Testing the ubiquitous presence of very high energy emission in GRBs with the MAGIC telescopes

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TeVPA 2025, Valencia, 4/11/2025

Overview

Goal:

- Deliver a catalog of the non-detected GRBs with MAGIC
- Discuss the implications of non-detections

Criteria:

- Non-detected GRBs followed up by MAGIC from **2013** (post automatic procedure update catalog) to **2019** (change of follow-up strategy)
- GRBs observed in good conditions (stereo, good weather, no strong moonlight)

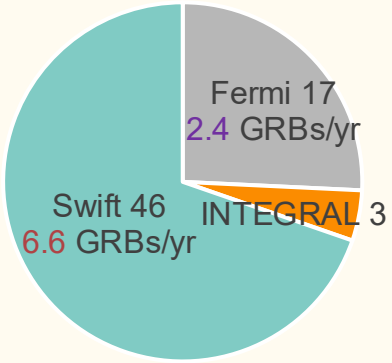
Analysis workflow:

- MAGIC: MAGIC std data analysis + Upper Limit (UL) calculation (Zanin et al. 2013, Aleksic et al. 2016, Rolke et al. 2005)
- MWL: *Swift-XRT* and *Fermi-LAT* simultaneous observations

The sample

GRB name	Redshift	Instrument (position)	T_{90} [s]	T_0 [UTC]	T_{start} [UTC]	T_{delay} [s]	Zenith angle [deg]
130502A		Swift-BAT	3	17:50:30	20:57:03	11193	33.9-40.1
130504A		Swift-BAT	50	02:05:34	02:13:09	455	44.7-56.5
130606A	5.913	Swift-BAT	277	21:04:39	21:15:28	649	1.7-46.1
130612A	2.006	Swift-BAT	5.6	03:22:22	03:23:08	46	38.0-53.0
130701A	1.155	Swift-BAT	4.4	04:17:43	04:18:32	49	15.9-22.6
130903A		INTEGRAL	69	00:47:20	03:57:32	11412	51.9-62.8
131030A	1.295	Swift-BAT	41	20:56:19	20:56:45	26	33.7-39.7
140430A	1.60	Swift-BAT	174	20:33:36	20:52:06	1110	45.6-73.3
140709A		Swift-BAT	98.6	01:13:41	03:22:13	7712	24.6-37.0
140930B		Swift-BAT	0.84	19:41:42	21:10:05	5303	18.8-51.4
141026A	3.35	Swift-BAT	146	02:36:51	02:38:27	96	16.3-54.1
141220A	1.32	Swift-BAT	7.21	06:02:52	06:03:47	55	18.9-24.0
150213A		Fermi-GBM	4.1	00:01:48	00:03:08	80	48.2-60.6
150428A		Swift-BAT	53.2	01:30:40	01:32:11	91	27.0-57.7
150428B		Swift-BAT	131	03:12:03	03:13:03	60	27.0-57.7
150819A		Swift-BAT	52.1	00:50:08	02:11:51	4903	37.4-54.4
151118A		Swift-BAT	23.4	03:06:30	03:07:14	44	42.8-57.4
151215A	2.59	Swift-BAT	17.8	03:01:28	03:01:58	30	15.8-58.0
160119A		Swift-BAT	116	03:06:07	03:17:09	662	13.2-58.7
160310A		Fermi-LAT	18.2	00:22:57	20:30:16	72439	35.5-40.9
160313A		Swift-BAT	42.6	02:37:14	02:39:01	107	30.3-53.3
160504A		Swift-BAT	53.9	19:30:36	20:56:29	5153	26.9-33.7
160509A	1.17	Fermi-LAT	370	08:59:04	21:21:07 (+2d)	217323	49.2-72.2
160623A	0.367	Fermi-LAT	50	05:00:34	02:05:31	75897	27.0-54.7
160625B	1.406	Fermi-LAT	460	22:43:24	23:29:38	2774	21.8-54.9
160821B	0.16	Swift-BAT	0.48	22:29:13	22:29:37	24	33.4-43.6
160910A		Fermi-GBM	24.3	17:19:38	20:21:54	10936	45.4-72.9
160927A		Swift-BAT	0.48	18:04:49	20:03:00	7091	32.0-58.8
161229A		Fermi-GBM	33.5	21:03:48	23:05:54	7326	22.0-26.1
170728B		Swift-BAT	47.7	23:03:19	23:03:58	39	41.8-52.7
170921B		Fermi-GBM	39.4	04:02:11	04:48:04	2753	48.4-60.6
171020A	1.87	Swift-BAT	41.9	23:07:09	23:08:37	88	13.5-34.9
171210A		Fermi-LAT	12	11:49:15	20:33:11	31436	30.9-61.9
180512A		Swift-BAT	24.0	22:01:46	22:03:11	85	7.6-38.4
180715A		Swift-BAT	0.68	18:07:05	21:27:24	12019	27.9-34.5
180720C		Swift-BAT	124.2	22:23:57	22:25:44	107	55.3-55.4
180904A		Swift-BAT	5.39	21:28:32	21:30:07	95	23.7-60.2
181225A		Fermi-LAT	41.5	11:44:10	19:56:06 (+1d)	115916	46.7-62.6
190106B		Fermi-GBM	11.8	20:47:10	20:49:13	123	60.0-60.4
190114C	0.425	Swift-BAT	25*	20:57:03	20:58:01	58	55.6-80.0
190829A	0.078	Swift-BAT	62.9	19:55:53	02:23:48 (+2d)	109624	37.7-59.6
191004A		Swift-BAT	2.44	18:07:02	00:42:30	23728	65.4-69.9

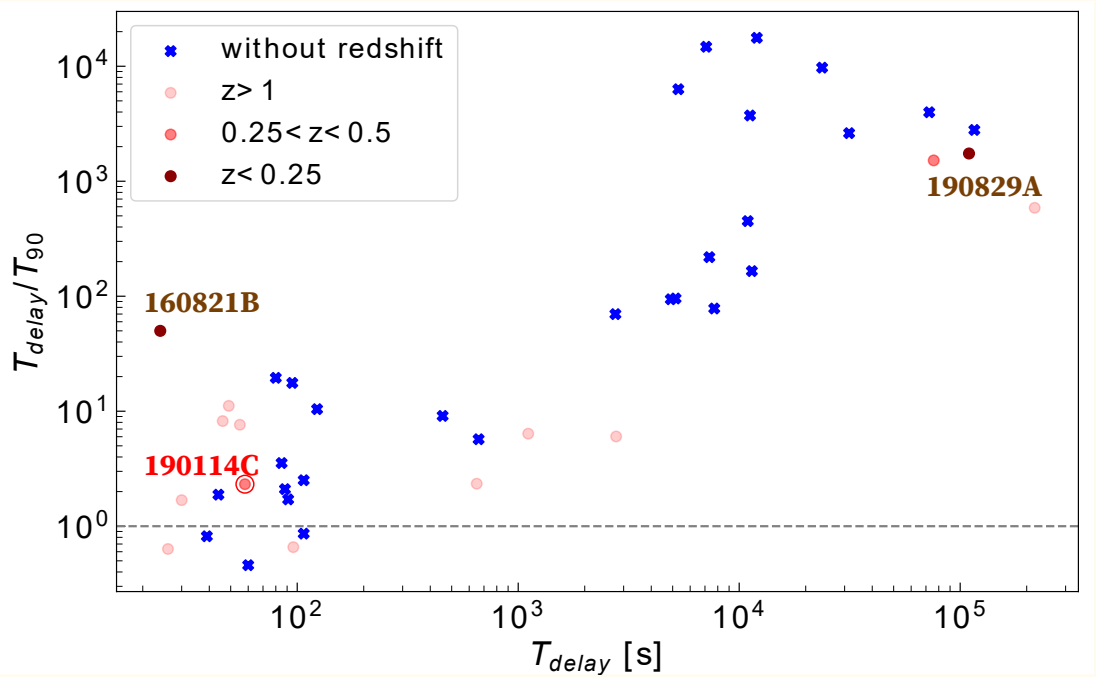
- **66 GRBs followed-up** (9.4 GRBs/yr):
  - **24 discarded:**
    - degraded/unstable atmospheric transmission (21 out of 24)
    - Technical issues affected data quality (3 out of 24)
  - **42 GRBs selected for data analysis**



Estimated expected rate of followed-up alerts (Alert criteria, moon break, safety limits, tech problems):

- 9.6 GRBs/yr = 6.7 GRBs/yr (Swift) + 2.9 GRBs/yr (Fermi)

The sample



- **42 GRBs selected for data analysis**
  - 38 lGRBs and 4 sGRBs
  - 15 has a measured redshift z (14 lGRBs and 1 sGRB)

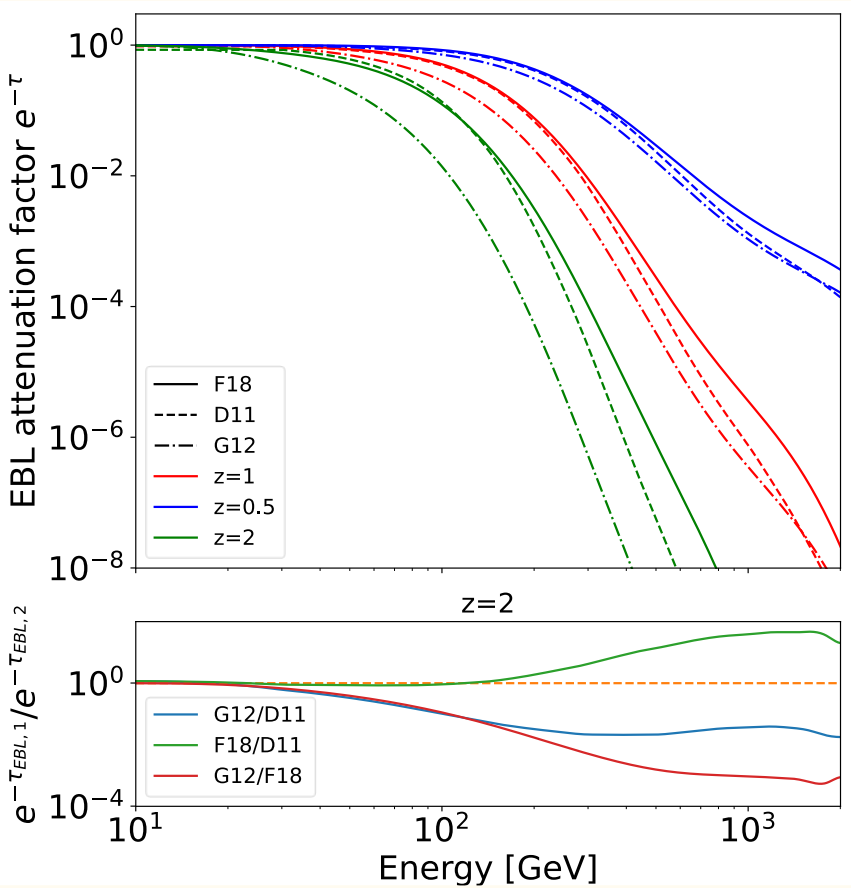
- 5 GRBs observed during prompt phase ($T_{delay} / T_{90} < 1$)
  - 3 with unknown redshift
  - GRB131030A (z = 1.295) → bad atmospheric conditions
  - GRB141026A z =3.35

Best GRB candidates for VHE emission have short delays ($T_{delay} < 10^4$ s) and low redshift (z < 1)

The MAGIC analysis

- MAGIC Upper Limits (ULs) estimated assuming:
  - Spectral shape and photon index for intrinsic or observed spectrum
  - EBL models: Dominguez+11 (D11), Gilmore+12 (G12), Franceschini+18 (F18)
  - Defined time and energy intervals
  - Tests performed on collection area, energy threshold and energy range (less than 30% systematic uncertainty required)

- 39 GRBs (excluded 3 hints of detections) splitted into two samples:
  - ***S1:* GRBs with unknown z or z > 2 or Zd > 40°** (33 out of 39)
  - ***S2:* GRBs with z < 2 and Zd < 40°** (6 out of 39)



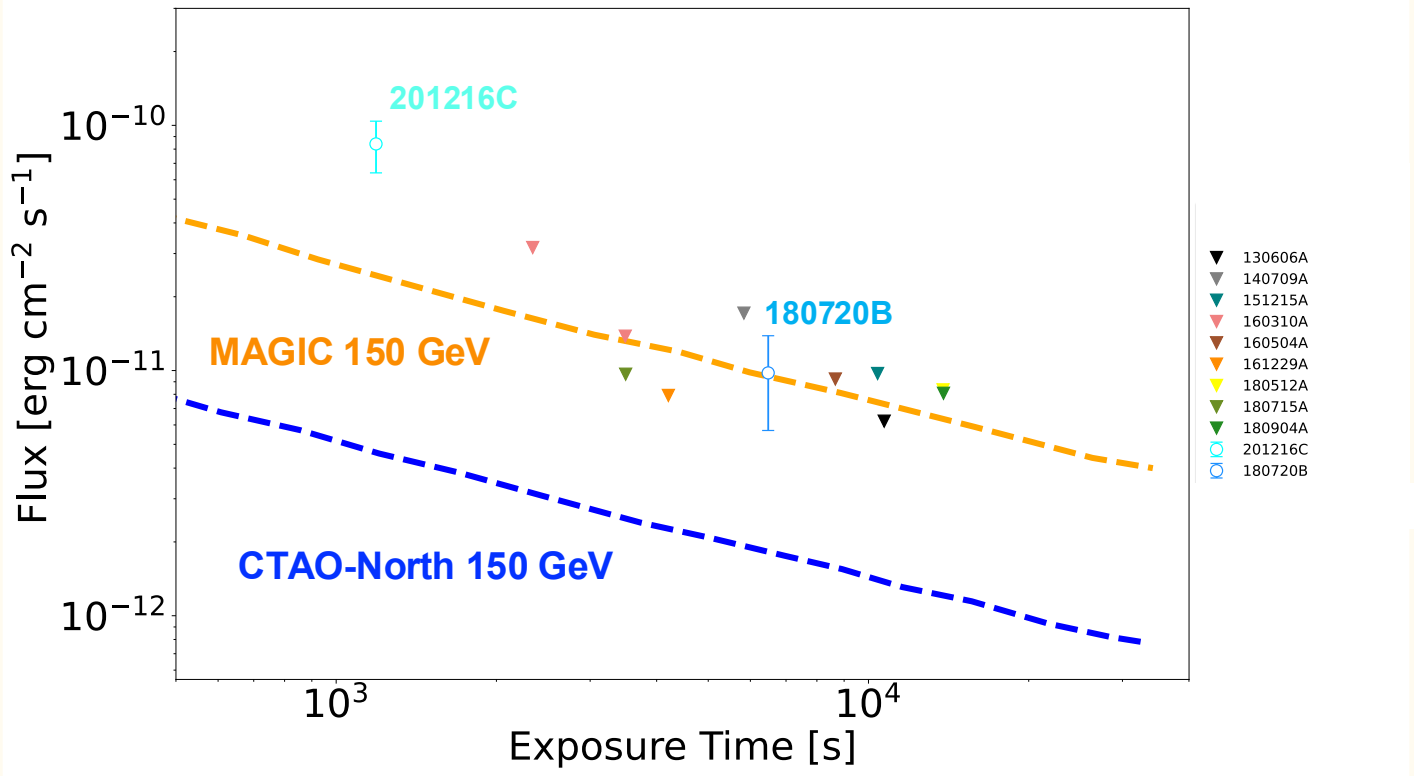
S1: GRBs with unknown z or z > 2 or Zd > 40°

- Deliver a list of ULs on the **observed** flux in several energy bins
- *Assumed observed spectrum*: pwl $dN/dE = E^{-\alpha}$ with α=3.5 (optimistic scenario, similar to GRB190829A) or α=5.5 (similar to GRB190114C and GRB201216C) (2 ULs)
- *Energy range* estimated from:
  - lower edge: analysis threshold or systematics uncertainties on coll. Area < 30%
  - upper edge: E_{bin} with 1 TeV (avoid huge uncertainties due to EBL absorption)
- *Time intervals*: night-wise ULs

GRB name	T_{obs} [s]	T_{start} - T_{stop} [s]	E [TeV]	α = 3.5 10^{-12} [TeV cm^{-2} s^{-1}]	α = 5.5 10^{-12} [TeV cm^{-2} s^{-1}]
GRB130502A	1775	11769 - 13599	0.16 - 0.22	14.6	10.9
			0.22 - 0.30	15.1	10.2
			0.30 - 0.41	7.41	5.36
			0.41 - 0.55	9.81	5.15
			0.55 - 0.75	8.01	4.38
			0.75 - 1.02	21.0	9.20
GRB130504A	10481	455 - 11487	0.22 - 0.30	4.31	2.95
			0.30 - 0.41	4.06	2.89
			0.41 - 0.55	2.48	1.64
			0.55 - 0.75	2.02	1.07
			0.75 - 1.02	1.86	1.02
GRB130606A	10704	1747 - 12868	0.12 - 0.16	5.26	3.88
			0.16 - 0.22	4.24	3.23
			0.22 - 0.30	5.66	4.40
			0.30 - 0.41	2.95	2.31
			0.41 - 0.55	2.34	1.62
			0.55 - 0.75	1.74	0.93
			0.75 - 1.02	4.82	2.54
GRB130612A	3822	688 - 4664	0.16 - 0.22	15.8	11.4
			0.22 - 0.30	7.16	5.27
			0.30 - 0.41	12.7	7.63
			0.41 - 0.55	5.11	2.98
			0.55 - 0.75	4.20	1.76
			0.75 - 1.02	3.57	1.53
GRB130903A	2560	11412 - 14476	0.41 - 0.55	9.40	6.18
			0.55 - 0.75	11.2	6.74
			0.75 - 1.02	7.50	4.10

S1: GRBs with unknown z or z > 2 or Zd > 40°

A comparison: observed ULs at selected energies (150 GeV and 250 GeV) and MAGIC and CTA-North 2σ sensitivities (Fioretti et al. 2019)



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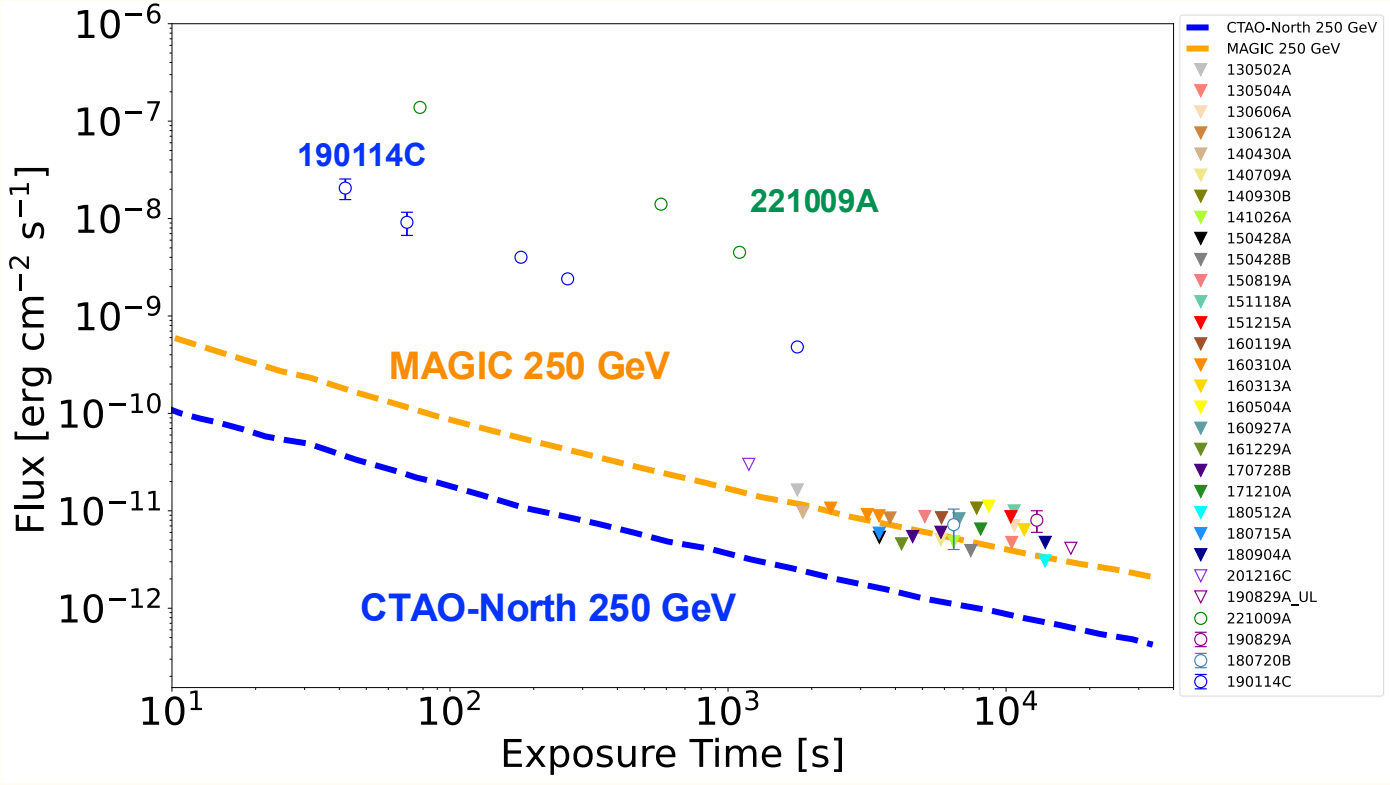


S2: GRBs with z < 2 and Zd < 40°

- Compute ULs on the **EBL de-absorbed** flux in selected energy range and time intervals
- *Assumed EBL de-absorbed spectrum:* pwl $dN/dE = E^{-\alpha}$ with $\alpha=1.6$ or $\alpha=2.2$ → best-fit value of GRB180720B and GRB190114C+ SSC theoretical scenario (2 ULs)
- *EBL models:* D11/**F18** and **G12** (2x2 ULs)
- *Energy range* estimated from:
  - lower edge: analysis threshold or systematics uncertainties on coll. Area < 30%
  - upper edge: 1.5 TeV in energy rest-frame (highest photon for GRB190114C)
- *Time intervals*:
  - Single night-wise ULs or two ULs for each night (observational duration, conditions)

S2: GRBs with z < 2 and Zd < 40°

GRB name	T_{obs} [s]	E_{min} [GeV]	E_{max} [GeV]	F18,1.6 10^{-10} [erg cm^{-2} s^{-1}]	F18,2.2 10^{-10} [erg cm^{-2} s^{-1}]	G12,1.6 10^{-10} [erg cm^{-2} s^{-1}]	G12,2.2 10^{-10} [erg cm^{-2} s^{-1}]
130701A	403	100	696	4.45	2.70	11.4	6.57
130701A	1935	100	696	1.76	1.06	4.45	2.55
131030A	5795	120	654	1.64	1.00	5.72	3.30
141220A	314	75	647	4.10	2.39	10.7	5.85
141220A	2386	75	647	1.92	1.11	4.97	2.70
160623A	9324	165	1097	0.56	0.40	0.71	0.50
160623A	8388	140	1097	0.14	0.10	0.22	0.12
160625B	13968	200	625	7.58	5.11	56.3	35.9
160625B	8100	110	625	1.54	0.95	5.94	3.45
171020A	942	110	523	5.36	3.20	36.7	19.9
171020A	11906	110	523	5.42	3.32	41.1	23.3

S2: GRBs with z < 2 and Zd < 40°: MWL analysis

TeV-detected GRBs (so far): L_{VHE} similar to $L_{X\text{-}ray} \rightarrow P_{IC}$ and P_{sync}

Open questions:

- do all GRBs have a VHE emission component with luminosity similar to the simultaneous X-ray luminosity?
- are the VHE-detected GRBs a peculiar population with particularly bright VHE emission?

We tackled these open questions comparing the MAGIC ULs and the XRT de-absorbed X-ray fluxes

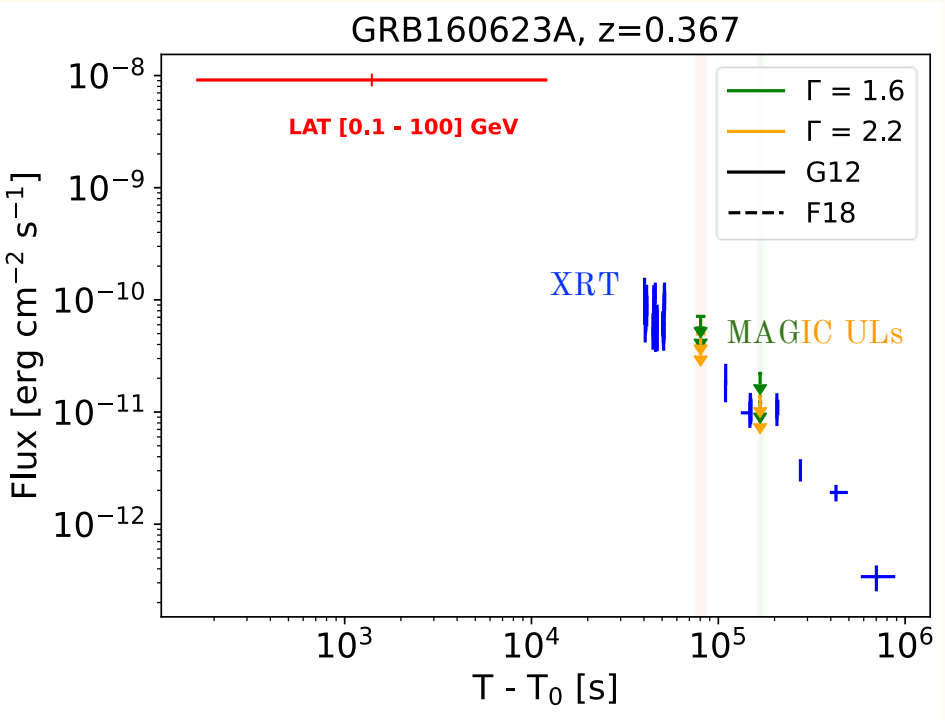
S2: GRBs with z < 2 and Zd < 40°: MWL analysis

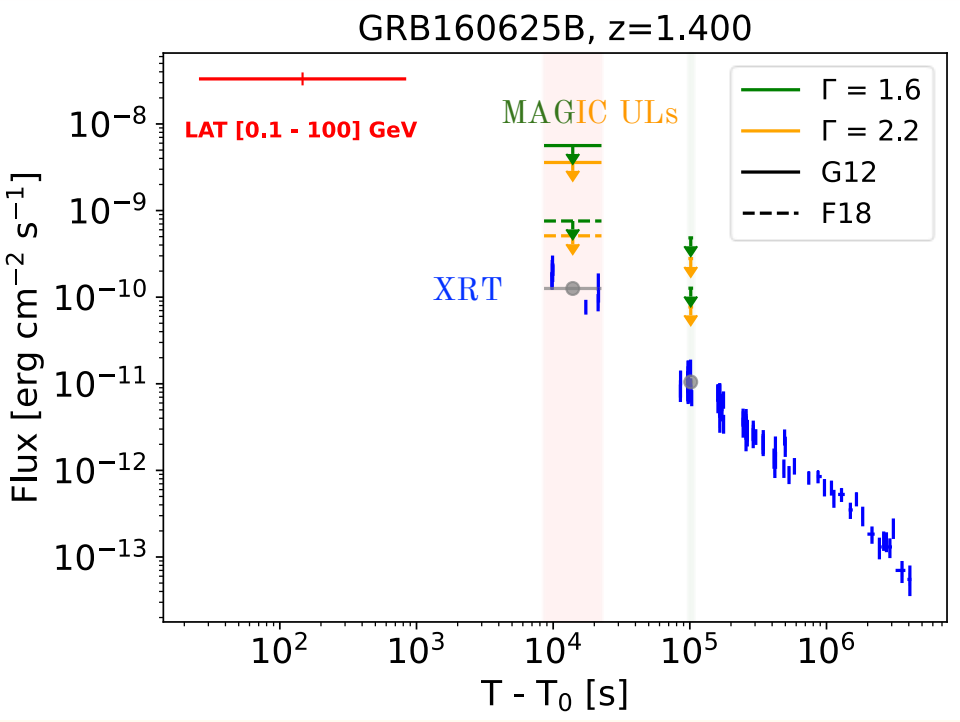
We tackled these open questions comparing the MAGIC ULs and the XRT de-absorbed X-ray fluxes

- MAGIC ULs: EBL de-absorbed (F18, G12) x PWL spectrum (1.6, 2.2); z < 2 and Zd < 40° (avoid EBL and systematics): 6 cases
- XRT fluxes: de-absorbed X-ray fluxes integrated in 0.3 - 10 keV (observer frame)
- XRT average flux: same time interval of MAGIC flux UL
- Swift-BAT fluxes

S2: Comparison with X-ray fluxes

Late-time MAGIC follow-up ($T_{delay} > 10^4$ s), night-wise ULs, add LAT fluxes

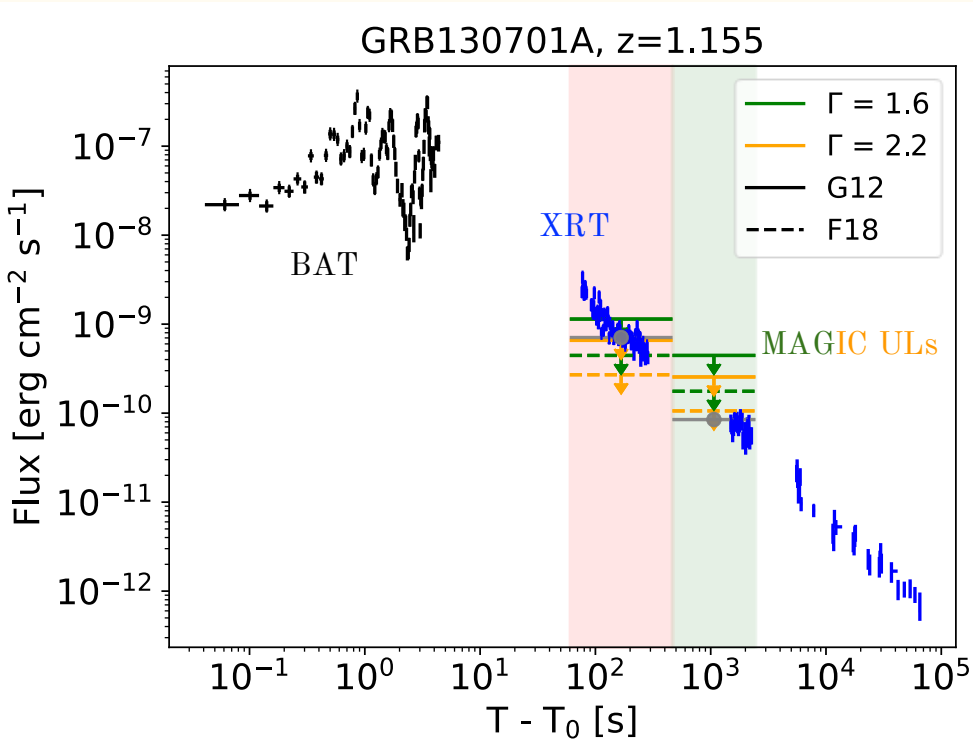


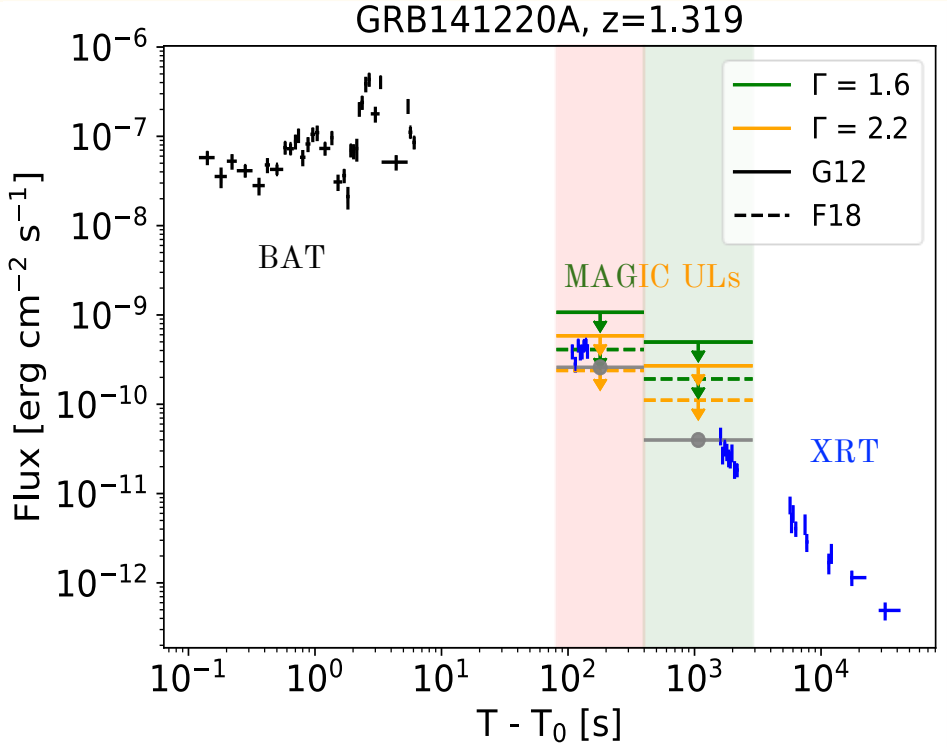


MAGIC ULs above XRT flux or no simultaneous X-ray data

S2: Comparison with X-ray fluxes

Early MAGIC follow-up (T_{delay} < 100 s), splitted ULs

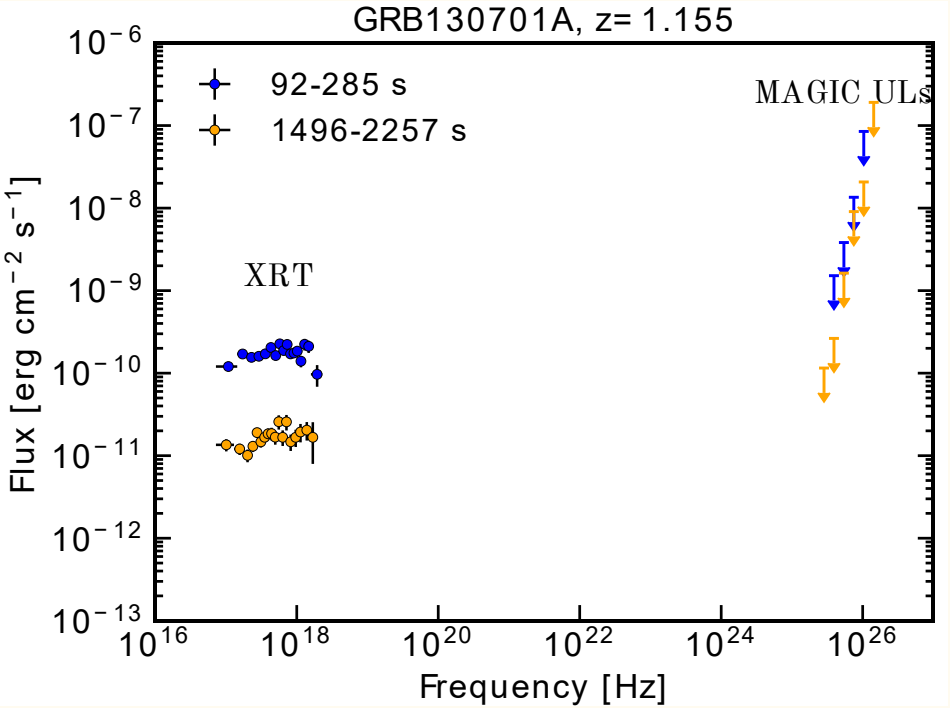


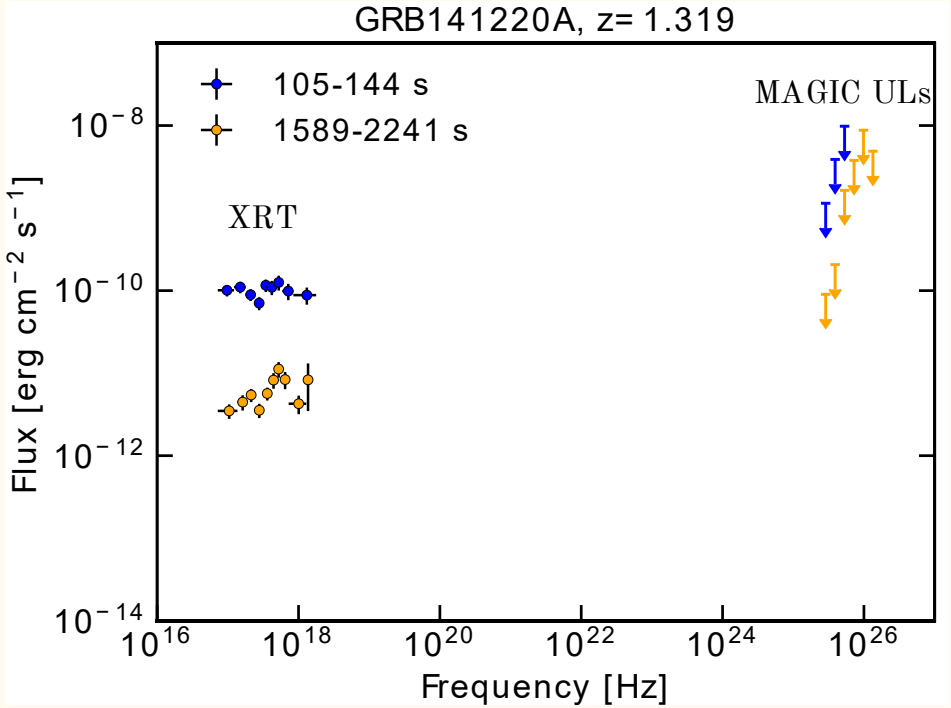


MAGIC ULs lies very close (or below) the average XRT flux: **can VHE be constrained?**

S2: Comparison with X-ray fluxes

Spectral MAGIC and XRT analysis in simultaneous time intervals





MAGIC differential ULs well above XRT flux

Conclusions

- **66 GRBs** followed-up by MAGIC ('13-'19) presented here:
  - 42 GRBs with successful data taking and analysis → 39 non-detected; 15 with redshift
  - 33 GRBs with no z or z > 2 or Zd > 40° (S1); 6 GRBs with z < 2 and Zd < 40° (S2)
  - Best candidates for detection: $T_{delay} < 10^4$ s and z < 1 → (190114C and 160821B)

- MAGIC flux UL derived for non-detected GRBs (EBL, spectrum, systematics, time/energy intervals)
  - S1: 33 GRBs (no z or z > 2 or Zd > 40°): no different intrinsic properties wrt TeV-detected GRBs; ULs at level of 2σ MAGIC sensitivity → fainter or farther (strong EBL)
  - S2: 6 GRBs with z < 2 and Zd < 40°: MWL analysis and comparison (TeV - X-ray) performed

- **VHE emission** from MAGIC is constrained to be **no more than 5-10 times brighter** than the simultaneous **X-ray** emission

- The presence of a **universal VHE component** in GRBs similar to current population of TeV detected GRBs ($\mathbf{L_{VHE} \sim L_{X\text{-}ray}}$) is still open and **cannot be excluded**

- **CTAO** improved sensitivity will provide an increased number of **detections** but also a larger number of **constraining ULs → crucial information for VHE GRB population**