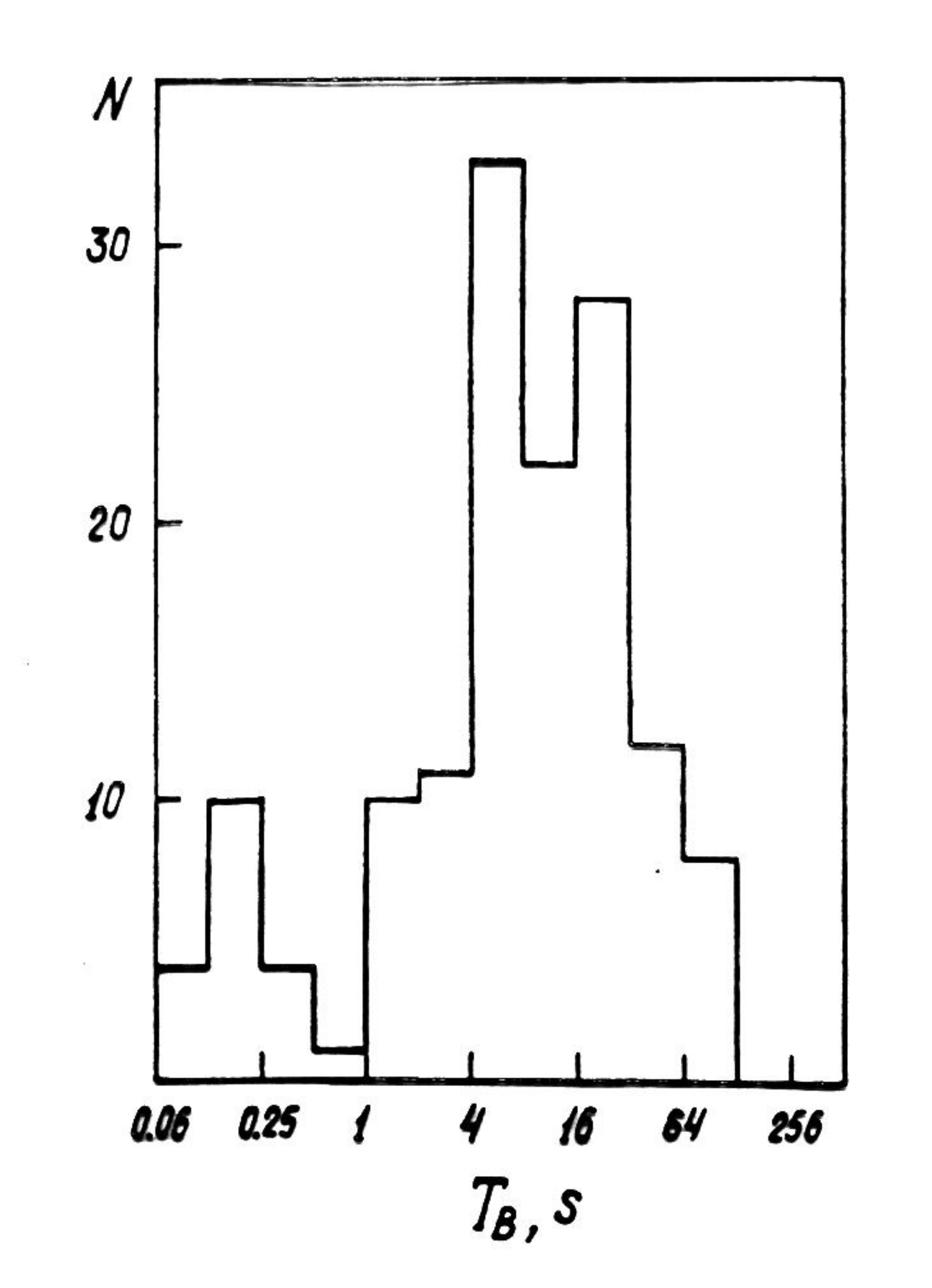
GRB taxonomy: Looking for the third class on the E_p-T_{90} plane in the rest frame

Submitted to A&A

Anastasia Tsvetkova
University of Cagliari

Current classification

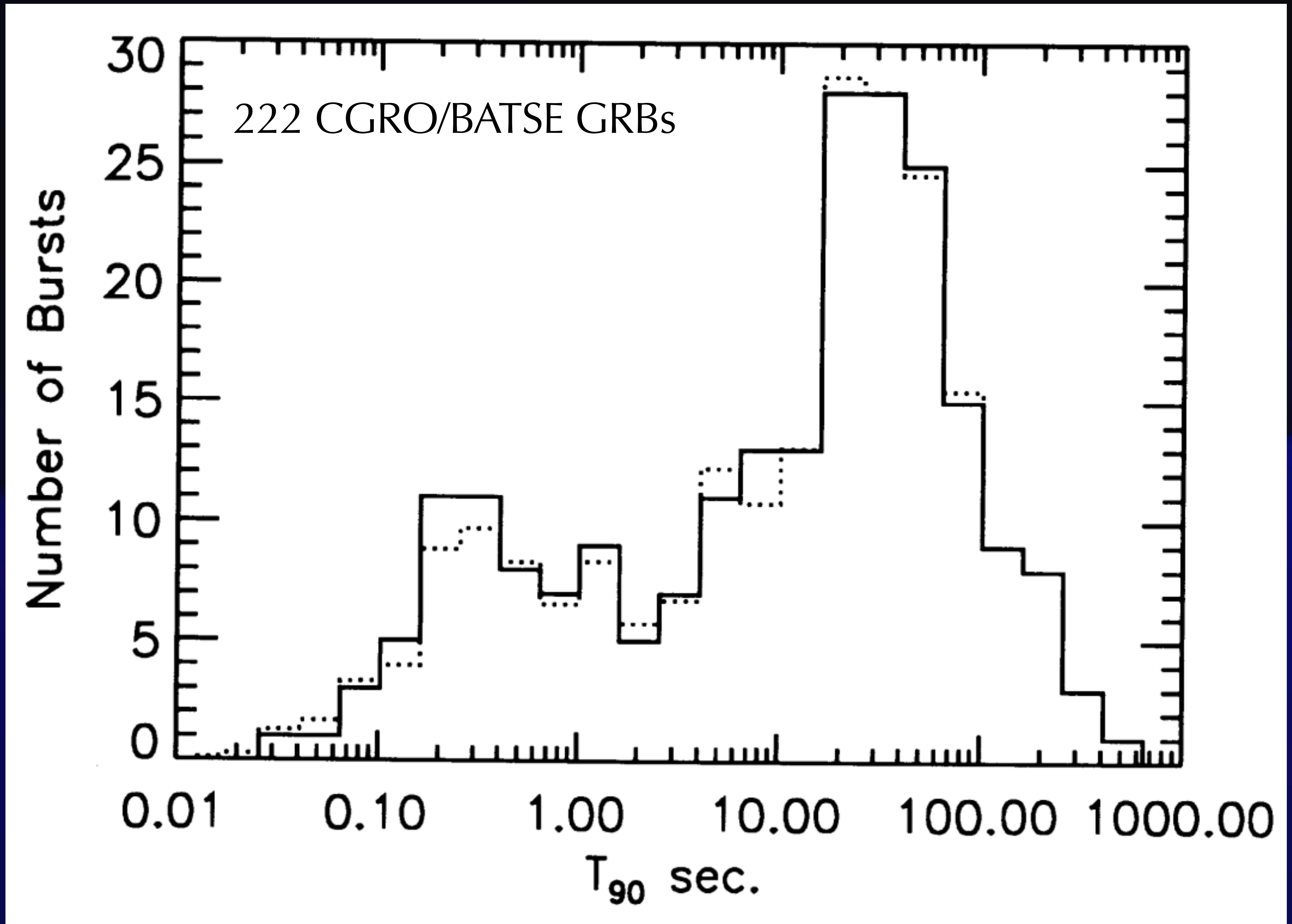


Mazets+ (1981)

~150 GRBs detected in the KONUS experiments on board Venera 11-14 missions in 1979-1983

Norris+ (1984)
Dezalay+ (1991)
Kouveliotou+ (1993)
Zhang+ (2009)

Horváth (1998) : the 3rd class?
Horváth (2002)
Tarnopolski (2015)
Horváth+ (2008, 2010)
Zhang & Choi (2008)
Huja+ (2009)
Zitouni+ (2015)
Zhang+ (2016)
Tarnopolski (2016)
Kulkarni & Desai (2017)
…



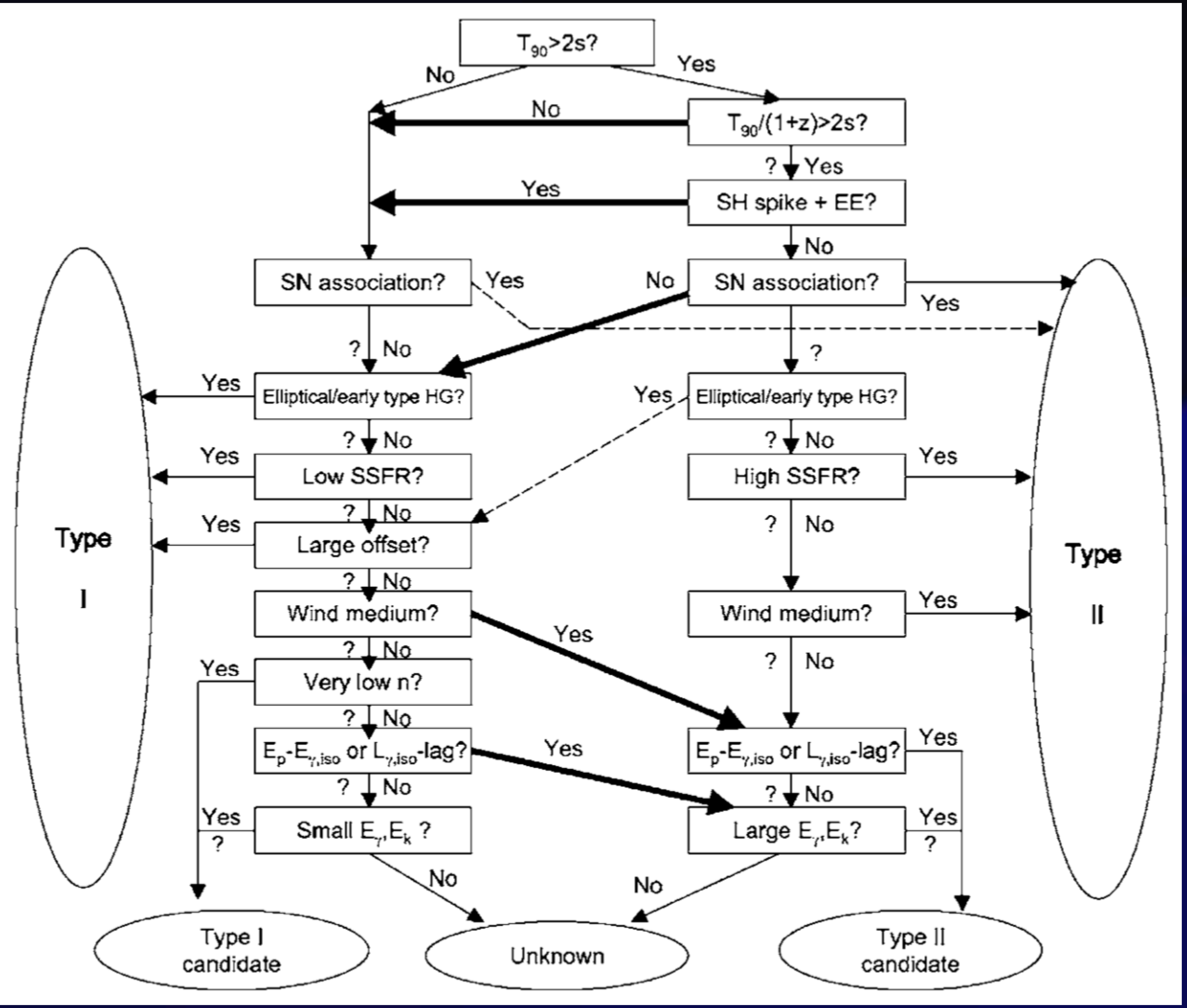
Kouveliotou+ (1993)

Physical GRB classification

The Astrophysical Journal, 703:1696–1724, 2009 October 1 doi:10.1088/0004-637X/703/2/1696

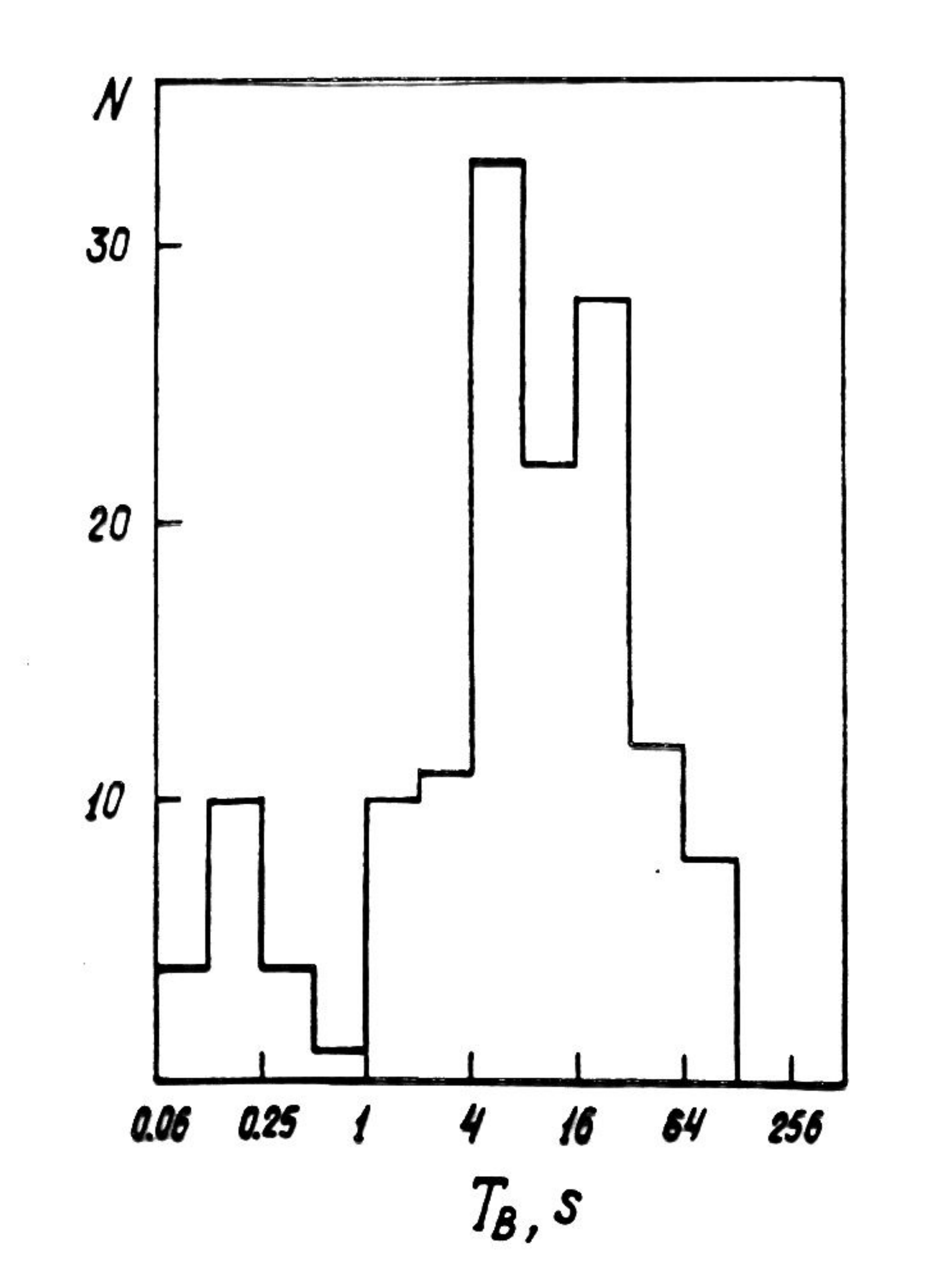
DISCERNING THE PHYSICAL ORIGINS OF COSMOLOGICAL GAMMA-RAY BURSTS BASED ON MULTIPLE OBSERVATIONAL CRITERIA: THE CASES OF $z = 6.7$ GRB 080913, $z = 8.2$ GRB 090423, AND SOME SHORT/HARD GRBs

Bing Zhang[1], Bin-Bin Zhang[1], Francisco J. Virgili[1], En-Wei Liang[2], D. Alexander Kann[3], Xue-Feng Wu[4,5], Daniel Proga[1], Hou-Jun Lv[2], Kenji Toma[4], Peter Mészáros[4,6], David N. Burrows[4], Peter W. A. Roming[4], and Neil Gehrels[7]



Zhang+ (2009)

Current classification



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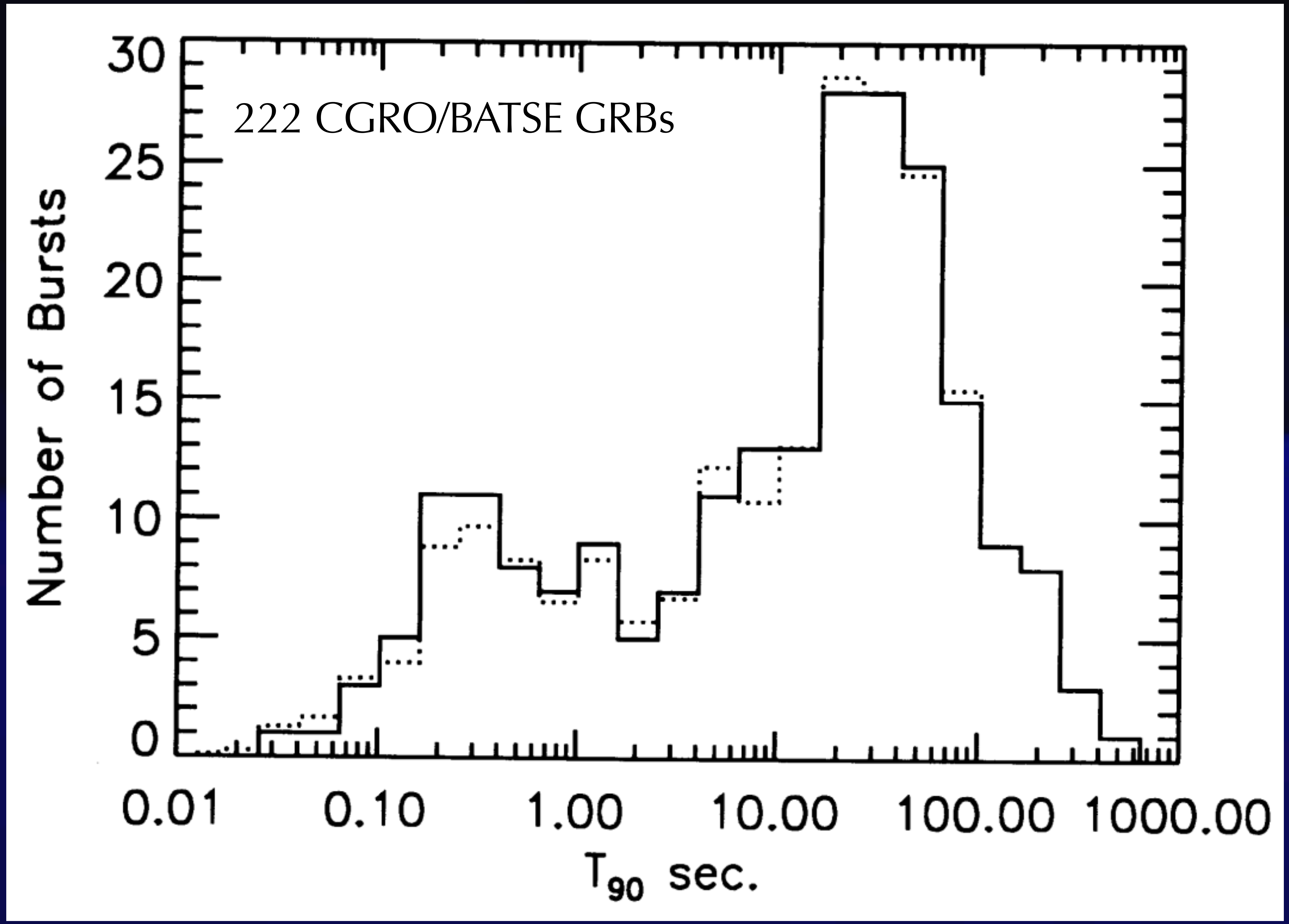
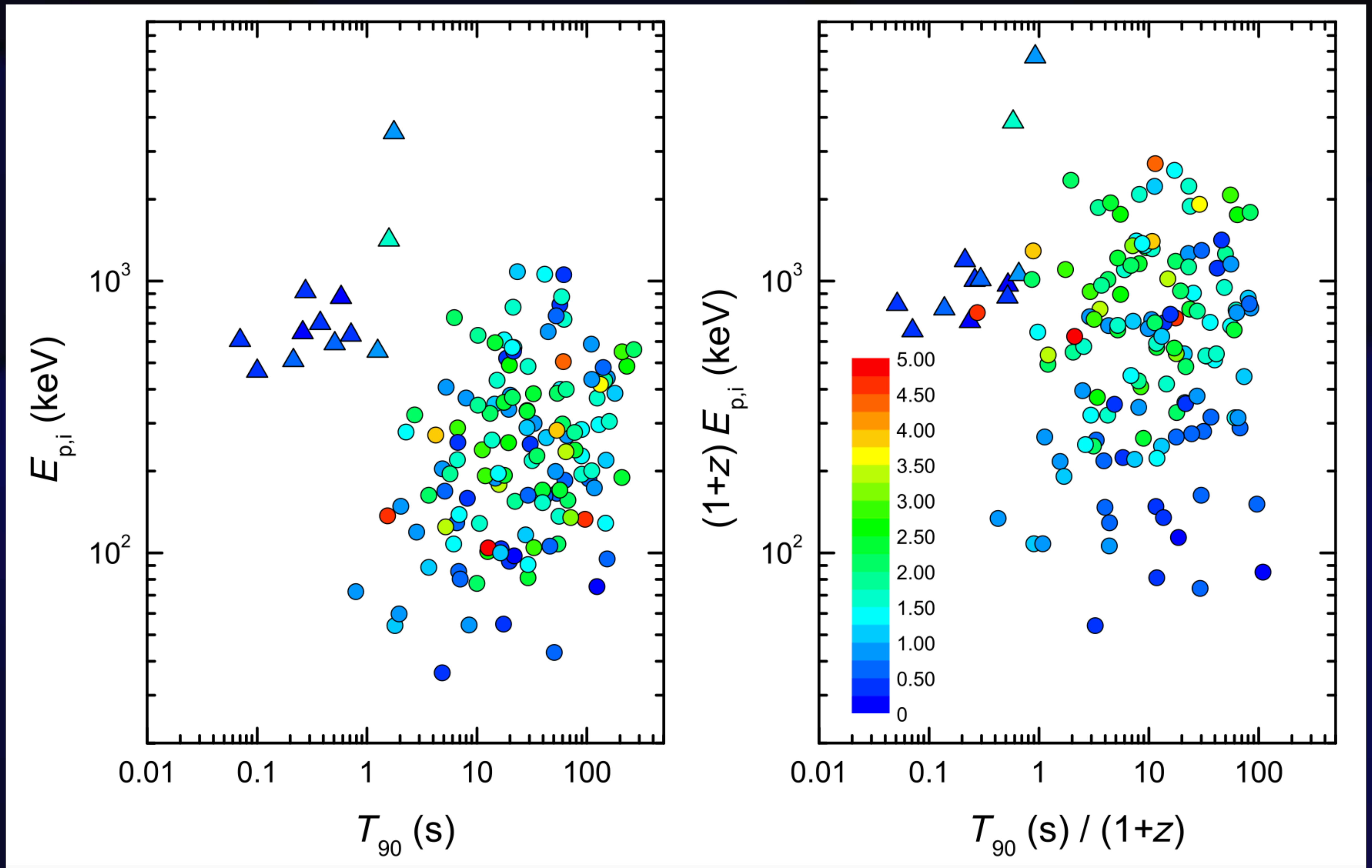


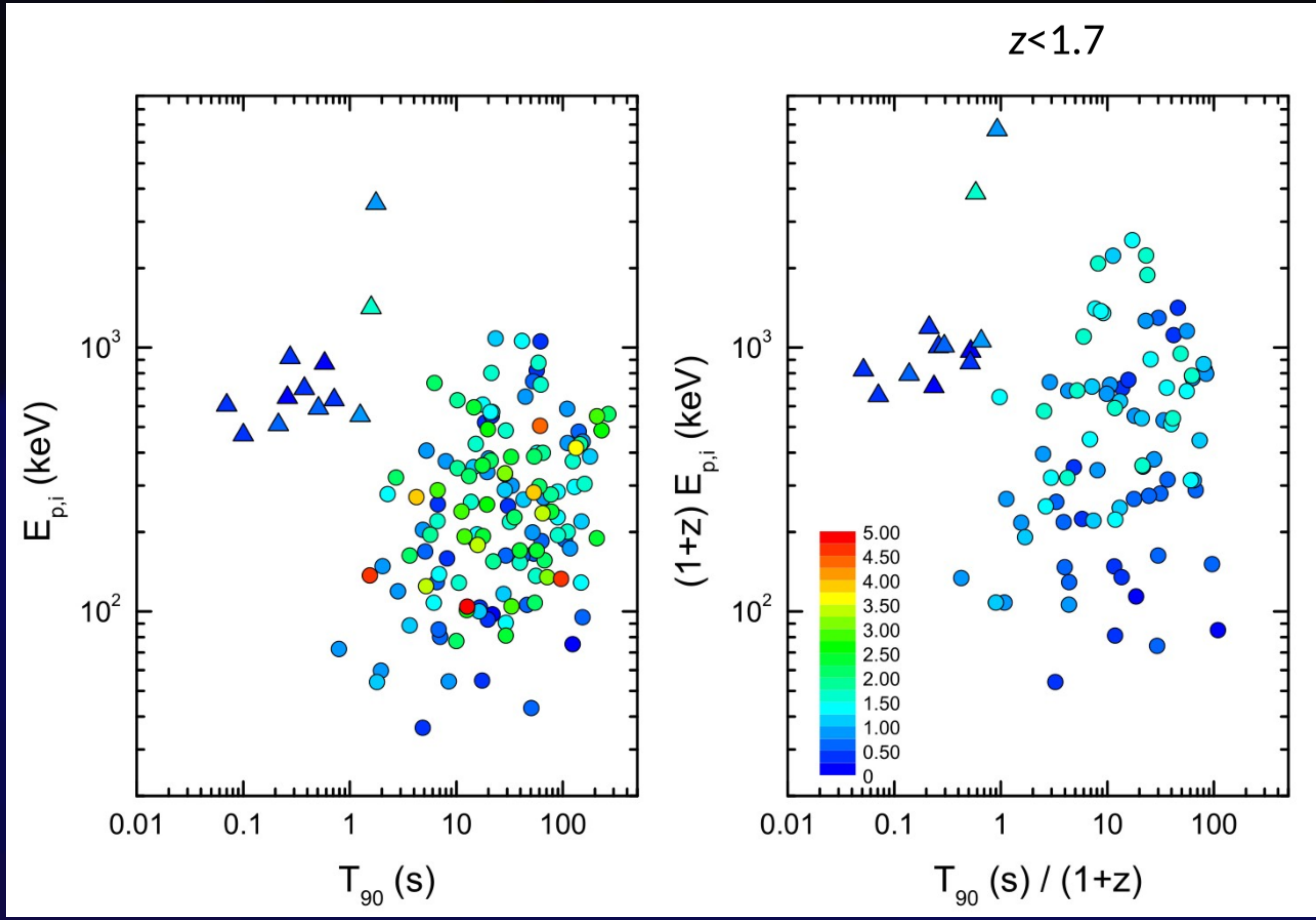
Kouveliotou+ (1993)

Intermediate-duration GRBs?

GRBs with z

Color mapping: z

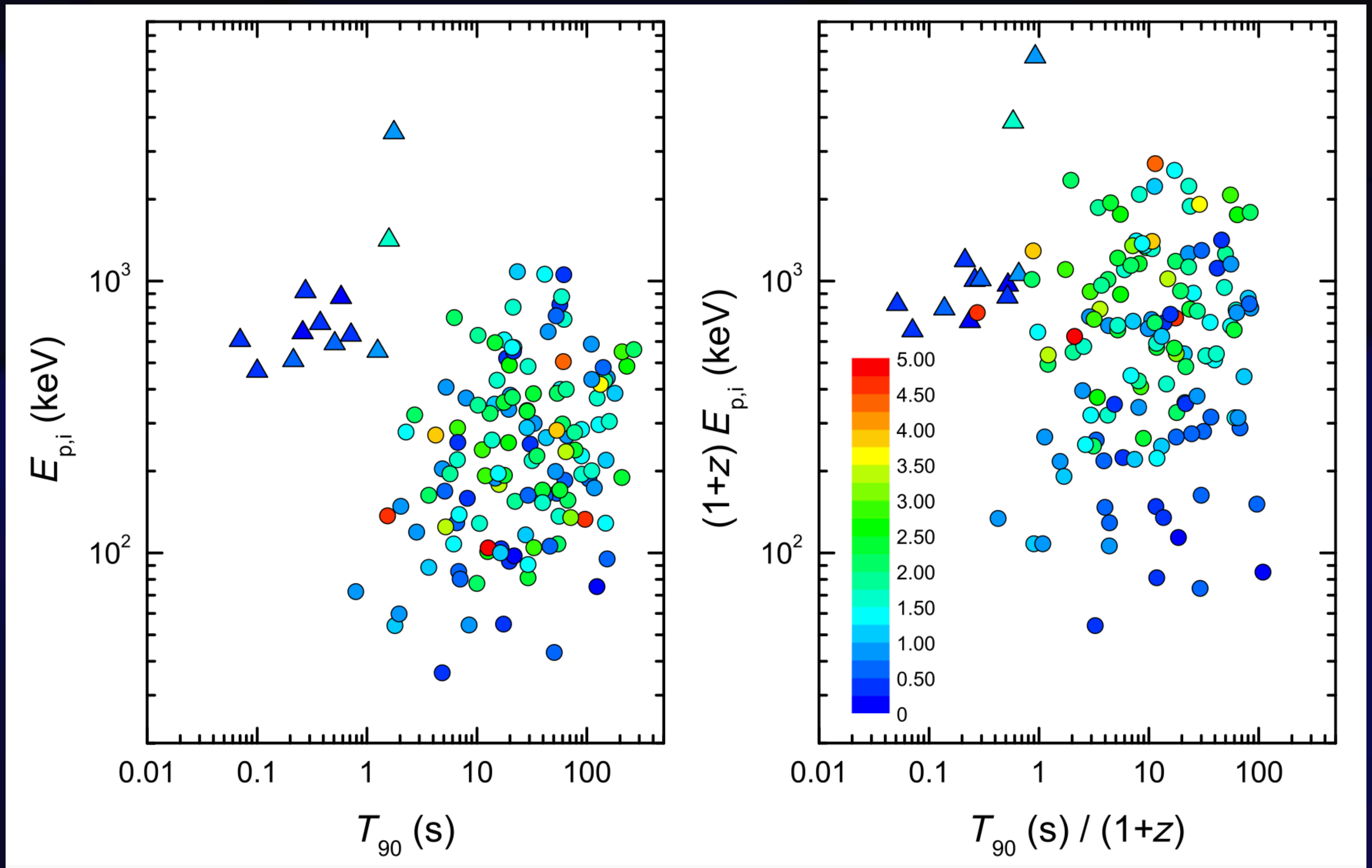


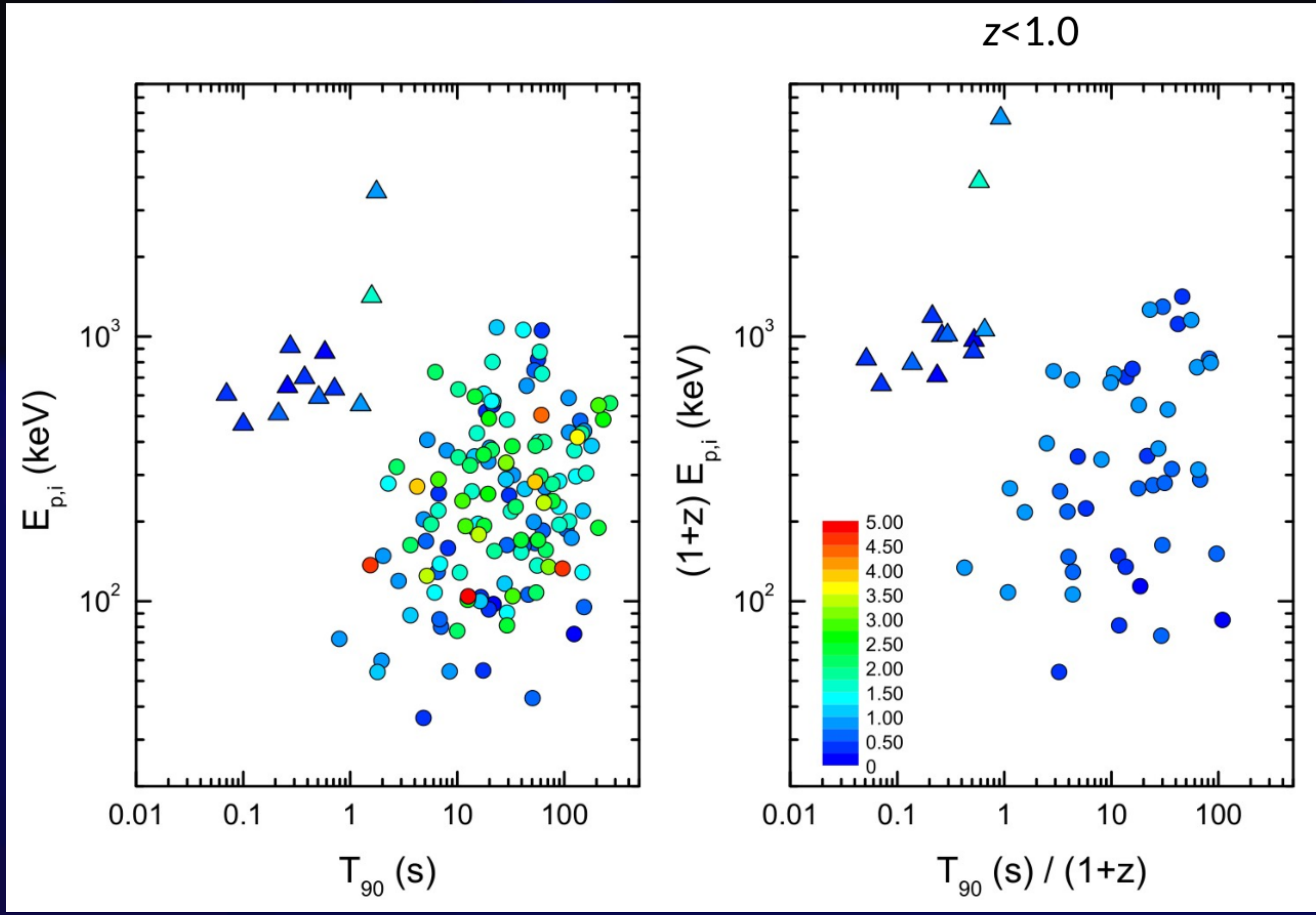


Tsvetkova+ (2017)

GRBs with z

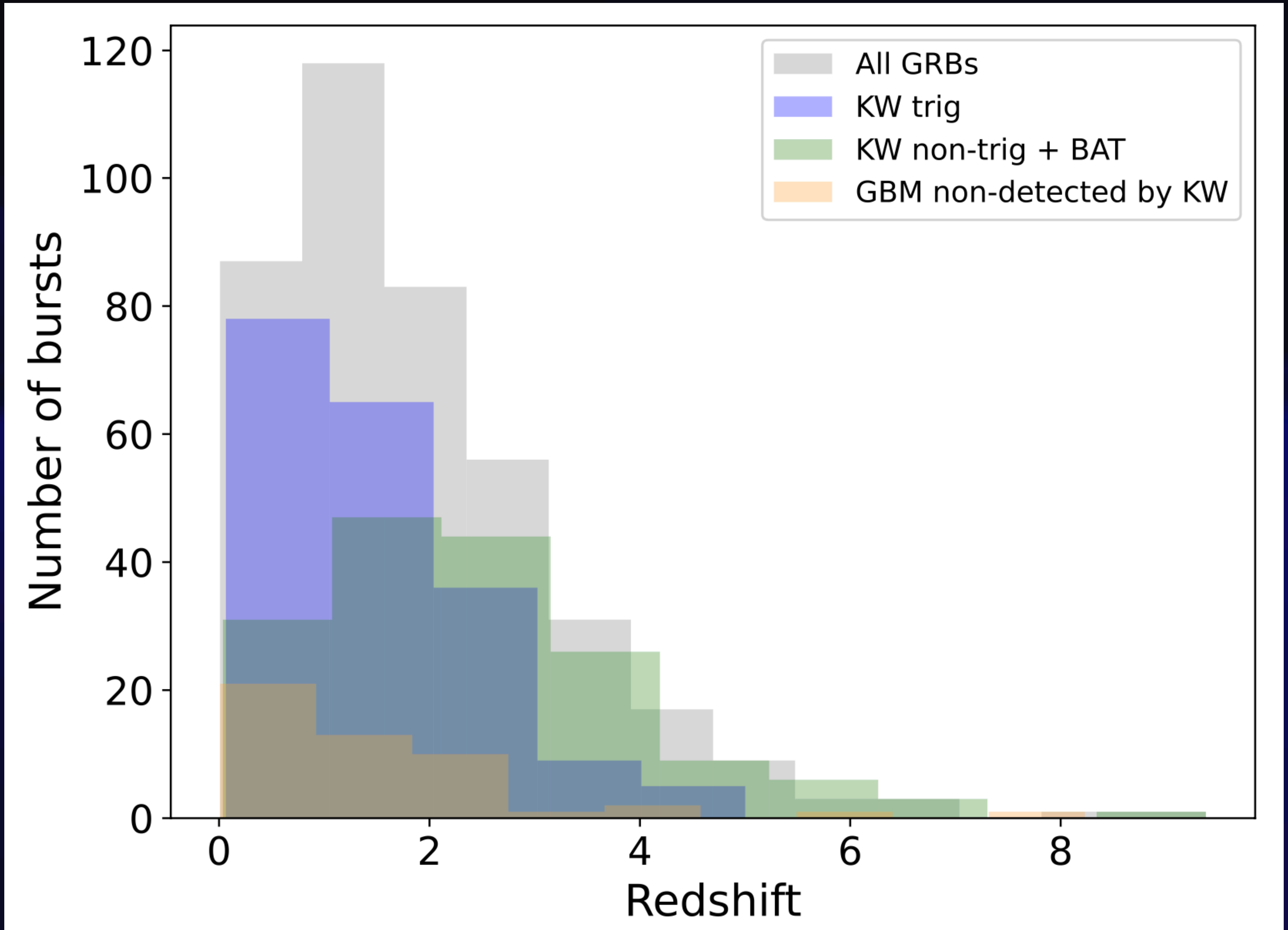
Color mapping: z





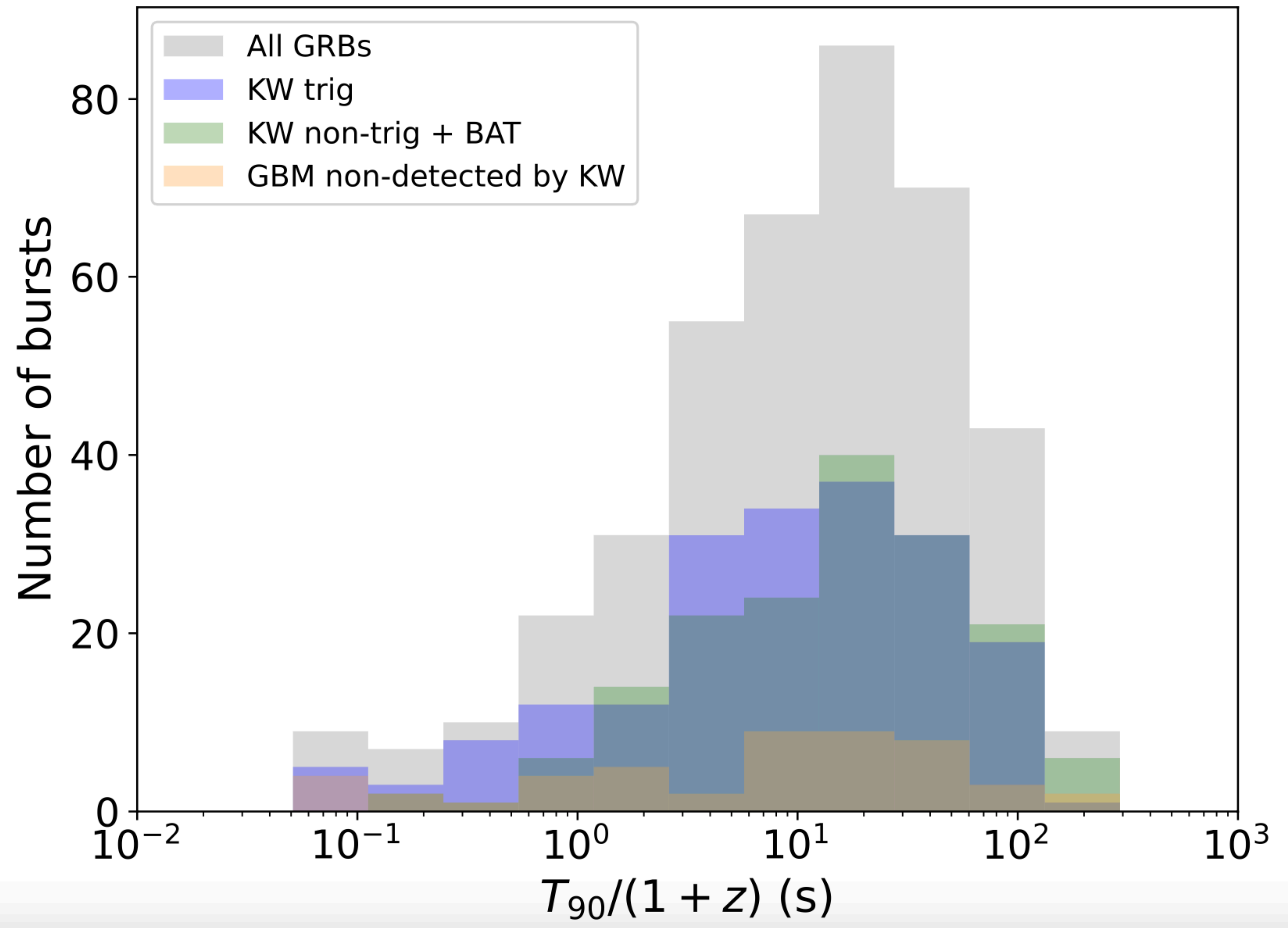
Tsvetkova+ (2017)

GRB sample

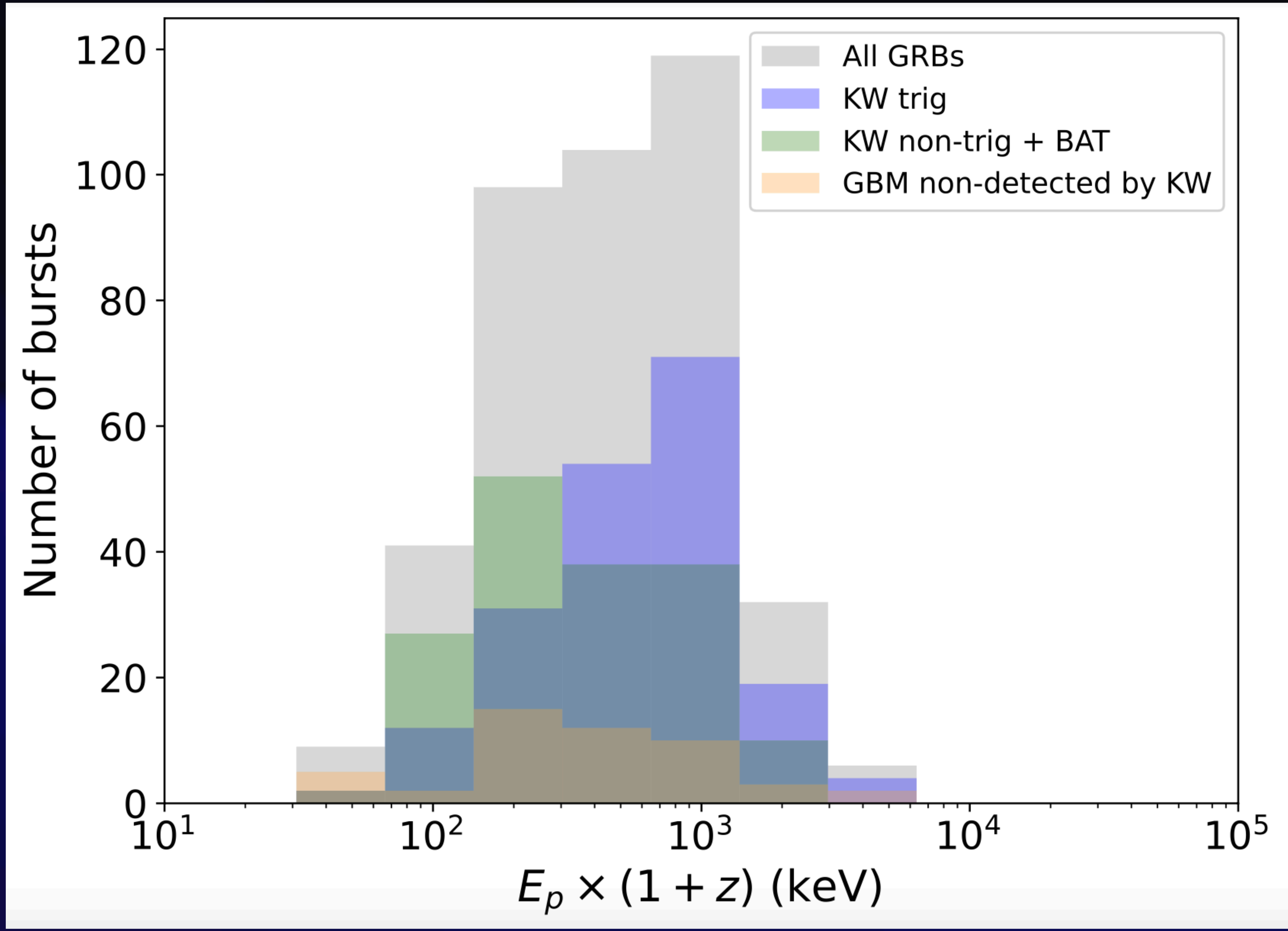


Sample	Number of bursts
"KW trig"	193
"KW & BAT"	167
"GBM only"	49
"Total"	409
"GBM all"	168

GRB sample



All GRBs
KW trig
KW non-trig + BAT
GBM non-detected by KW
Number of bursts
0
20
40
60
80
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$T_{90}/(1+z)$ (s)



All GRBs
KW trig
KW non-trig + BAT
GBM non-detected by KW
Number of bursts
0
20
40
60
80
100
120
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
$E_p \times (1+z)$ (keV)

Facilities

	KW	BAT	GBM
Crystal	NaI(Tl)	CdZnTe	NaI(Tl)/BGO
Number of detectors	2	– [a]	12/2
Diameter (cm)	12.7	–	12.7/12.7
Thickness(cm)	7.5	–	1.27/12.7
Approx. max. eff. area (cm^2)	160	5200	120/110
Energy range	20 keV–20 MeV [b]	14–150 keV [c]	8 keV–40 MeV
Approx. sensitivity ($erg\ cm^{-2}\ s^{-1}$)	5×10^{-7}	1×10^{-8}	5×10^{-8}
FoV (sr)	4π	1.4 [d]	> 8
Operation time (yrs)	27	17	13
SGRB-to-LGRB rate	1:5	1:9	1:5

[a]: BAT is an assembly of 32,768 planar CdZnTe detectors (4×4 mm^2 large, 2 mm thick) to form a 1.2 m $\times$ 0.6 m sensitive area; [b]: Drifts with time; [c]: For coded FoV and up to 350 keV with no position information; [d]: For >50% coded FoV; $\sim$2.2 sr for >10% coded FoV.

Tsvetkova+ (2022)

Methodology

e.g. Tarnopolski (2019)

Distributions

- Gaussian
  - Skewed
  - Non-skewed
- t-Student
  - Skewed
  - Non-skewed

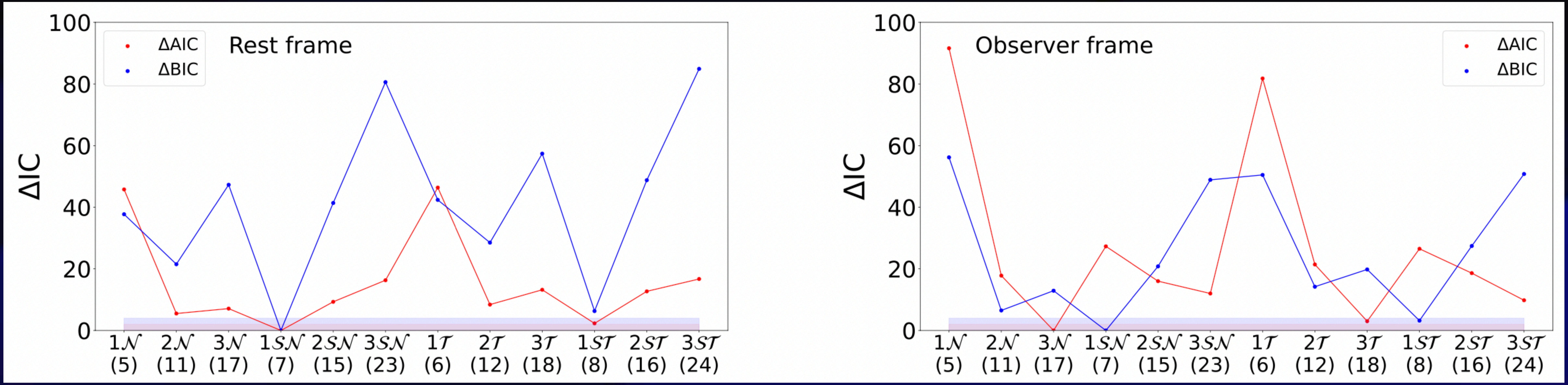
1 cluster | 2 clusters | 3 clusters

$$\mathcal{L}_p(\theta) = \sum_{i=1}^{N} \ln f(x_i, \theta),$$

$$\mathrm{AIC} = 2p - 2\mathcal{L}_{\mathrm{p,max}}$$

$$\mathrm{BIC} = p \ln N - 2\mathcal{L}_{\mathrm{p,max}}$$

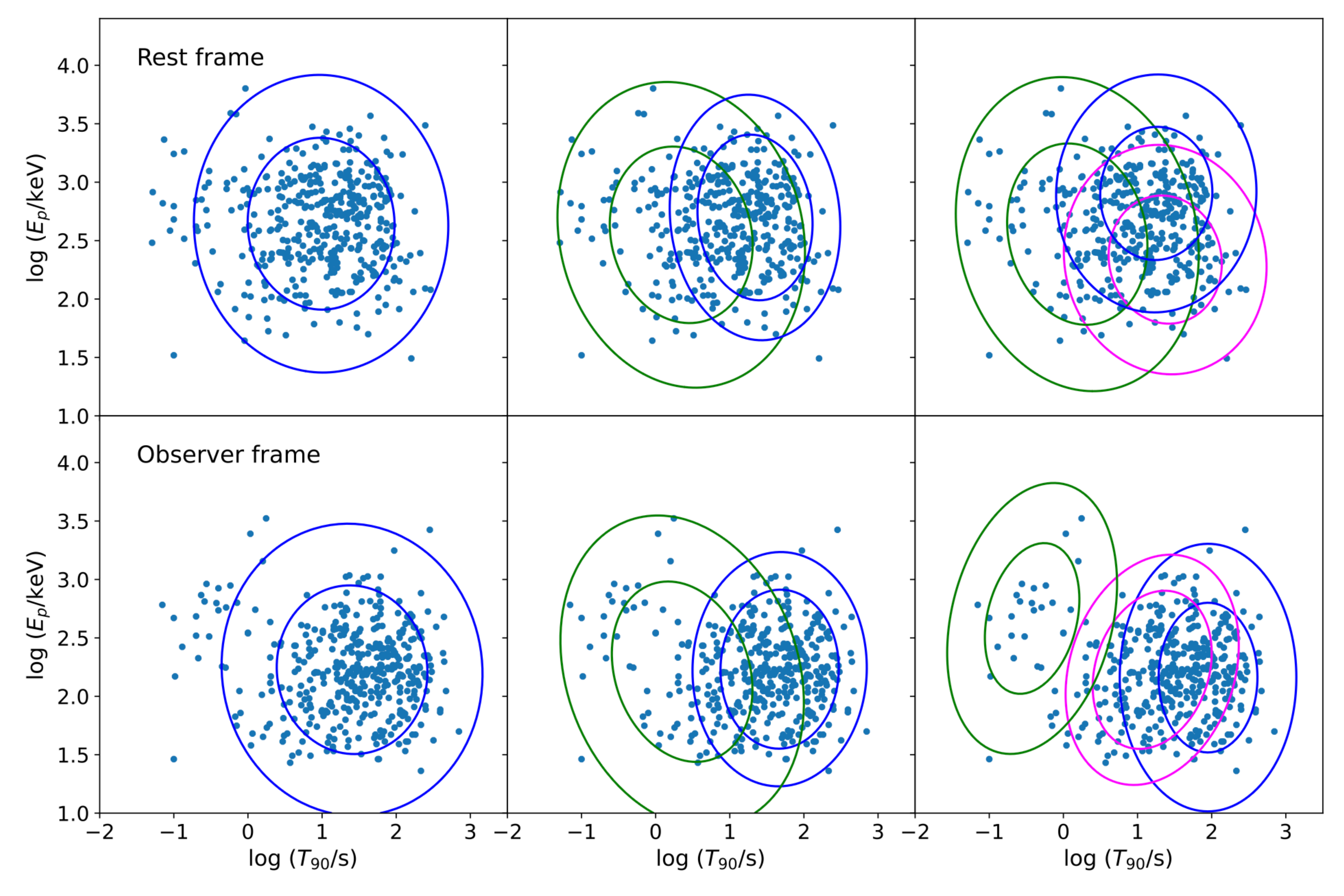
Information criteria



Acceptable models:
$AIC_i - AIC_{min} < 4$
$BIC_i - BIC_{min} < 2$

AIC - overfits the data
BIC - underfits the data

Examples of clusters



Rest frame

Statistics	Sample	Bursts	Cl.	Δ_{AIC}	Δ_{BIC}
Gaussian	Total	409	1	45.8	37.7
Gaussian	Total	409	2	5.5	21.5
Gaussian	Total	409	3	7.1	47.3
Sk. Gauss.	Total	409	1	0.0	0.0
Sk. Gauss.	Total	409	2	9.3	41.4[l]
Sk. Gauss.	Total	409	3	16.3	80.6
Student	Total	409	1	46.4	42.4[l]
Student	Total	409	2	8.4	28.5
Student	Total	409	3	13.2	57.4
Sk. Stud.	Total	409	1	2.3	6.3[l]
Sk. Stud.	Total	409	2	12.7	48.8
Sk. Stud.	Total	409	3	16.7	84.9
Gaussian	KW trig	193	1	23.3	16.8
Gaussian	KW trig	193	2	2.4	15.5
Gaussian	KW trig	193	3	14.3	46.9
Sk. Gauss.	KW trig	193	1	0.0	0.0
Sk. Gauss.	KW trig	193	2	5.6	31.8
Sk. Gauss.	KW trig	193	3	10.9	63.2
Student	KW trig	193	1	23.3	20.0
Student	KW trig	193	2	4.8	21.2
Student	KW trig	193	3	16.3	52.2
Sk. Stud.	KW trig	193	1	1.5	4.8
Sk. Stud.	KW trig	193	2	8.5	37.9
Sk. Stud.	KW trig	193	3	24.5	80.0

Statistics	Sample	Bursts	Cl.	Δ_{AIC}	Δ_{BIC}
Gaussian	KW + BAT	167	1	1.6	0.0
Gaussian	KW + BAT	167	2	0.0	17.1
Gaussian	KW + BAT	167	3	1.4	37.2
Sk. Gauss.	KW + BAT	167	1	6.5	11.1
Sk. Gauss.	KW + BAT	167	2	6.3	35.9
Sk. Gauss.	KW + BAT	167	3	9.7	64.3
Student	KW + BAT	167	1	4.4	5.9
Student	KW + BAT	167	2	2.9	23.1
Student	KW + BAT	167	3	4.3	43.3
Sk. Stud.	KW + BAT	167	1	8.8	16.5
Sk. Stud.	KW + BAT	167	2	7.0	39.7
Sk. Stud.	KW + BAT	167	3	11.5	69.1
Gaussian	GBM all	168	1	22.4	12.1
Gaussian	GBM all	168	2	9.0	17.5
Gaussian	GBM all	168	3	8.1	35.3
Sk. Gauss.	GBM all	168	1	6.3	2.3
Sk. Gauss.	GBM all	168	2	10.0	31.0
Sk. Gauss.	GBM all	168	3	23.1	69.1
Student	GBM all	168	1	10.9	3.8
Student	GBM all	168	2	5.3	16.9
Student	GBM all	168	3	0.0	30.3
Sk. Stud.	GBM all	168	1	0.9	0.0
Sk. Stud.	GBM all	168	2	11.3	35.4
Sk. Stud.	GBM all	168	3	15.6	64.7

Observer frame

Statistics	Sample	Bursts	Cl.	Δ_{AIC}	Δ_{BIC}
Gaussian	Total	409	1	91.6	56.2
Gaussian	Total	409	2	17.8	6.5
Gaussian	Total	409	3	0.0	12.9
Sk. Gauss.	Total	409	1	27.3	0.0
Sk. Gauss.	Total	409	2	16.0	20.8
Sk. Gauss.	Total	409	3	12.0	48.9
Student	Total	409	1	81.8	50.5
Student	Total	409	2	21.4	14.2
Student	Total	409	3	3.0	19.8
Sk. Stud.	Total	409	1	26.5	3.2
Sk. Stud.	Total	409	2	18.6	27.4
Sk. Stud.	Total	409	3	9.8	50.8
Gaussian	KW trig	193	1	58.8	33.4
Gaussian	KW trig	193	2	13.6	7.8
Gaussian	KW trig	193	3	0.0	13.8
Sk. Gauss.	KW trig	193	1	18.9	0.0
Sk. Gauss.	KW trig	193	2	23.0	30.2
Sk. Gauss.	KW trig	193	3	10.1	43.5
Student	KW trig	193	1	50.7	28.5
Student	KW trig	193	2	16.2	13.7
Student	KW trig	193	3	1.9	18.9
Sk. Stud.	KW trig	193	1	17.5	1.9
Sk. Stud.	KW trig	193	2	25.5	36.0
Sk. Stud.	KW trig	193	3	19.5	56.1

Statistics	Sample	Bursts	Cl.	Δ_{AIC}	Δ_{BIC}
Gaussian	KW + BAT	167	1	13.6	7.4
Gaussian	KW + BAT	167	2	7.9	20.4
Gaussian	KW + BAT	167	3	4.4	35.6
Sk. Gauss.	KW + BAT	167	1	0.0	0.0
Sk. Gauss.	KW + BAT	167	2	13.1	38.1
Sk. Gauss.	KW + BAT	167	3	5.0	54.9
Student	KW + BAT	167	1	16.3	13.2
Student	KW + BAT	167	2	10.2	25.9
Student	KW + BAT	167	3	3.5	37.8
Sk. Stud.	KW + BAT	167	1	3.0	6.1
Sk. Stud.	KW + BAT	167	2	15.8	43.9
Sk. Stud.	KW + BAT	167	3	7.5	60.5
Gaussian	GBM all	168	1	57.1	40.1
Gaussian	GBM all	168	2	11.2	12.9
Gaussian	GBM all	168	3	0.0	20.4
Sk. Gauss.	GBM all	168	1	24.4	13.5
Sk. Gauss.	GBM all	168	2	8.1	22.3
Sk. Gauss.	GBM all	168	3	9.1	48.3
Student	GBM all	168	1	26.4	12.5
Student	GBM all	168	2	1.9	6.7
Student	GBM all	168	3	2.0	25.5
Sk. Stud.	GBM all	168	1	7.7	0.0
Sk. Stud.	GBM all	168	2	7.6	24.9
Sk. Stud.	GBM all	168	3	0.7	43.0

T_{90} vs T_{50}

Svinkin+ (2019):

T_{50} is more robust measure of durations for clustering

Statistics	Cl.	Sample	n	Δ_{AIC}	w_i (AIC)	Δ_{BIC}	w_i (BIC)
$\mathcal{N}$	1	KW trig	193	13.4	< 0.001	6.9	0.029
$\mathcal{N}$	2	KW trig	193	3.7	0.056	16.8	< 0.001
$\mathcal{N}$	3	KW trig	193	4.2	0.044	36.8	< 0.001
$\mathcal{SN}$	1	KW trig	193	0.0	0.355	0.0	0.907
$\mathcal{SN}$	2	KW trig	193	0.9	0.227	27.0	< 0.001
$\mathcal{SN}$	3	KW trig	193	8.3	0.006	60.6	< 0.001
$\mathcal{T}$	1	KW trig	193	13.1	0.001	9.9	0.006
$\mathcal{T}$	2	KW trig	193	2.1	0.124	18.5	< 0.001
$\mathcal{T}$	3	KW trig	193	6.4	0.014	42.3	< 0.001
$\mathcal{ST}$	1	KW trig	193	2.2	0.118	5.5	0.058
$\mathcal{ST}$	2	KW trig	193	3.8	0.053	33.2	< 0.001
$\mathcal{ST}$	3	KW trig	193	11.0	0.001	66.5	< 0.001

Selection effects

-10% of the GRBs with lowest SNR

Statistics	Cl.	Sample	n	Δ_{AIC}	w_i (AIC)	Δ_{BIC}	w_i (BIC)
$\mathcal{N}$	1	Total	409	44.7	< 0.001	36.8	< 0.001
$\mathcal{N}$	2	Total	409	5.7	0.040	21.3	< 0.001
$\mathcal{N}$	3	Total	409	8.9	0.008	47.9	< 0.001
$\mathcal{SN}$	1	Total	409	0.0	0.692	0.0	0.953
$\mathcal{SN}$	2	Total	409	10.3	0.004	41.5	< 0.001
$\mathcal{SN}$	3	Total	409	16.8	< 0.001	79.2	< 0.001
$\mathcal{T}$	1	Total	409	45.4	< 0.001	41.5	< 0.001
$\mathcal{T}$	2	Total	409	8.4	0.010	27.9	< 0.001
$\mathcal{T}$	3	Total	409	10.7	0.003	53.6	< 0.001
$\mathcal{ST}$	1	Total	409	2.1	0.242	6.0	0.047
$\mathcal{ST}$	2	Total	409	14.6	< 0.001	49.8	< 0.001
$\mathcal{ST}$	3	Total	409	19.2	< 0.001	85.6	< 0.001
$\mathcal{N}$	1	KW trig	193	20.2	< 0.001	13.9	0.001
$\mathcal{N}$	2	KW trig	193	0.8	0.252	13.4	0.001
$\mathcal{N}$	3	KW trig	193	3.7	0.059	35.3	< 0.001
$\mathcal{SN}$	1	KW trig	193	0.0	0.375	0.0	0.915
$\mathcal{SN}$	2	KW trig	193	4.6	0.038	29.9	< 0.001
$\mathcal{SN}$	3	KW trig	193	7.0	0.011	57.6	< 0.001
$\mathcal{T}$	1	KW trig	193	19.8	< 0.001	16.7	< 0.001
$\mathcal{T}$	2	KW trig	193	3.2	0.076	19.0	< 0.001
$\mathcal{T}$	3	KW trig	193	6.2	0.017	41.0	< 0.001
$\mathcal{ST}$	1	KW trig	193	1.7	0.160	4.8	0.083
$\mathcal{ST}$	2	KW trig	193	7.2	0.010	35.7	< 0.001
$\mathcal{ST}$	3	KW trig	193	11.0	0.002	64.7	< 0.001

Statistics	Cl.	Sample	n	Δ_{AIC}	w_i (AIC)	Δ_{BIC}	w_i (BIC)
$\mathcal{N}$	1	KW & BAT	167	0.0	0.451	0.0	0.943
$\mathcal{N}$	2	KW & BAT	167	1.5	0.213	19.6	< 0.001
$\mathcal{N}$	3	KW & BAT	167	5.0	0.037	41.2	< 0.001
$\mathcal{SN}$	1	KW & BAT	167	4.3	0.053	10.4	0.005
$\mathcal{SN}$	2	KW & BAT	167	7.8	0.009	38.0	< 0.001
$\mathcal{SN}$	3	KW & BAT	167	13.4	0.001	67.7	< 0.001
$\mathcal{T}$	1	KW & BAT	167	2.8	0.111	5.8	0.052
$\mathcal{T}$	2	KW & BAT	167	4.3	0.053	25.4	< 0.001
$\mathcal{T}$	3	KW & BAT	167	4.2	0.055	43.4	< 0.001
$\mathcal{ST}$	1	KW & BAT	167	6.8	0.015	15.9	< 0.001
$\mathcal{ST}$	2	KW & BAT	167	10.3	0.003	43.5	< 0.001
$\mathcal{ST}$	3	KW & BAT	167	15.5	< 0.001	72.8	< 0.001
$\mathcal{N}$	1	GBM all	168	18.7	< 0.001	10.8	0.003
$\mathcal{N}$	2	GBM all	168	6.0	0.031	16.2	< 0.001
$\mathcal{N}$	3	GBM all	168	11.7	0.002	40.0	< 0.001
$\mathcal{SN}$	1	GBM all	168	5.4	0.041	3.5	0.101
$\mathcal{SN}$	2	GBM all	168	7.8	0.012	30.1	< 0.001
$\mathcal{SN}$	3	GBM all	168	20.4	< 0.001	66.8	< 0.001
$\mathcal{T}$	1	GBM all	168	4.9	0.053	0.0	0.579
$\mathcal{T}$	2	GBM all	168	3.7	0.097	16.9	< 0.001
$\mathcal{T}$	3	GBM all	168	3.1	0.131	34.4	< 0.001
$\mathcal{ST}$	1	GBM all	168	0.0	0.615	1.2	0.318
$\mathcal{ST}$	2	GBM all	168	7.0	0.019	32.3	< 0.001
$\mathcal{ST}$	3	GBM all	168	26.5	< 0.001	75.9	< 0.001

Obs.-frame T_{90} vs rest-frame E_p

Statistics	Cl.	Sample	n	Δ_{AIC}	w_i (AIC)	Δ_{BIC}	w_i (BIC)
$\mathcal{N}$	1	Total	409	66.7	< 0.001	56.2	< 0.001
$\mathcal{N}$	2	Total	409	0.6	0.179	14.2	0.001
$\mathcal{N}$	3	Total	409	0.7	0.170	38.3	< 0.001
$\mathcal{SN}$	1	Total	409	2.5	0.069	0.0	0.950
$\mathcal{SN}$	2	Total	409	5.2	0.018	34.8	< 0.001
$\mathcal{SN}$	3	Total	409	0.0	0.241	61.7	< 0.001
$\mathcal{T}$	1	Total	409	61.3	< 0.001	54.8	< 0.001
$\mathcal{T}$	2	Total	409	4.0	0.033	21.6	< 0.001
$\mathcal{T}$	3	Total	409	2.4	0.073	44.1	< 0.001
$\mathcal{ST}$	1	Total	409	4.4	0.027	5.9	0.050
$\mathcal{ST}$	2	Total	409	8.9	0.003	42.5	< 0.001
$\mathcal{ST}$	3	Total	409	0.5	0.188	66.2	< 0.001

Effective redshift dependence of GRB durations:

(1) Cosmological time dilation;

(2) The "tip of the iceberg" effect;

(3) Different energy windows.

Uncertainties on IC from sampling

Distr.	Cl.	n	IC type	IC value
Jackknife 10%				
$\mathcal{N}$	1	368	AIC	1198.2 ± 13.0
$\mathcal{N}$	2	368	AIC	1162.7 ± 12.9
$\mathcal{N}$	3	368	AIC	1164.8 ± 12.7
$\mathcal{SN}$	1	368	AIC	1156.9 ± 12.9
$\mathcal{SN}$	2	368	AIC	1166.9 ± 12.9
$\mathcal{SN}$	3	368	AIC	1172.1 ± 13.1
$\mathcal{N}$	1	368	BIC	1217.8 ± 12.9
$\mathcal{N}$	2	368	BIC	1205.7 ± 12.9
$\mathcal{N}$	3	368	BIC	1231.2 ± 12.7
$\mathcal{SN}$	1	368	BIC	1184.3 ± 12.9
$\mathcal{SN}$	2	368	BIC	1225.5 ± 12.9
$\mathcal{SN}$	3	368	BIC	1262.0 ± 13.1

Distr.	Cl.	n	IC type	IC value
Jackknife 30%				
$\mathcal{N}$	1	286	AIC	930.0 ± 21.6
$\mathcal{N}$	2	286	AIC	904.3 ± 21.4
$\mathcal{N}$	3	286	AIC	907.3 ± 21.8
$\mathcal{SN}$	1	286	AIC	898.6 ± 21.6
$\mathcal{SN}$	2	286	AIC	908.1 ± 21.0
$\mathcal{SN}$	3	286	AIC	914.0 ± 21.1
$\mathcal{N}$	1	286	BIC	948.3 ± 21.6
$\mathcal{N}$	2	286	BIC	944.5 ± 21.4
$\mathcal{N}$	3	286	BIC	969.5 ± 21.8
$\mathcal{SN}$	1	286	BIC	924.2 ± 21.6
$\mathcal{SN}$	2	286	BIC	962.9 ± 21.0
$\mathcal{SN}$	3	286	BIC	998.1 ± 21.1

Distr.	Cl.	n	IC type	IC value
Bootstrap				
$\mathcal{N}$	1	409	AIC	1329.7 ± 38.3
$\mathcal{N}$	2	409	AIC	1282.8 ± 36.3
$\mathcal{N}$	3	409	AIC	1276.5 ± 36.4
$\mathcal{SN}$	1	409	AIC	1281.2 ± 36.0
$\mathcal{SN}$	2	409	AIC	1283.4 ± 35.8
$\mathcal{SN}$	3	409	AIC	1277.6 ± 38.3
$\mathcal{N}$	1	409	BIC	1349.8 ± 38.3
$\mathcal{N}$	2	409	BIC	1327.0 ± 36.2
$\mathcal{N}$	3	409	BIC	1344.7 ± 36.4
$\mathcal{SN}$	1	409	BIC	1309.3 ± 36.0
$\mathcal{SN}$	2	409	BIC	1343.7 ± 35.8
$\mathcal{SN}$	3	409	BIC	1369.9 ± 38.3

Acceptable models:
$AIC_i - AIC_{min} < 4$
$BIC_i - BIC_{min} < 2$

Uncertainties on IC from the T_{90} and E_p errors

Distr.	Cl.	AIC	BIC
$\mathcal{N}$	1	1356.8 ± 19.2	1376.9 ± 19.3
$\mathcal{N}$	2	1316.8 ± 17.3	1360.9 ± 17.3
$\mathcal{N}$	3	1320.1 ± 16.9	1388.3 ± 16.9
$\mathcal{SN}$	1	1314.1 ± 18.5	1342.2 ± 18.5
$\mathcal{SN}$	2	1321.0 ± 17.0	1381.2 ± 17.0
$\mathcal{SN}$	3	1327.2 ± 16.6	1419.5 ± 16.6
$\mathcal{T}$	1	1355.8 ± 16.5	1379.9 ± 16.5
$\mathcal{T}$	2	1319.1 ± 17.1	1367.3 ± 17.1
$\mathcal{T}$	3	1322.2 ± 16.7	1394.5 ± 16.7
$\mathcal{ST}$	1	1315.1 ± 16.6	1347.2 ± 16.6
$\mathcal{ST}$	2	1324.1 ± 17.1	1388.3 ± 17.1
$\mathcal{ST}$	3	1329.7 ± 17.0	1426.0 ± 17.0

Acceptable models:
AIC_i - AIC_{min} < 4
BIC_i - BIC_{min} < 2

Summary

We fitted the data on the Ep – T_{90} plane with **1, 2, 3-component skewed and non-skewed distributions** using the sample of **409 GRBs with known redshifts** detected in a **wide energy range**, one of the largest to date.

The results, in terms of informational criteria, **do not show evidence of the third class** of GRBs in the rest-frame.

The uncertainty of the method is high for a relatively small sample.
Importance of the prospective missions aimed at substantial increase of reliable GRB redshift estimates, e.g., THESEUS.

Future prospects: Multivariate clustering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Thank you!