High-energy GRB observations in the Multi-Messenger context

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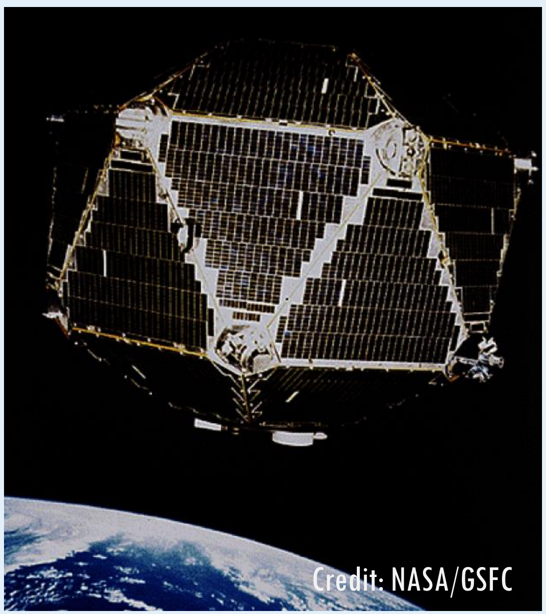
Multimessenger Data analysis in the era of CTA

Gamma–Ray Bursts

→ The keV emission kicked off the GRB show in the '70s!

VELA-5B satellite (1969) in low earth orbit



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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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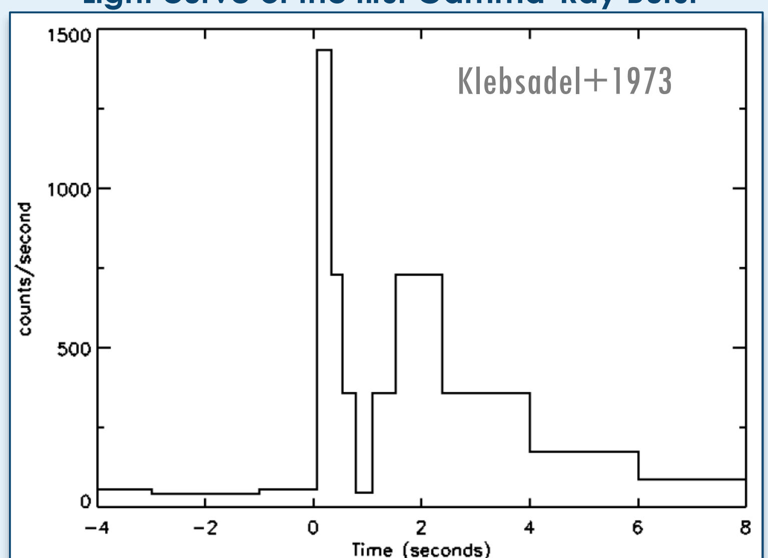
ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim10^{-5}$ ergs cm^{-2} to $\sim2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

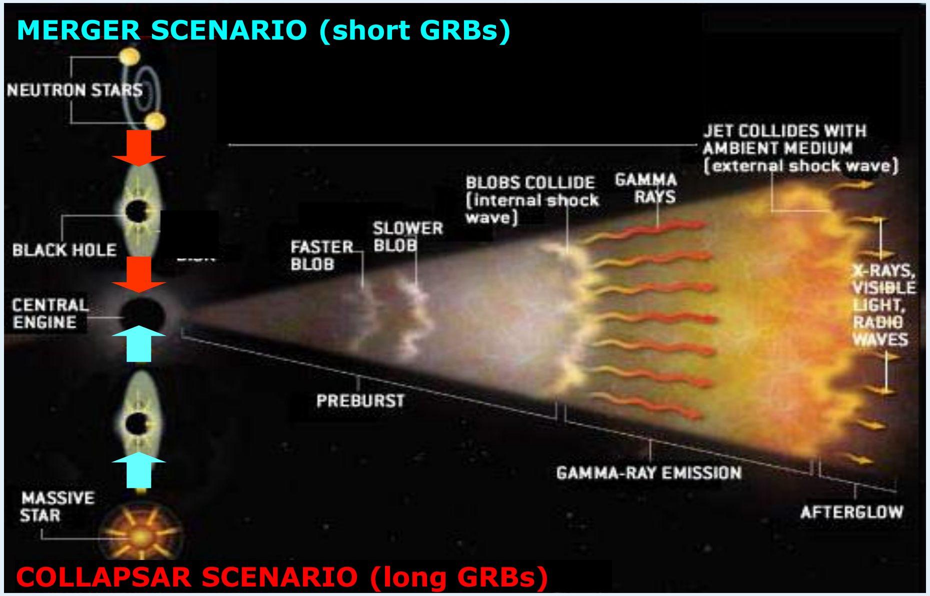
Light curve of the first Gamma-Ray Burst



Gamma–Ray Bursts

→ The keV emission kicked off the GRB show in the '70s!

- What we know now:
  1. GRBs are cosmological (Optical, Radio/GeV)
  2. GRBs have large bulk Lorentz factors
  3. 2 emission phases: Prompt and afterglow (Optical/GeV)
  4. Long and short GRBs (keV/MeV)
  5. Spikes have same durations
  6. Supernova connection (Optical)
  7. Common behaviors and trends (X-ray/keV)



«Pillars of knowledge» (Ghisellini 2010)

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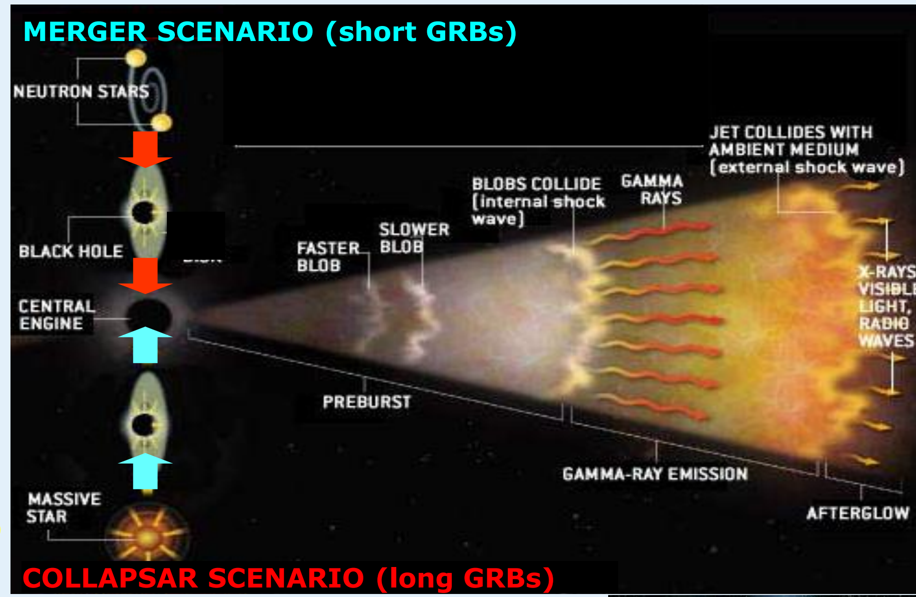


Multi-Wavelength is always the key!
Now also **Multi-Messenger**!
Synergy between instruments (and community!) is crucial

Gamma–Ray Bursts

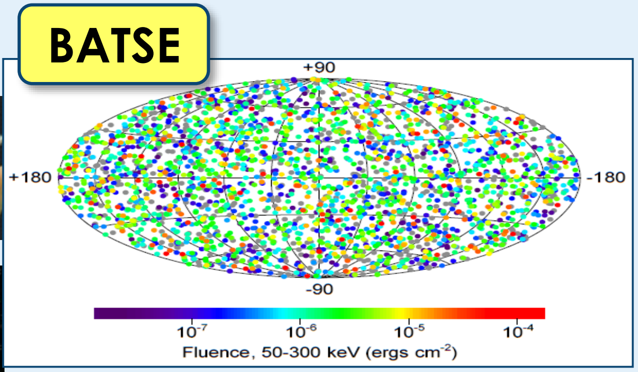
→ Unveiling the GRB phenomenon still represents a large field of research

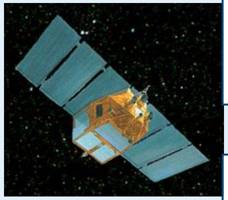
- **HE to VHE** observations can be crucial to answer many open questions
  - What is the physics behind?
    - Prompt: mechanism, jet properties, central engine
    - Early afterglow: mechanism (plateau phase), particle acceleration, B field generation
  - Tools to probe the Universe
    - Cosmological relations
    - Extragalactic background light (deeper than AGN)
  - Tests of UHECR origin, fundamental physics
    - Signatures of accelerated hadrons
    - Lorentz invariance violation

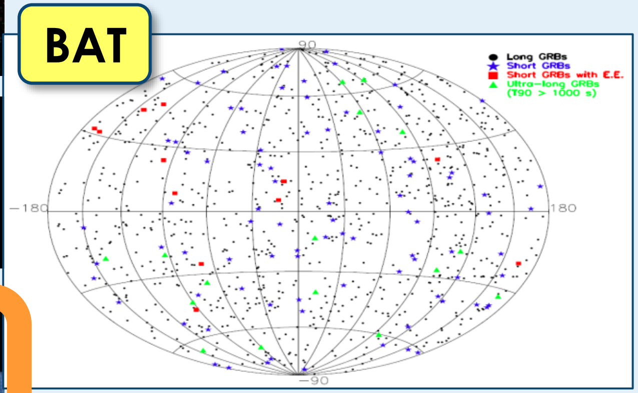
GRB 130427A

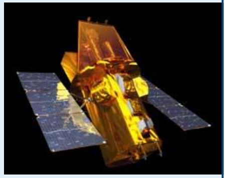
1. The keV–MeV energy range

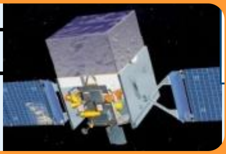
- Past and present **observations**
  - BATSE [1991-2000; 20 – 2000 keV]
    2704 GRBs **(~300 GRBs/yr)**
  - BeppoSAX [1996-2002; 40–700 keV]
    1082 GRBs **(~180 GRBs/yr)**
  - Swift-BAT [since 2004; 15–150 keV]
    ~1300 GRBs **(~100 GRBs/yr)**
  - Fermi-GBM [since 2008; 8 keV–40MeV]
    ~2600 GRBs **(~240 GRBs/yr)**
  - Other Missions (AGILE, Suzaku, Konus, INTEGRAL, CALET, Insight-HXMT, Astrosat-CZTI, etc.): **~150 GRBs/yr**

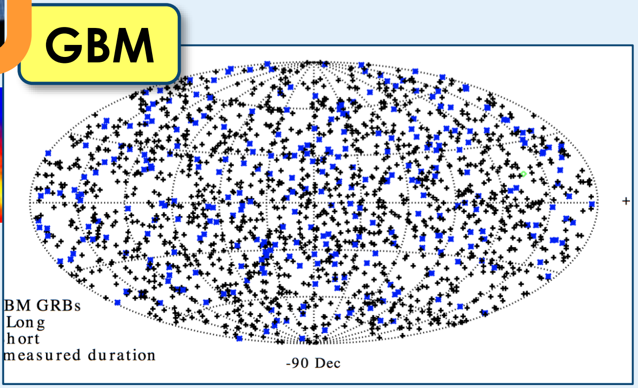












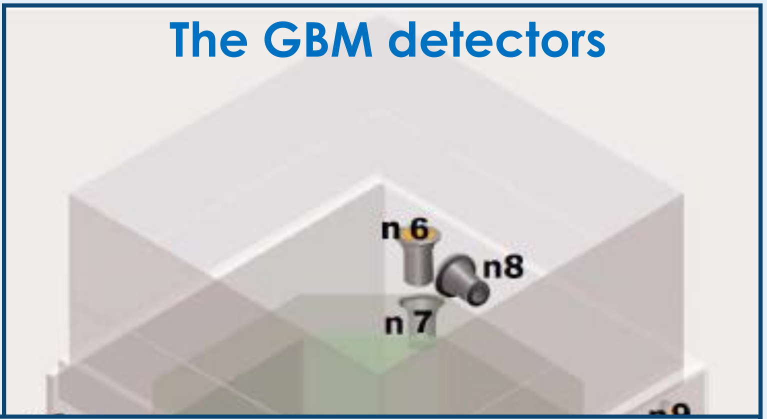
The Fermi Gamma-Ray Burst Monitor

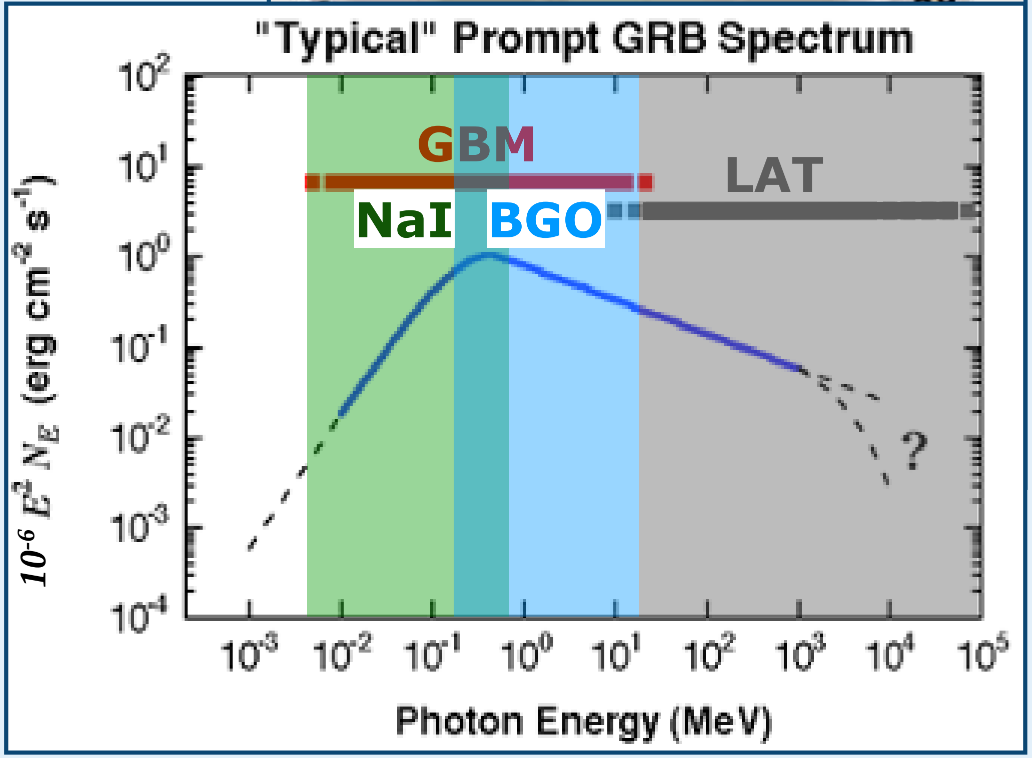
Secondary Fermi Instrument, specifically **designed to study GRBs**

- GBM primary **objectives**:

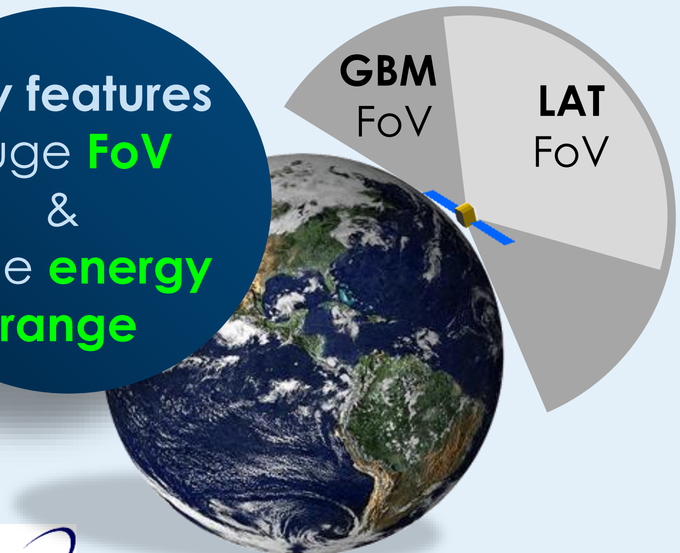
1. **Extend** the energy range downward from the Fermi-LAT one (100 MeV – 300 GeV)
2. Compute burst **locations** onboard to allow re-orienting the spacecraft

The GBM detectors

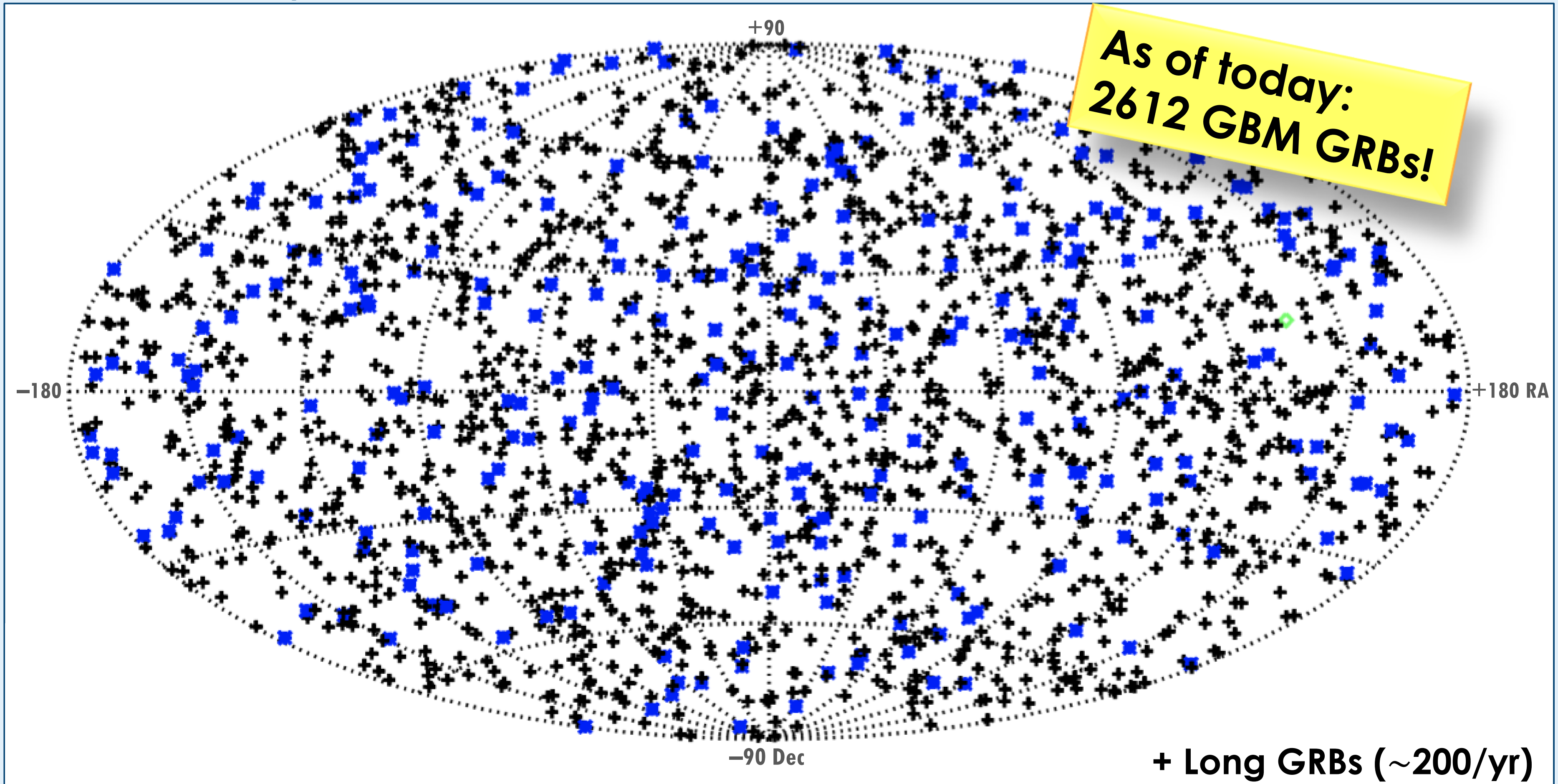




Key features
huge **FoV**
&
huge **energy range**



Fermi–GBM GRB skymap



Fermi-GBM 8-year GRB map ©Connaughton/Fermi GBM Collaboration

Online GBM catalog
http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html

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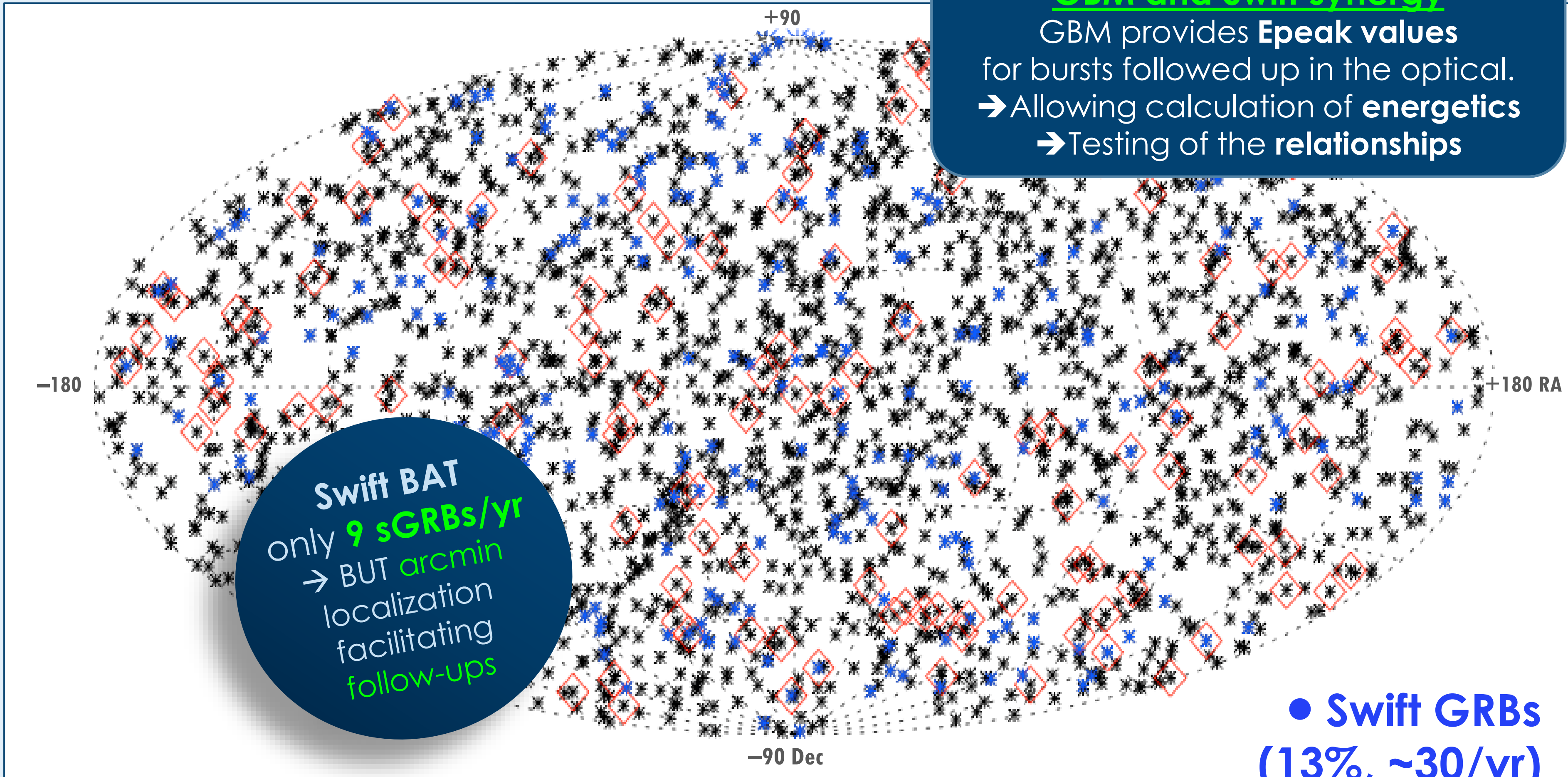


Fermi-GBM 9.5-year GRB map ©Connaughton/Fermi GBM Collaboration

GBM and Swift synergy

GBM provides **Epeak values** for bursts followed up in the optical.

➔ Allowing calculation of **energetics**

➔ Testing of the **relationships**

Fermi–GBM GRB highlights

GBM GRB rate: 242±6/yr
GBM: ~ 40 sGRBs/yr
Swift: ~ 9 sGRBs/yr

3rd GBM GRB Catalog (Bhat+2016,ApJSS223)

For each GRB: **location, duration, peak flux & fluence**

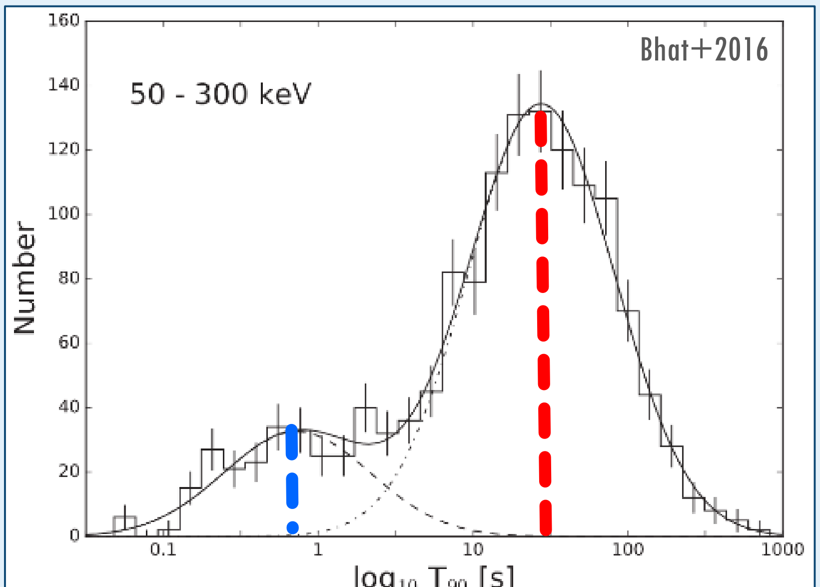
Distribution of GRB durations

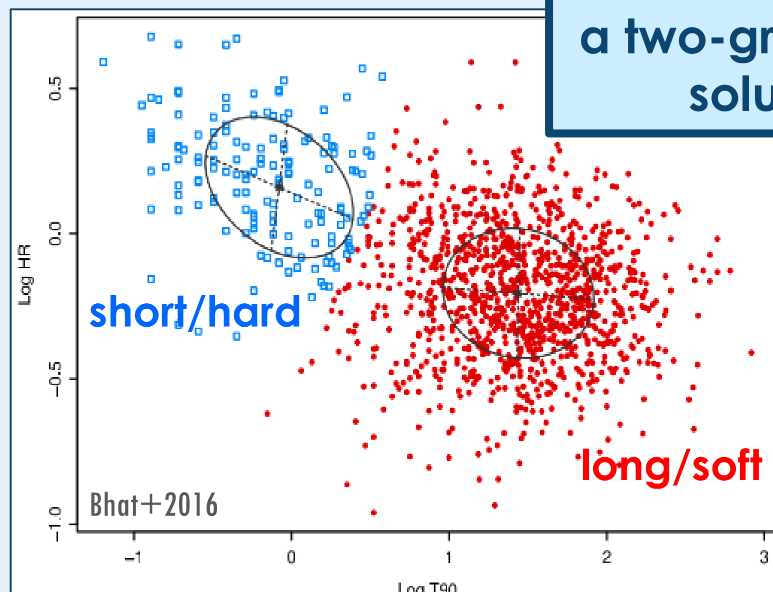
- "T_{90}" interval between the times where the burst has reached 5% and 95% of its maximum fluence
- **Median T_{90} values:**
  - **0.58 s (short)**, **26.62 s (long)**

Hardness-duration diagram

- "**Hardness**": Ratio of burst fluence during the T_{90} intervals in the energy band **50–300 keV** to that in the **10–50 keV** band

→ Strong evidence for a two-group solution





Ellipses show the best-fitting multivariate Gaussian models

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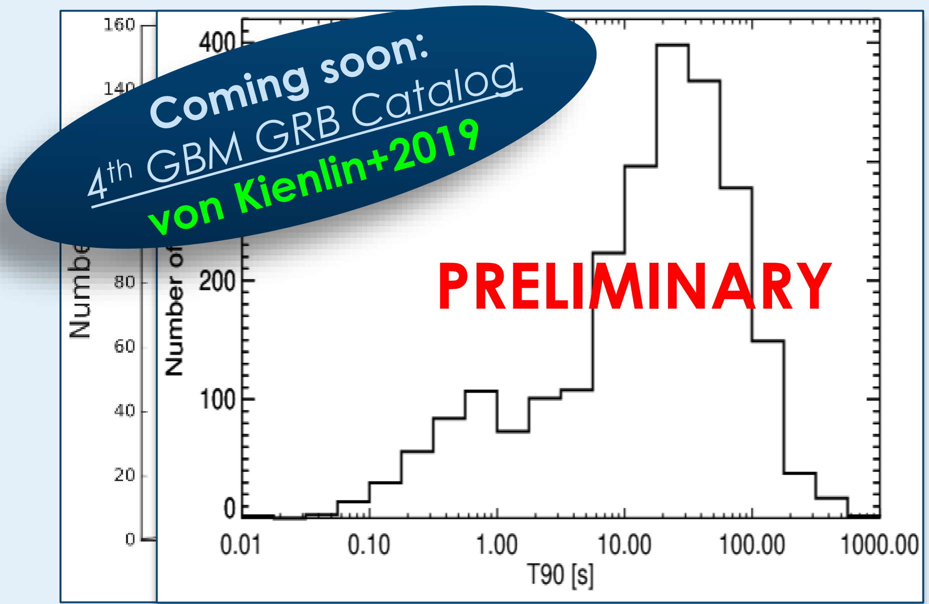

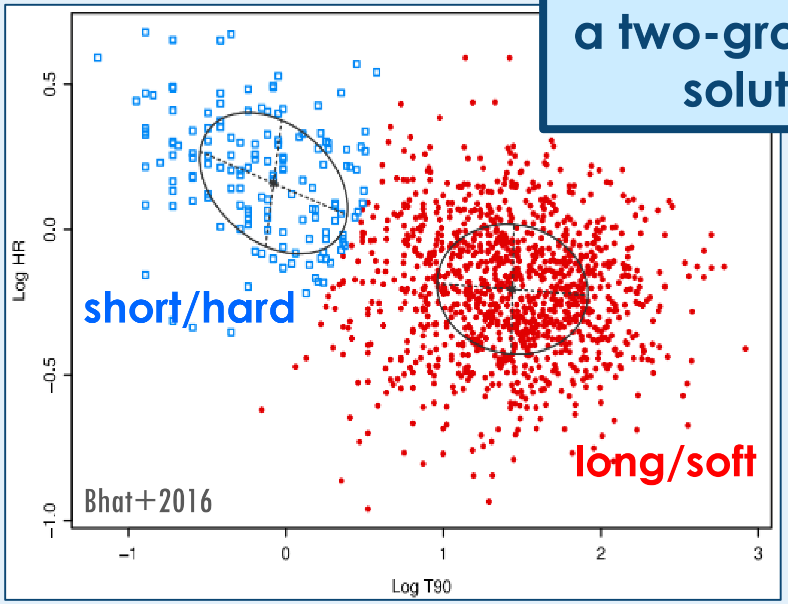

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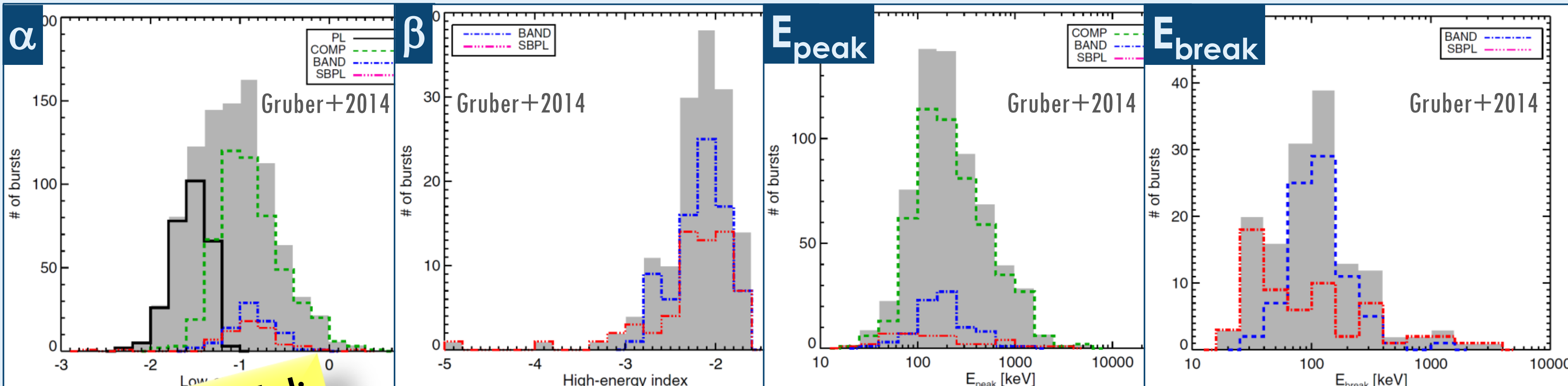
Fermi–GBM GRB highlights

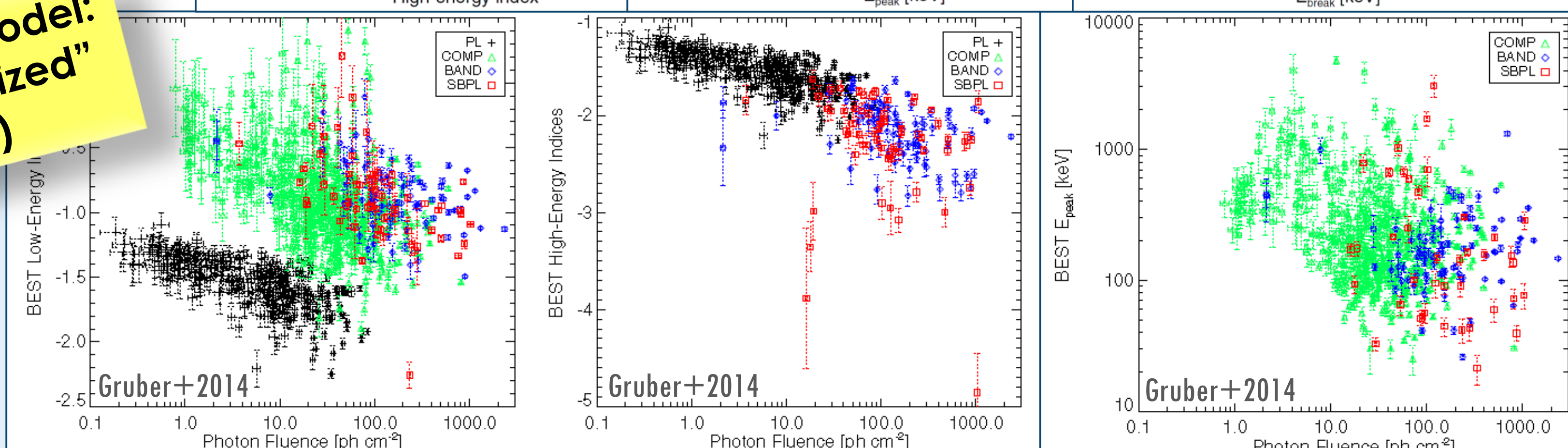
Fermi Gamma-ray Space Telescope

2rd GBM GRB Spectral Catalog (Gruber+2014,ApJ211)

Time-integrated spectral fits + spectral fits at the brightest time bin fitted with **4 spectral models** (PL, SBPL, Band, Comp)



Preferred model: "Comptonized" (55%)



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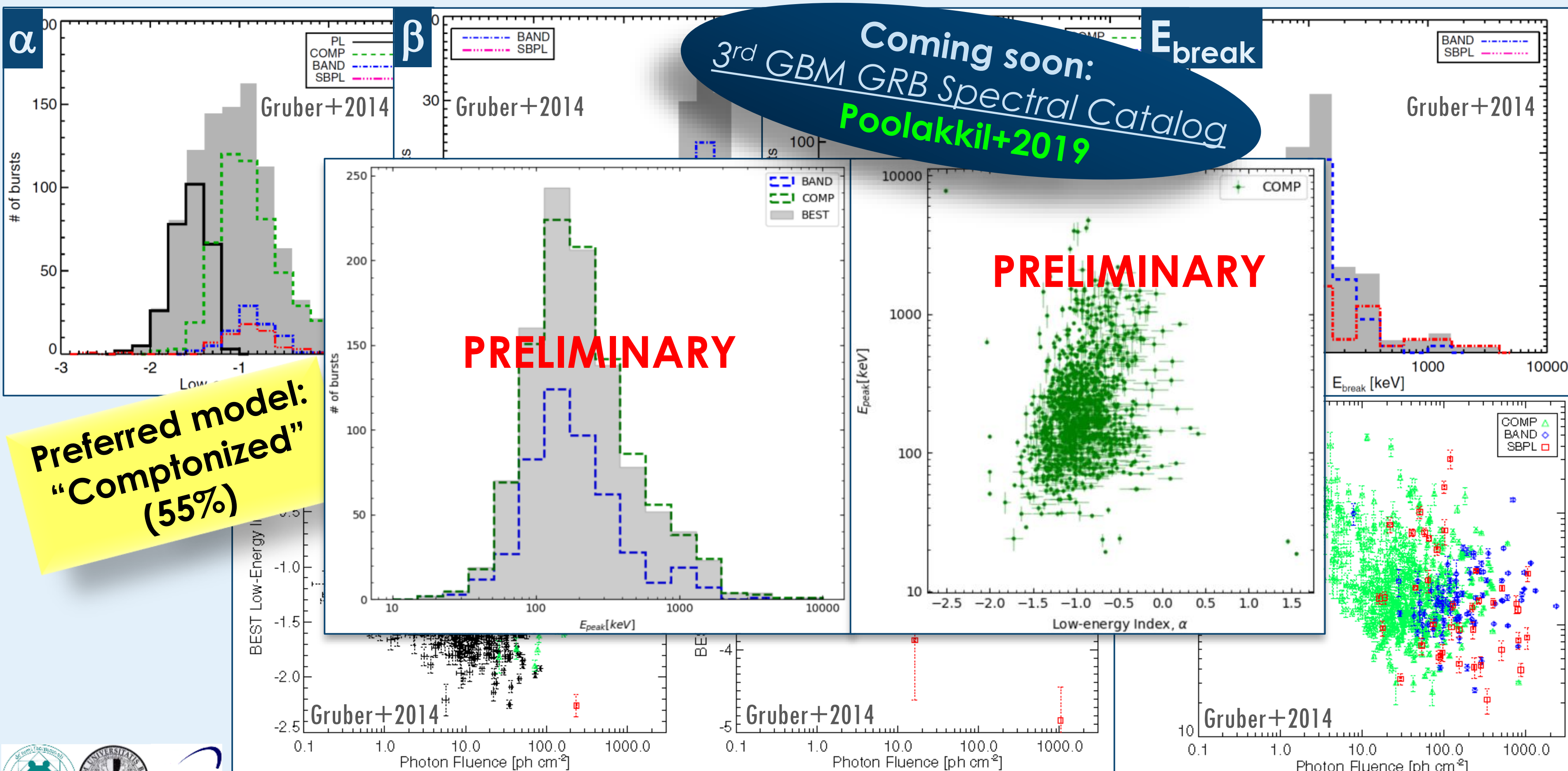


Fermi–GBM GRB highlights

1st Time-resolved spectral catalog (Yu+2016,A&A588)

Distributions of parameters, **statistics** of parameter populations, **correlations**

Coming soon:
2nd time-res spectral Catalog
Bissaldi+2020

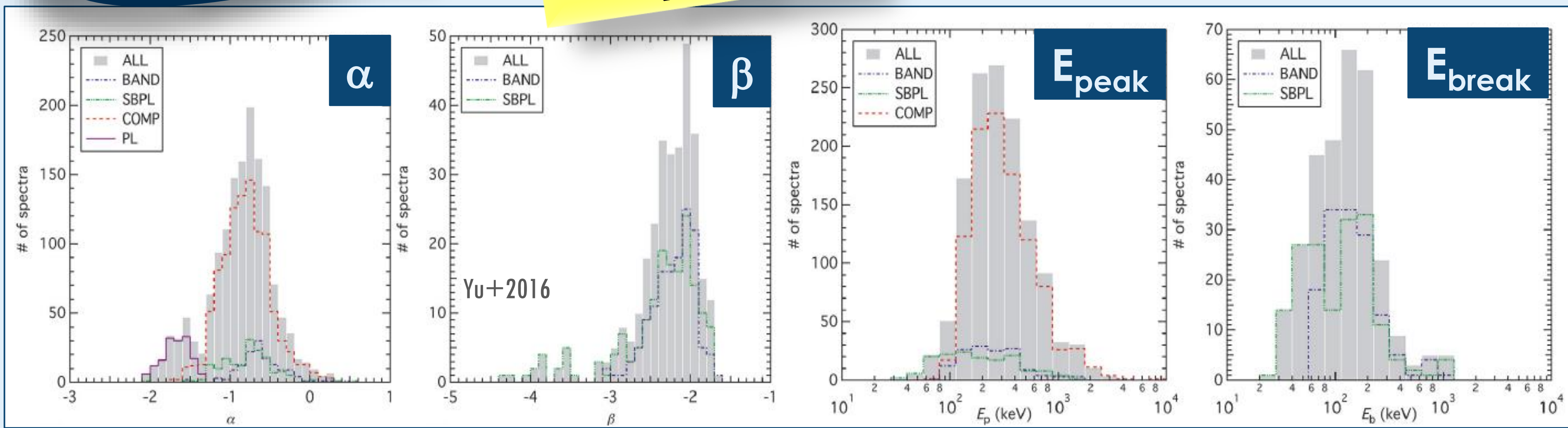
Preferred model: "Comptonized" (70%)

Bright GRB subsample

- **Selection criteria**
  - **fluence** ($f > 4 \times 10^{-5}$ erg cm^{-2})
  - **peak flux** ($F_p > 20$ ph s^{-1}cm^{-2})
  - **(S/N)**=30 in at least 5 time bins

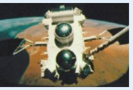
➔ 81 GRBs for a total of **1802 spectra**

- **Four empirical models** fit to each spectrum: **PL, COMP, Band, SBPL**



2. The MeV–GeV energy range

- Past and present observations



CGRO [1991-2000]

- COMPTEL [0.75-30 MeV]: **~4.5 GRBs/yr**
- EGRET TASC [1-200 MeV]: **~3 GRBs/yr**
- EGRET Spark chamber [20 MeV – 30 GeV] **< 1 GRB/yr**
  ➔ Highest energy photon: 18 GeV

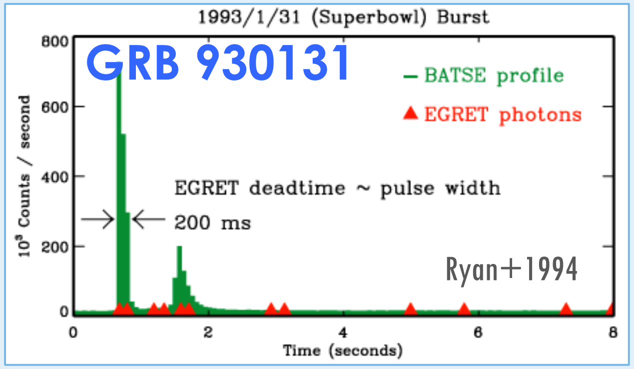
HE photons seen both during the prompt and afterglow phases

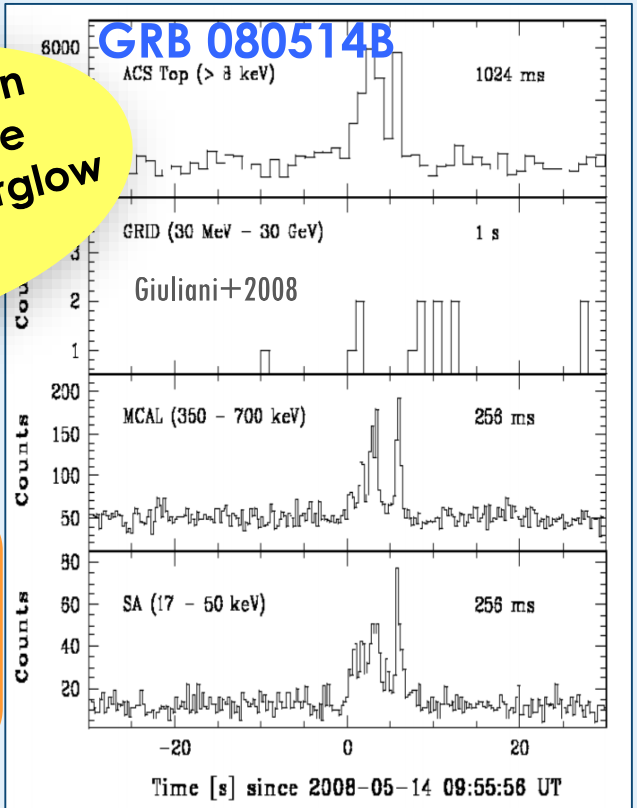
AGILE [since 2007]

- GRID [30 MeV – 50 GeV]: **~1 GRB/yr**

Fermi-LAT [since 2008]

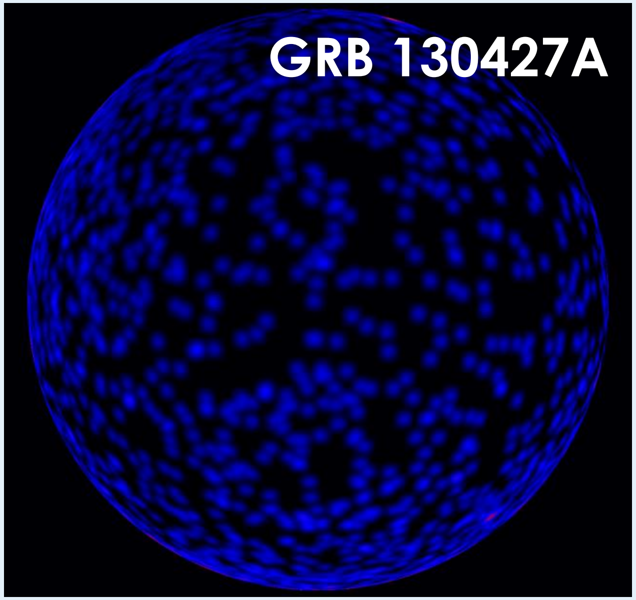
- [>30 MeV – 300 GeV]: **~18 GRBs/yr**
  ➔ Highest energy photon: 95 GeV

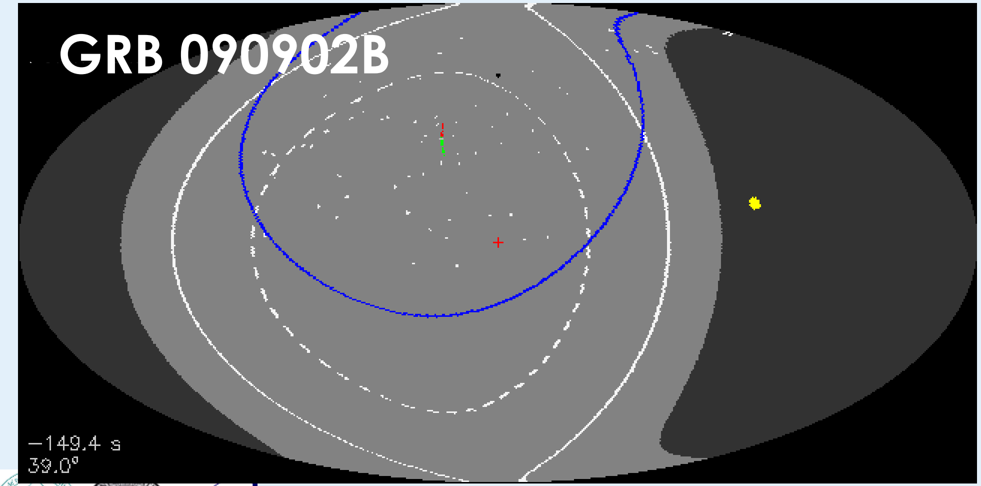




Follow–up of Fermi–GBM GRBs

- GBM trigger localization suffering from large uncertainties (5 – 10 deg error radius)
- **BUT**: Trigger criteria: high peak flux, or high fluence GBM to LAT → Autonomous Repoint Request (ARR)
  - Occured with rate of >1/month (>170 positive **ARRs** in 10 yrs)
  - ALSO: 6 onboard LAT triggers!
- **LAT automated pipelines** for GRB searches
  - Also triggers from **Swift, INTEGRAL, and MAXI**
  - Search for **excess emission** at trigger time plus in **various intervals** over a large RoI



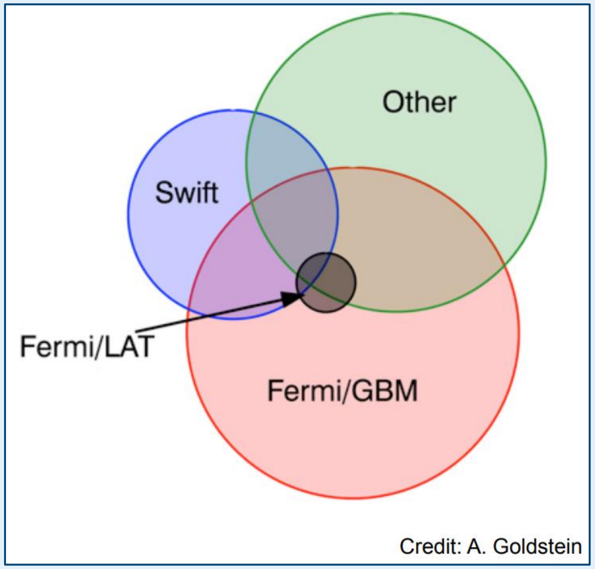


Hammer-Aitoff representation of the whole sky in celestial coordinates

RED CROSS (center)	GRB
YELLOW DOT	Sun
GREEN/RED LINES	Fermi solar panels
BLUE CIRCLE	LAT FoV
DARK AREA	Earth
WHITE CIRCLE	20° Earth avoidance
DASHED WHITE CIRCLE	50° Earth avoidance

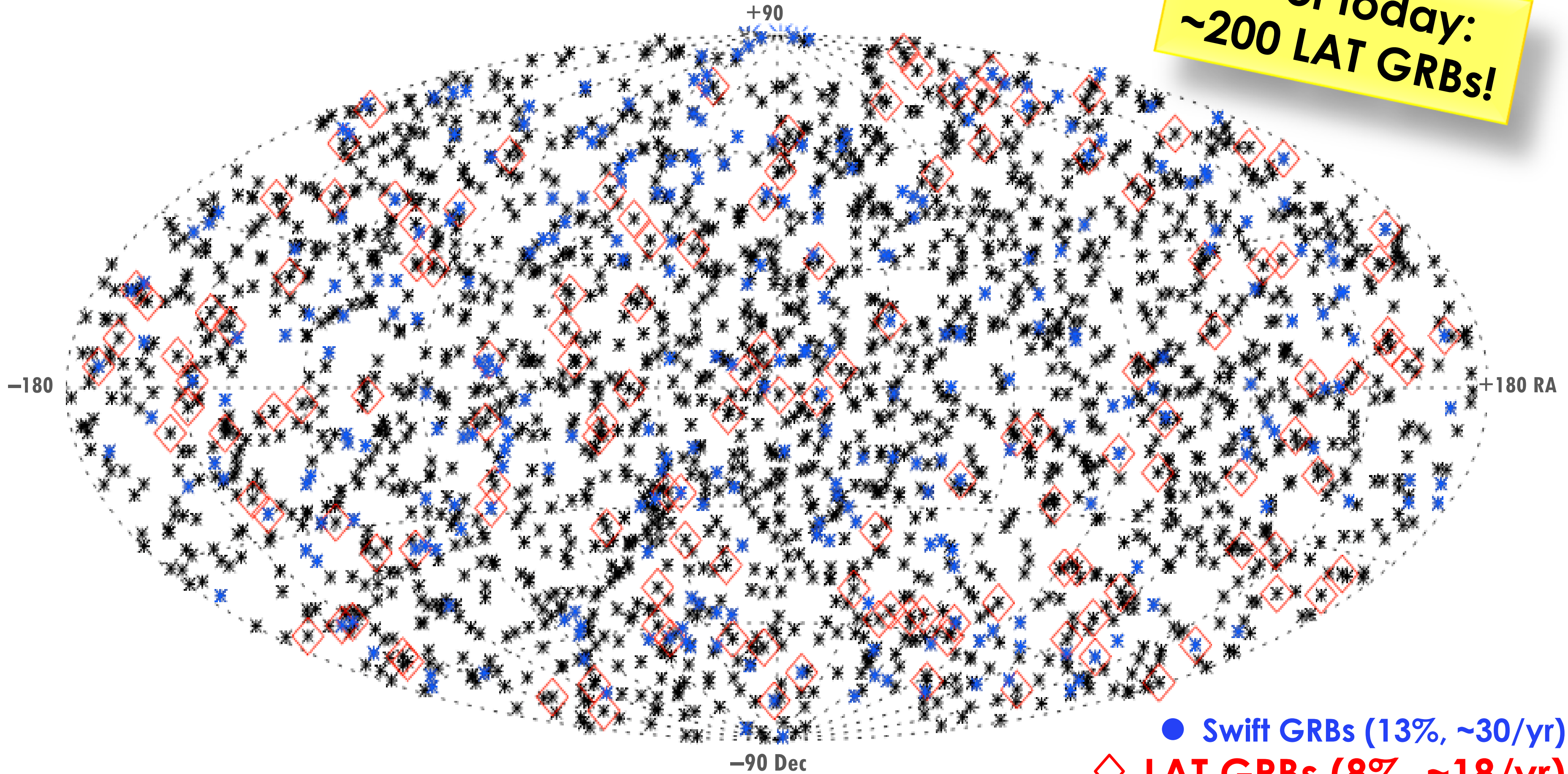
Follow–up of Fermi–GBM GRBs

- GRB **observation timeline**
  - Fermi GBM high peak flux trigger → ARR XXX → **disabled since March 2018**
    - LAT data comes to ground and is processed in ~6-10 hours
    - Ground analysis finds positions (errors ~0.1-1 deg radius)
  - **Swift Follow-up** (ideally)
    - Arcsec position
    - Ground-based telescopes find afterglow → redshift
- Best Observed Subset
  - GRBs with both **low** and **high energy** coverage + **multi-wavelength** (X-ray, optical, radio, etc) follow-up allowing **redshift** determination and **energetics** studies



Fermi GBM+LAT+Swift skymap

As of today: ~200 LAT GRBs!

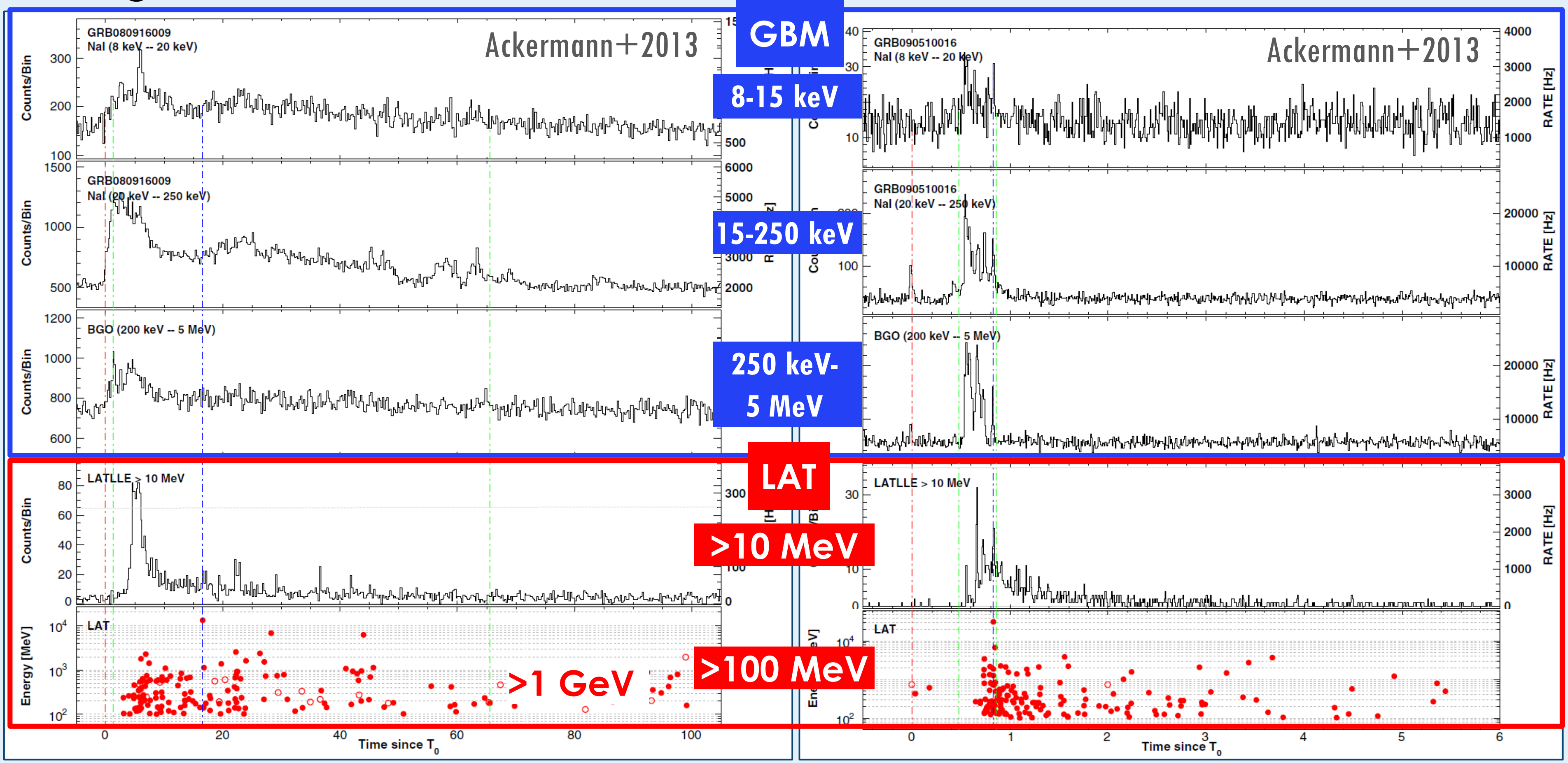


Fermi-GBM 9.5-year GRB map ©Connaughton/Fermi GBM Collaboration

Fermi LAT highlights

1st LAT GRB Catalog (3 years, **35 GRBs**)

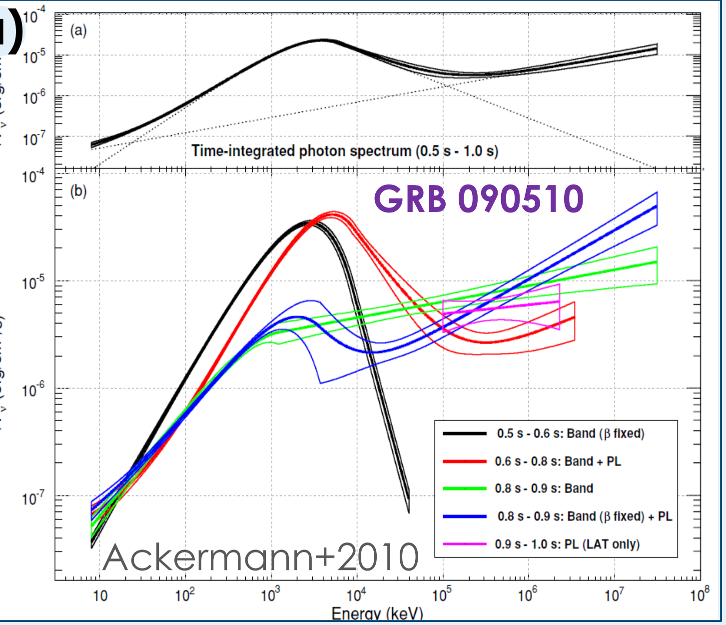
Long **GRB 080916C** Short **GRB 090510**



Fermi LAT highlights

1st LAT GRB Catalog (3 years)

- High-energy features:
  a) Extra **PL component** required to fit spectra
  b) Emission >100 MeV systematically **delayed**
  c) Emission >100 MeV systematically **longer**
  d) Emission >100 MeV decays smoothly as a **PL (index -1)**

a)


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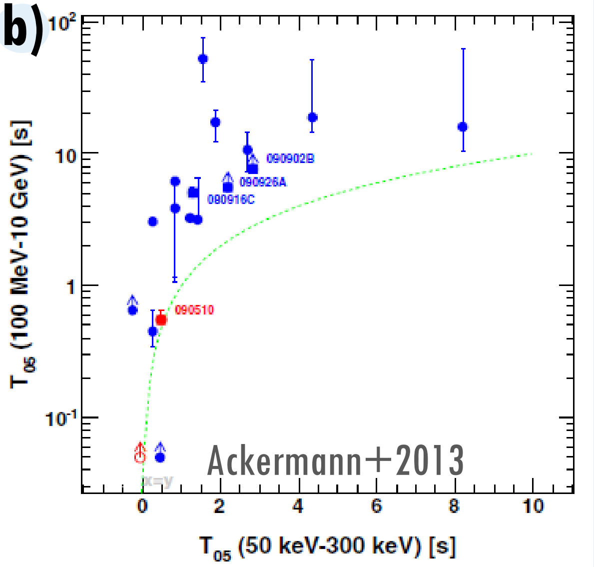

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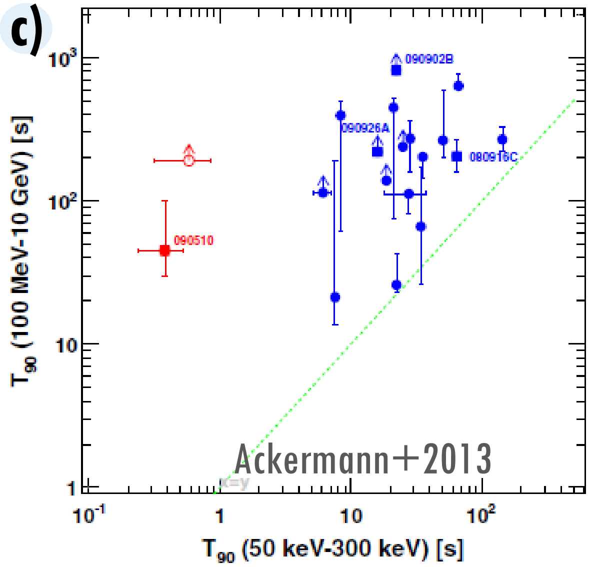

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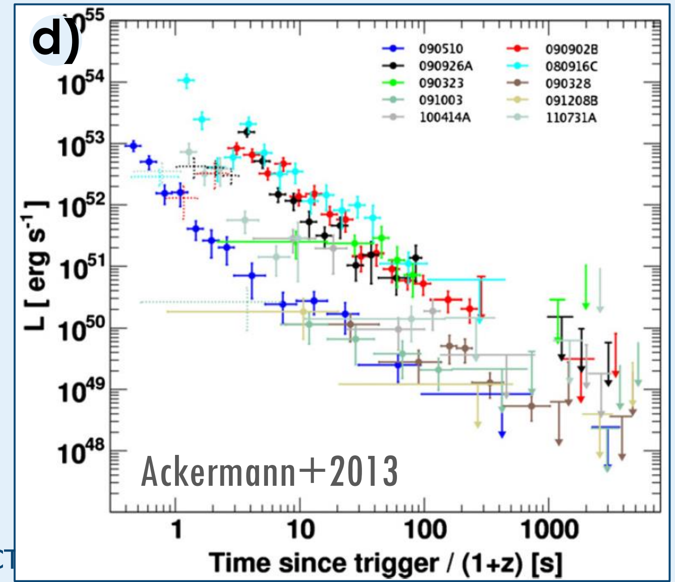

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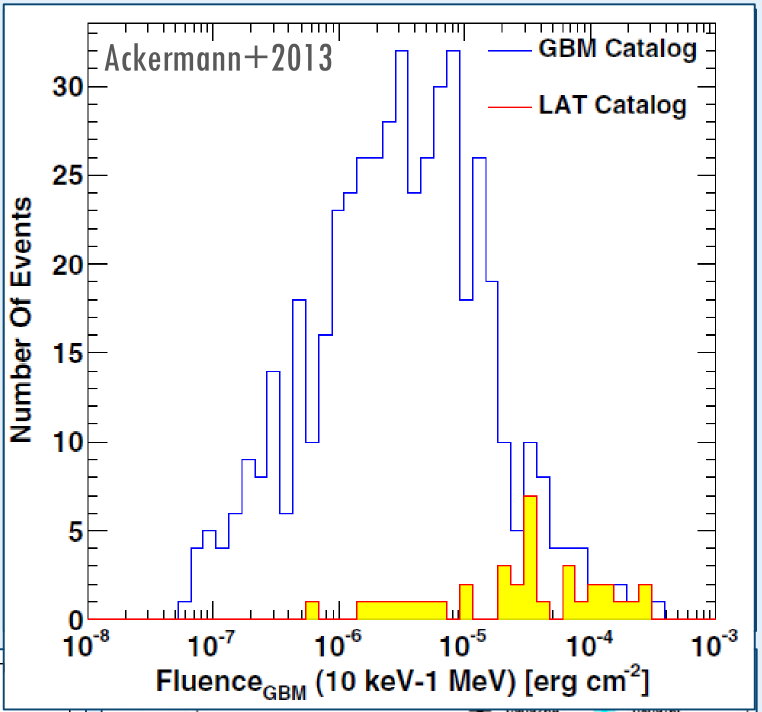
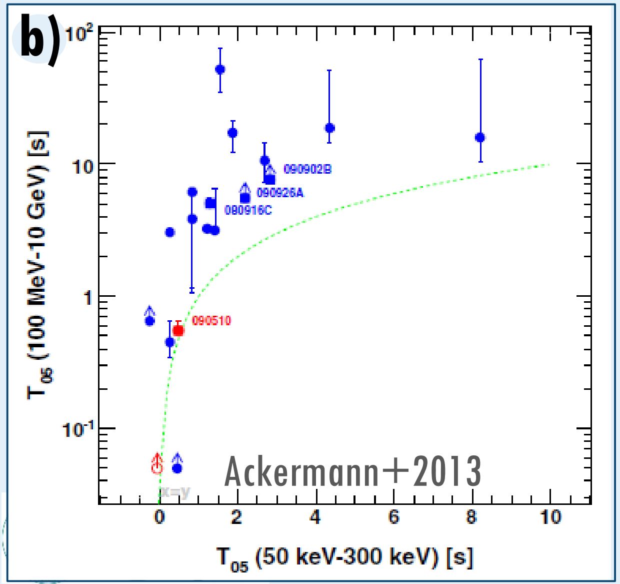
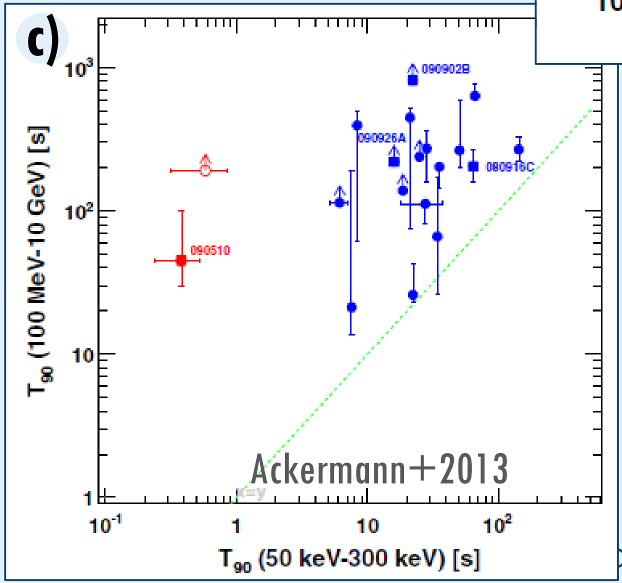
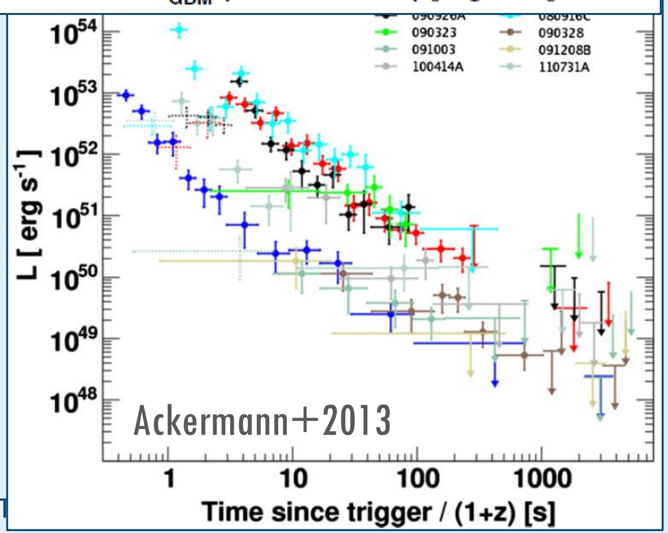
➔ **Not surprisingly, LAT GRBs are among the brightest GBM ones!**



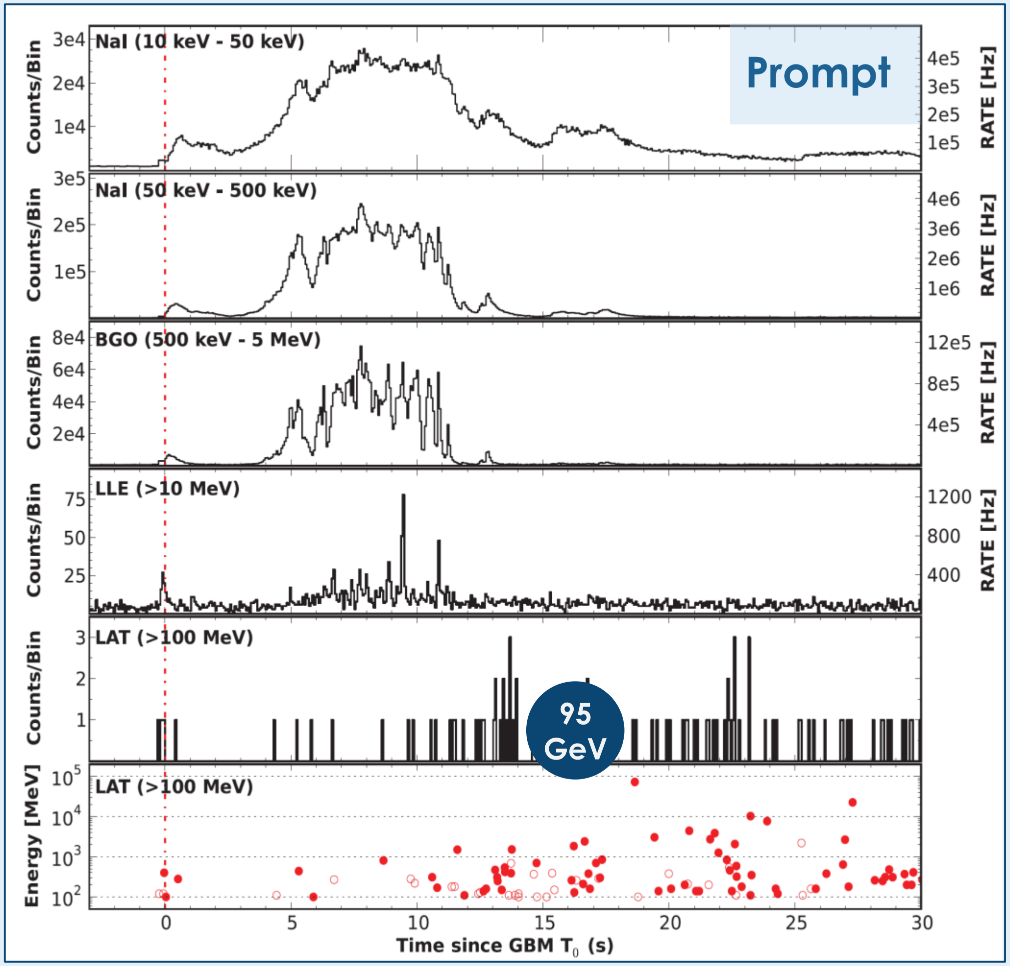


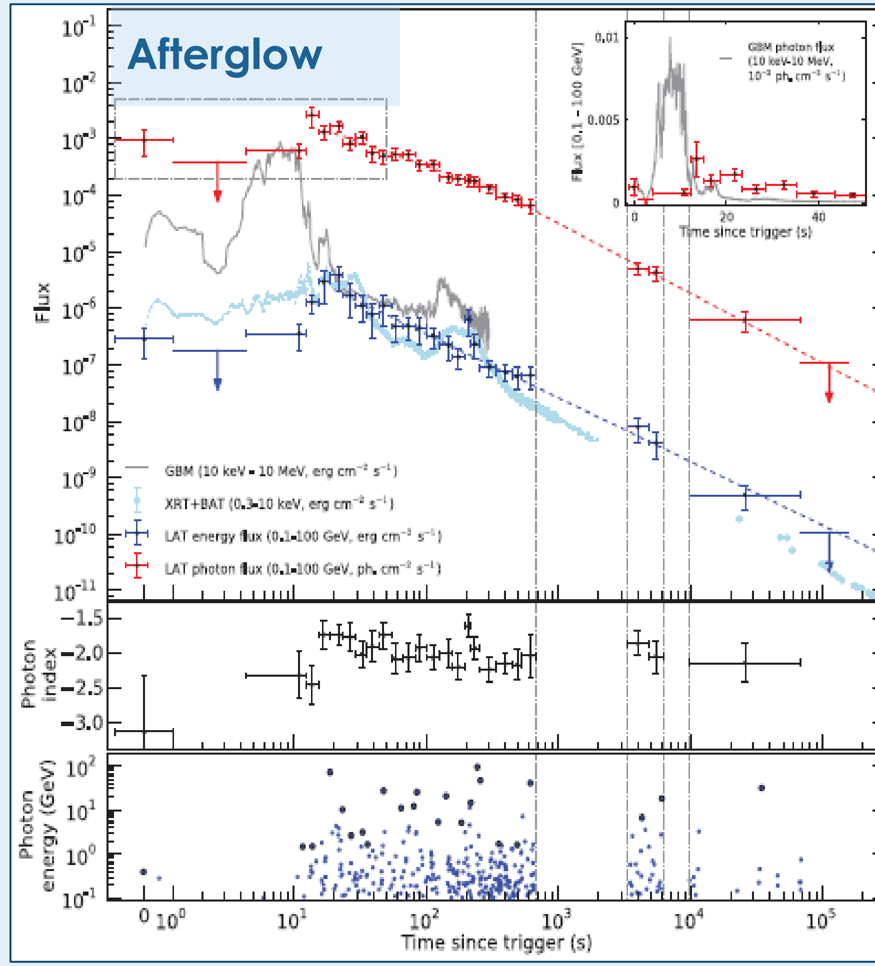




Fermi LAT highlights

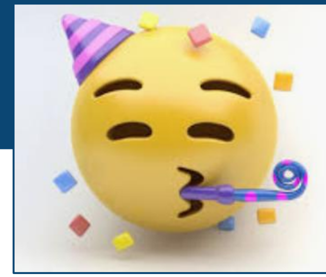
GRB 130427A – The "monster" burst





Preece+2014, Ackermann+2014 Science

Fermi LAT highlights



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https://doi.org/10.3847/1538-4357/ab1d4e

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A Decade of Gamma-Ray Bursts Observed by *Fermi*-LAT: The Second GRB Catalog

M. Ajello[1], M. Arimoto[2], M. Axelsson[3,4], L. Baldini[5], G. Barbiellini[6,7], D. Bastieri[8,9], R. Bellazzini[10], P. N. Bhat[11], E. Bissaldi[12,13], R. D. Blandford[14], R. Bonino[15,16], J. Bonnell[17,18], E. Bottacini[14,19], J. Bregeon[20], P. Bruel[21], R. Buehler[22], R. A. Cameron[14], R. Caputo[23], P. A. Caraveo[24], E. Cavazzuti[25], S. Chen[8,19], C. C. Cheung[26], G. Chiaro[24], S. Ciprini[27,28], D. Costantin[29], M. Crnogorcevic[18], S. Cutini[30], M. Dainotti[14], F. D'Ammando[31,32], P. de la Torre Luque[12], F. de Palma[15], A. Desai[1], R. Desiante[15], N. Di Lalla[5], L. Di Venere[12,13], F. Fana Dirirsa[33], S. J. Fegan[21], A. Franckowiak[22], Y. Fukazawa[34], S. Funk[35], P. Fusco[12,13], F. Gargano[13], D. Gasparrini[28,30], N. Giglietto[12,13], F. Giordano[12,13], M. Giroletti[31], D. Green[36], I. A. Grenier[37], J. E. Grove[26], S. Guiriec[17,38], E. Hays[17], J. W. Hewitt[39], D. Horan[21], G. Jóhannesson[40,41], D. Kocevski[17], M. Kuss[10], L. Latronico[15], J. Li[22], F. Longo[6,7], F. Loparco[12,13], M. N. Lovellette[26], P. Lubrano[30], S. Maldera[15], A. Manfreda[5], G. Martí-Devesa[42], M. N. Mazziotta[13], I. Mereu[43], M. Meyer[14], P. F. Michelson[14], N. Mirabal[17,44], W. Mitthumsiri[45], T. Mizuno[46], M. E. Monzani[14], E. Moretti[47], A. Morselli[27], I. V. Moskalenko[14], M. Negro[15,16], E. Nuss[20], M. Ohno[34], N. Omodei[14], M. Orienti[31], E. Orlando[14], M. Palatiello[6,7], V. S. Paliya[22], D. Paneque[36], M. Persic[6,48], M. Pesce-Rollins[10], V. Petrosian[14], F. Piron[20], S. Poolakkil[11], H. Poon[34], T. A. Porter[14], G. Principe[35], J. L. Racusin[17], S. Rainò[12,13], R. Rando[8,9], M. Razzano[10,61], S. Razzaque[33], A. Reimer[14,42], O. Reimer[14,42], T. Reposeur[49], F. Ryde[4,50], D. Serini[12], C. Sgrò[10], E. J. Siskind[51], E. Sonbas[52], G. Spandre[10], P. Spinelli[12,13], D. J. Suson[53], H. Tajima[14,54], M. Takahashi[36], D. Tak[17,18], J. B. Thayer[14], D. F. Torres[55,56], E. Troja[17,18], J. Valverde[21], P. Veres[11], G. Vianello[14], A. von Kienlin[57], K. Wood[58], M. Yassine[6,7], S. Zhu[59], and S. Zimmer[42,60]

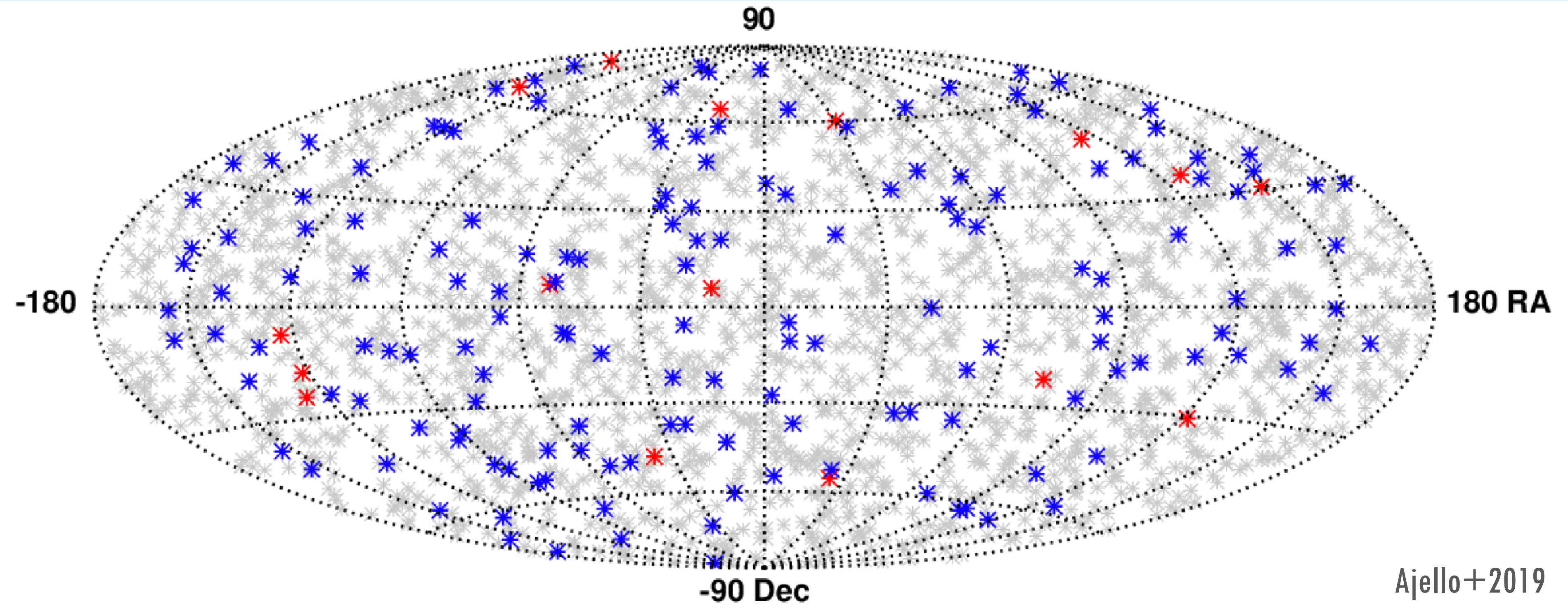
- Time period: **August 2008 to 2018 (10 years)**
  - Search from 3044 GRBs triggered by other instruments (GBM, Swift, Integral, AGILE, IPN)
- Detection algorithm searching 5 time windows [10 s to 10 ks] (**LTF**: Vianello+2015).
  - Every detection analysed by a **standardized analysis pipeline**
    - Compared with the 1FLGC

➔ **New detection algorithm**: **50% improvement**

➔ **Using Pass8 data**: **20% improvement**

Fermi LAT highlights

- **186 LAT detections** (169 long, 17 short)
  - **91 LLE** GRBs (85 long, 6 short), with **17 LLE only** GRBs (15 long, 2 short)



  - 176 joint detections with **GBM** (160 long, 16 short)
    - 2 Swift-BAT, 8 IPN

➔ 34 GRBs have redshift measurments

Fermi LAT highlights

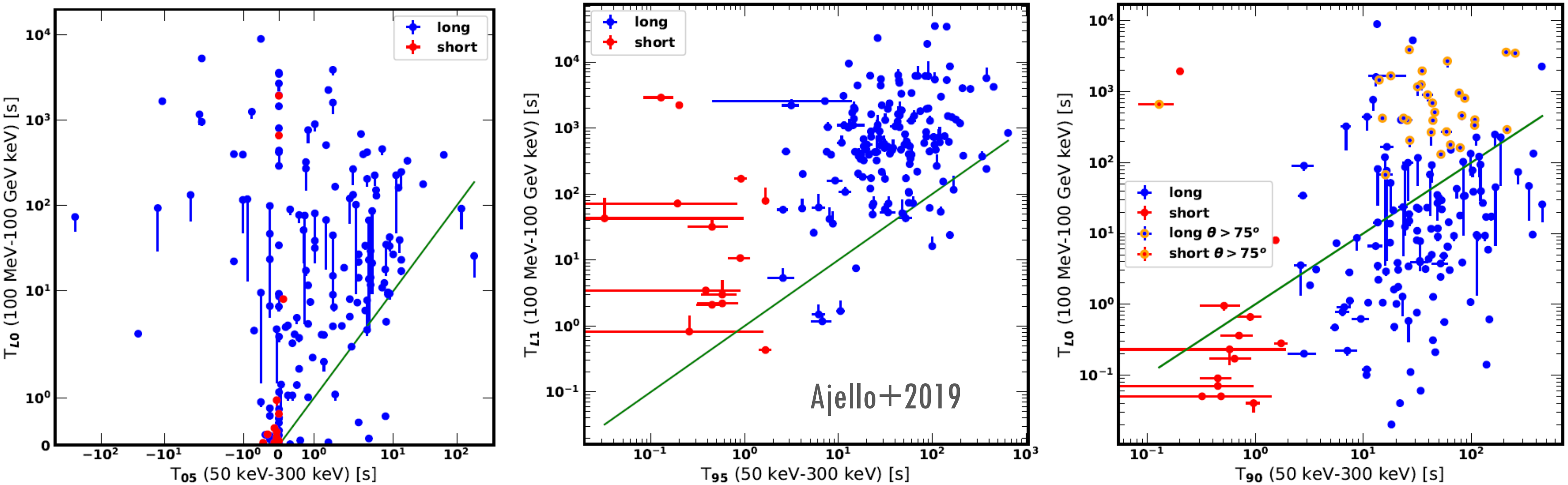
- **HE GRB temporal properties**

T_{90} : Canonical GRB duration measured by GBM [**50 – 300 keV**]

- $T_{90} = \mathbf{T_{95}} - \mathbf{T_{05}}$

T_{L100} : **new** GRB duration measured by LAT [**100 MeV – 100 GeV**]

- $T_{L100} = \mathbf{T_{L1}} - \mathbf{T_{L0}}$ (Arrival time of last and first photon, respectively)



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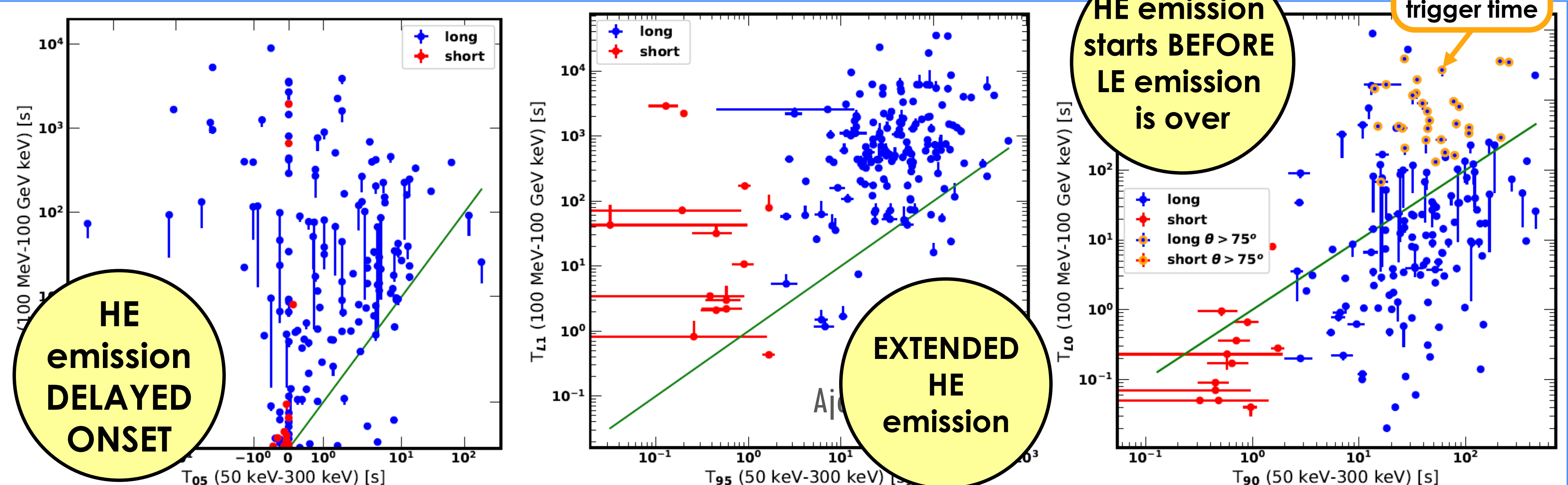


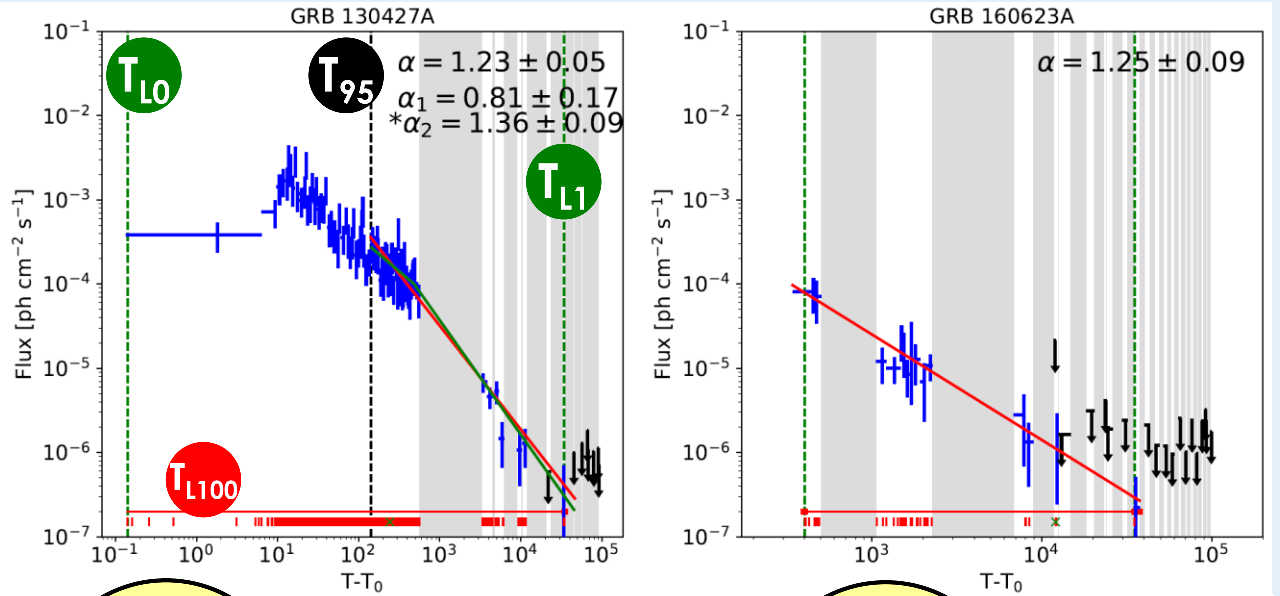
Fermi LAT highlights

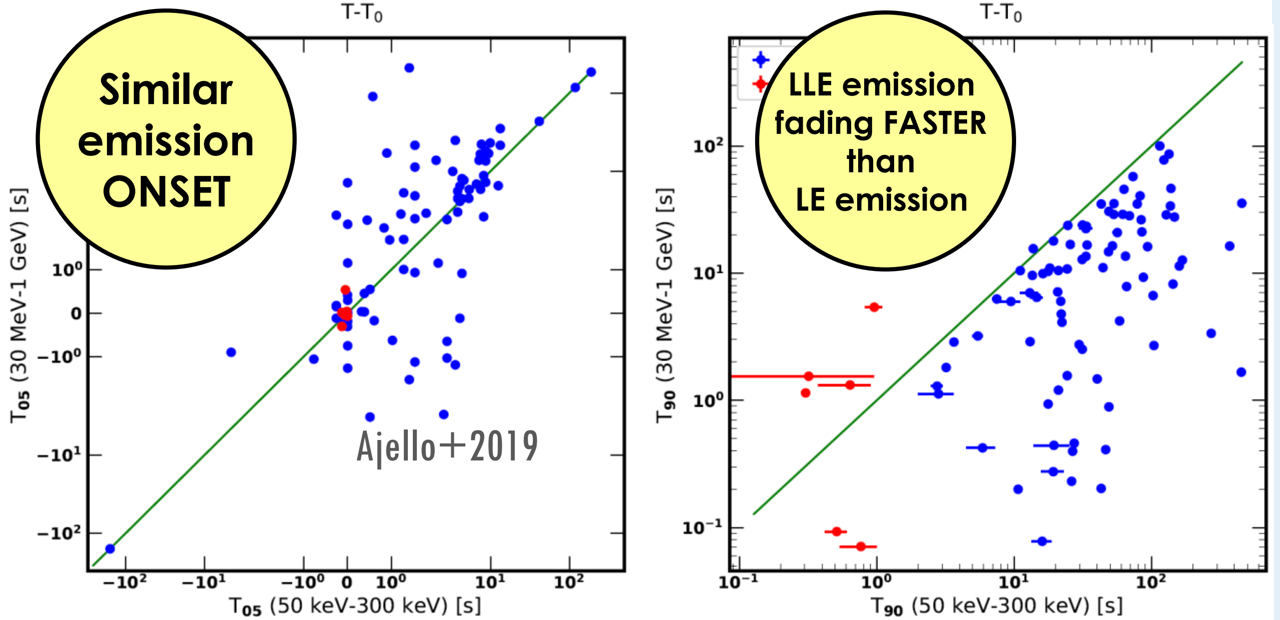
Longest bursts

1. GRB 130427A
   T_{L100} = 34 ks
2. GRB 160623A
   T_{L100} = 35 ks

LLE bursts

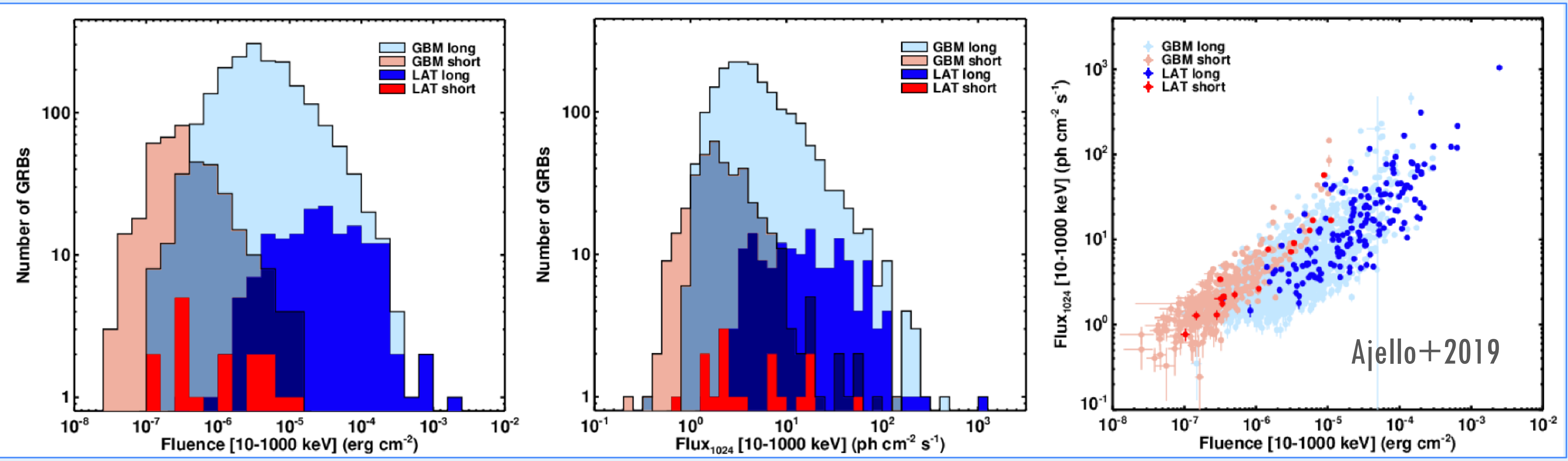
- **[30 MeV – 1 GeV]**
- Definition of duration similar to the GBM
- Behavior similar to low-energy emission





Fermi LAT highlights

- **HE GRB Energetics:**
  Comparison of low-energy properties of LAT-detected GRBs with the entire **10yr GBM sample** (**~2400 GRBs**)

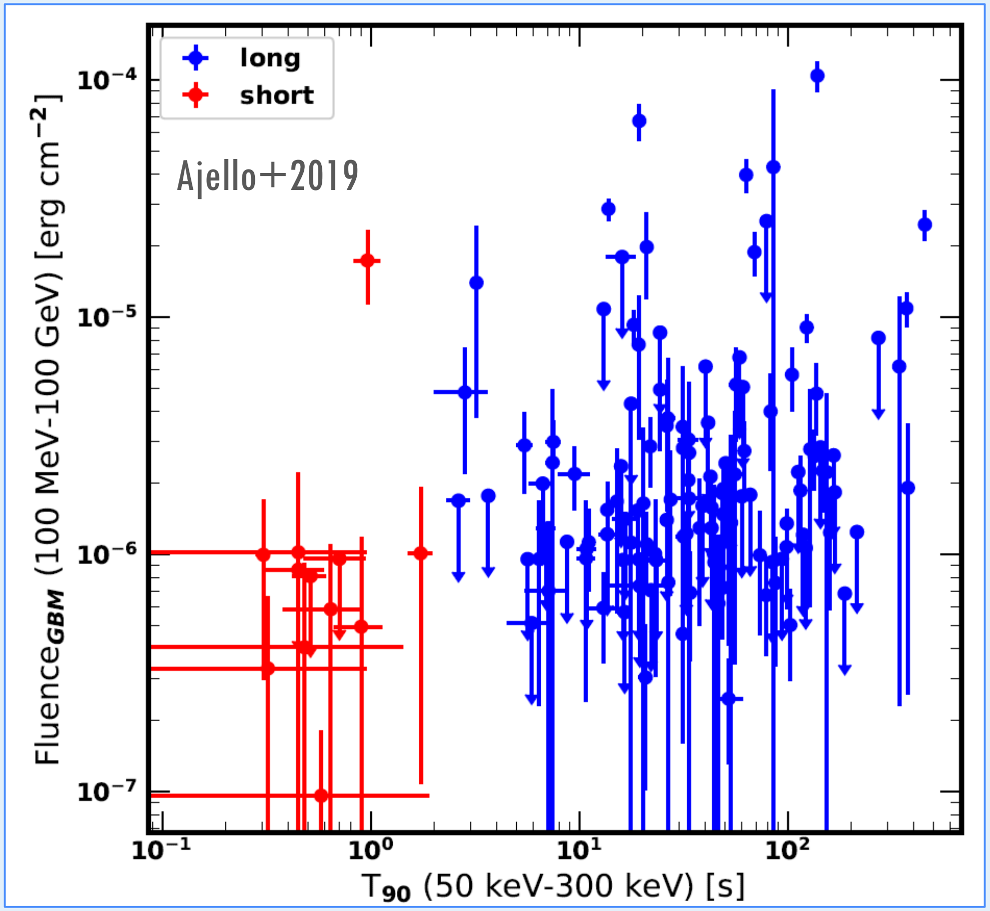


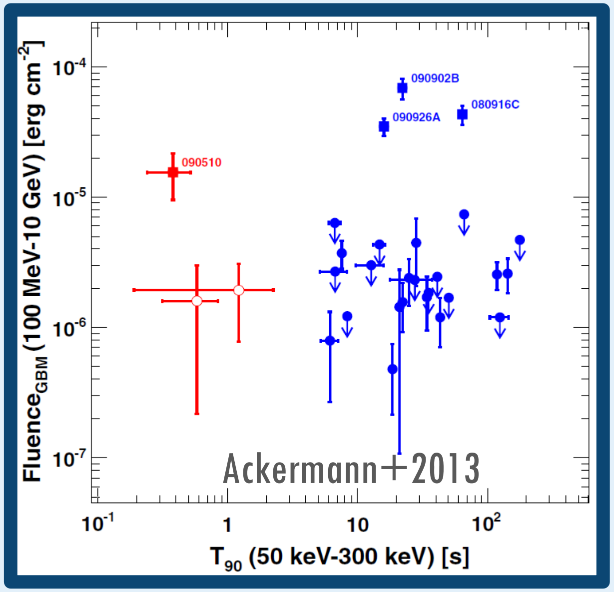
- Distribution of short and long bursts are **different**
- LAT tends to sample brighter bursts
  - BUT: **MUCH LARGER SPREAD** now than in the first LAT catalog!
  - We now detect HE emission also from **weak GBM bursts**!

Fermi LAT highlights

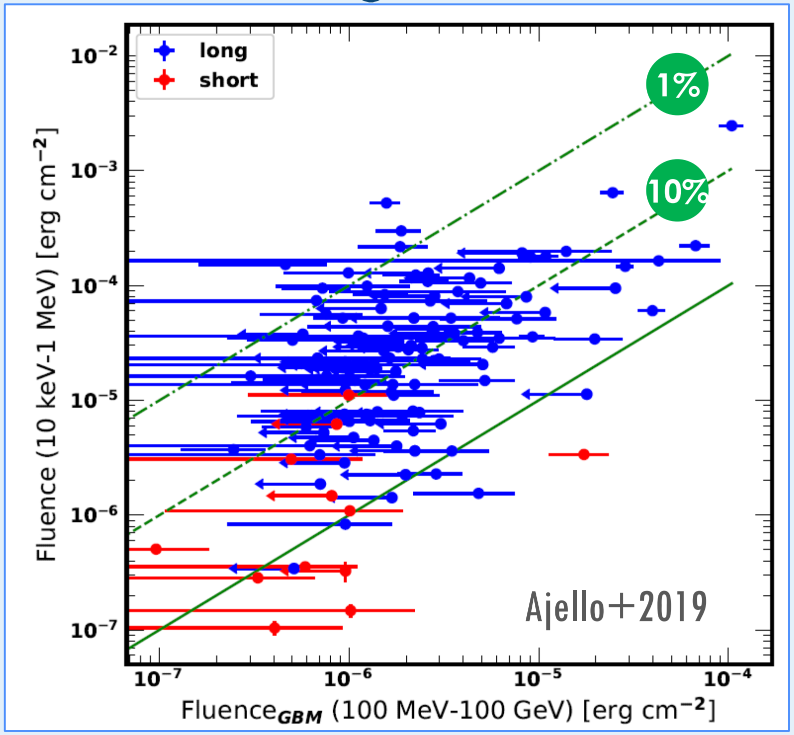
LAT Fluence calculated over the prompt time window (T_{90}) vs duration

- No clear correlation
- Hint of **distinction** between short and long bursts
- Comparing 1FLGC: Much wider range and **no more clear outliers**!

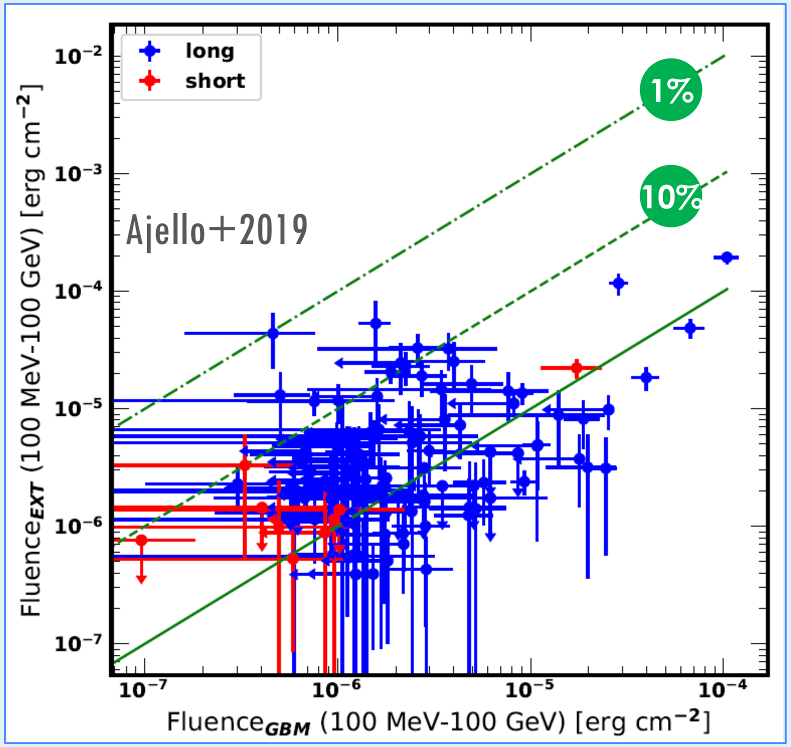




Fermi LAT highlights



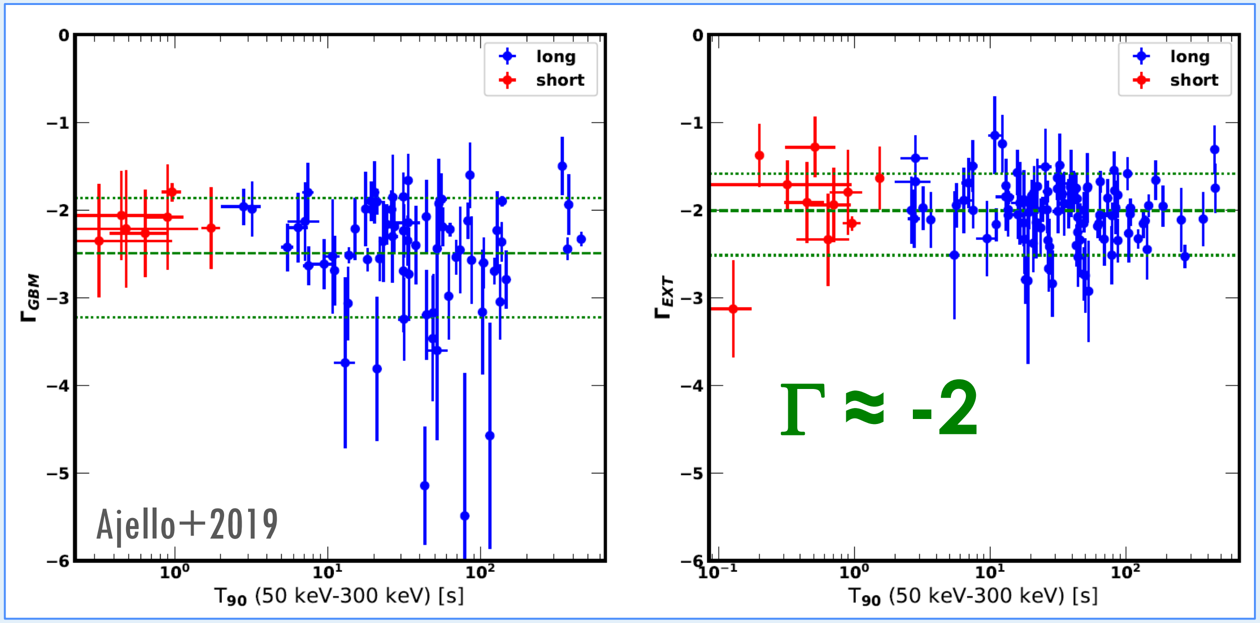
- GBM (10-1000 keV) fluence is >10 x larger than LAT (100 Mev-100 GeV) fluence
  - The majority of the burst **energy** is emitted at **lower energies**!



- In the LAT energy range, the fluence at late times is **comparable** to the prompt phase

Fermi LAT highlights

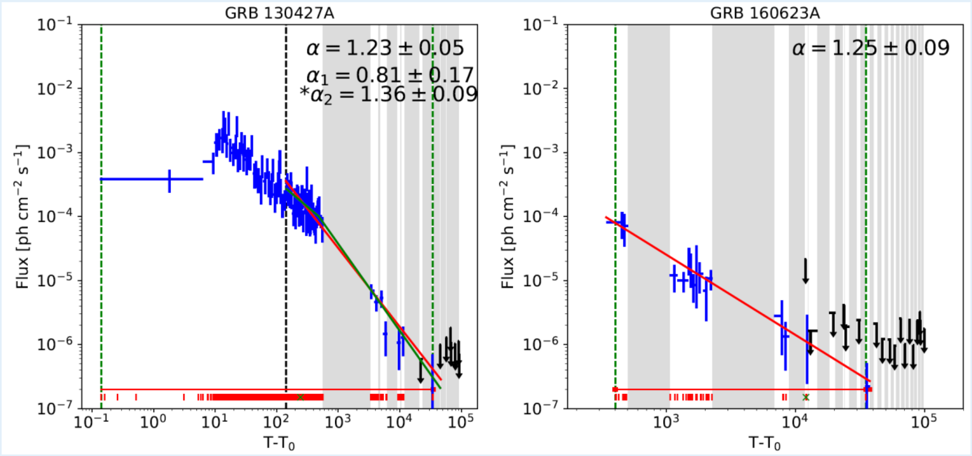
Photon index Γ vs duration in the prompt and late time windows



- No sign of correlation
  - Slightly **harder** at late times
- **Same component at work** in the LAT energy range the whole time
  - Is it the **same emission**? Possible **contamination** from the component that dominates in the **10-1000 keV** GBM energy range

Fermi LAT highlights

- **Time-resolved analysis**
  - 86 **long** and 2 **short** GRBs



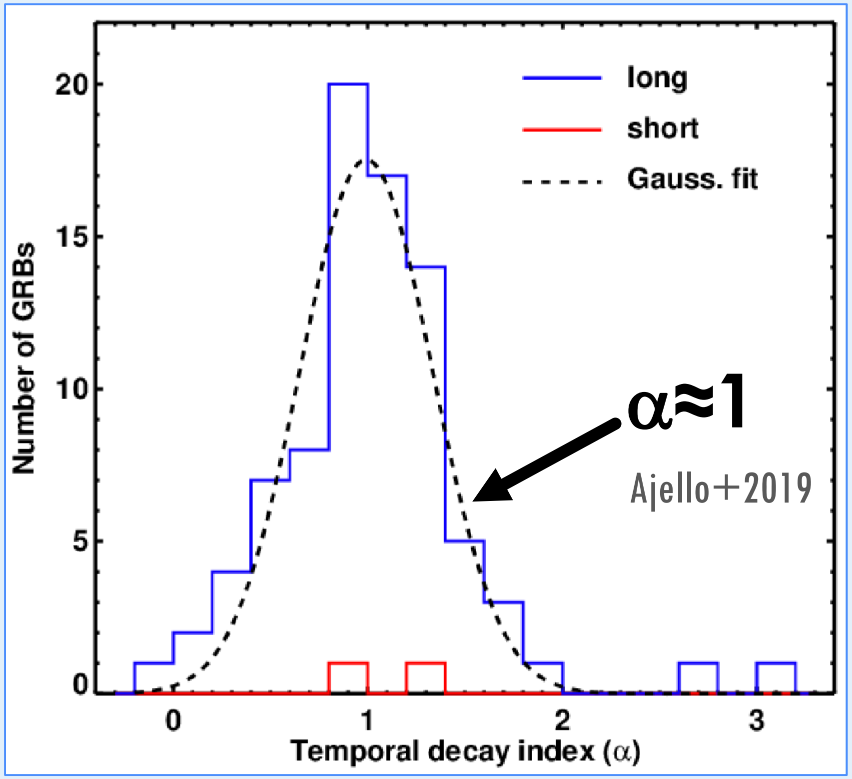
  - **Simple** and **broken** PL fits

$$F(t) = F_0 \left(\frac{t}{T_0}\right)^{-\alpha}$$

$$F(t) \propto t^{-p} \quad \begin{cases} p = \alpha_1 & \text{for } t < T_b \\ p = \alpha_2 & \text{for } t \geq T_b, \end{cases}$$

  - 12 bursts best fit with **BPL**

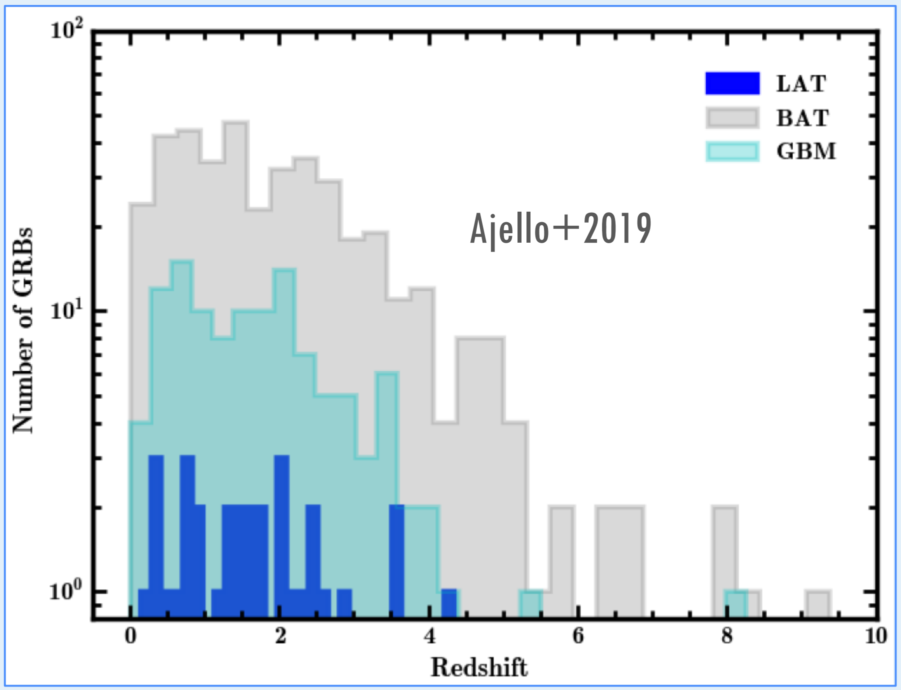
➔ Compatible with 1FLGC, but **better constrained**!



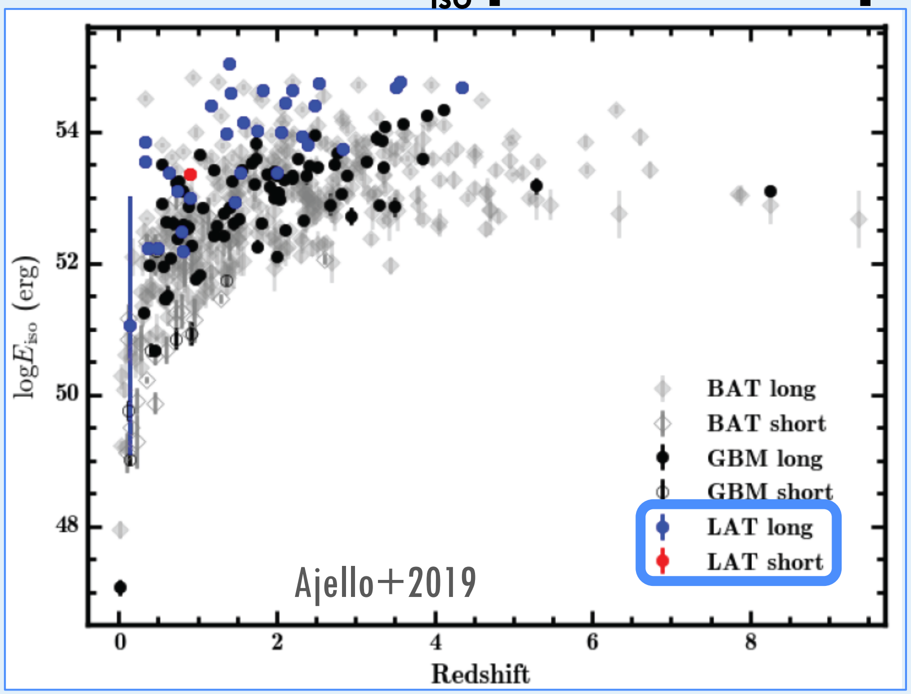
Fermi LAT highlights

- **The redshift sample: 34 GRBs** (33 long and 1 short)
  - Study of properties in the **source** frame

➔ Comparing with ***Swift*** and **GBM samples** we detect **brighter bursts!**

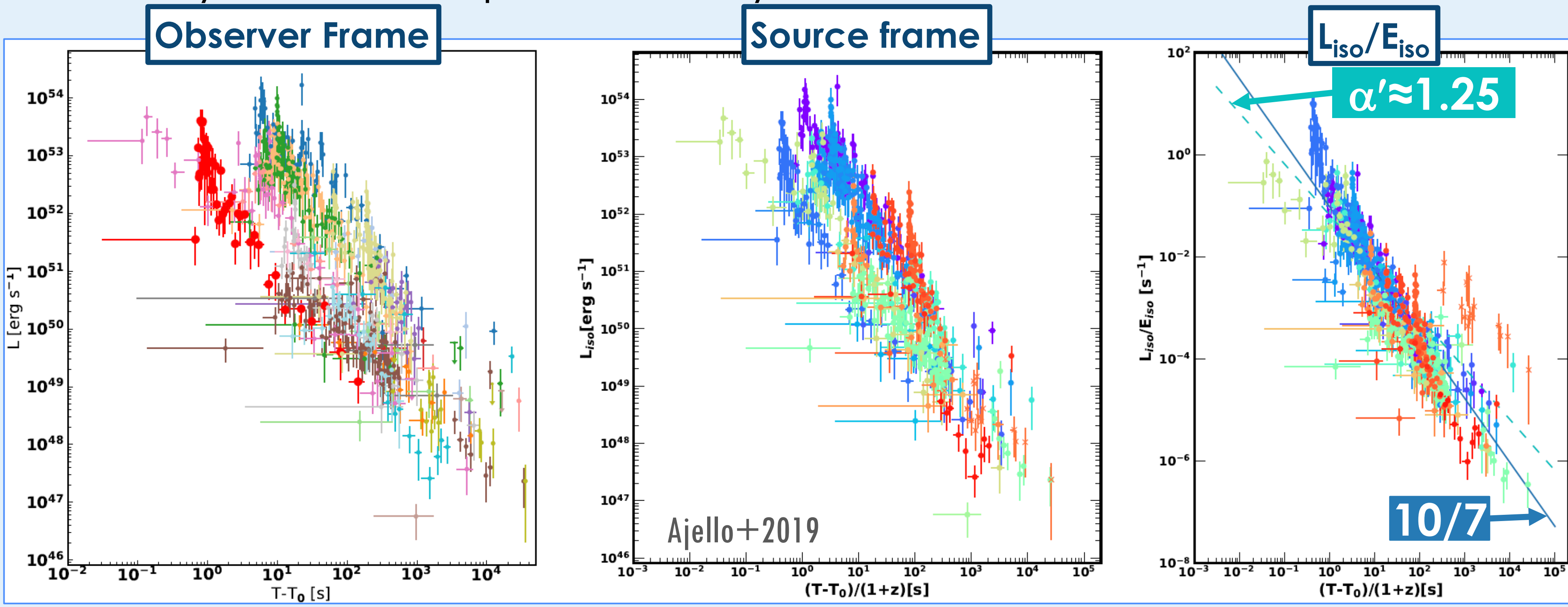


E_{iso} [1 keV – 10 MeV]



Fermi LAT highlights

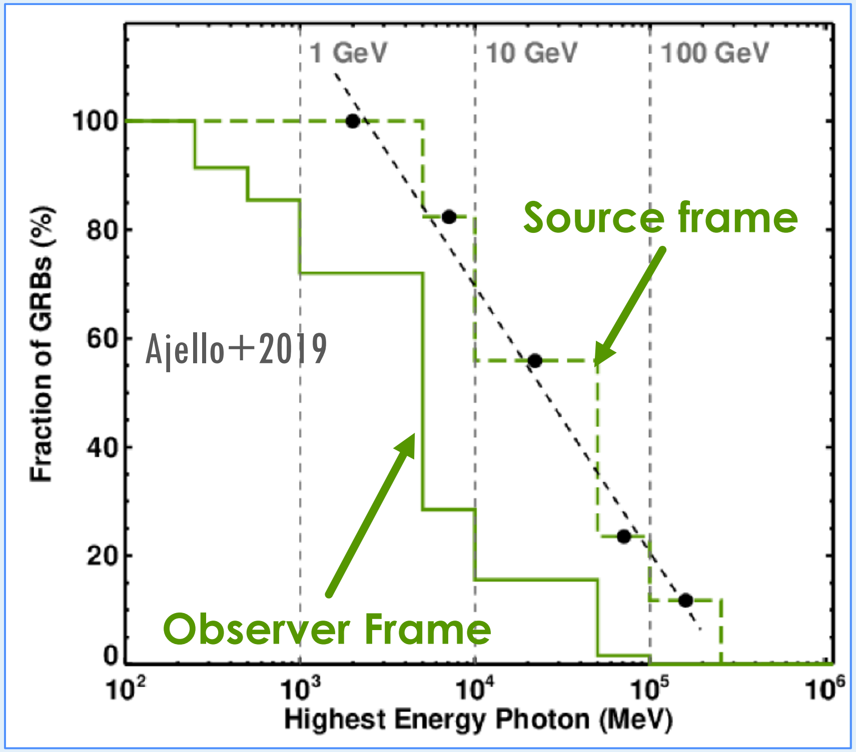
- Study of the temporal decay in **the source frame**

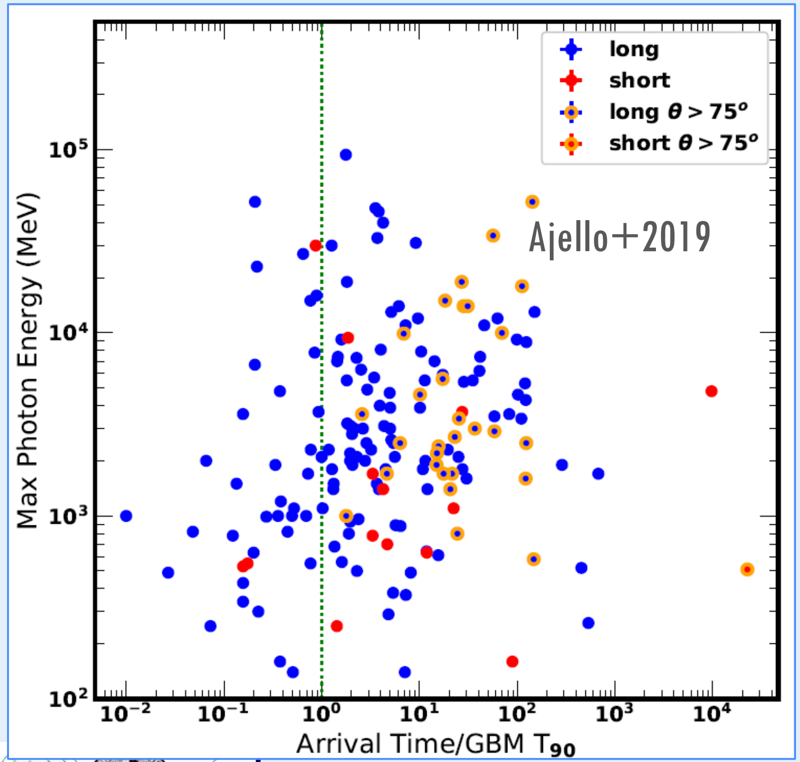


- For each correction, the **spread is reduced** and all points seem to **line up** (Ghisselini et al. 2010, Nava et al. 2014)
  - *In the rightmost plot: division by **E_{iso}** (proxy for **total energy budget**)*
    - ***Fit result** shown together with **theoretical** expectation*

Fermi LAT highlights

- Highest-energy photons from GRBs
  - **<5%** of GRBs have **E > 50 GeV**
  - Sharp drop @5 GeV (obs.frame)
  - Record holder: **GRB 130427A**
    - **95 GeV @243 s, 77 GeV @19s, 34 GeV @34 ks**





- HE photons often arrive after the low-energy emission is over BUT

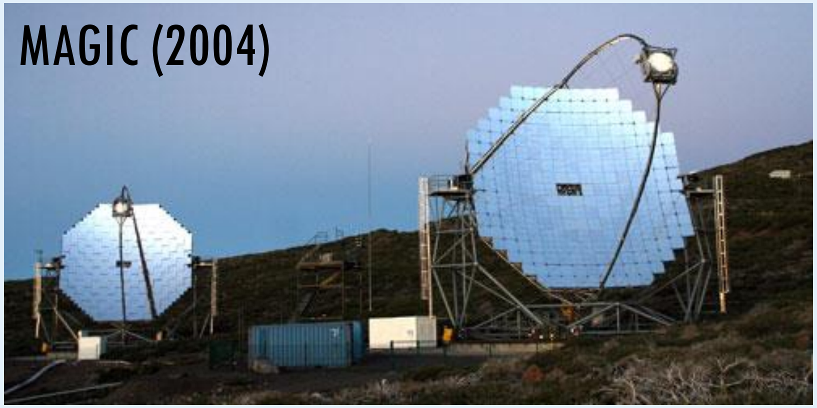
➡ Highest energies can be produced either very quickly or very late: challenge for models!

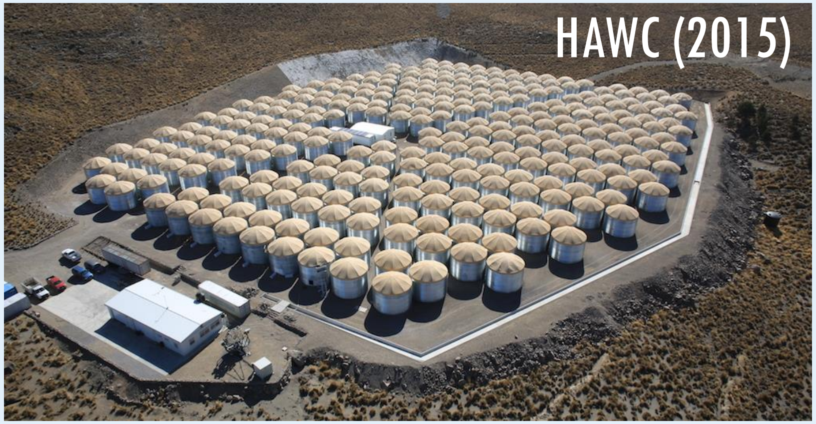
Fermi LAT highlights

Tricky to simultaneosly explain all LAT results!

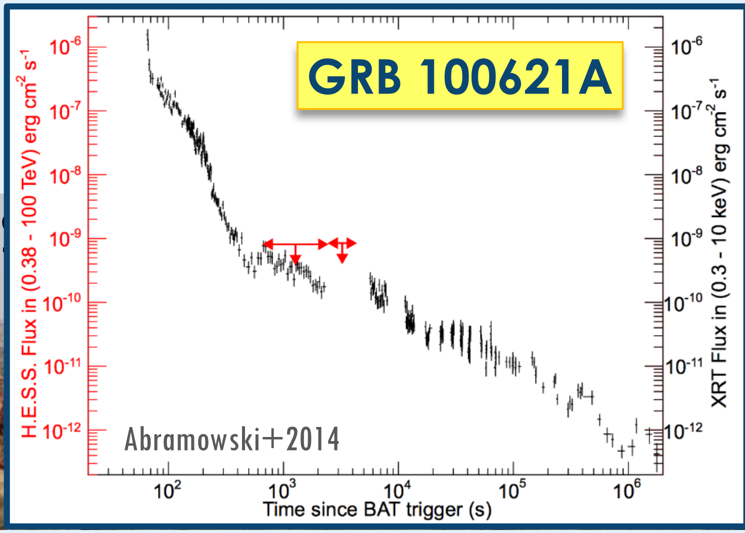
- Detection of HE emission implies **high Lorentz factors**
- Difficult to explain both delayed onset and long duration at the same time
  - **SSC**: difficulties with **very large delays**
    - Comptonization kicks off very quickly
  - **External Forward shock**: difficulties with **HE seen at very late times**
  - **Pair loading model**: difficulties with very large delays and large differences in **duration between LE and HE emission**
- **Closure relations**: Testing wind and ISM environments

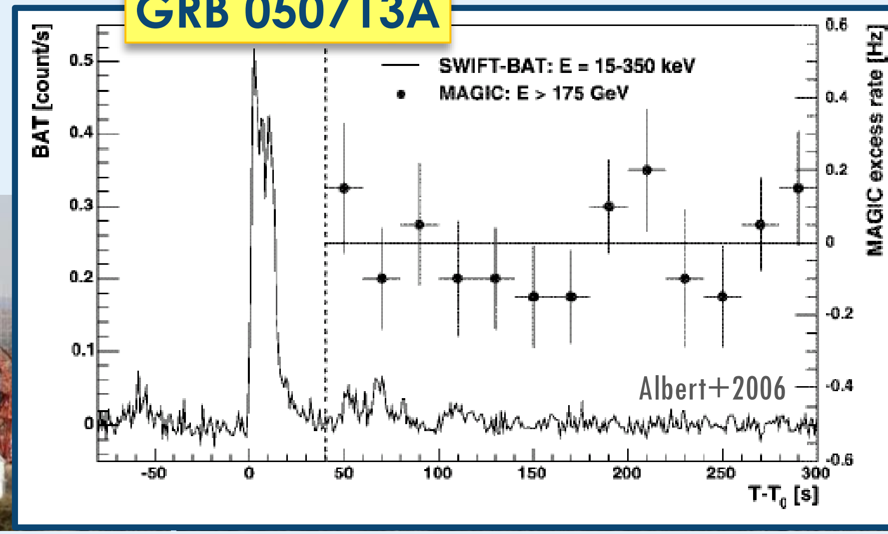
Ground-based detectors today…

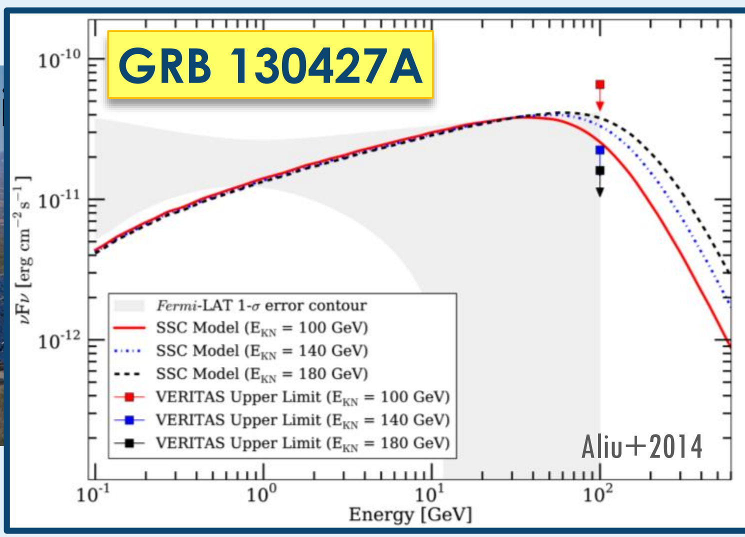


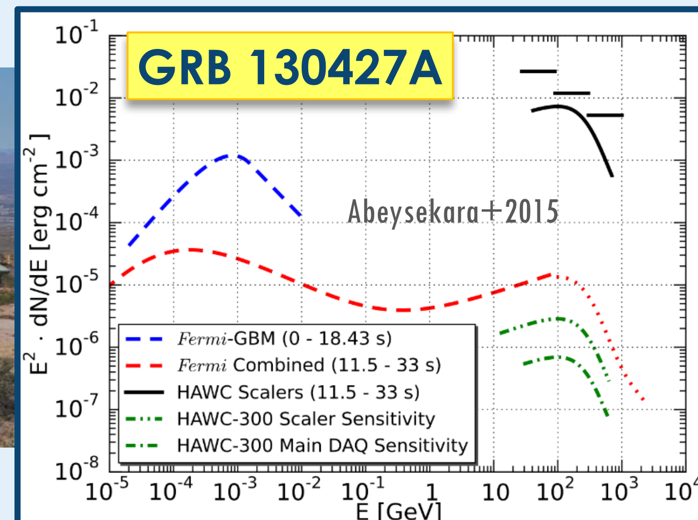


VHE GRB observations (pre-2018!)

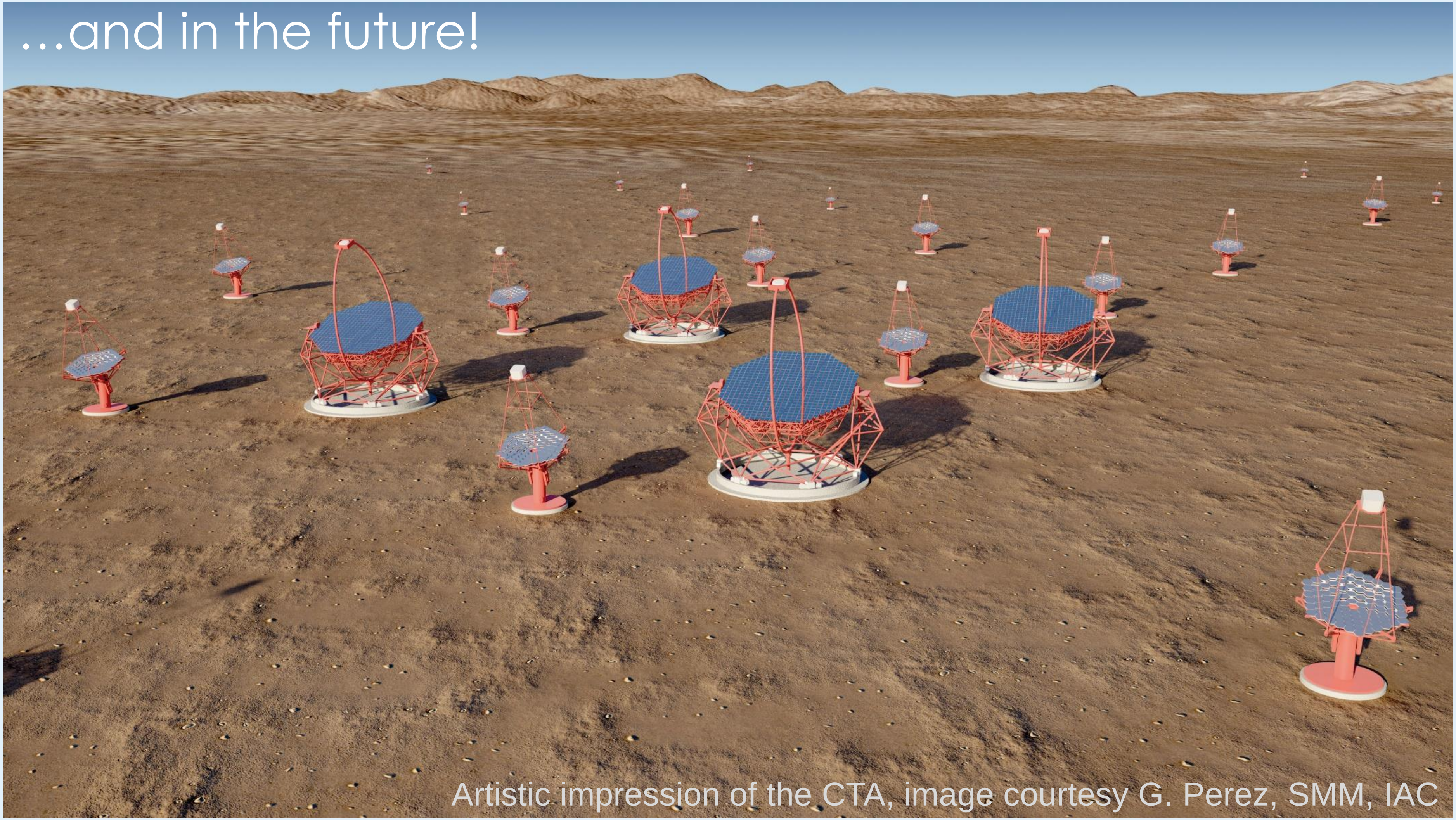






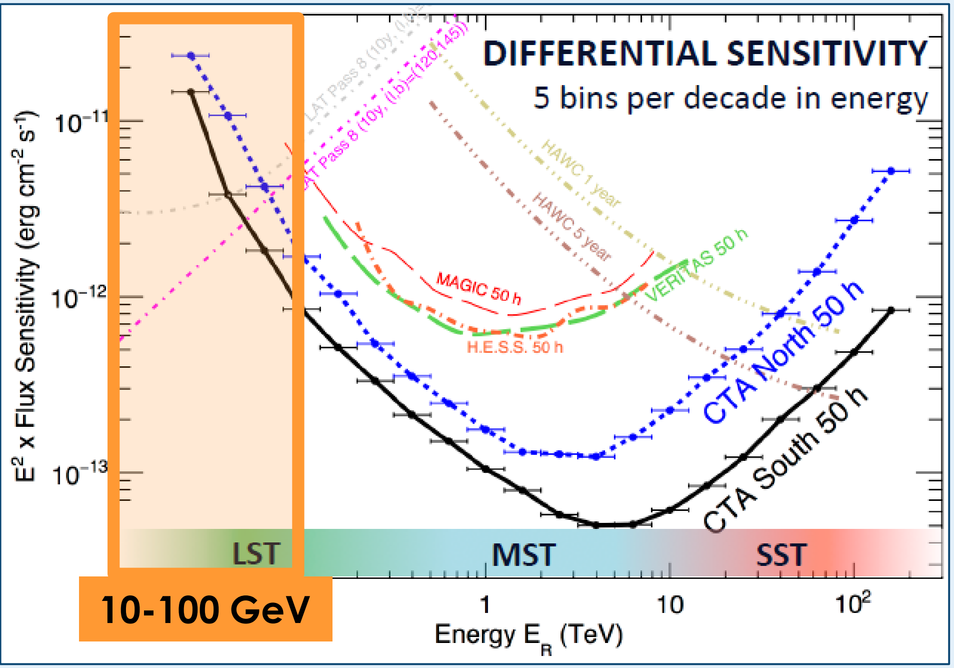


The Cherenkov Telescope Array (CTA)

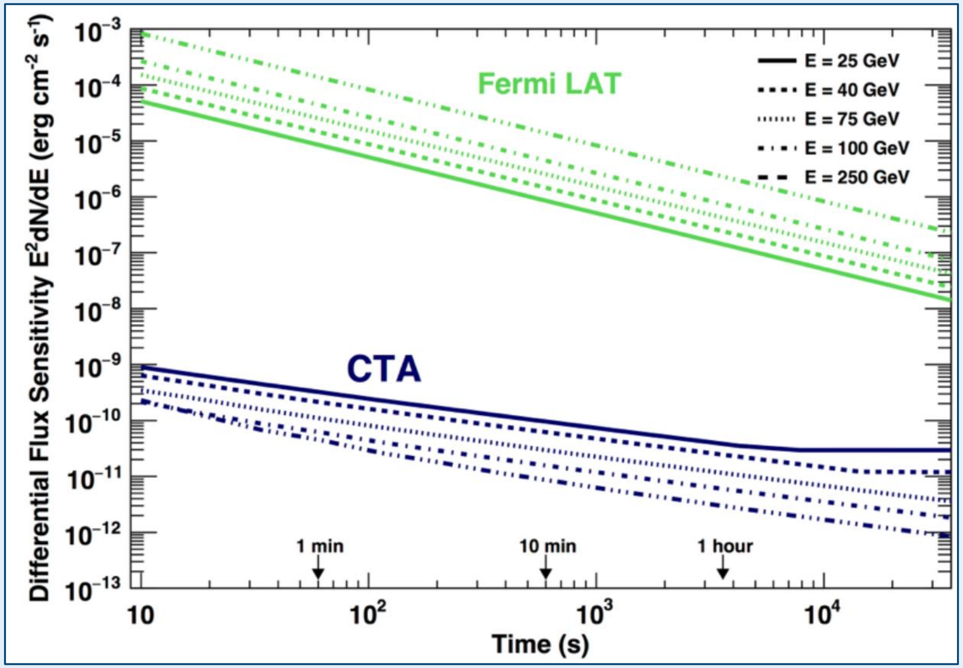


CTA sensitivity

Differential energy flux sensitivity for a point–like γ–ray source



Sensitivity per energy bin as a function of observation time



Pros: – Big advantage for **transients observation**
– CTA Effective area ~**10^4** x LAT @30GeV
Cons: Limited FoV, limited duty cycle

CTA KSP: Transients

cta cherenkov telescope array

Key Science Projects

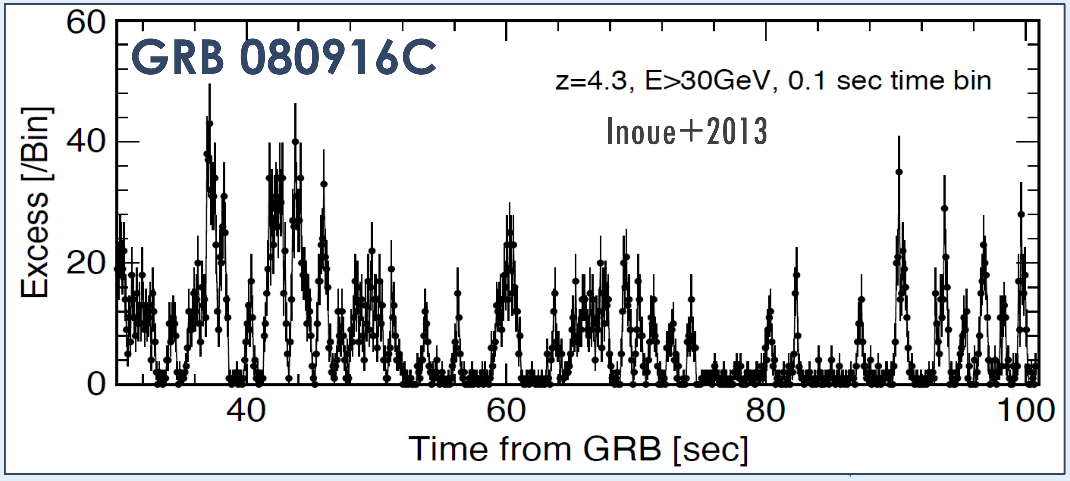
- X-ray, optical & radio transients
- Galactic transients
- GRBs
- HE ν transients
- GW transients
- Serendipitous transients

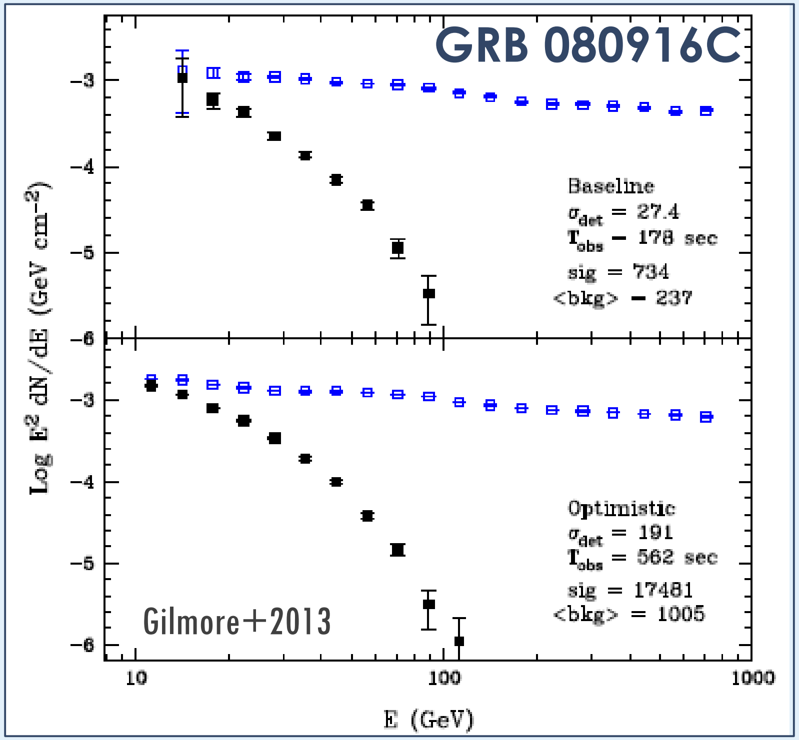
- **VHE transient survey:** To be performed via *divergent pointing* and concurrently with parts of the extragalactic survey
  - Comprehensive Monte Carlo predictions for the expected performance are ongoing!

Prospects for GRB detection by CTA

cta cherenkov telescope array

- Early studies rely on extrapolations taken from:
  - Spectral parameters from the **BATSE and Swift** catalogs
  - A couple of **very energetic GRBs** detected by Fermi before 2012





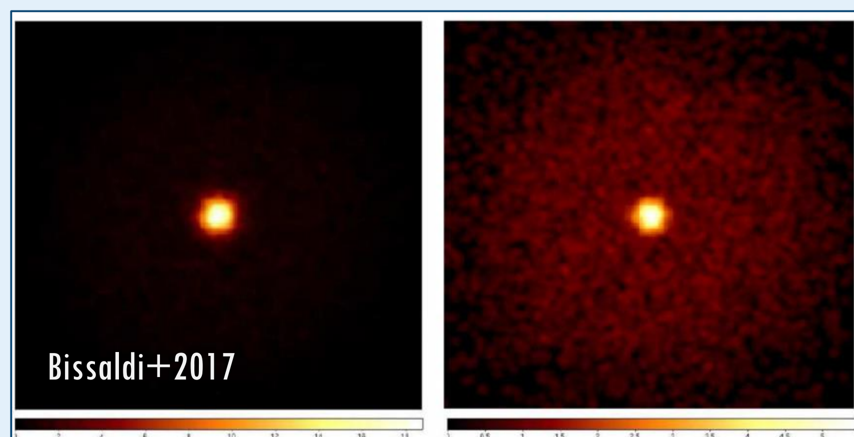
Prospects for GRB detection by CTA

- More recent work based again on a phenomelogical approach
  - Setting up a **library of high-energy GRBs** observed by Fermi over 10 years into the mission

  - **Procedure**:
    - Extrapolation of the LAT flux to CTA energies
      - Flux estimation at different post triggers epochs, taking into account the flux temporal evolution
    - Taking into account EBL absorption placing the GRB at various redshifts
    - Convolution with the most recent official CTA IRFs
    - Using ctools

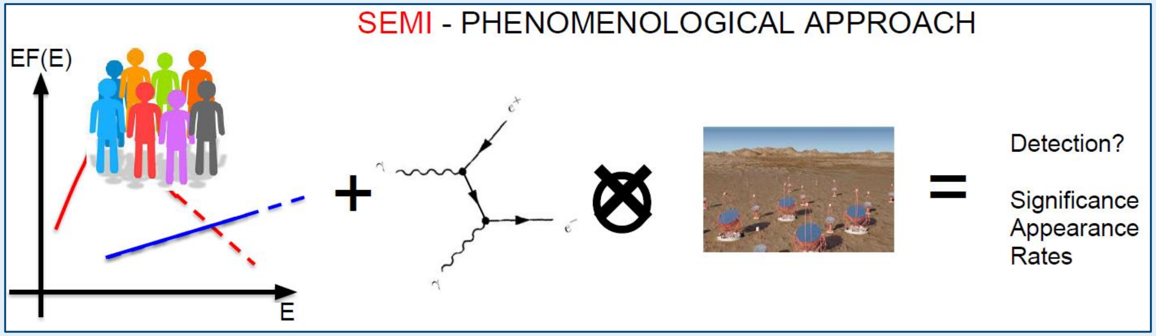
→ Test case GRBs:

- **GRB 090510 (short)**
- **GRB 130427A (long)**



Prospects for GRB detection by CTA

- **The POSyTIVE project**
  - Idea: **theory-based model for estimates of GRB detection rate**
  - **CTA Subgroup**: M. G. Bernardini, E. Bissaldi, Z. Bosnjak, A. Carosi, P. D'Avanzo, T. Gasparetto, G. Ghirlanda, S. Inoue, J. Lefaucheur, F. Longo, A. Melandri, L. Nava, P. O'Brien, Q. Piel, I. Sadeh, F. Schussler, T. Stolarczyk, S. Vergani
- We combine:
  a) Population models for both short and long GRBs (**Population Synthesis**)
     - Calibrated on **presently observed populations**
  b) Theoretical modeling for both prompt and afterglow emission (Theory Integrated code for Very high energy Emission)
     - Prompt emission: calibrated on Fermi GBM & LAT observations
     - Afterglow emission: calibrated with multi-wavelength observations of GRB afterglows
  c) CTA simulation tools
     - Gammapy
     - ctools



Prospects for GRB detection by CTA

POpulation Synthesis
Long
[Ghirlanda+2012;2015]
Short
[Ghirlanda+2016]

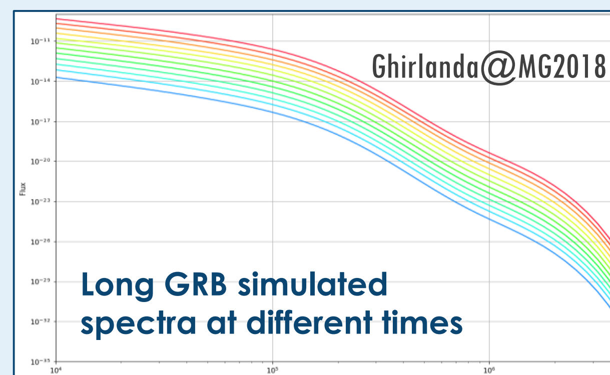
+

Theory Integrated code for Very high Energy emission

→ **PROMPT EMISSION**
Z. Bosnjak
Bosnjak et al. 2009, 2014

→ **AFTERGLOW EMISSION**
L. Nava
Nava et al. 2014
Beniamini, Nava et al. 2015

- **Goal**: Obtain CTA detection rates for prompt and afterglow of both short and long GRBs
  - As a function of physical parameters
  - As a function of the external GRB alert (Swift, Fermi, SVOM, THESEUS, …)
- First tests on a small sample of simulated GRBs (afterglow) are being carried out with both Ctools and GammaPy
- Evaluation of the role of CTA in the multiwavelength/multimessanger context for the study of GRBs



Conclusions

There is still a lot of discovery potential in the GRB field!

1. **keV energy range**: Gathering since the '90's a nice sample of several thousands events
   - Highlight: **Fermi-GBM**. New catalogs coming very soon!
   - Also: many other instruments at play
     - Waiting for **SVOM**, **Theseus**, etc.
2. **MeV energy range**: Still small numbers of events
   - Highlight: **Fermi-GBM+Fermi-LAT (LLE)**
     - Waiting for **Amego**, **eAstrogam**, etc.
3. **GeV energy range**: Sample of the order of 200 bursts
   - Highlight: **Fermi-LAT**. New 10-years catalog just released!
4. **TeV energy range**: The fun has just began!
   - Highlight: **CTA**. New predictions currently evaluated
   - Highlight: **HESS GRB 180720B**

Thank you!