Fermi
Gamma-ray
Space Telescope

Fermi observations of Gamma-ray Bursts

Magnus Axelsson
KTH Royal Institute of Technology and
Stockholm University (Sweden)
Tokyo Metropolitan University (Japan)

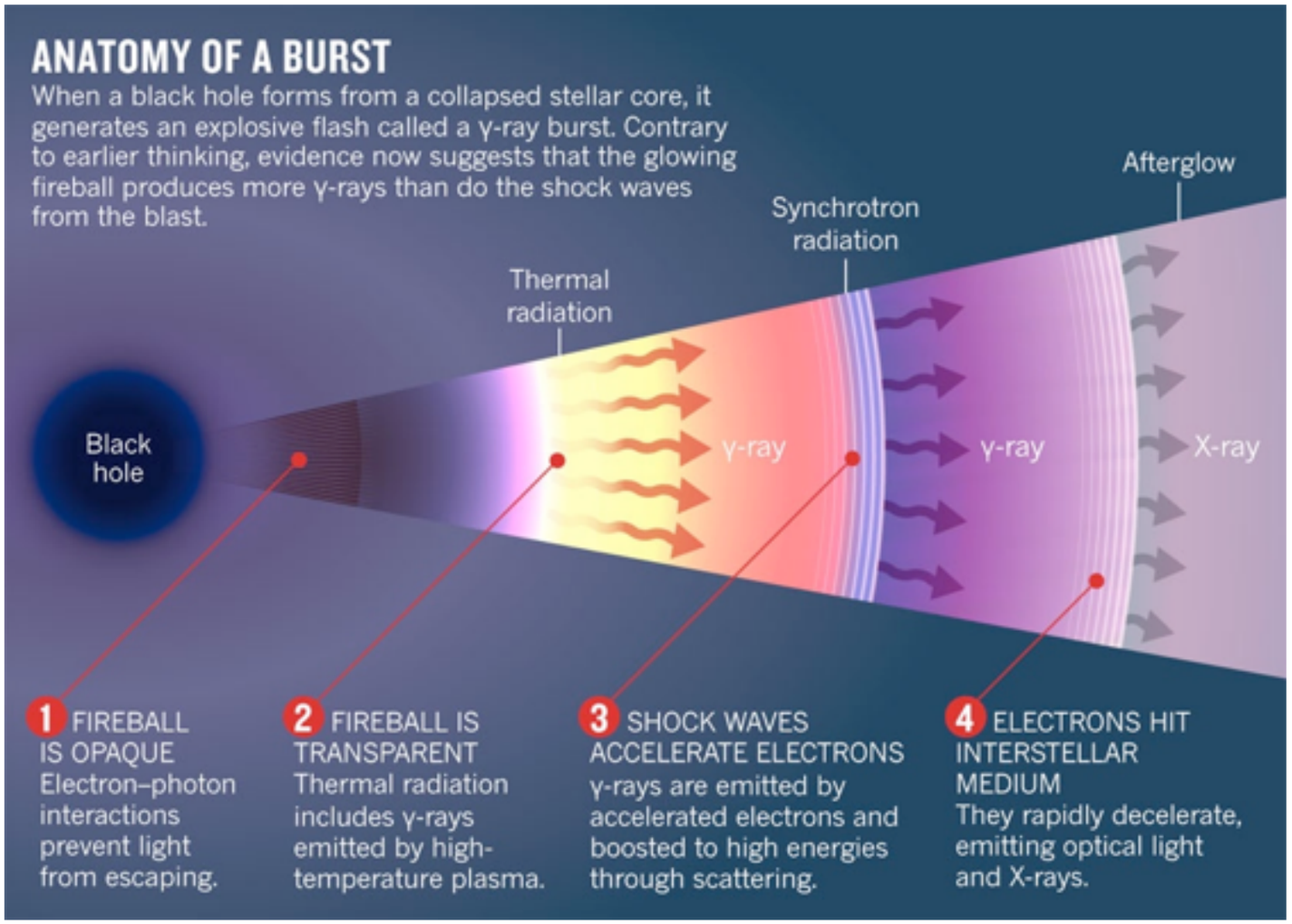
on behalf of the *Fermi* collaboration

Introduction to GRBs

Γ ≈ few x 100

$(\Gamma \equiv [1 - \beta^2]^{-1/2}, \beta \equiv v/c)$

- Transient, very bright sources
- Observe ~1 per day
- Isotropically distributed on sky
- Cosmological distance (highest z~9)
- Seen in keV to GeV energies



"Fireball" model, Mészáros (2006)

Questions before *Fermi*

Compton Gamma-Ray Observatory (1991-2000)

- COMPTEL [0.75-30 MeV]: ~40 GRBs
- EGRET TASC [1-200 MeV]: ~30 GRBs
- EGRET Spark chamber [20 MeV – 30 GeV]: 7 GRBs

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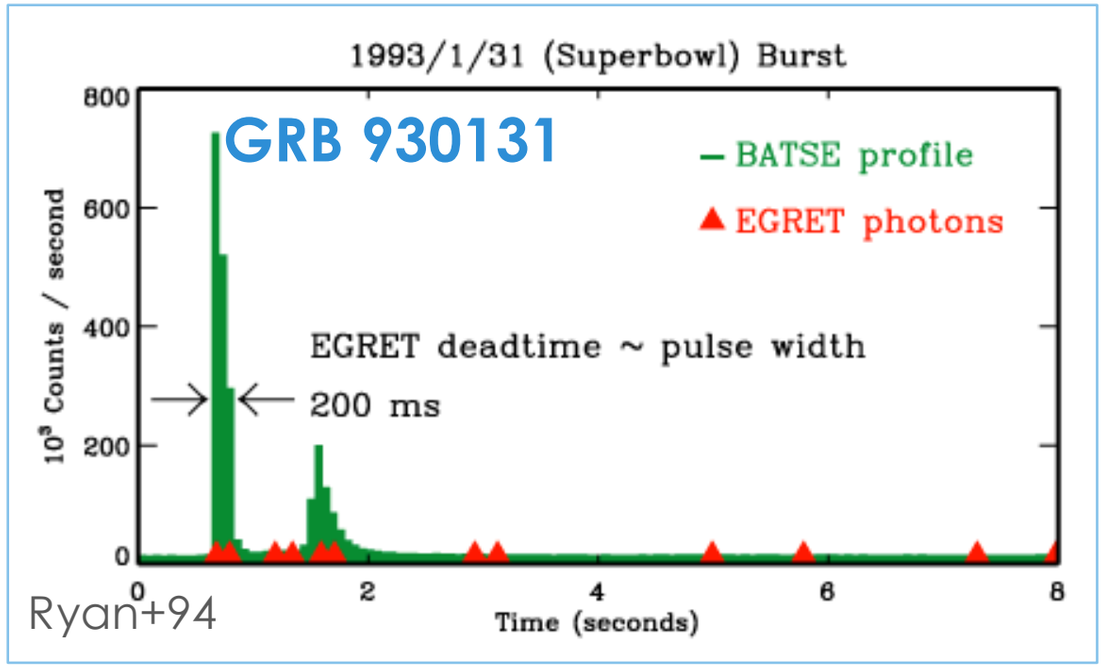

Prompt high-energy emission?

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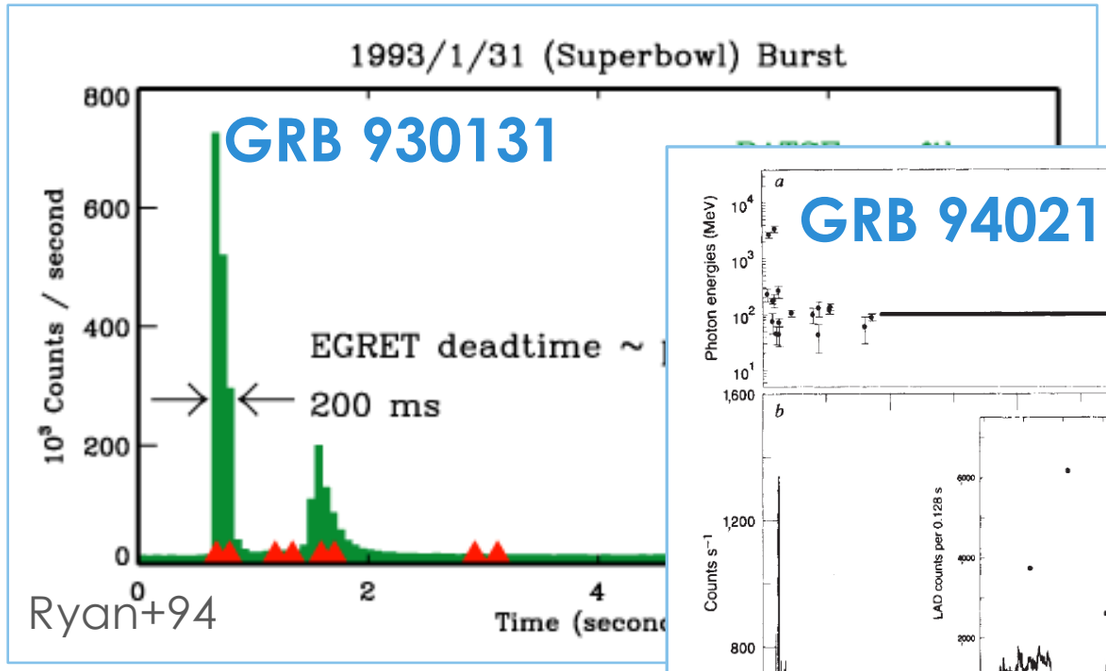

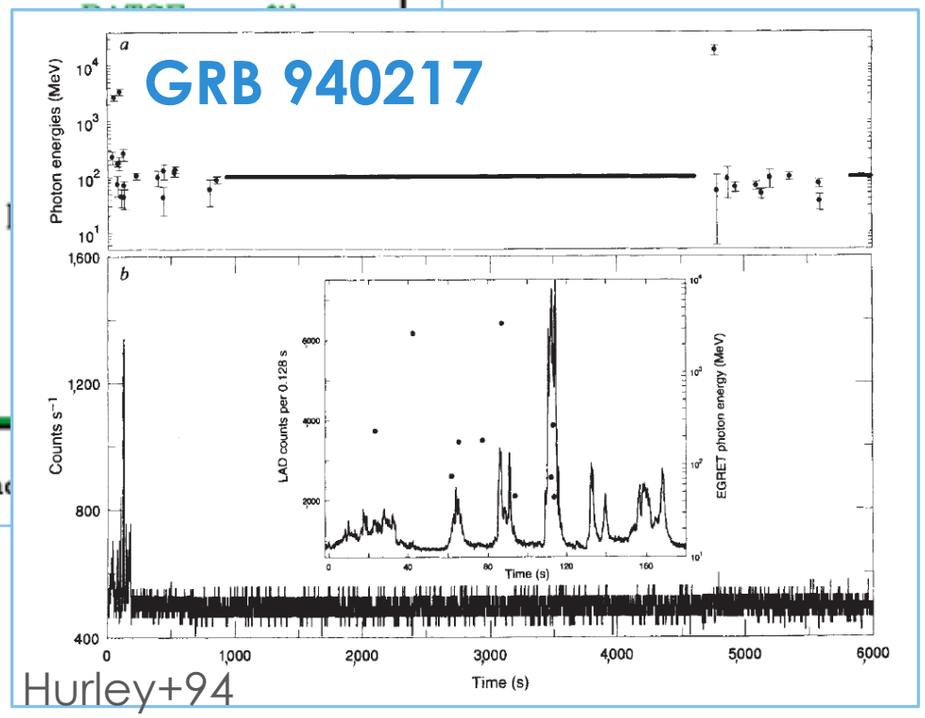

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Extended high-energy emission?

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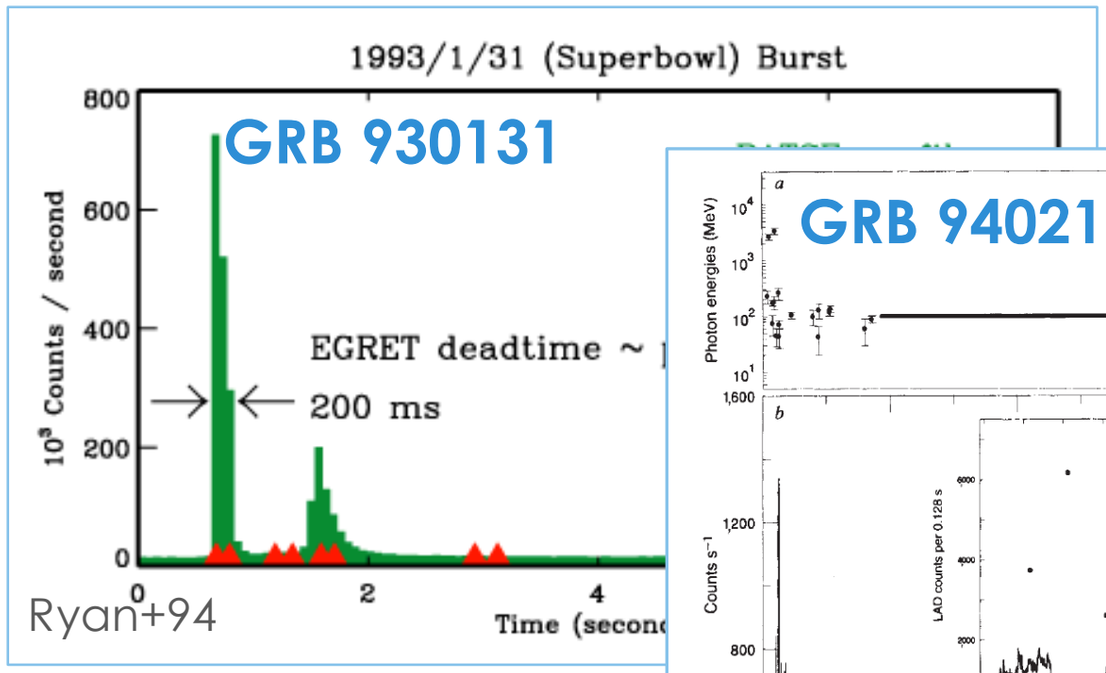
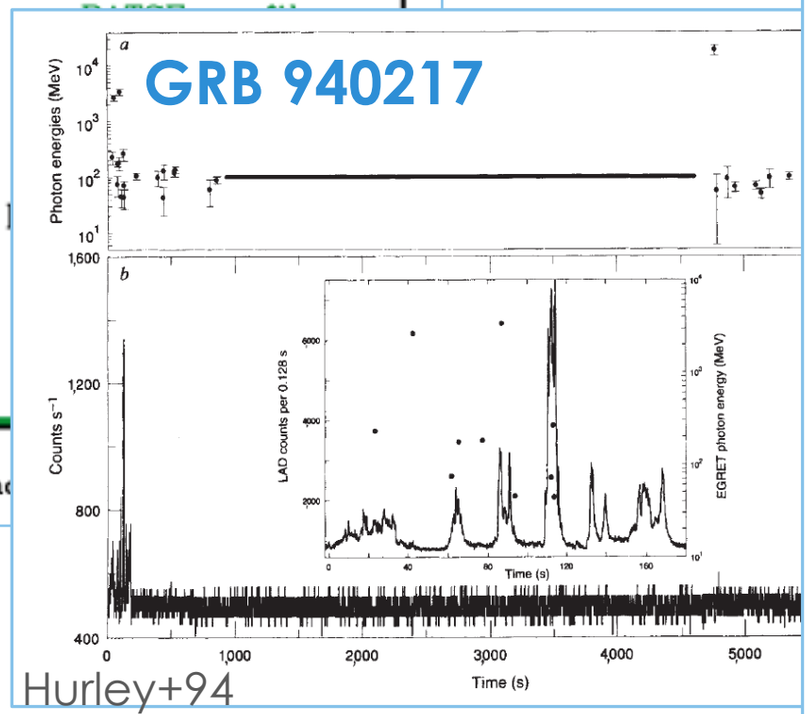
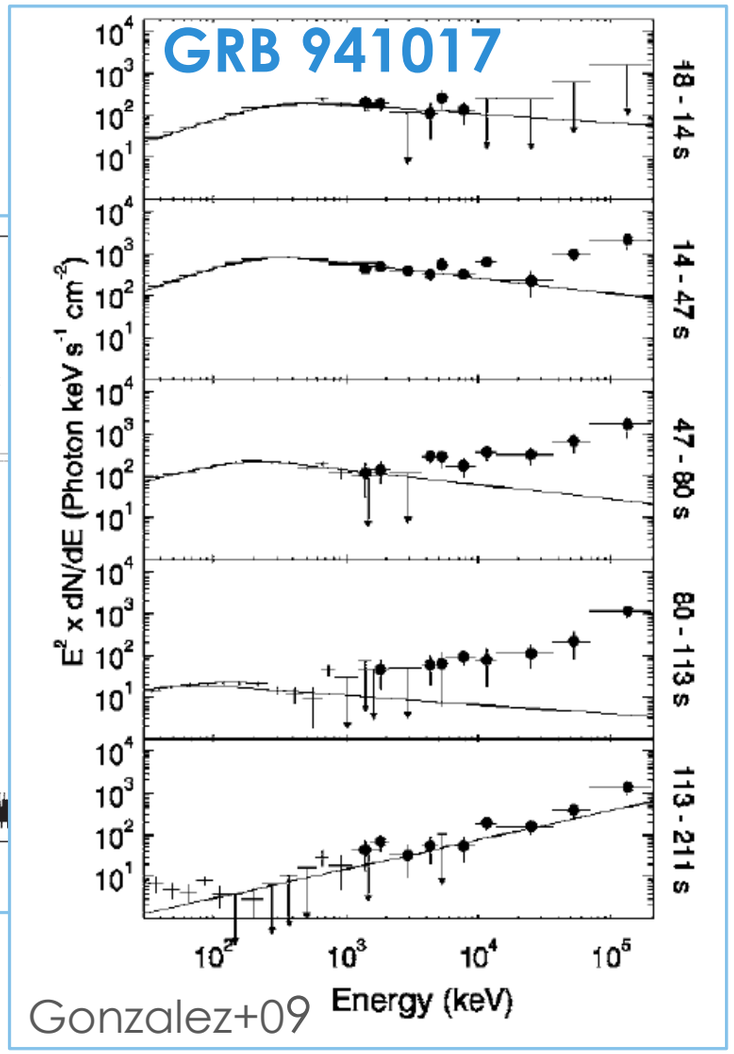






Prompt high-energy emission?

Extended high-energy emission?

Additional spectral components?

GBM-LAT synergy for GRB studies

Fermi Gamma-ray Burst monitor (GBM)

Scintillation detectors

12 NaI: 8 keV - 1 MeV

2 BGO: 200 keV - 40 MeV

Fermi Large Area Telescope (LAT)

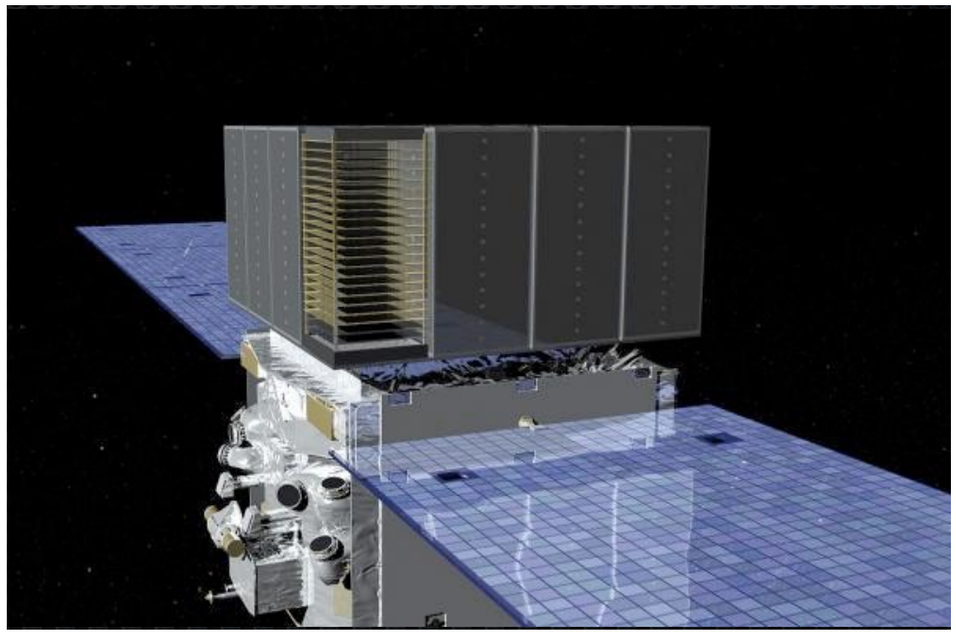
Pair conversion telescope

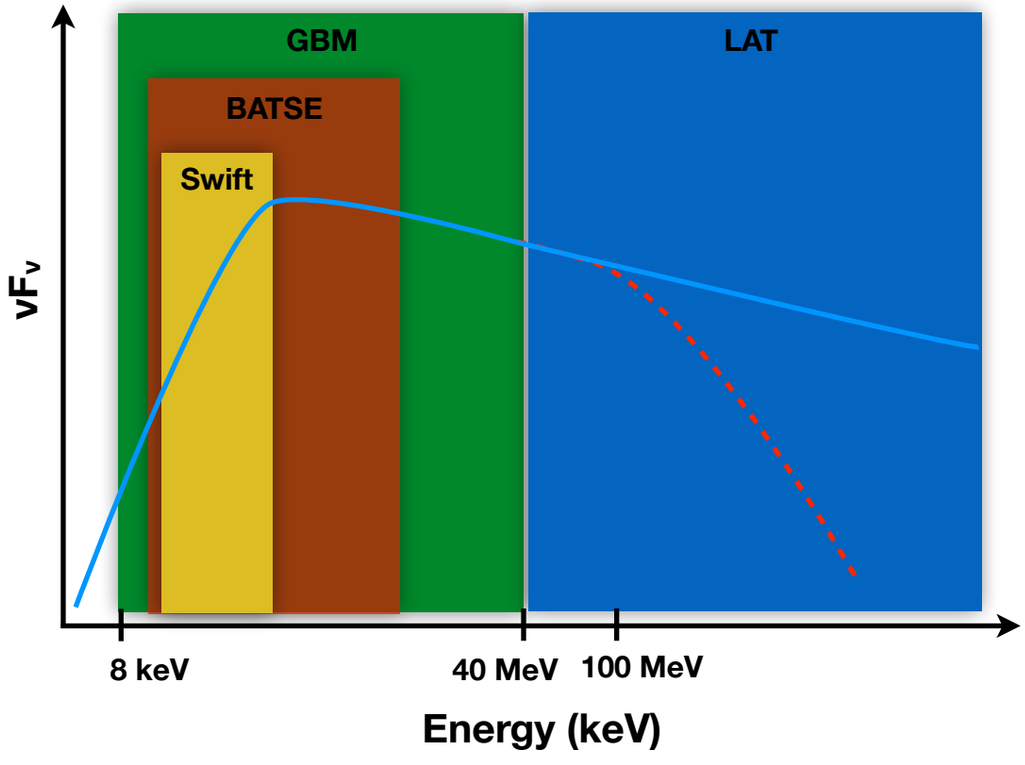
Energy coverage: 100 MeV to >300 GeV

LAT Low Energy data: >30 MeV

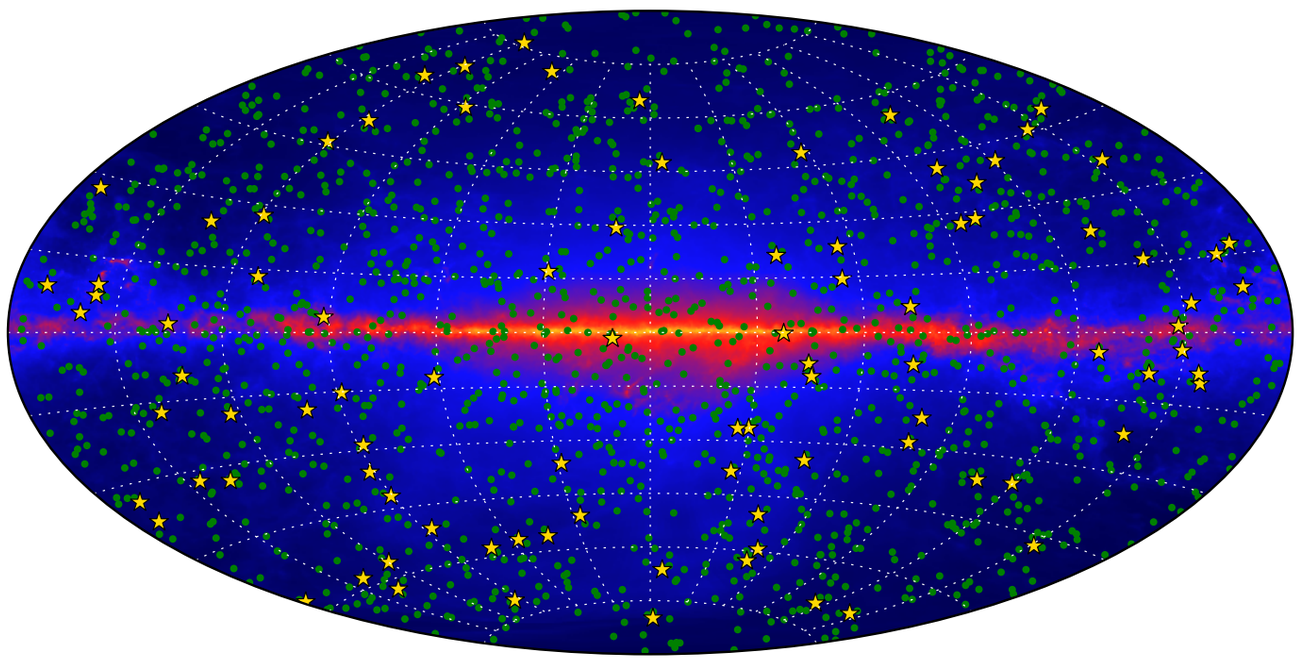
Unprecedented energy coverage

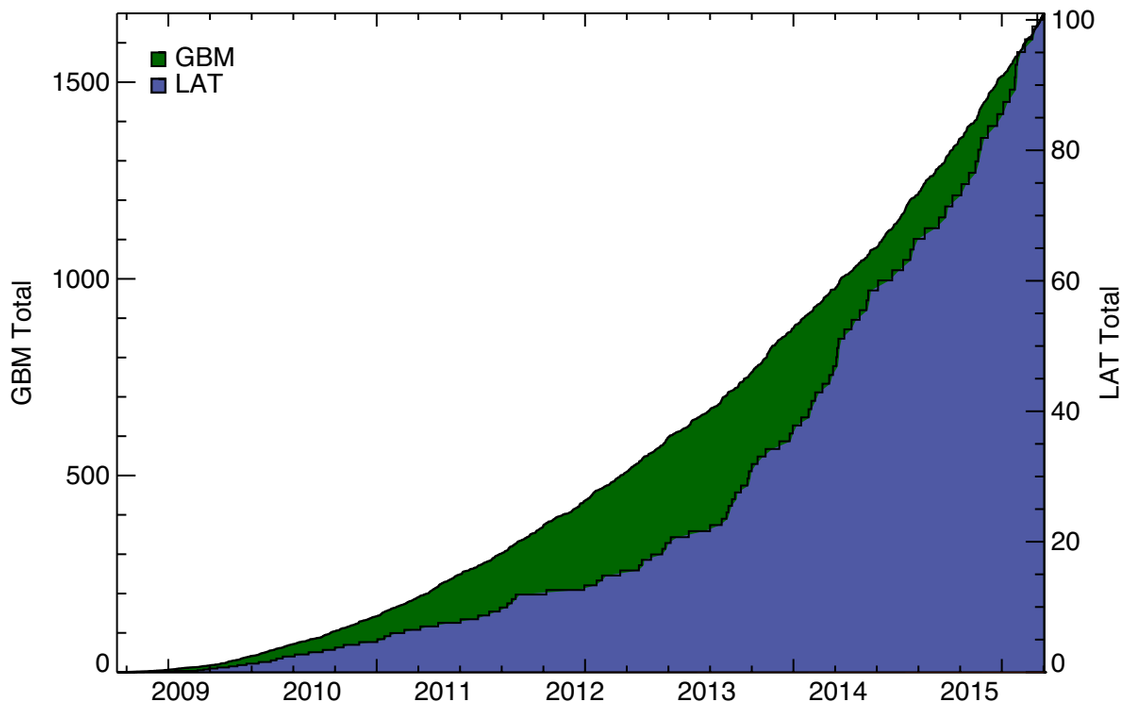
Both instruments can independently trigger on bright transients





GRB detections

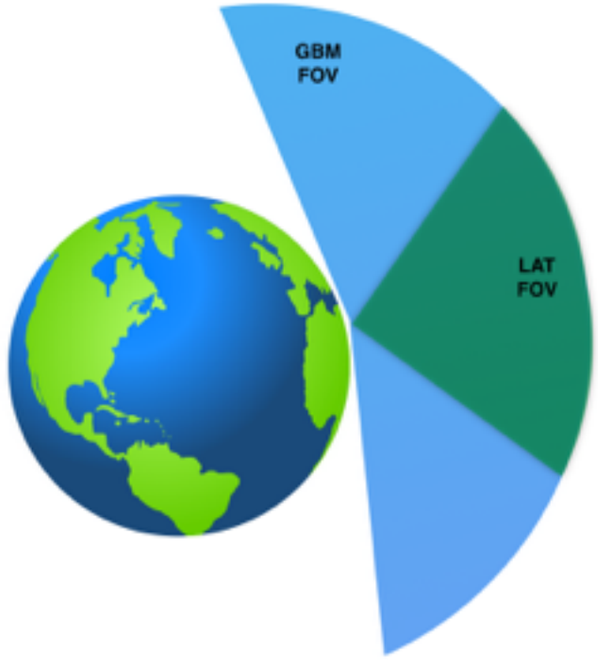




GBM detections: ~250/year - Green

LAT detections: ~15/year - Gold

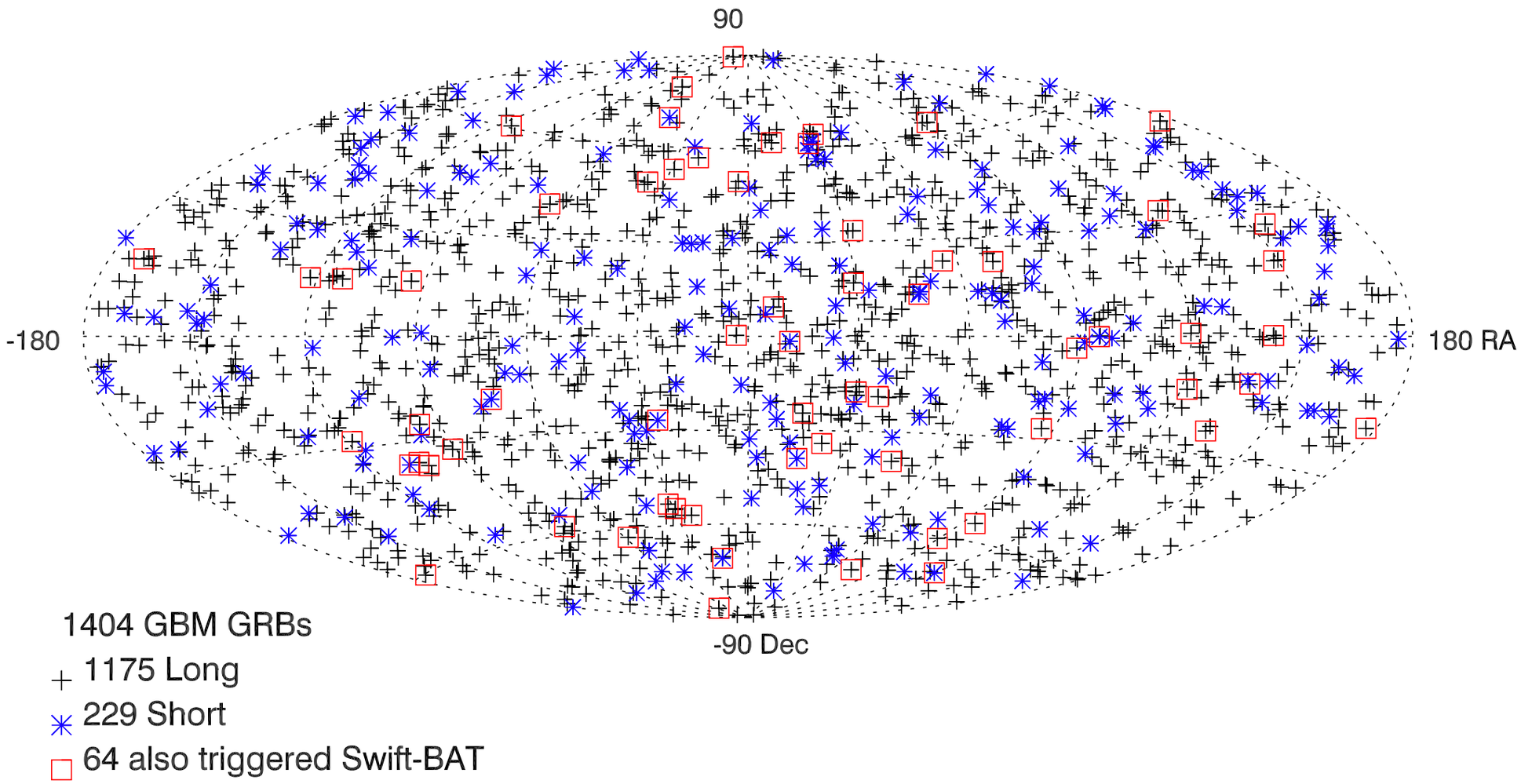
- GRBs in LAT field of view: ~46%
- LAT detections: ~8%



Fermi GRB results

- ***Fermi* GRB publications**
  - ~30 GBM-led papers
    - 5 catalogs
    - Individual GRBs, population studies, correlations
  - ~40 LAT-led papers
    - ~25 papers dedicated to individual GRBs
    - Prospects, upper limits, **catalog**, techniques

GBM catalogs

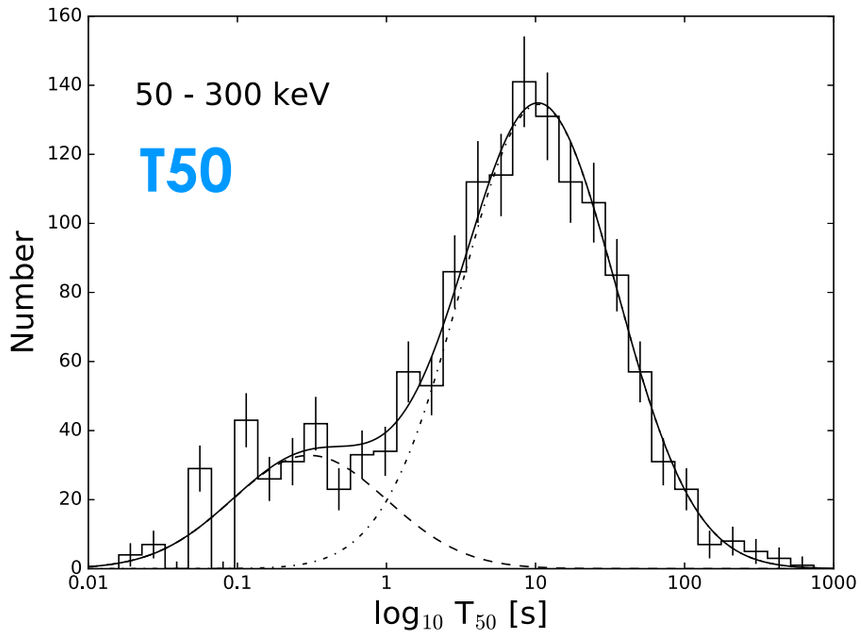


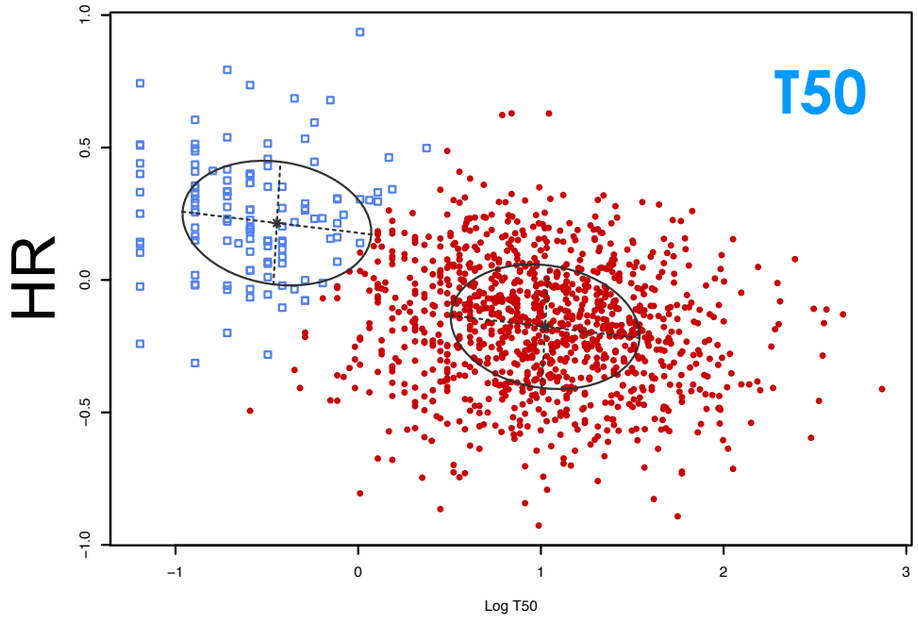
The third *Fermi* GBM Gamma Ray burst catalog: the first six years (Bhat et al. 2016)

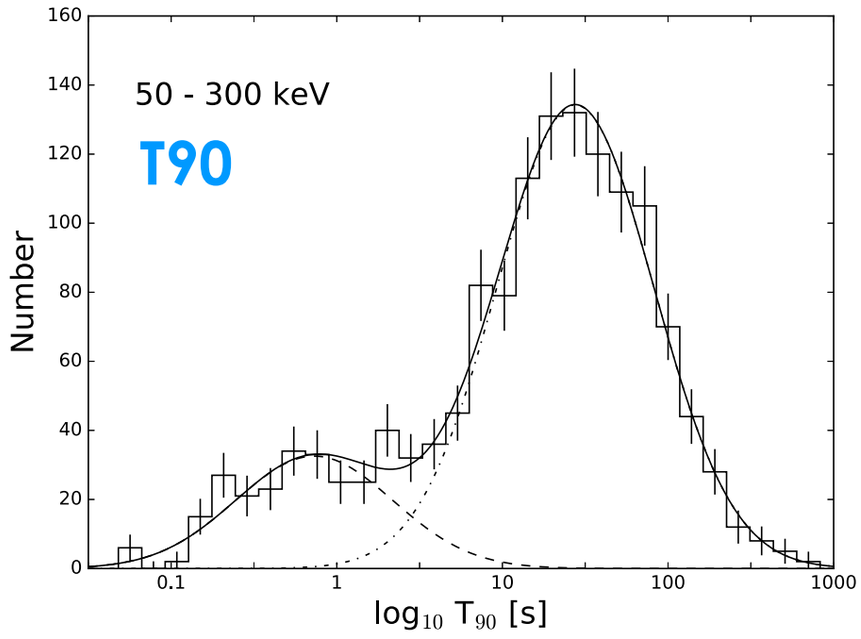
The *Fermi* GBM Gamma-Ray burst **spectral catalog:** four years of data (Gruber et al. 2014)

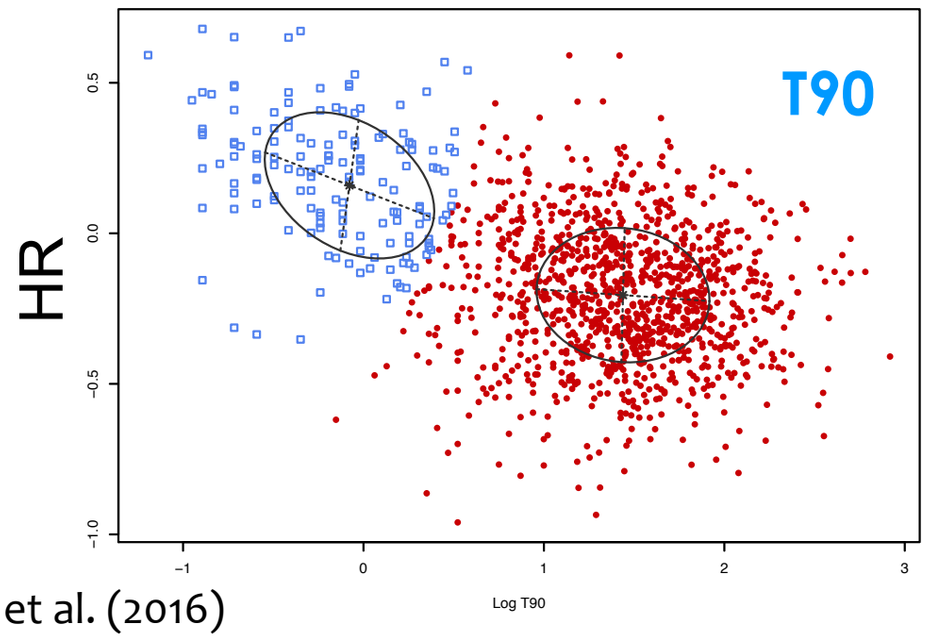
Systematic studies

- With the large sample of GRBs detected by the GBM, systematic studies are possible.









Bhat et al. (2016)

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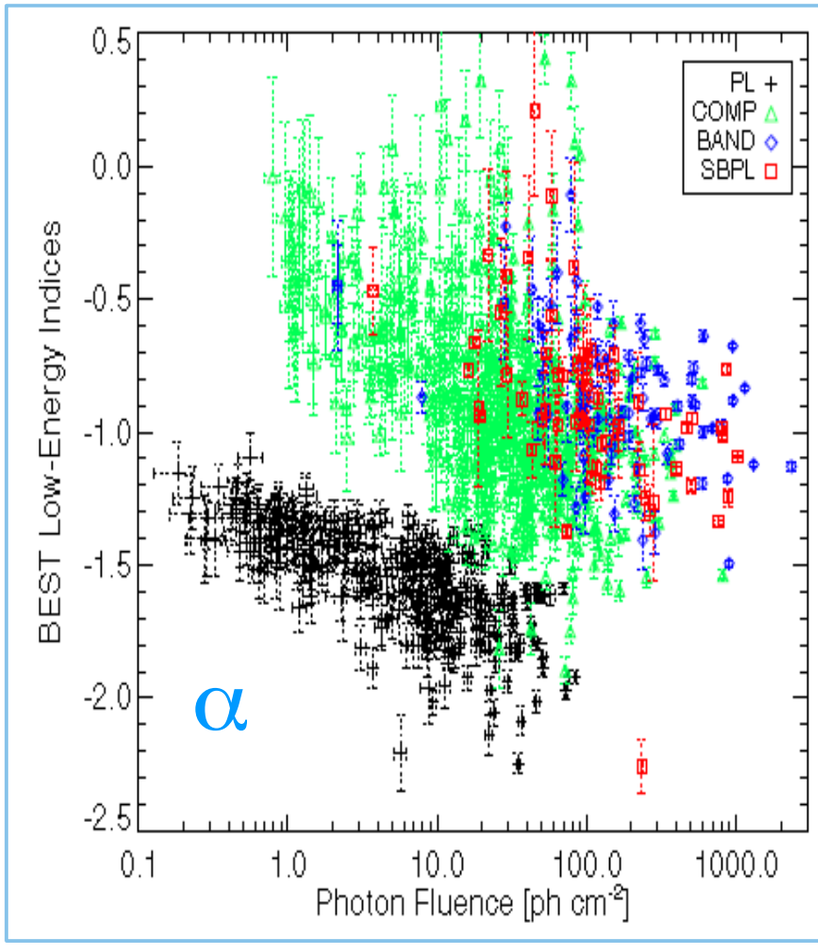
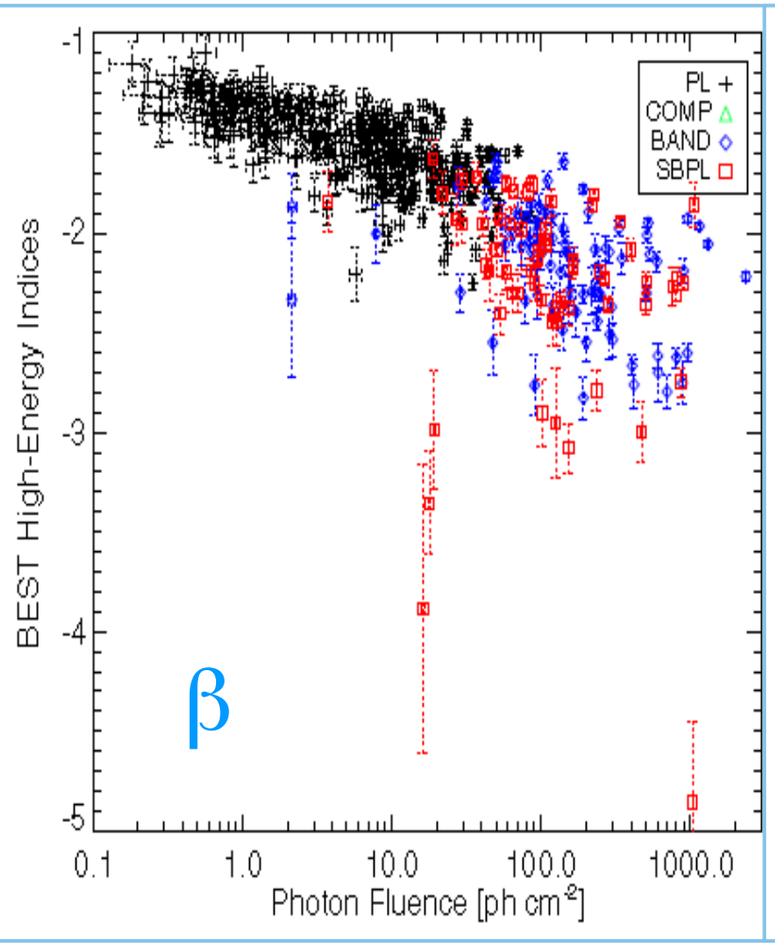
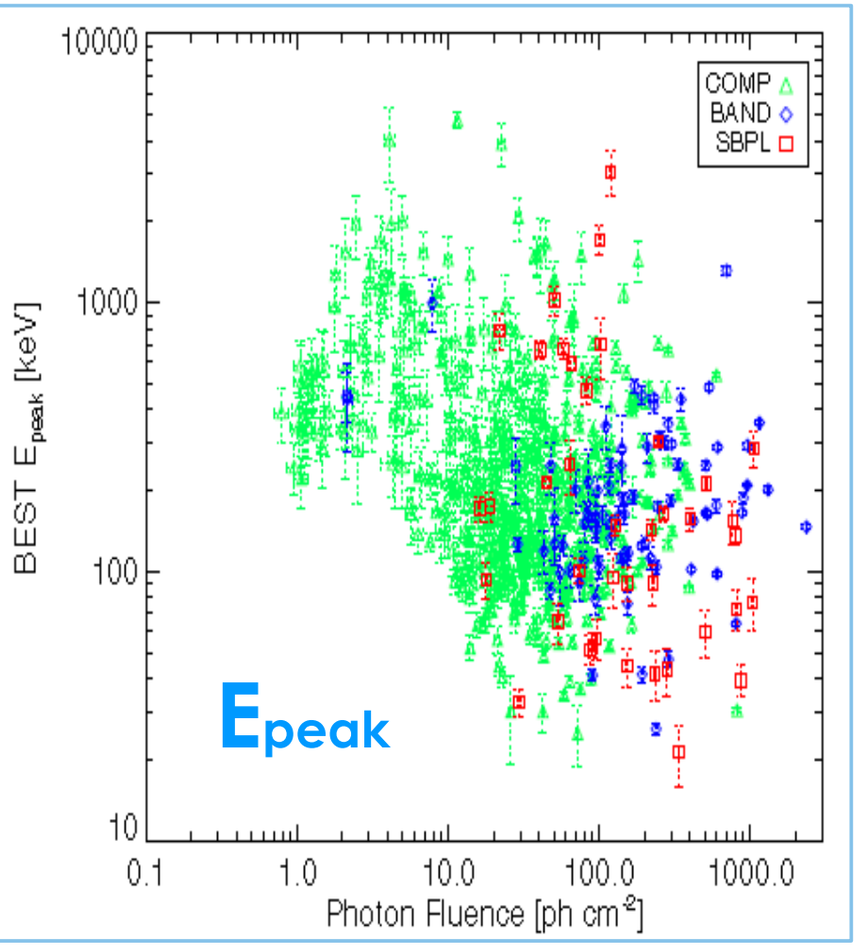
Spectral parameters

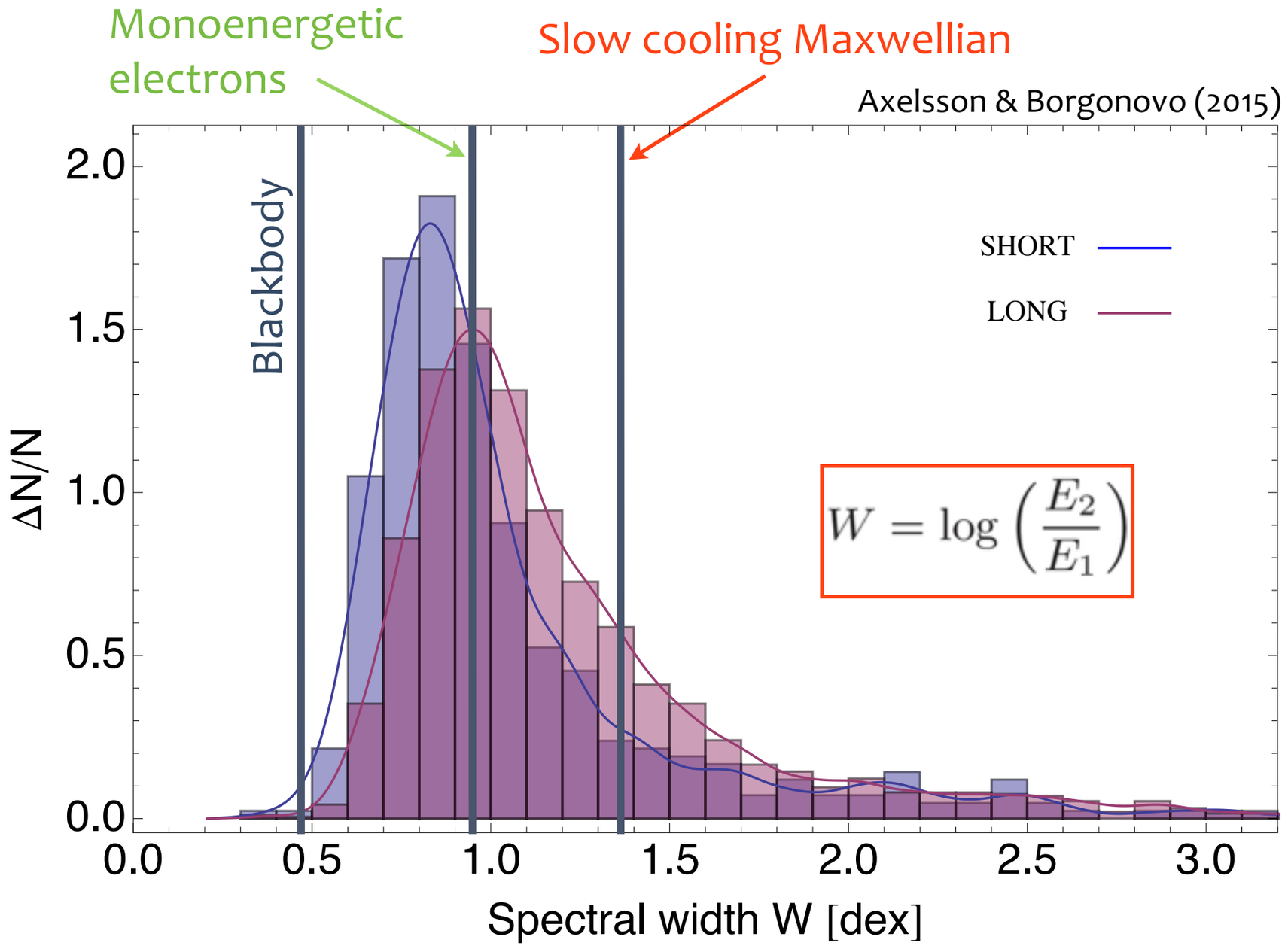






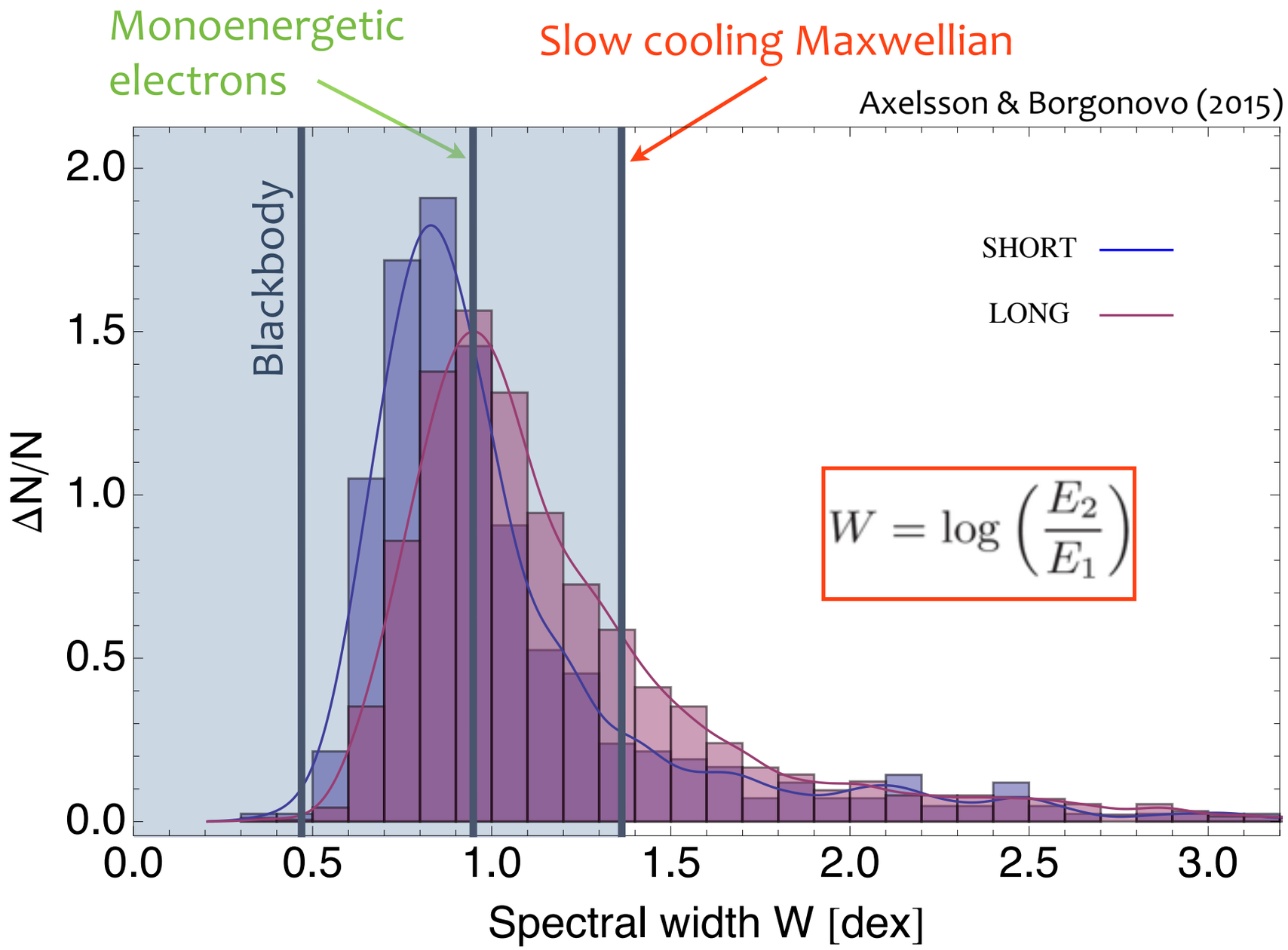
Gruber et al. (2014)

Systematic studies



- Study the width of spectra
- Significant difference between long and short GRBs
- Most spectra are too narrow for synchrotron!

Systematic studies



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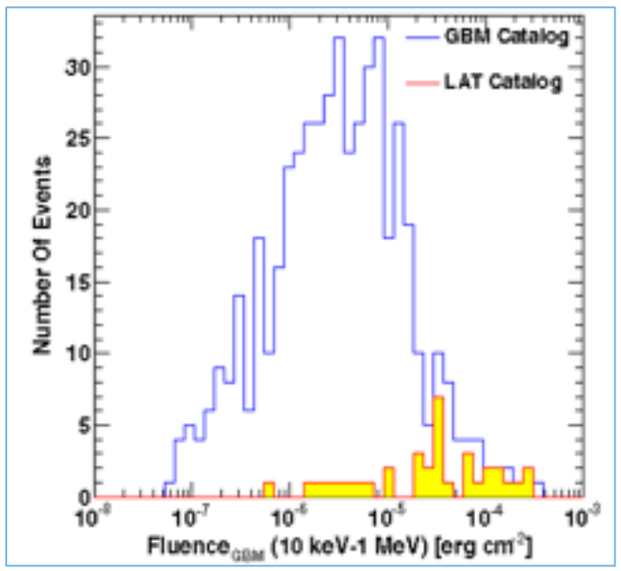
First LAT Catalog

35 LAT-detected GRBs

(Ackermann et al. 2013, ApJSS)

GRB Name	Date	GBM Trigger Time (MET[a])	R.A. Deg., J2000	Decl. Deg., J2000	θ Deg.	Loc. Err[b]	Like.	LLE	Redshift	LAT GCN Number
080825C	2008 Aug 25 14:13:48.1	241366429.105	233.9	−4.5	60.3	0.°75[y]	1	0	...	8183
080916C	2008 Sep 16 00:12:45.6	243216766.614	119.85	−56.64	48.8	0.°36[e]	1	1	4.35	8246
081006	2008 Oct 6 14:29:34.1	244996175.173	136.32	−62.05	11.0	0.°52[y]	1	0	...	
081024B	2008 Oct 24 21:22:40.8	246576161.864	322.95	21.2	18.7	0.°22[y]	1	1	...	8407
090217	2009 Feb 17 04:56:42.5	256539404.560	204.83	−8.42	34.5	0.°35[y]	1	1	...	8903
090227B	2009 Feb 27 18:31:01.4	257452263.410	10.48	29.24	71.0	1.°00[A]	1	1	...	
090323	2009 Mar 23 00:02:42.6	259459364.630	190.71	17.053	57.2	0.°36*	1	1	3.57	9021
090328	2009 Mar 28 09:36:46.5	259925808.510	90.67	−41.715	64.6	0.°72*	1	1	0.74	9044, 9077
090510	2009 May 10 00:22:59.9	263607781.971	333.55	−26.583	13.6	1.°44*	1	1	0.90	9334, 9350
090531B	2009 May 31 18:35:56.4	265487758.490	252.07	−36.015	21.9	2.°10*	0	1	...	
090626	2009 Jun 26 04:32:08.8	267683530.880	170.03	−33.49	18.3	0.°22[y]	1	0	...	9584
090720B	2009 Jul 20 17:02:56.9	269802178.905	202.99	−54.21	56.1	0.°33[y]	1	0	...	
090902B	2009 Sep 2 11:05:08.3	273582310.313	264.94	27.324	50.8	3.°60*	1	1	1.82	9867, 9872
090926A	2009 Sep 26 04:20:26.9	275631628.990	353.4	−66.32	48.1	0.°60*	1	1	2.11	9934, 9972
091003	2009 Oct 3 04:35:45.5	276237347.585	251.52	36.625	12.3	1.°80*	1	0	0.90	9985
091031	2009 Oct 31 12:00:28.8	278683230.850	71.49	−57.65	23.9	0.°23[y]	1	1	...	10163
091208B	2009 Dec 8 09:49:57.9	281958599.956	29.392	16.89	55.6	1.°80*	1	0	1.06	
100116A	2010 Jan 16 21:31:00.2	285370262.240	305.01	14.43	26.6	0.°17[y]	1	1	...	10333
100225A	2010 Feb 25 02:45:31.1	288758733.147	310.3	−59.4	55.5	3.°13[t]	0	1	...	10450
100325A	2010 Mar 25 06:36:08.0	291191770.020	330.24	−26.45	7.1	0.°60[y]	1	0	...	10548
100414A	2010 Apr 14 02:20:21.9	292904423.990	192.11	8.693	69.0	1.°80*	1	0	1.37	10594
100620A	2010 Jun 20 02:51:29.1	298695091.100	86.9	−50.91	24.3	0.°71[y]	1	0	...	
100724B	2010 Jul 24 00:42:05.9	301624927.980	119.89	76.55	48.9	0.°88[y]	1	1	...	10978
100728A	2010 Jul 28 02:17:30.6	301976252.610	88.758	−15.255	59.9	0.°36[e]	1	0	...	
100826A	2010 Aug 26 22:58:22.8	304556304.898	279.593	−22.128	73.3	1.°20[A]	0	1	...	11155
101014A	2010 Oct 14 04:11:52.6	308722314.620	27.206	−50.819	54.0	1.°0[t]	0	1	...	11349
101123A	2010 Nov 23 22:51:34.9	312245496.973	135.16	1.91	78.2	3.°16[t]	0	1	...	
110120A	2011 Jan 20 15:59:39.2	317231981.230	61.5	−12.0	13.6	0.°36[y]	1	0	...	11597
110328B	2011 Mar 28 12:29:19.1	323008161.194	121.06	45.84	31.7	3.°23[t]	0	1	...	11835
110428A	2011 Apr 28 09:18:30.4	325675112.410	5.59	64.849	34.6	0.°04*	1	0	...	11982
110529A	2011 May 29 00:48:42.8	328322924.872	118.33	67.91	30.0	3.°35[t]	0	1	...	12044
110625A	2011 Jun 25 21:08:18.2	330728900.236	286.73	6.755	87.9	0.°36*	1	0	...	12097, 12100
110709A	2011 Jul 9 15:24:27.4	331917869.400	238.895	40.918	53.4	1.°08*	1	0	...	
110721A	2011 Jul 21 04:47:43.7	332916465.760	333.2	−38.5	40.7	0.°20[A]	1	1	...	12188
110731A	2011 Jul 31 11:09:29.9	333803371.954	280.504	−28.537	3.4	0.°36*	1	1	2.83	12218



Typically the brightest GBM bursts

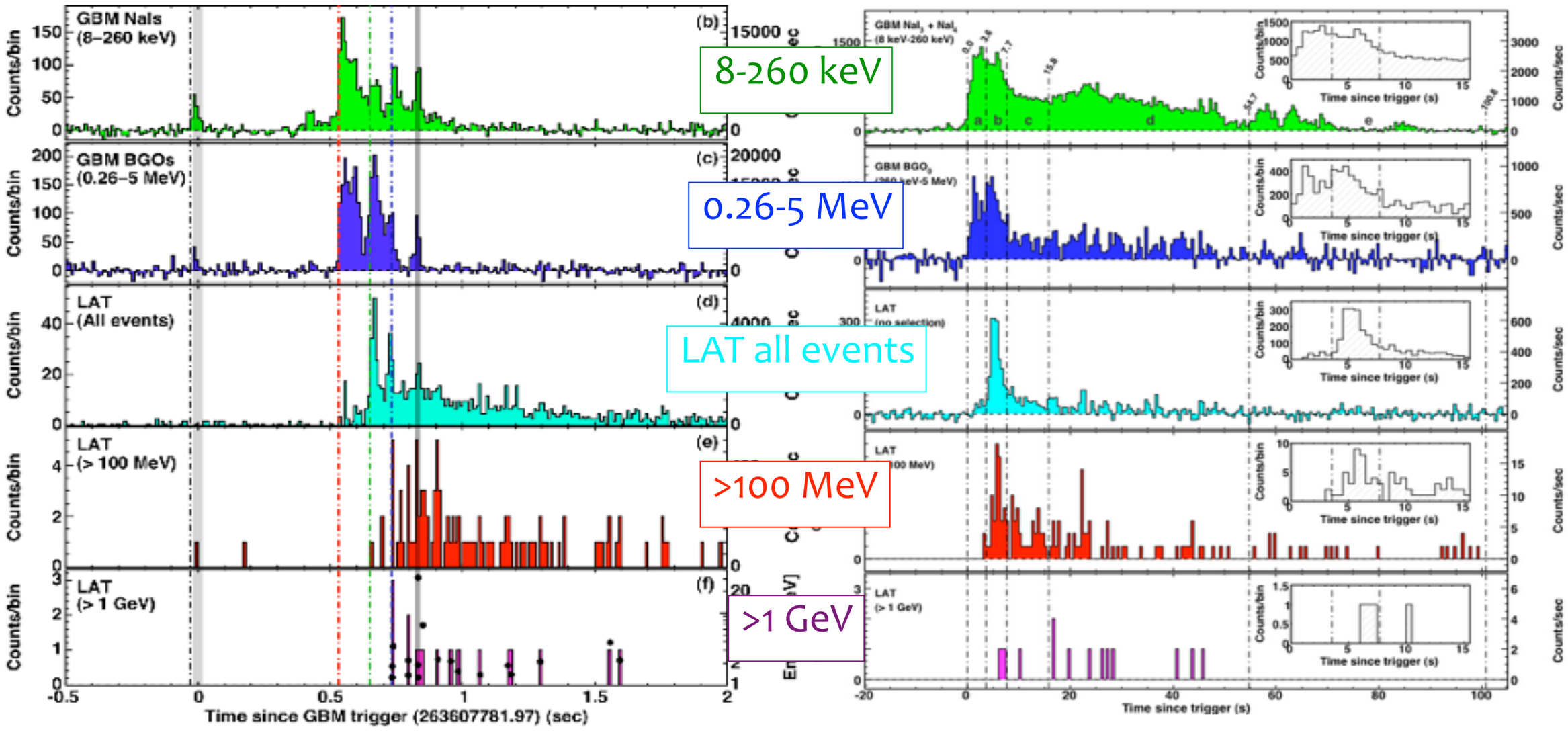
Properties: Delayed onset and extended emission

GRB 090510 (short)

Abdo et al. 2009, Nature 462, 331

GRB 080916C (long)

Abdo et al. 2009, Science 323, 1688



Delay: ~0.5s

Delay: ~5s

More than half of LAT-detected GRBs show delayed onset!

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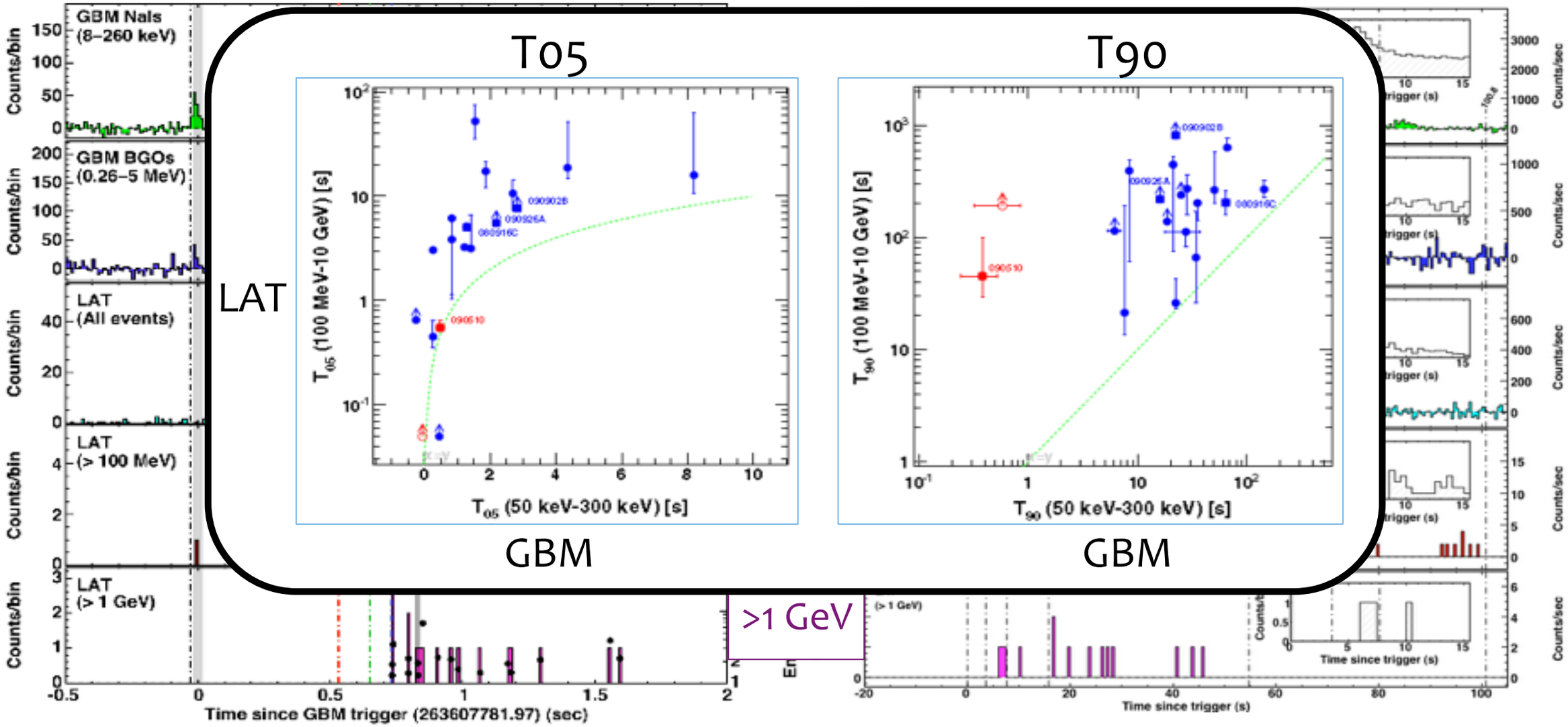


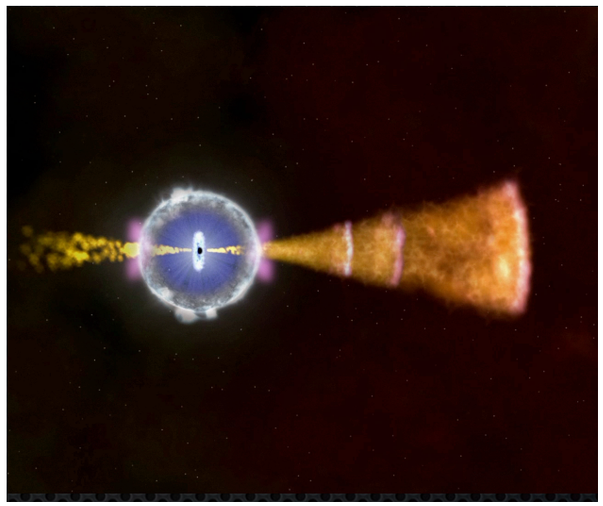
Delay: ~0.5s

Delay: ~5s

More than half of LAT-detected GRBs show delayed onset!

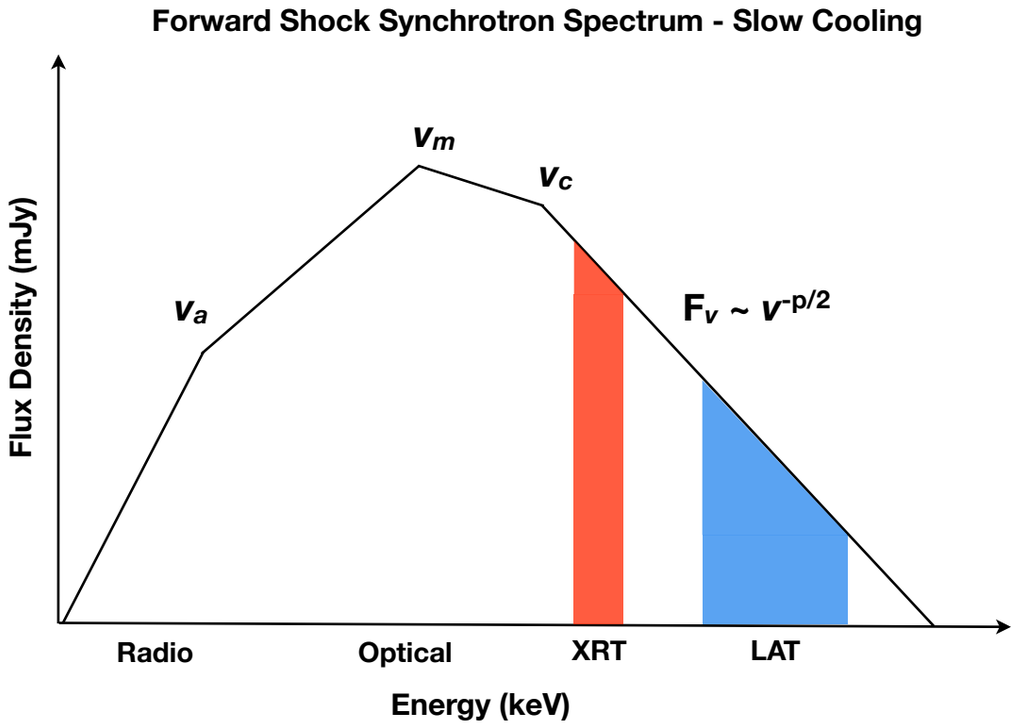
Origin of high-energy emission

Delayed onset and long duration of high-energy emission disfavors inverse Compton or SSC of low-E (keV) emission.



Synchrotron emission from external shock more likely.
(Kumar & Barniol Duran 2009)

In order to test this, good quality contemporaneous data is needed.



Origin of high-energy emission

GRB 110731A

Detected by LAT up to 1000s

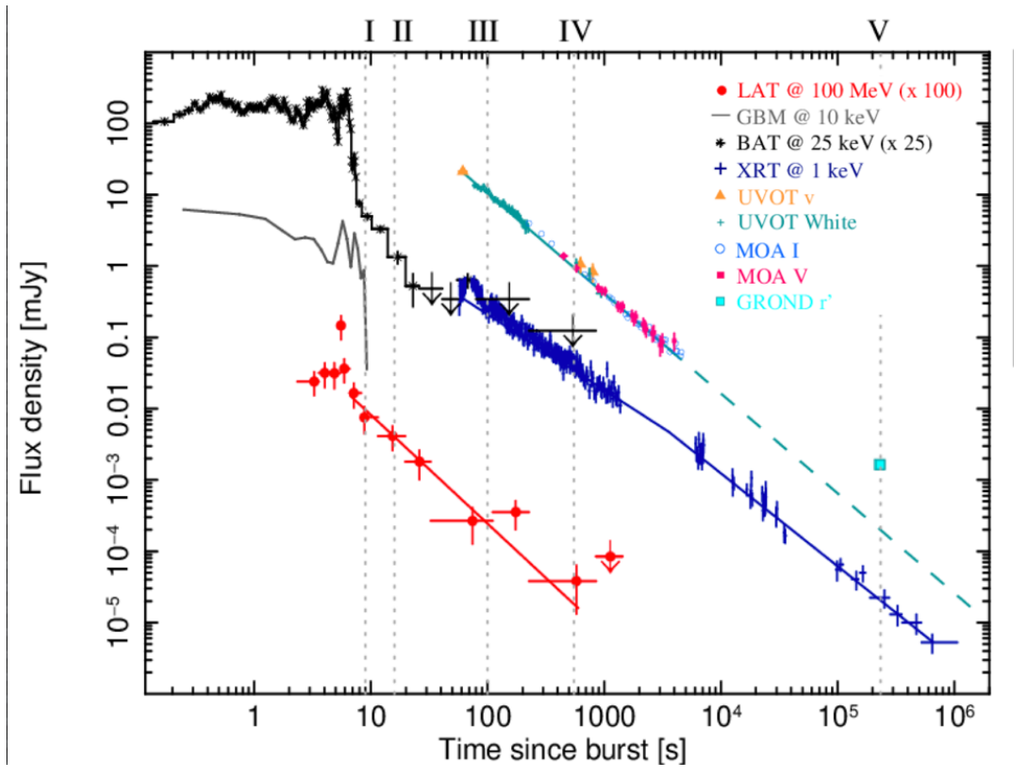
Simultaneous observations with Swift-XRT

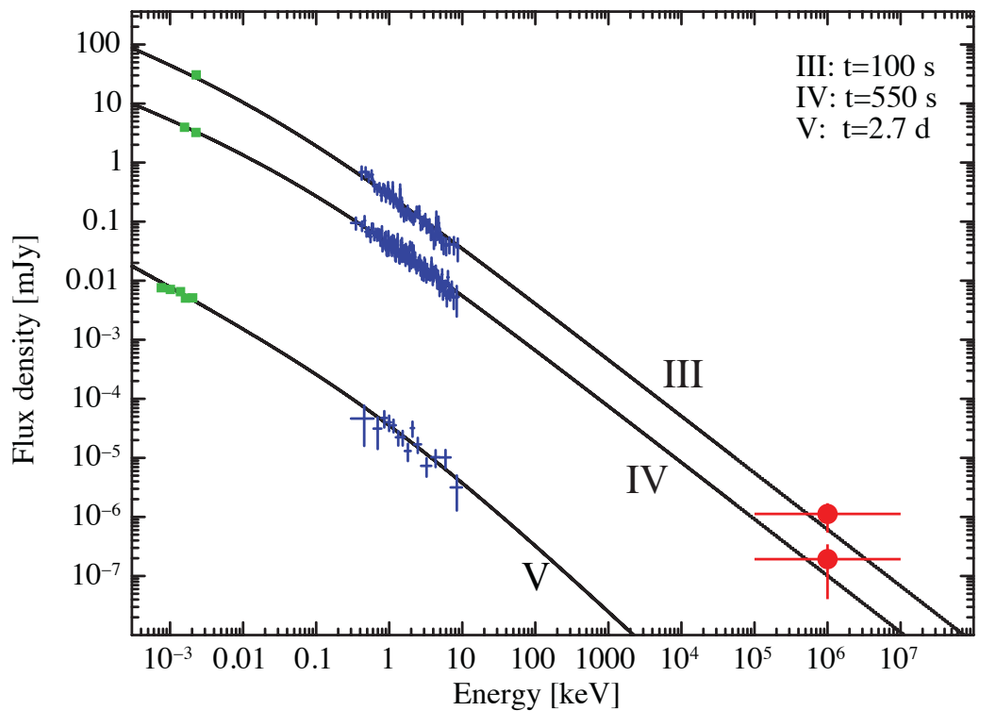
Contemporaneous data from UVOT, GROND and MOA.

In total, data span 10 orders of magnitude!

Broadband spectrum is well fit by a single power-law

Ackermann et al. (2013)





Origin of high-energy emission

GRB 130427A

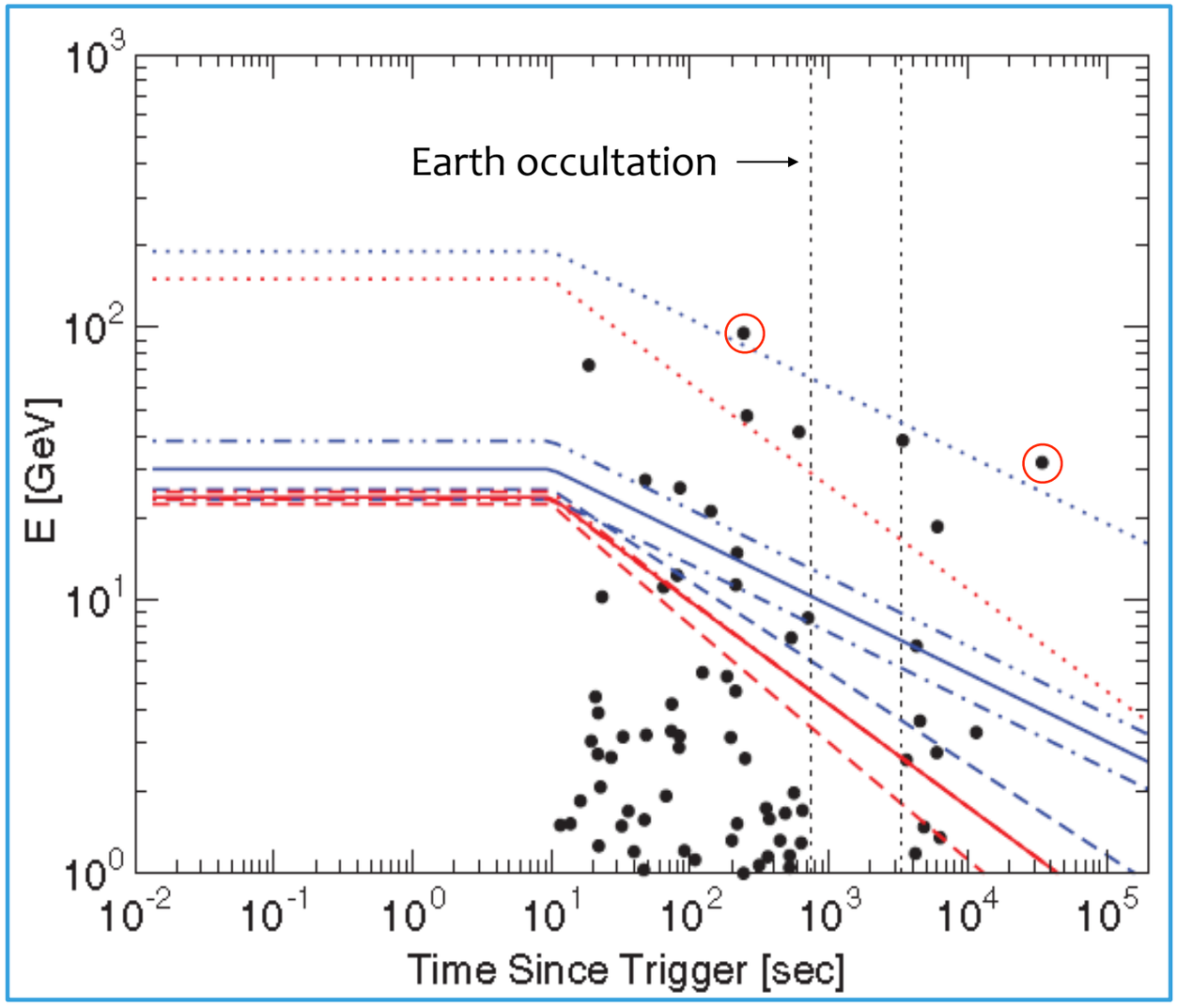
The brightest GRB detected by *Fermi*

High-energy emission detected for almost a day after the trigger

Good statistics means we can use LAT emission to constrain the circumburst medium --> wind-like density profile best fit.

Highest energy photon is 95 GeV at ~200 s after trigger - problematic for models.

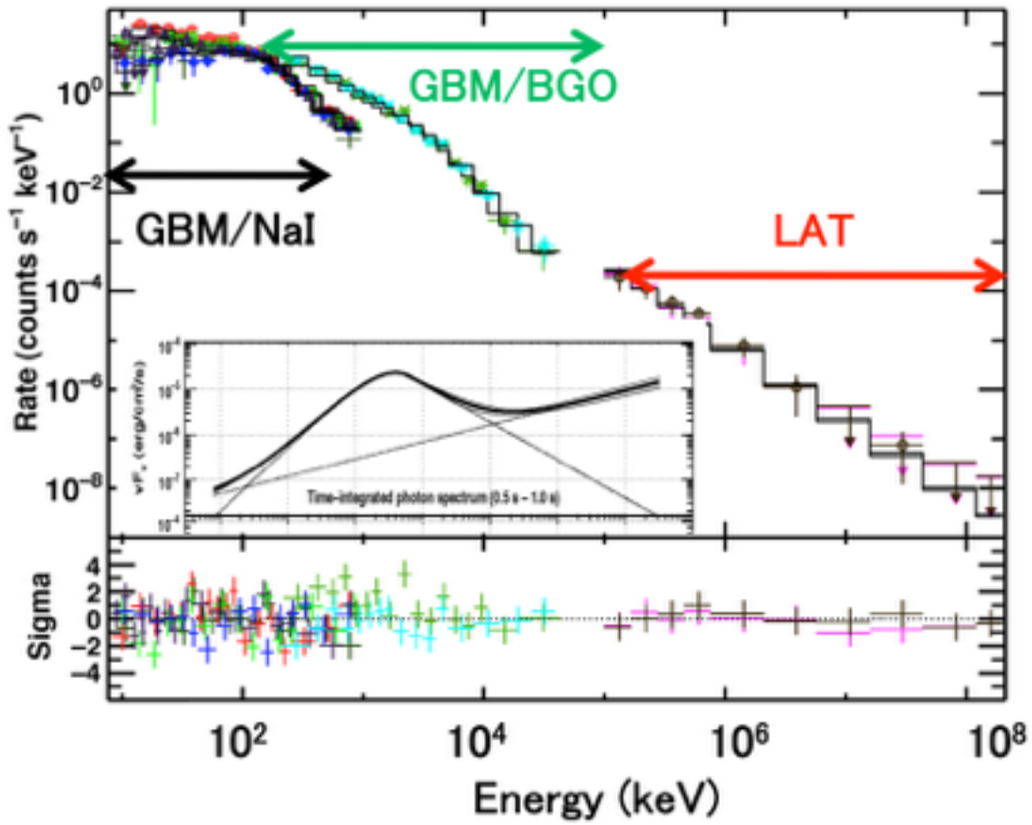
Ackermann et al. (2014)



Properties: Extra high-energy spectral component

GRB 090510 (short)

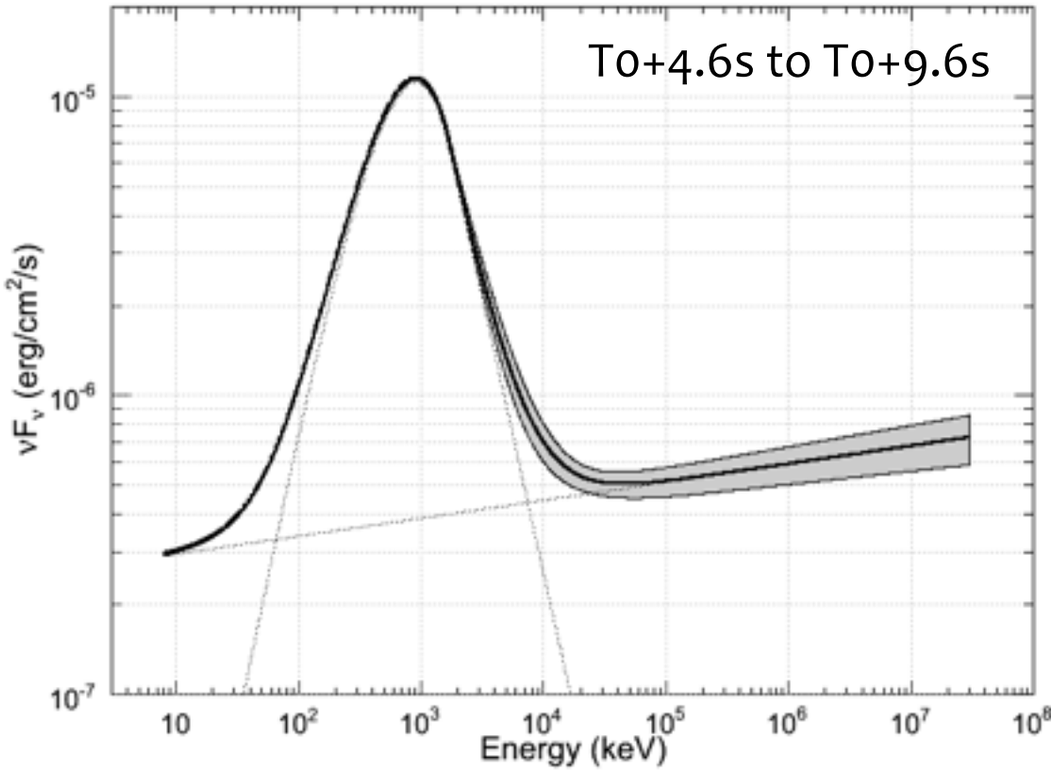
Abdo, A. A. et al. (2010)



First extra component seen by *Fermi* at > 5 sigma level

GRB 090902B (long)

Abdo, A. A. et al., ApJL 706, 138 (2009)



First time a low-energy extension of the PL component was seen

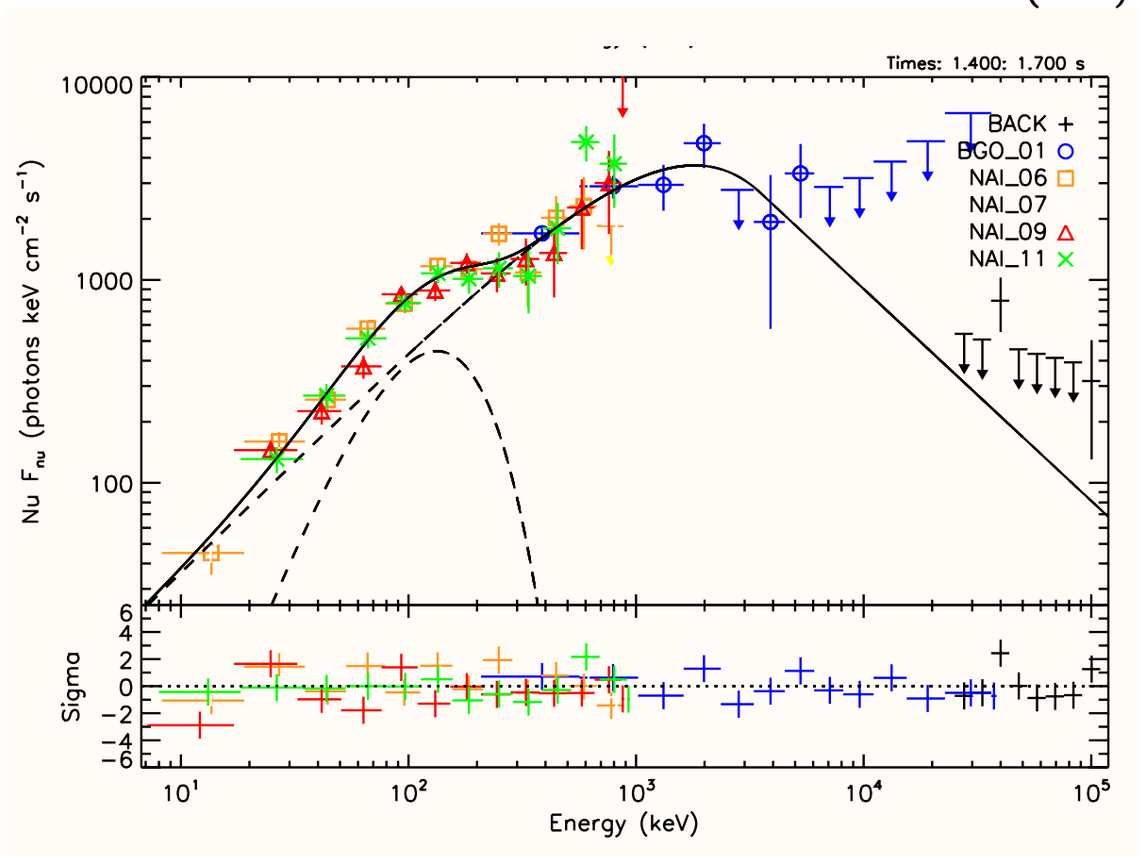
Photospheric emission?

Several GRBs also show signs of an extra component at low energies (~100 keV)

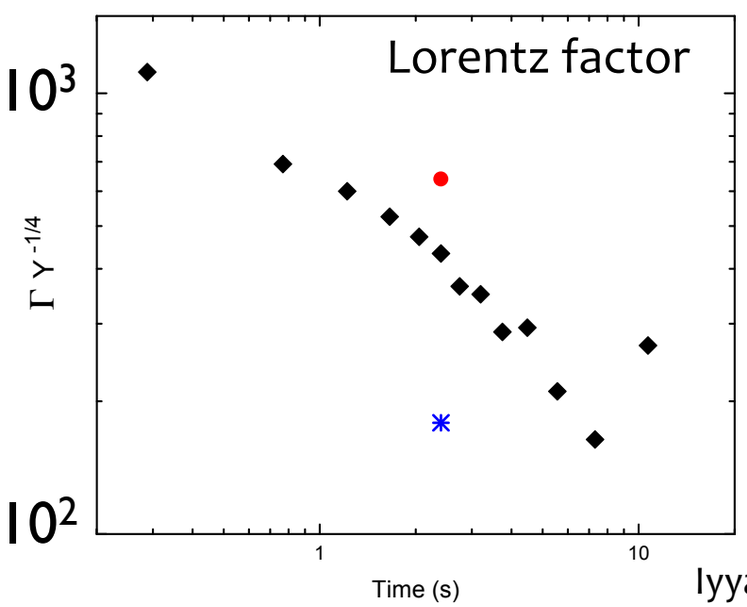
This has been interpreted as photospheric emission.

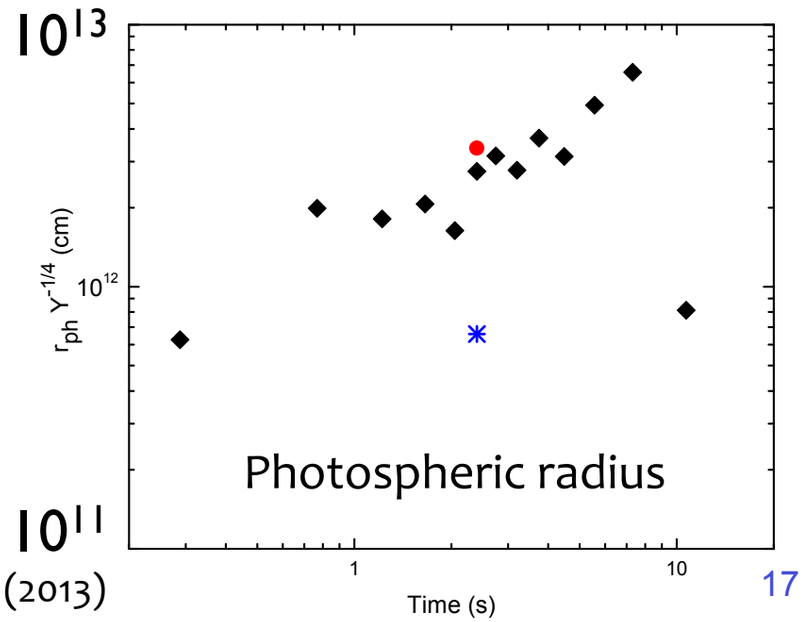
In GRB110721A, the significance is >5σ.

Axelsson et al. (2012)



Ties emission to a physical process - can derive properties of the outflow.





Iyyani et al. (2013)

Band crisis?

The Best Spectral Model for the GRB During the GBM Interval, Ordered by Fluence

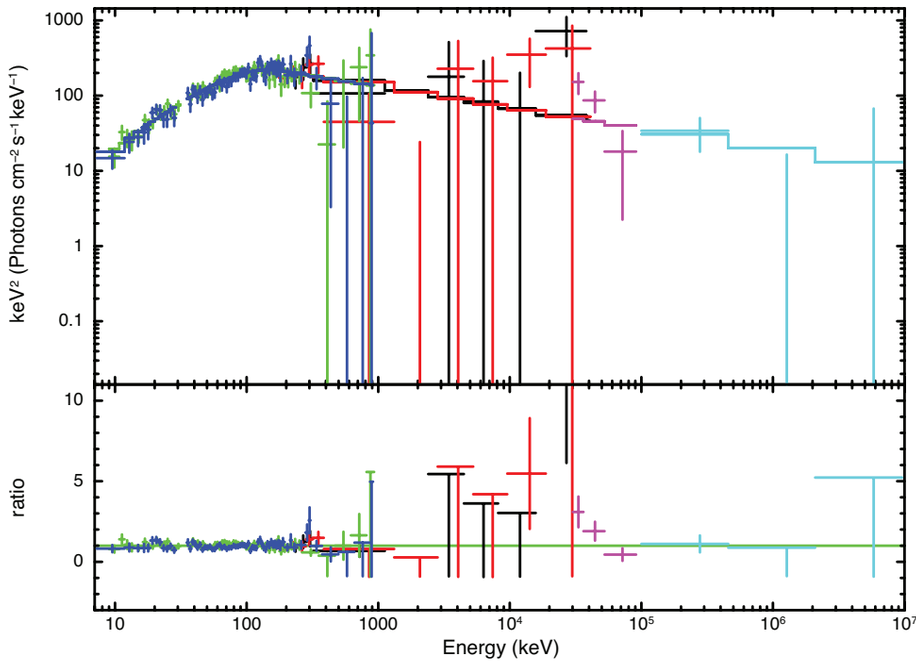
GRB Name	Fluence 10 keV–10 GeV (10^{-7} erg cm^{-2})	Best Model	θ (deg)
100724B	4665^{-76}_{+78}	Band with exponential cutoff	48.9
090902B	4058^{-24}_{+25}	Comptonized + power law	50.8
090926A	2225^{-48}_{+50}	Band + power law with exponential cutoff	48.1
080916C	1795^{-39}_{+41}	Band + power law	48.8
090323	1528^{-44}_{+44}	Band	57.2
100728A	1293^{-27}_{+28}	Comptonized	59.9
100414A	1098^{-27}_{+35}	Comptonized + power law	69.0
090626	927^{-16}_{+17}	Logarithmic parabola	18.3
110721A	876^{-28}_{+28}	Logarithmic parabola	40.3
090328	817^{-33}_{+34}	Band	64.6

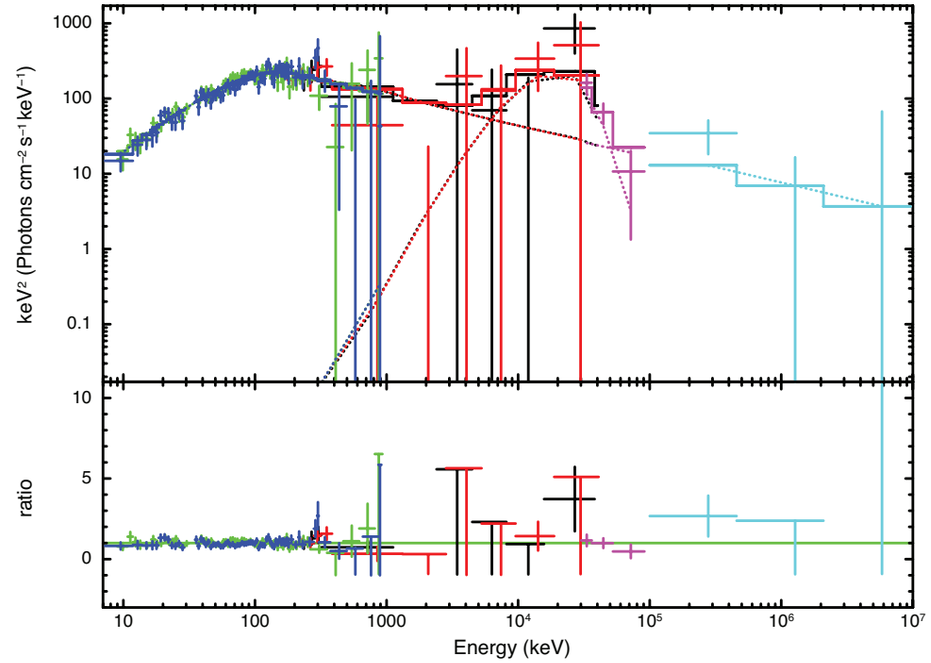
The brightest GRBs show deviations from the canonical Band function!

Still finding surprises!

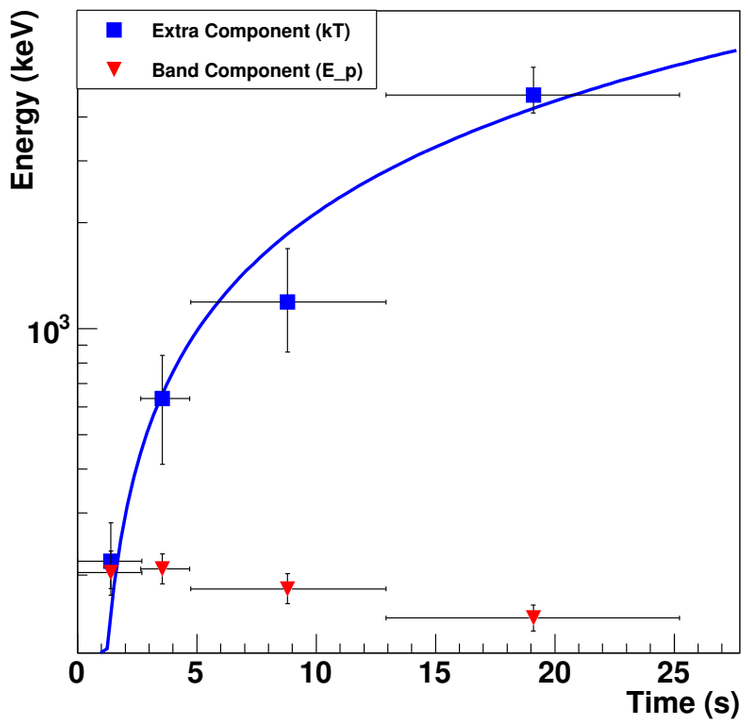
GRB 080825C

Moretti & Axelsson (2016)



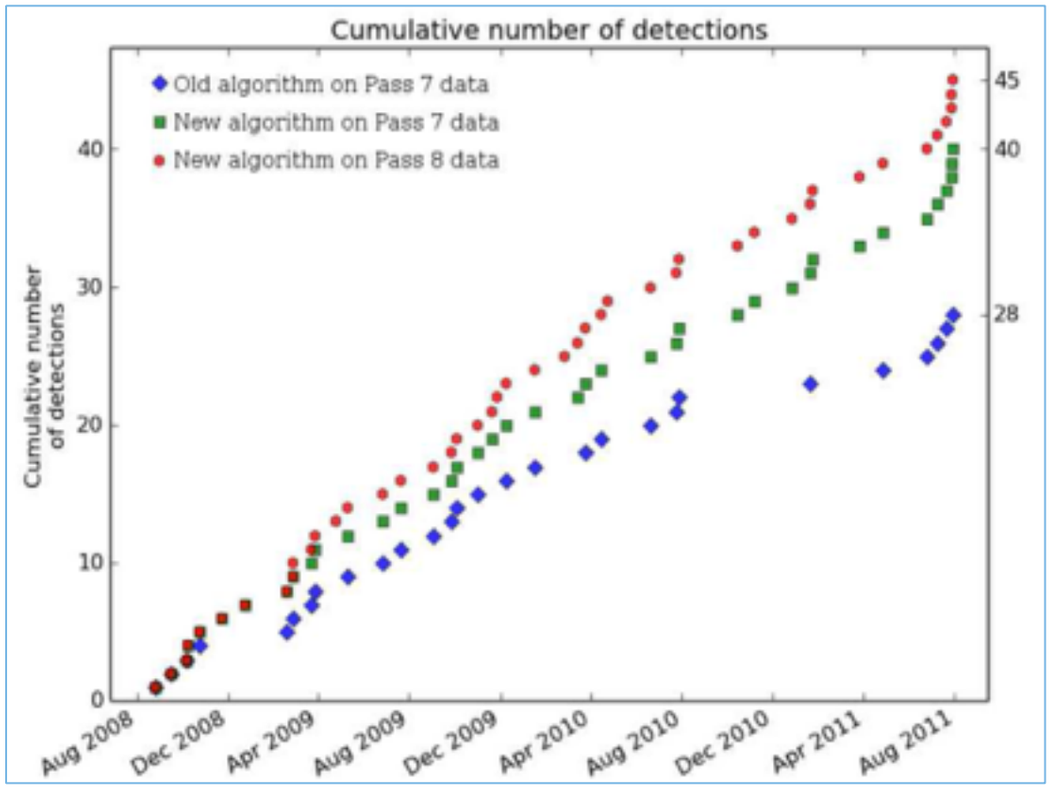


- Possible (3.5 σ) extra component at high energies
- Peak energy increases with time
- Band Epeak decreases as usual



Looking ahead: the 2nd LAT catalog

- **Pass 8:** A new low-level analysis and event reconstruction was developed during the past years. Data are available since June 24th 2015, giving
  - **improved effective area (100% improvement below 100 MeV, 25% above 1 GeV)**
  - **better PSF and localization accuracy**
  - **better background rejection**
  - **reduction in systematic effects**



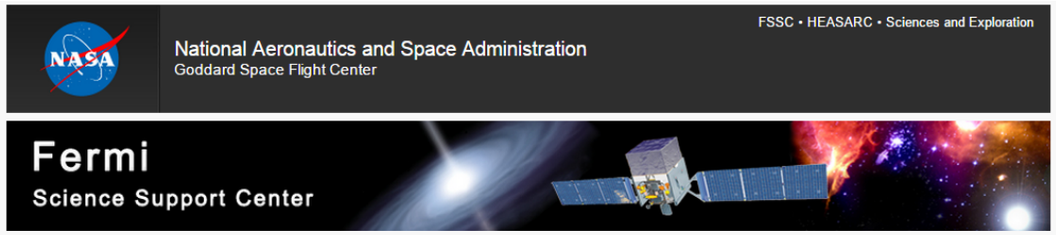
New detection algorithm:

- 10 searches running in parallel over different time intervals
- finding maps of 30×30 deg (covering the GBM position uncertainty!)
- increases the number of detections by >45%

Will contain more than 130 LAT-detected GRBs

On-line tables available

http://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/lat_grbs/table.php



Fermi LAT GRBs

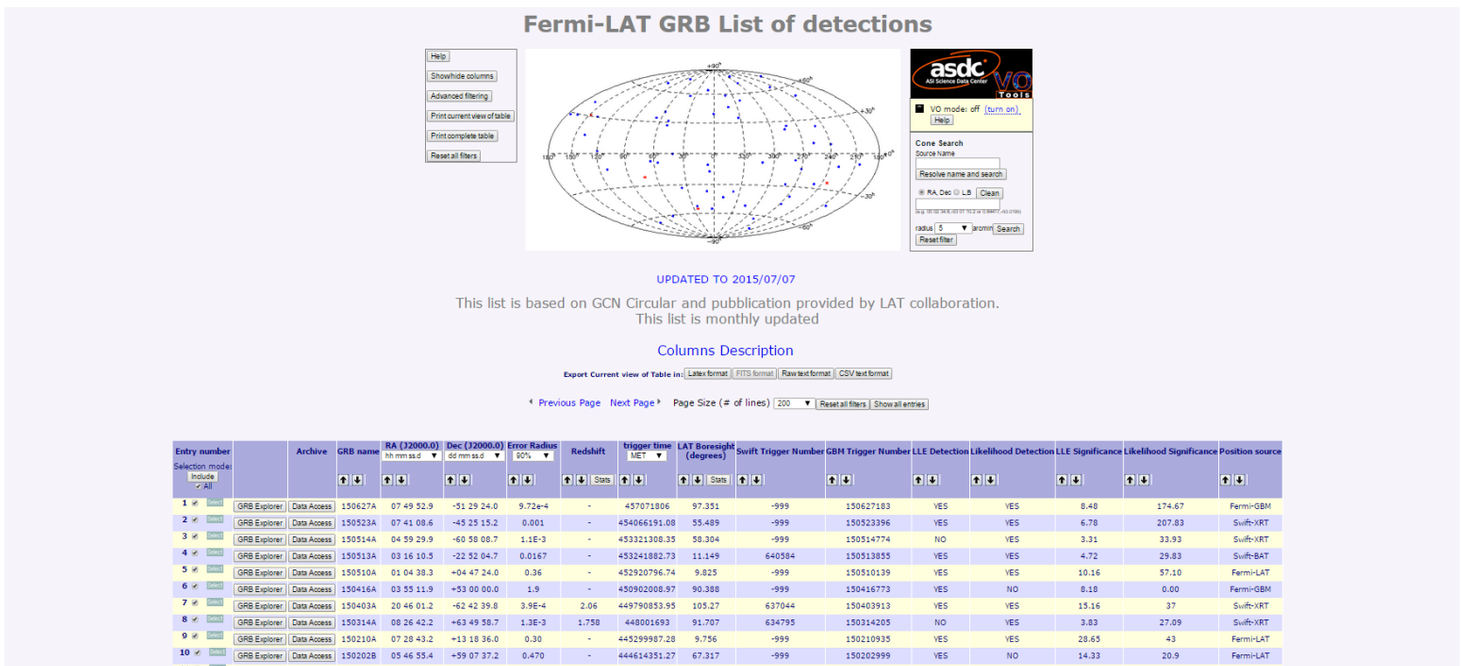
Important Table Information:

All analysis results presented here are preliminary and are not intended as an official catalog of Fermi-LAT detected GRBs. Please consult the table's caveat page for analysis details and other important information. The table is available in a machine readable format here.

Fermi SSC Home » LAT GRBs

GRB	GCN Name	MET	Date (UTC)	Time (UT)	RA (Degrees)	Dec (Degrees)	Error (Degrees)	Source	Theta (Degrees)	Zenith (Degrees)	LLE Detection	Likelihood Detection	LLE Significance	Likelihood TS	Analysis Start	Analysis Stop	Analysis RA (Degrees)	Analysis Dec (Degrees)	Error (Degrees)	IRFs
150702998	150702A	457574201.55	2015-07-02	23:56:37.55	52.78	-57.0	0.36	Fermi-LAT	117.60	88.222	NO	YES	--	31	600.0	2800.0	52.78	-57.00	0.36	P8_SOURCE
150627183	150627A	457071806.0	2015-06-27	04:23:23	117.4706	-51.4900	9.72e-4	Fermi-GBM	74.373	97.351	YES	YES	8.48	174.67	0.0	1500.0	117.49	-51.56	0.05	P8_SOURCE
150523396	150523A	454066191.08	2015-05-23	09:29:48.08	115.2859	-45.4209	0.001	Swift-XRT	25.741	55.489	YES	YES	6.78	207.83	0.0	1900.0	115.36	-45.41	0.08	P7REP_SOURCE_V15
150514774	150514A	453321308.35	2015-05-14	18:35:05.35	74.8750	-60.9691	1.1E-3	Swift-XRT	38.488	58.304	NO	YES	3.31	33.93	0.0	600.0	74.85	-60.91	0.13	P7REP_SOURCE_V15
150513855	150513A	453241882.73	2015-05-13	20:31:19.73	49.044	-22.868	0.0167	Swift-BAT	50.679	11.149	YES	YES	4.72	29.83	0.0	400.0	49.21	-23.20	0.26	P7REP_SOURCE_V15
150510139	150510A	452920796.74	2015-05-10	03:19:53.74	16.16	4.79	0.36	Fermi-LAT	55.763	9.8250	YES	YES	10.16	57.10	0.0	600.0	16.16	4.79	0.26	P7REP_SOURCE_V15
150416773	150416A	450902008.97	2015-04-16	18:33:25.97	58.8	53.0	1.9	Fermi-GBM	68.389	90.388	YES	NO	8.18	0.00	0.0	100.0	--	--	--	P7REP_TRANSIENT_V15
150403913	150403A	449790853.95	2015-04-03	21:54:10.95	311.50504	-62.71106	3.9E-4	Swift-XRT	55.196	105.27	YES	YES	15.16	37	0.0	2000	311.79	-62.76	0.50	P7REP_TRANSIENT_V15
150314205	150314A	448001693.0	2015-03-14	04:54:50	126.676	63.833	1.3E-3	Swift-XRT	47.130	91.707	NO	YES	3.83	27.09	0.0	250.0	125.49	64.45	0.59	P7REP_SOURCE_V15
150210935	150210A	445299987.28	2015-02-10	22:26:24.28	112.18	13.31	0.30	Fermi-LAT	53.87	9.756	YES	YES	28.65	43	0.0	200.0	112.15	13.27	0.33	P7REP_SOURCE_V15
GRB	GCN Name	MET	Date (UTC)	Time (UT)	RA (Degrees)	Dec (Degrees)	Error (Degrees)	Source	Theta (Degrees)	Zenith (Degrees)	LLE Detection	Likelihood Detection	LLE Significance	Likelihood TS	Analysis Start	Analysis Stop	Analysis RA (Degrees)	Analysis Dec (Degrees)	Error (Degrees)	IRFs

http://www.asdc.asi.it/grblat/



Entry number		Archive	GRB name	RA (J2000.0) hh mm ss.d	Dec (J2000.0) dd mm ss.d	Error Radius 90%	Redshift	trigger time MET	LAT Boresight (degrees)	Swift Trigger Number	GBM Trigger Number	LLE Detection	Likelihood Detection	LLE Significance	Likelihood Significance	Position source
1	GRB Explorer	Data Access	150627A	07 49 52.9	-51 29 24.0	9.72e-4	-	457071806	97.351	-999	150627183	YES	YES	8.48	174.67	Fermi-GBM
2	GRB Explorer	Data Access	150523A	07 41 08.6	-45 25 15.2	0.001	-	454066191.08	55.489	-999	150523396	YES	YES	6.78	207.83	Swift-XRT
3	GRB Explorer	Data Access	150514A	04 59 29.9	-60 58 08.7	1.1E-3	-	453321308.35	58.304	-999	150514774	NO	YES	3.31	33.93	Swift-XRT
4	GRB Explorer	Data Access	150513A	03 16 10.5	-22 52 04.7	0.0167	-	453241882.73	11.149	640584	150513855	YES	YES	4.72	29.83	Swift-BAT
5	GRB Explorer	Data Access	150510A	01 04 38.3	+04 47 24.0	0.36	-	452920796.74	9.825	-999	150510139	YES	YES	10.16	57.10	Fermi-LAT
6	GRB Explorer	Data Access	150416A	03 55 11.9	+53 00 00.0	1.9	-	450902008.97	90.388	-999	150416773	YES	NO	8.18	0.00	Fermi-GBM
7	GRB Explorer	Data Access	150403A	20 46 01.2	-62 42 39.8	3.9E-4	2.06	449790853.95	105.27	637044	150403913	YES	YES	15.16	37	Swift-XRT
8	GRB Explorer	Data Access	150314A	08 26 42.2	+63 49 58.7	1.3E-3	1.758	448001693	91.707	634795	150314205	NO	YES	3.83	27.09	Swift-XRT
9	GRB Explorer	Data Access	150210A	07 28 43.2	+13 18 36.0	0.30	-	445299987.28	9.756	-999	150210935	YES	YES	28.65	43	Fermi-LAT
10	GRB Explorer	Data Access	150202B	05 46 55.4	+59 07 37.2	0.470	-	444614351.27	67.317	-999	150202999	YES	NO	14.33	20.9	Fermi-LAT
11	GRB Explorer	Data Access	150127A	19 02 48.0	-08 24 00.0	2.8	-	444043967.14	54.477	-999	150127398	YES	NO	3.18	1.31	Fermi-GBM

Summary

- The LAT has continued the CGRO legacy and answered many observational questions about high-energy emission from GRBs
  - seen in the prompt phase
  - long duration
  - additional component.
- There are also new discoveries, such as the delayed onset.
- The large GBM sample allows statistical studies, but has also given information about individual bursts, such as the possible detection of photospheric emission.
- Both the LAT and GBM instruments on *Fermi* continue to provide valuable GRB data, from low to high energies, steadily increasing the number of detections and thus the possibility of understanding the nature and physics of GRBs.
- *Fermi* is continuously improving and is well prepared to play a key role in the upcoming GRB science: VHE detections, and GW counterpart searches.
- More discoveries to come!