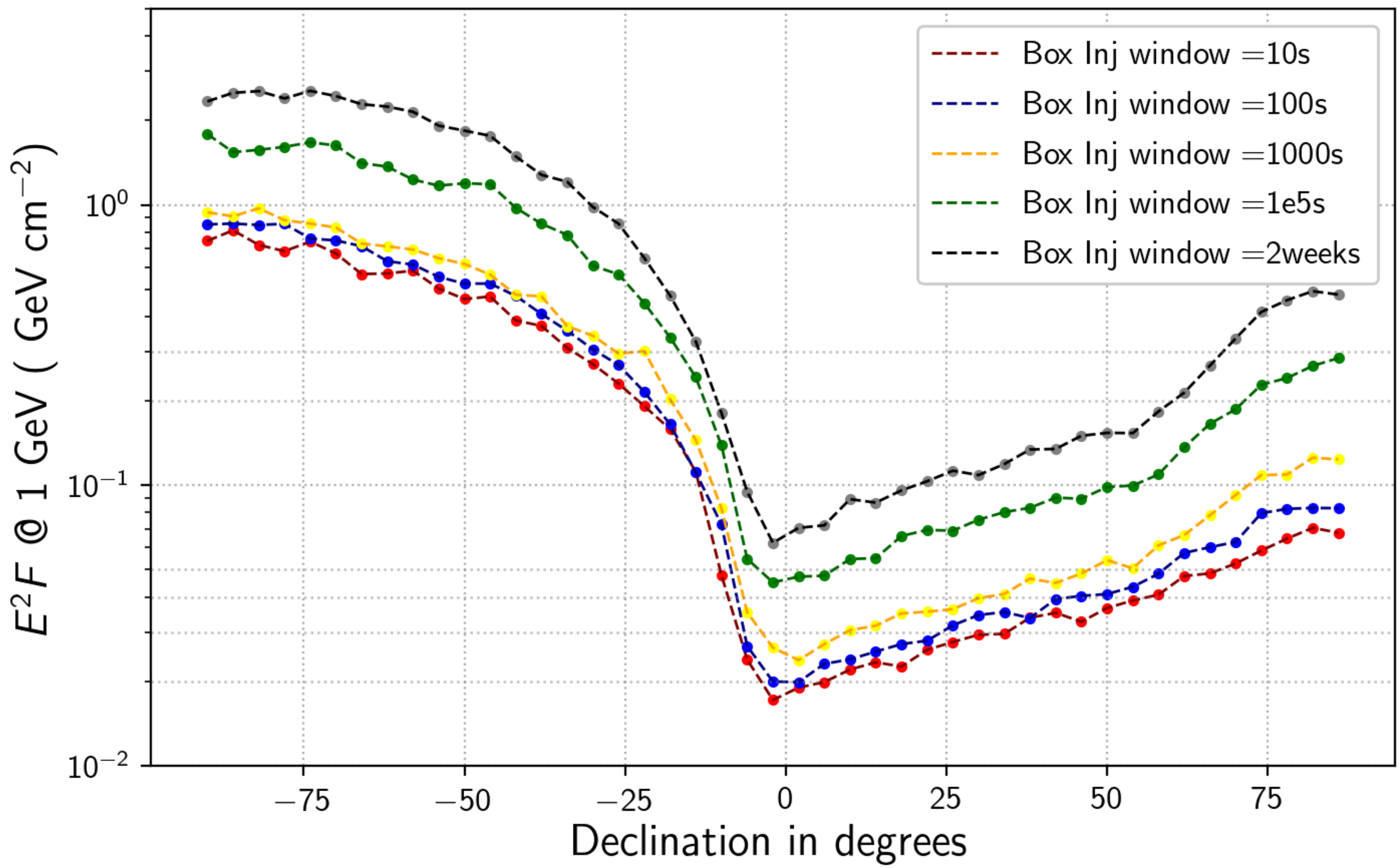


Simulated trials to estimate 5-σ cutoff
Cumulative distribution
10^−1
10^−3
10^−5
10^−7
corresponding Binomial p-value
5-σ Gaussian(1-sided) p value: 2.87e-7
simulated trials
4180 trials with corr.
−10
−8
−6
−4
−2
0
log (Binom P)

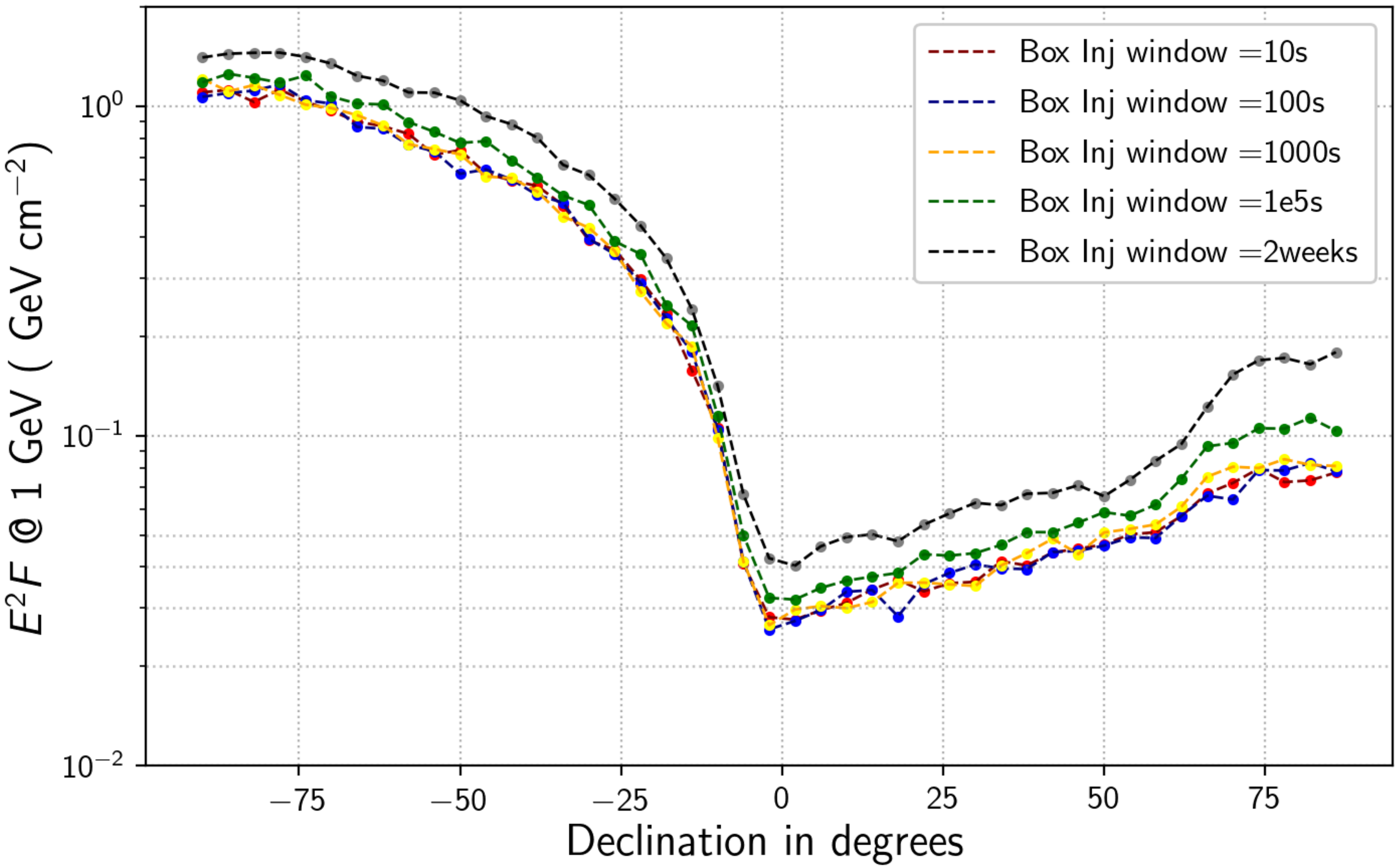


Kunal Deoskar

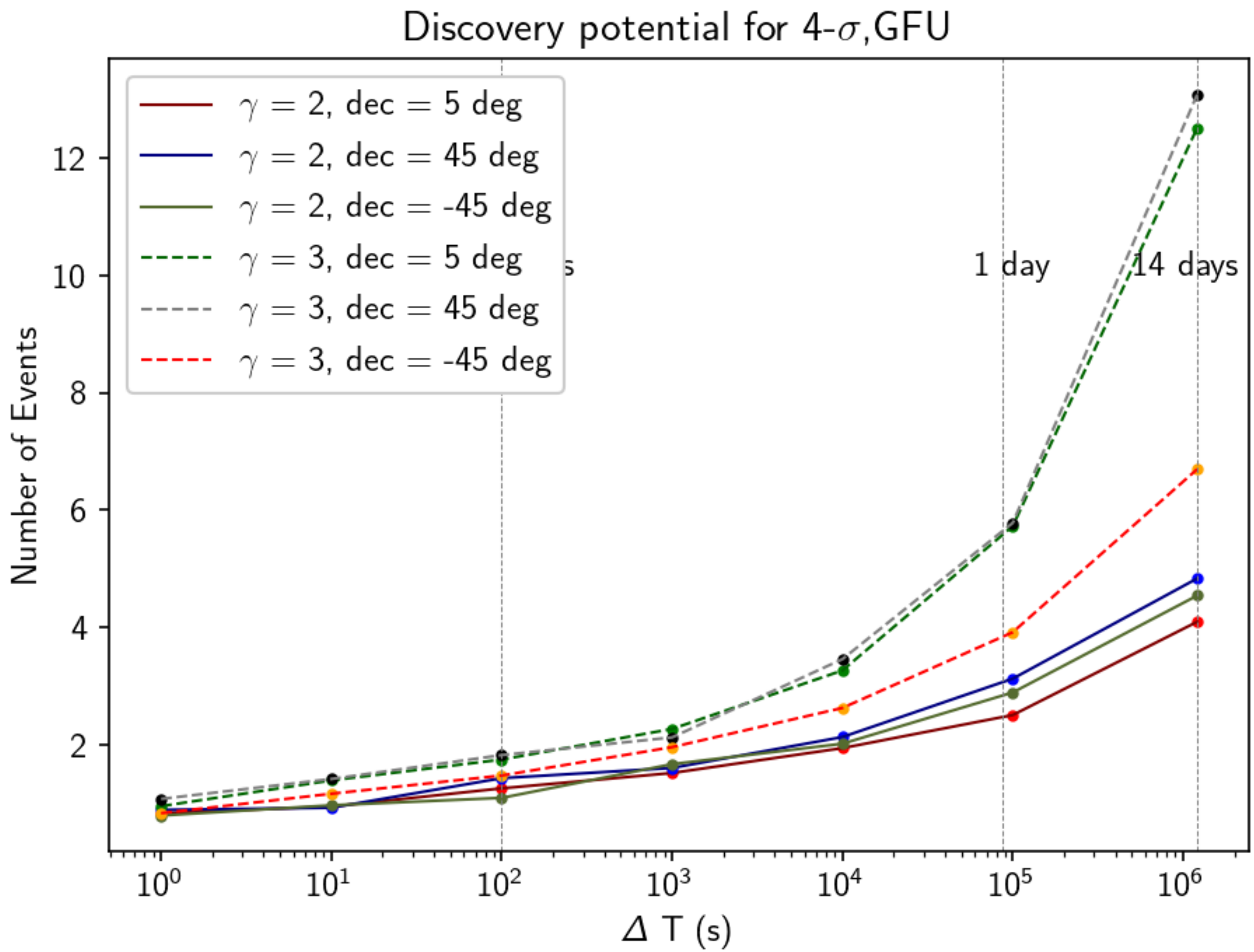
OKC / Stockholm University



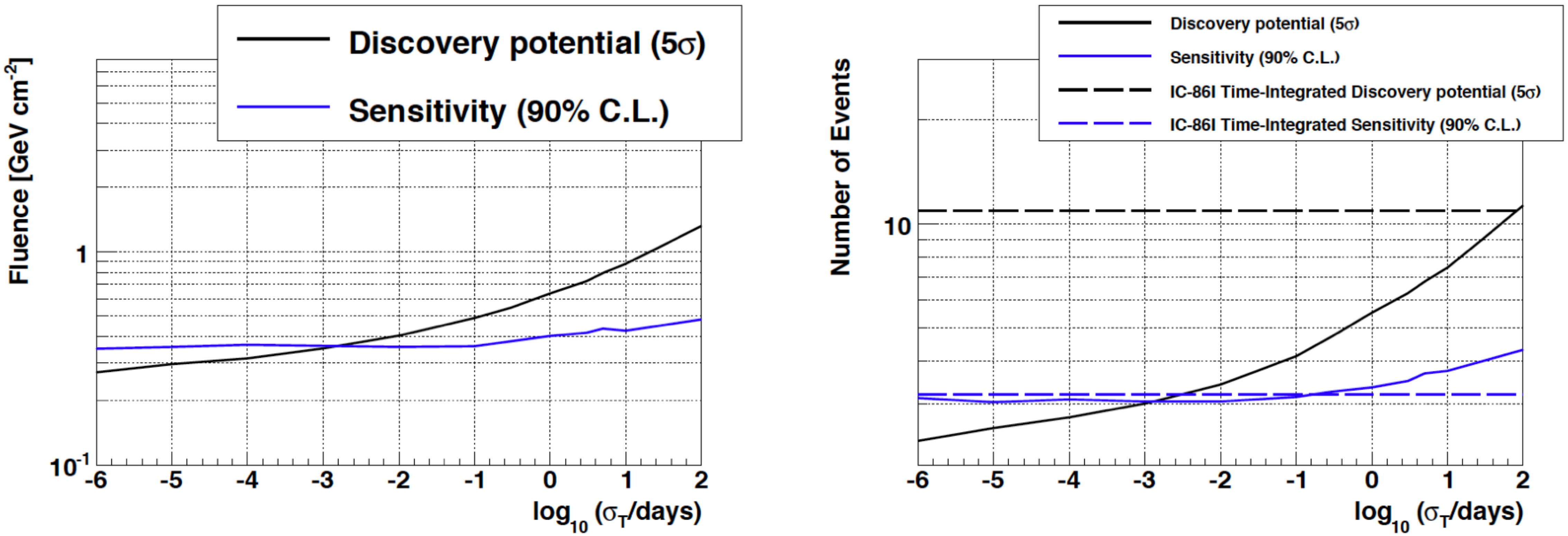
Box Inj window =10s
Box Inj window =100s
Box Inj window =1000s
Box Inj window =1e5s
Box Inj window =2weeks
10^0
10^{-1}
10^{-2}
−75
−50
−25
0
25
50
75
Declination in degrees
E^2F @ 1 GeV (GeV cm^{-2})



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}
E^2F @ 1 GeV (GeV cm^{-2})
−75
−50
−25
0
25
50
75
Declination in degrees



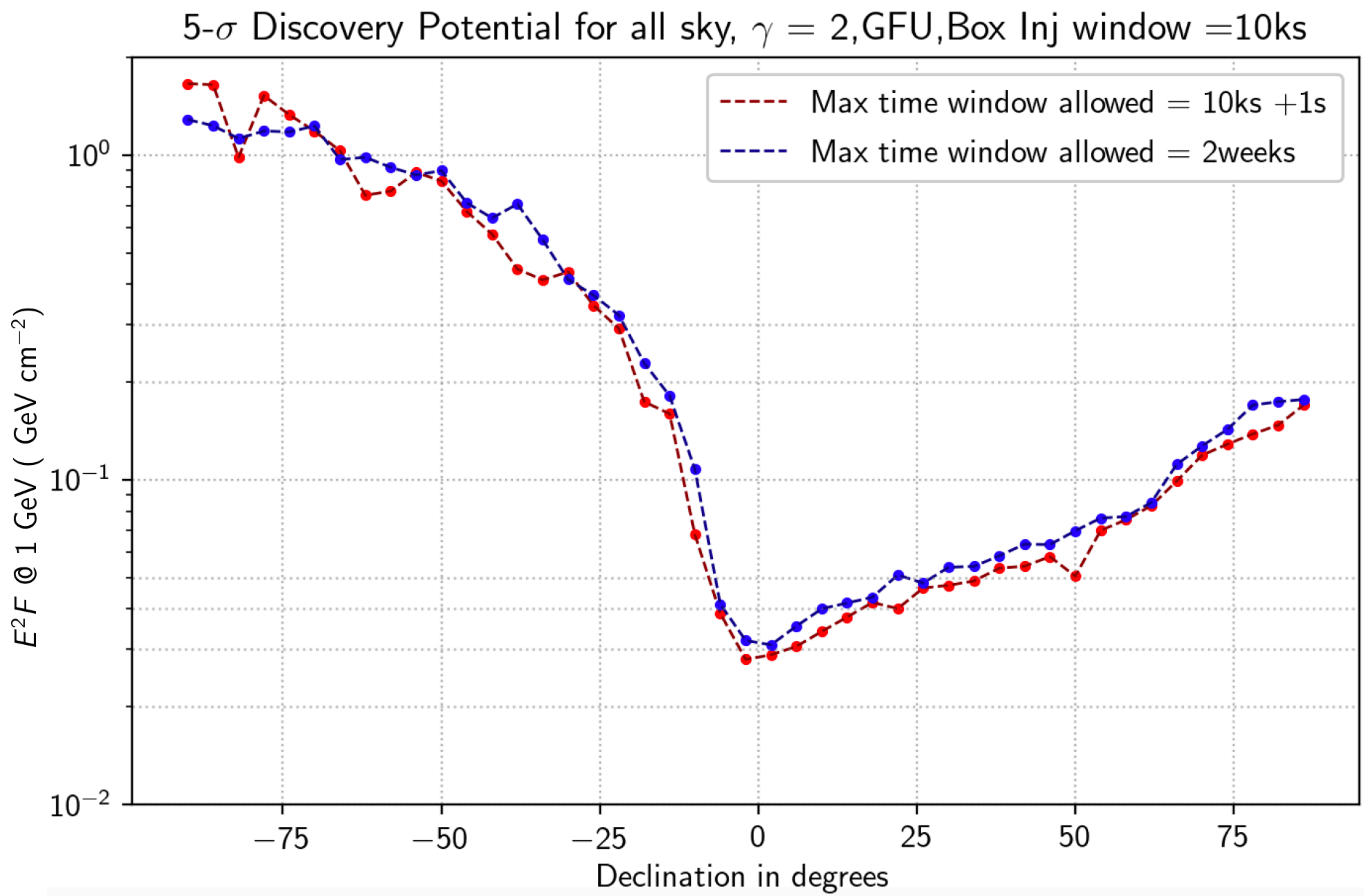
Discovery potential for 4-σ,GFU
γ = 2, dec = 5 deg
γ = 2, dec = 45 deg
γ = 2, dec = -45 deg
γ = 3, dec = 5 deg
γ = 3, dec = 45 deg
γ = 3, dec = -45 deg
1 day
14 days
Number of Events
Δ T (s)



(a) (b)

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, $\gamma = 2$,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