GRB prompt emission spectra: the synchrotron revenge

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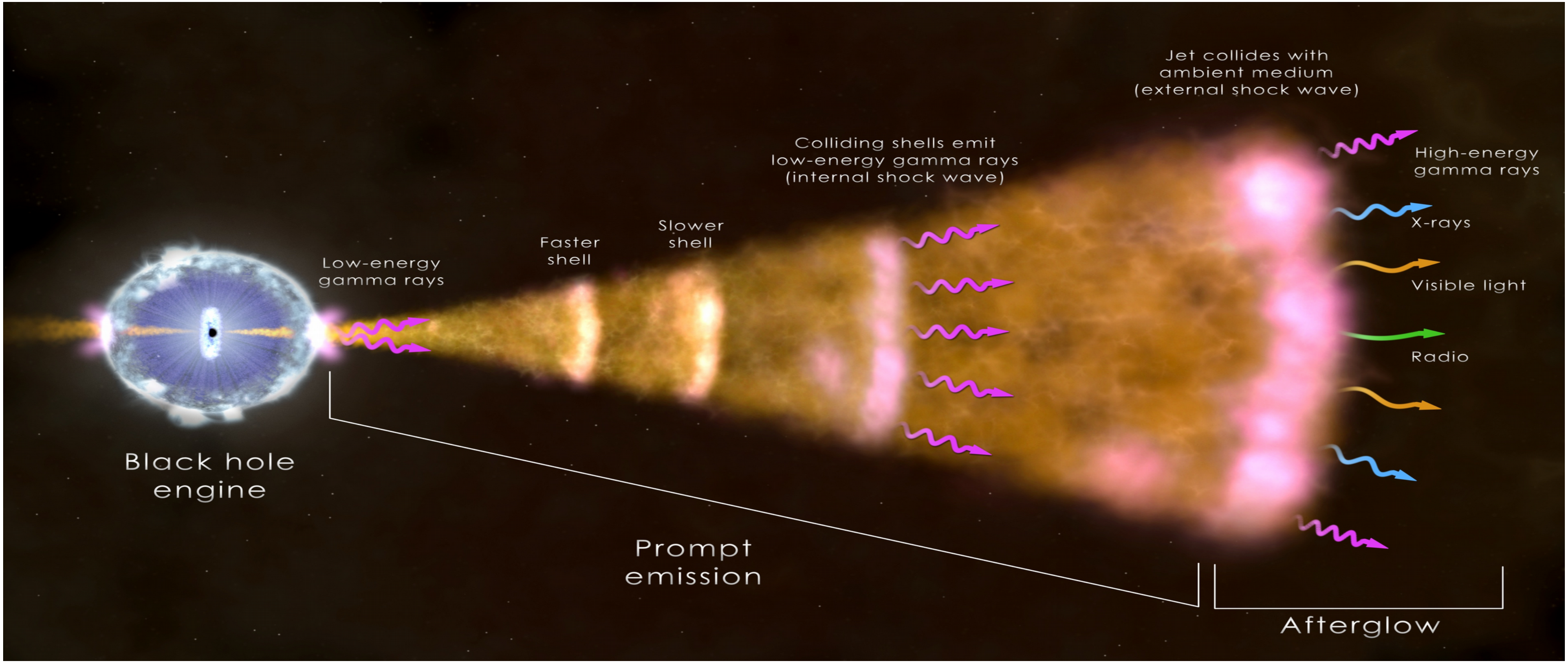
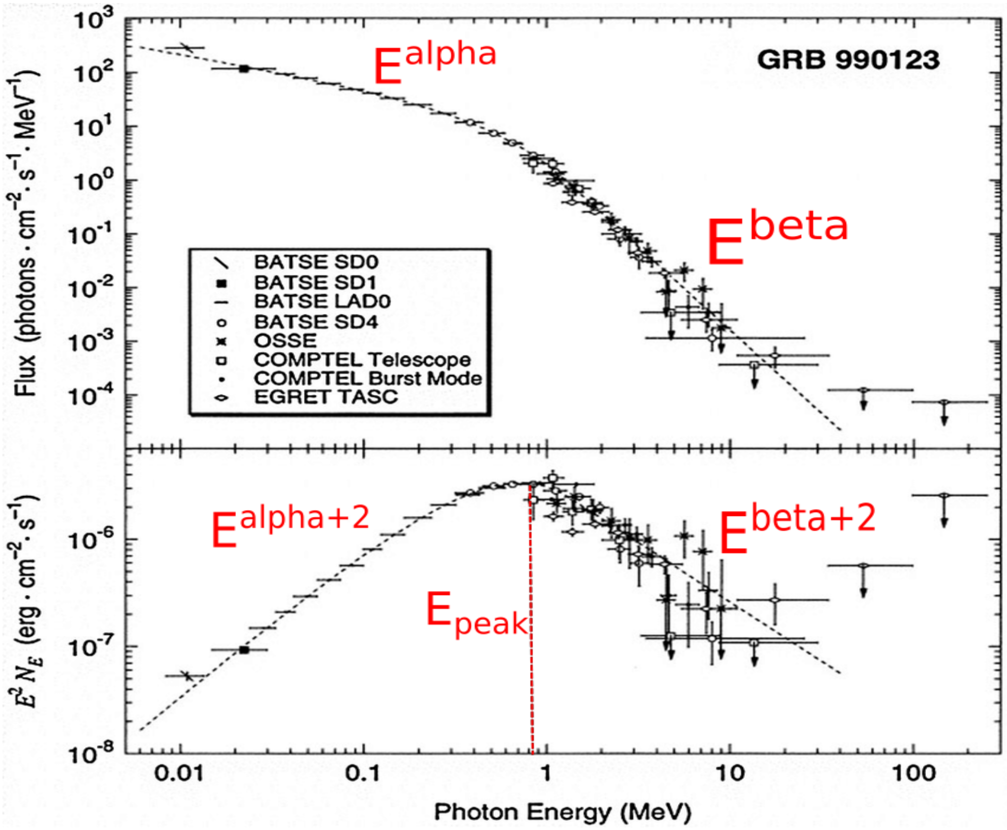
Ioffe Workshop on GRBs and other transient sources: 25 Years of Konus-Wind Experiment
09/09/2019 - St.Petersburg, Russia

Gamma-Ray Burst: standard model



Typical observed GRB prompt spectrum

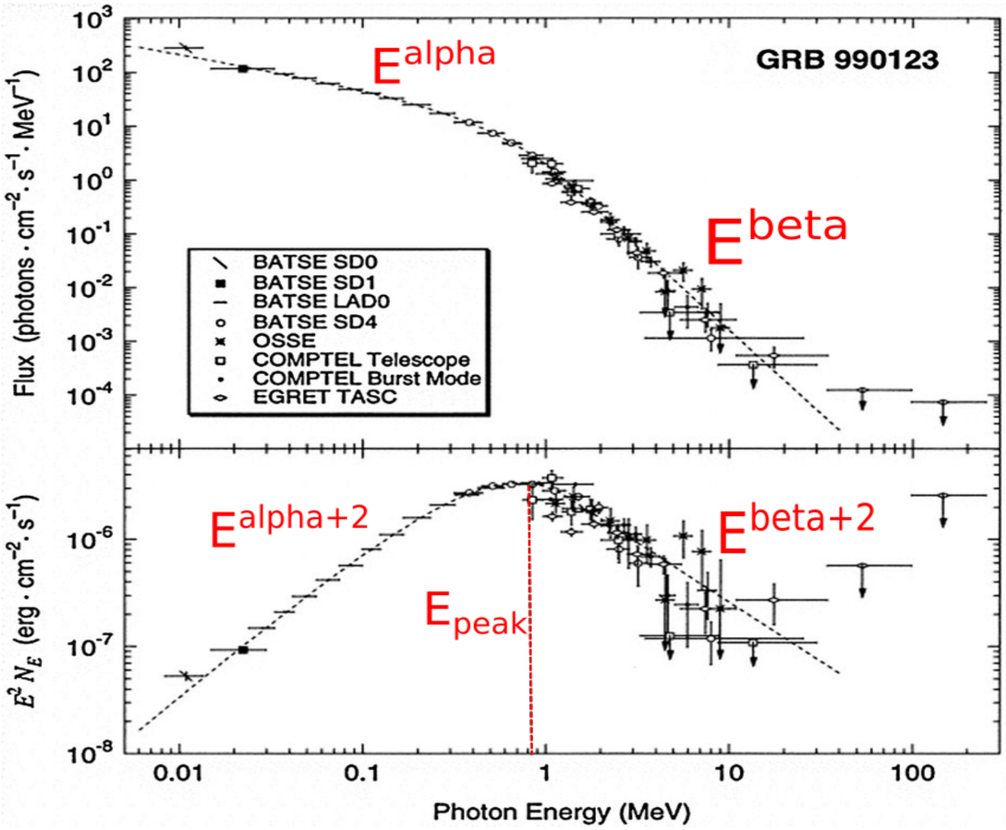


From Briggs et al., 1999

-Non-thermal spectrum

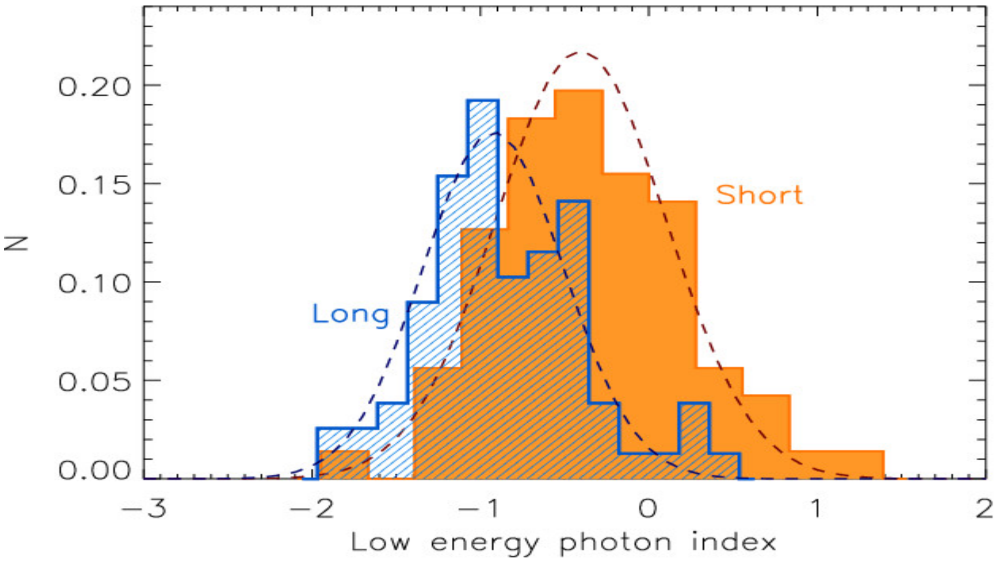
-Band function (Band et al., 1993) works most of the time (sometimes a power-law or a cut-off power-law is all that could be constrained, depending also from the energy range covered by the instrument)

Typical observed GRB prompt spectrum



From Briggs et al., 1999

LONG GRBs: <α> ~ -1
SHORT GRBs: <α> ~ -0.4



From Ghirlanda et al., 2009
(see also Preece 1998, Kaneko 2006, Nava 2011, Goldstein 2012, Gruber 2014)

Open problem of the GRB prompt emission

What is the radiative process responsible for the prompt emission?

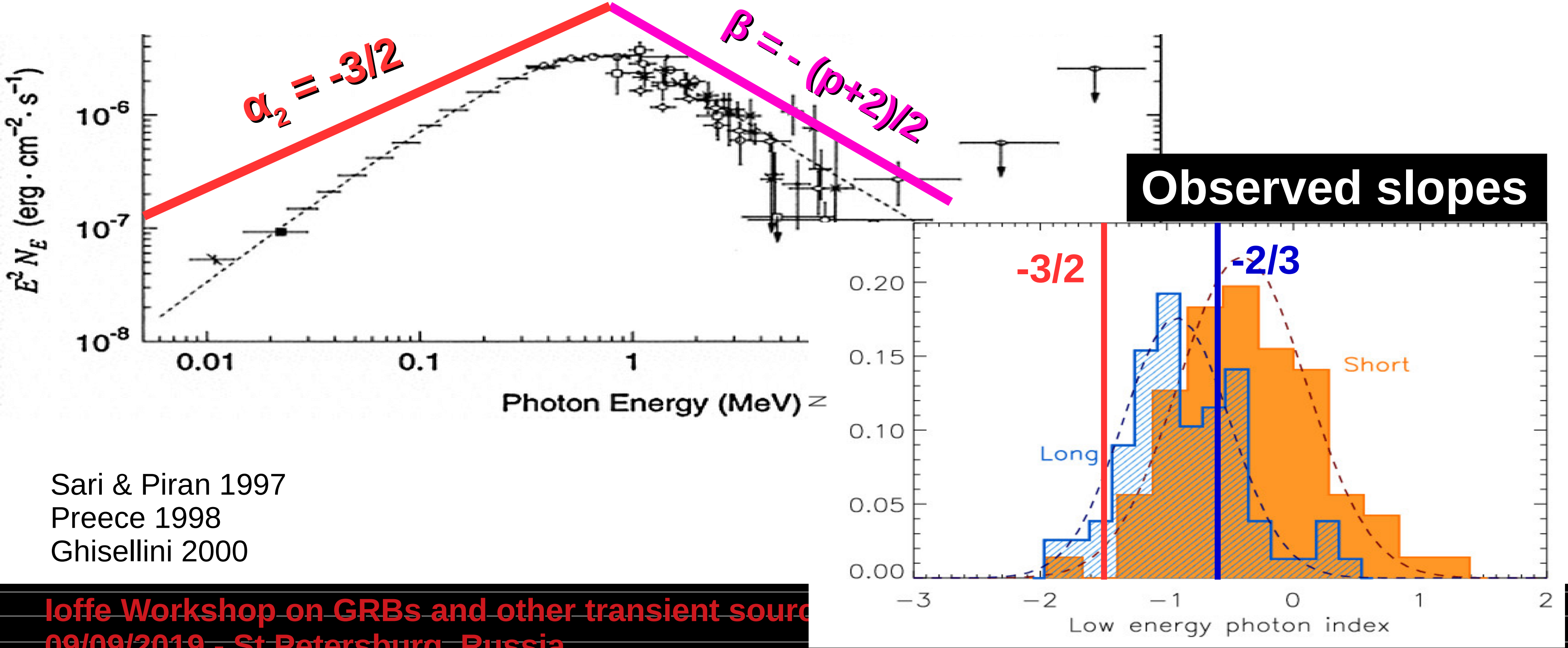
- Non-thermal spectrum
- Accelerated electrons in a magnetized region

→ Synchrotron?

Rees & Mészaros 1994
Sari et al. 1996, 1998

Synchrotron prediction for prompt spectrum - fast cooling regime

Theoretical predictions

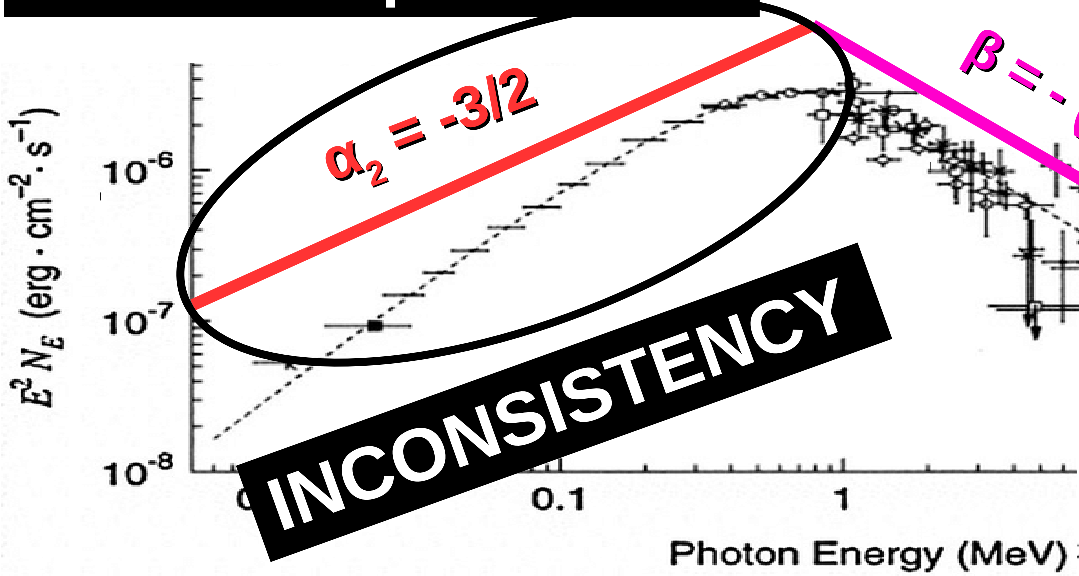


Observed slopes

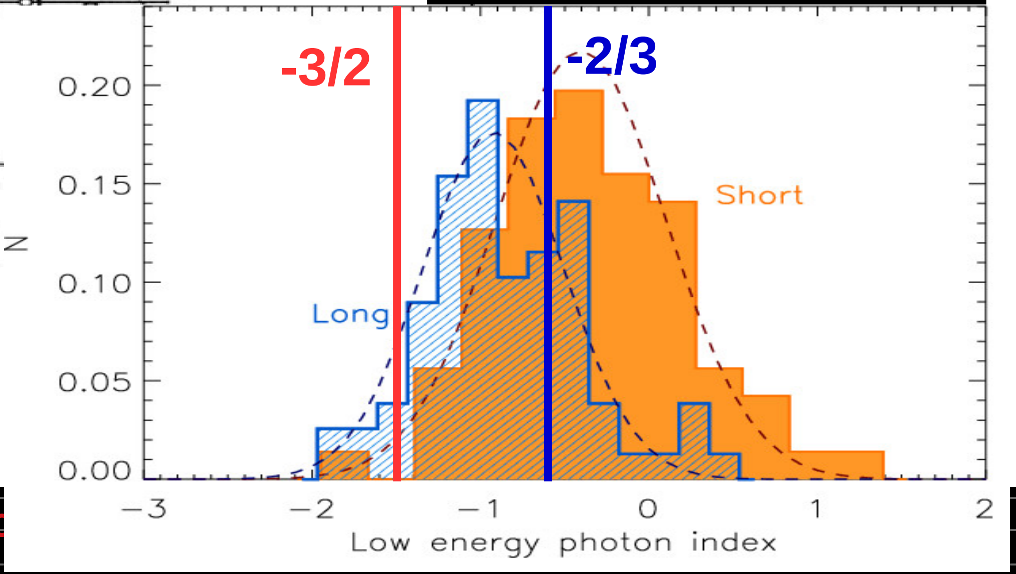
Sari & Piran 1997
Preece 1998
Ghisellini 2000

Synchrotron prediction for prompt spectrum - fast cooling regime

Theoretical predictions

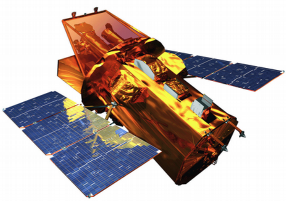


Observed slopes



Sari & Piran 1997
Preece 1998
Ghisellini 2000

Recent hints
Oganesyan et al., 2017; 2018

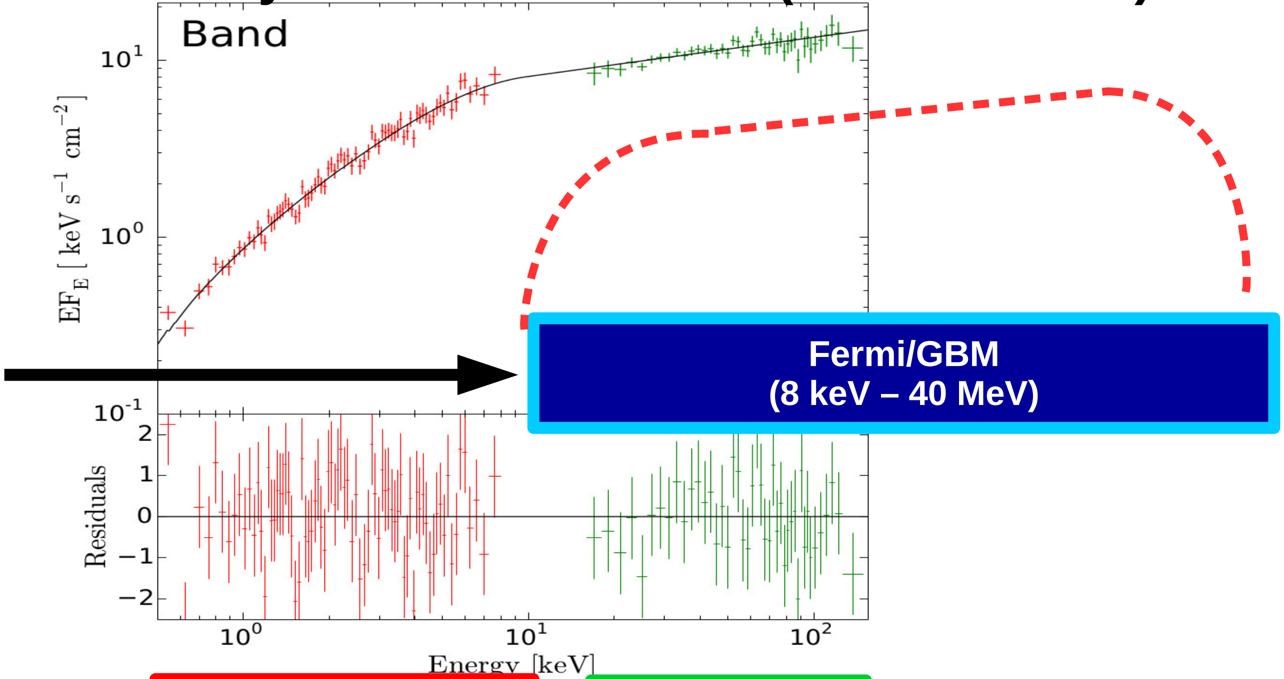


34 long GRBs observed simultaneously with XRT and BAT (Swift satellite)

- 62% of the prompt spectra display a break between 2 and 30 keV

- the spectral indices are
$\langle\alpha_1\rangle = -0.51 \pm 0.29$ and
$\langle\alpha_2\rangle = -1.54 \pm 0.26$

Consistent with synchrotron prediction!



Fermi/GBM
(8 keV – 40 MeV)

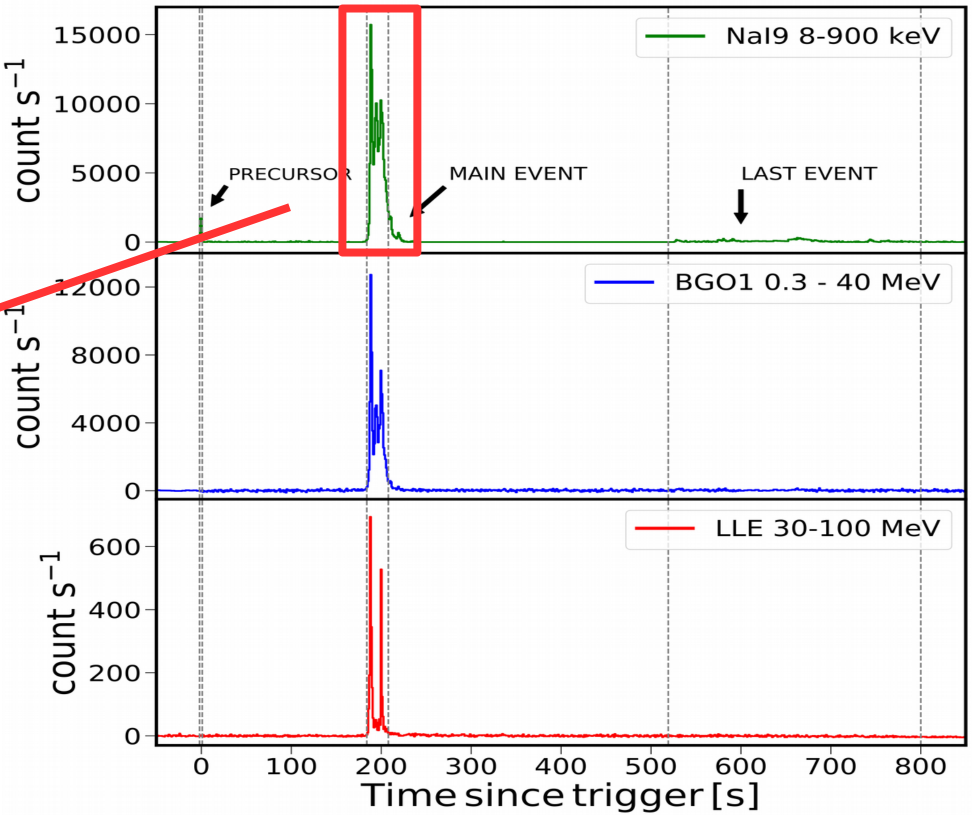
XRT
(0.3 – 10 keV)

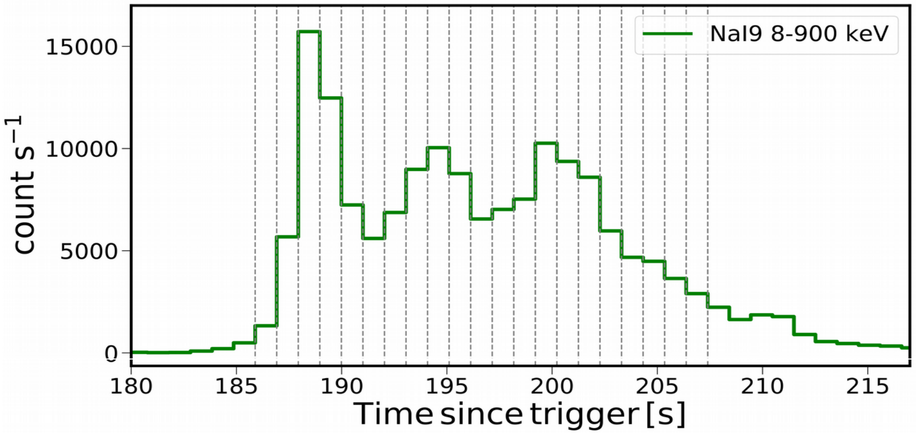
BAT
(15 – 150 keV)

GRB 160625B

Racusin et al GCN#19580 (LAT)
Burns et al GCN#19581 (GBM)

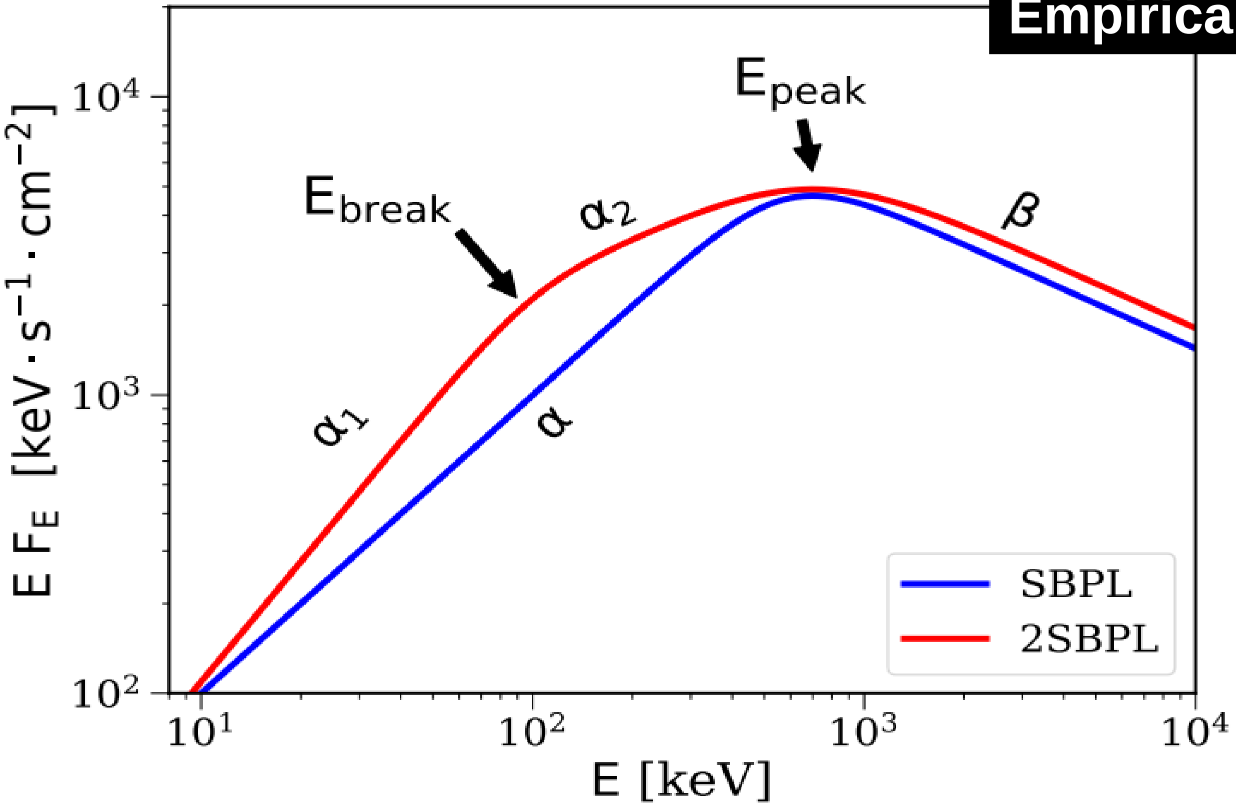
- **The GBM light curve consists of 3 distinct emission episodes**
- **Fluence = 5.7 x 10^{-4} erg/cm^2**
- **z = 1.406**



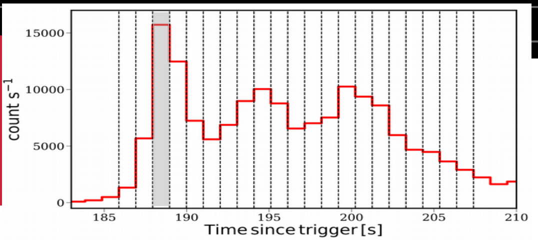


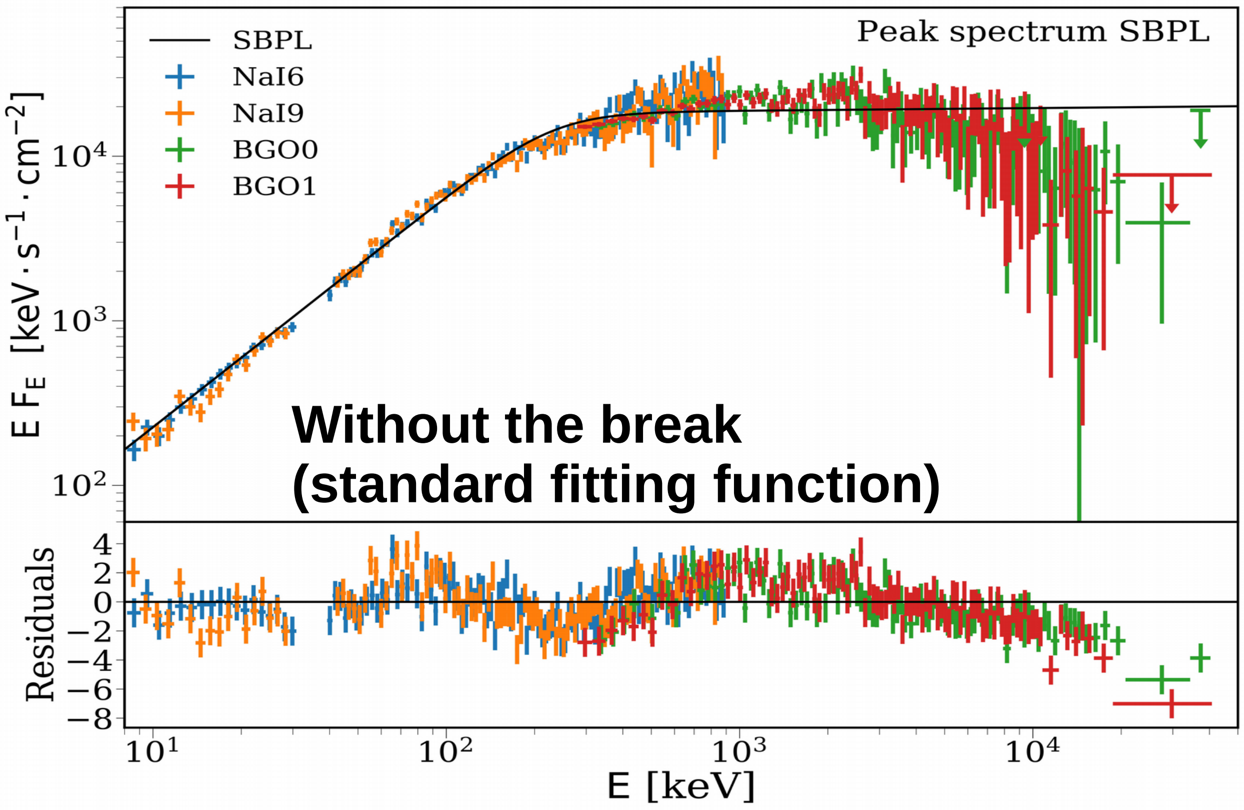
Comparison of the fitting functions

Empirical functions



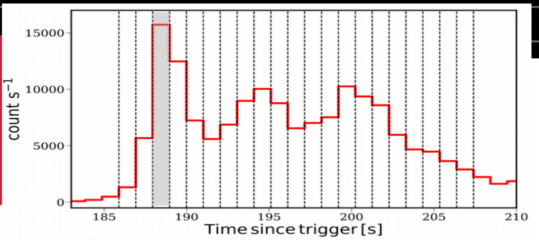
GRB 160625B:Time-resolved analysis

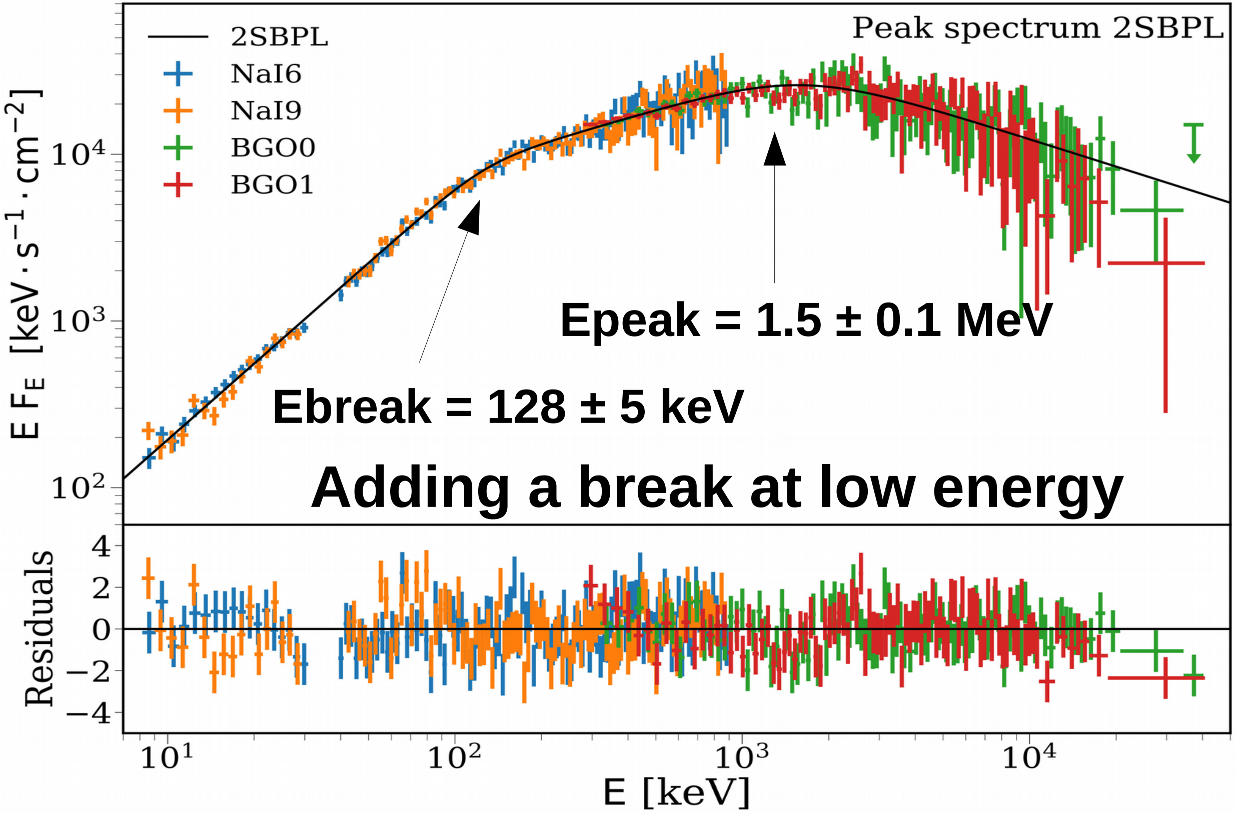




Without the break
(standard fitting function)

GRB 160625B:Time-resolved analysis



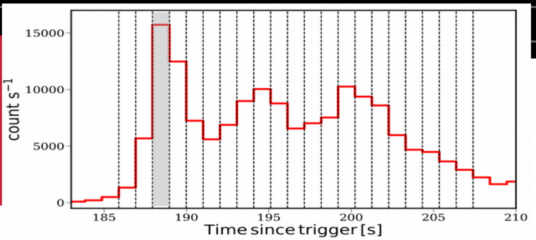


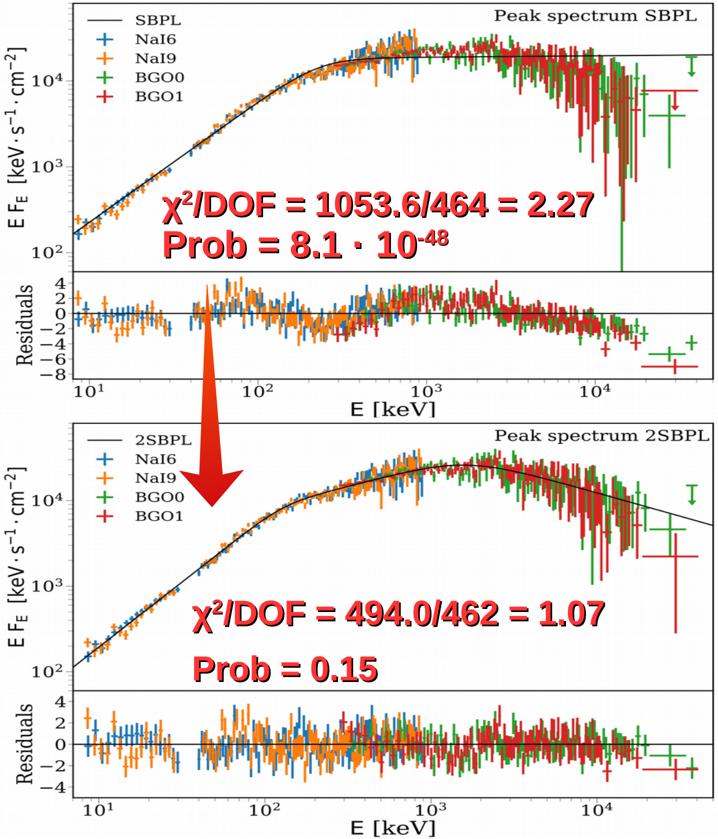
Epeak = 1.5 ± 0.1 MeV

Ebreak = 128 ± 5 keV

Adding a break at low energy

GRB 160625B:Time-resolved analysis





χ^2/DOF = 1053.6/464 = 2.27

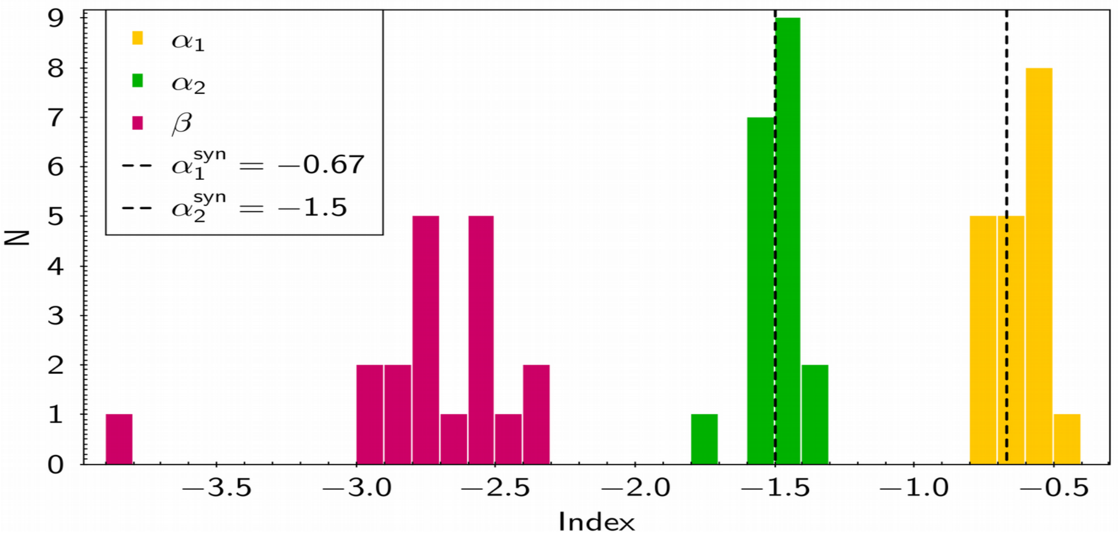
Prob = $8.1 \cdot 10^{-48}$

χ^2/DOF = 494.0/462 = 1.07

Prob = 0.15

The fit significantly improves! σ(F-test) > 8σ

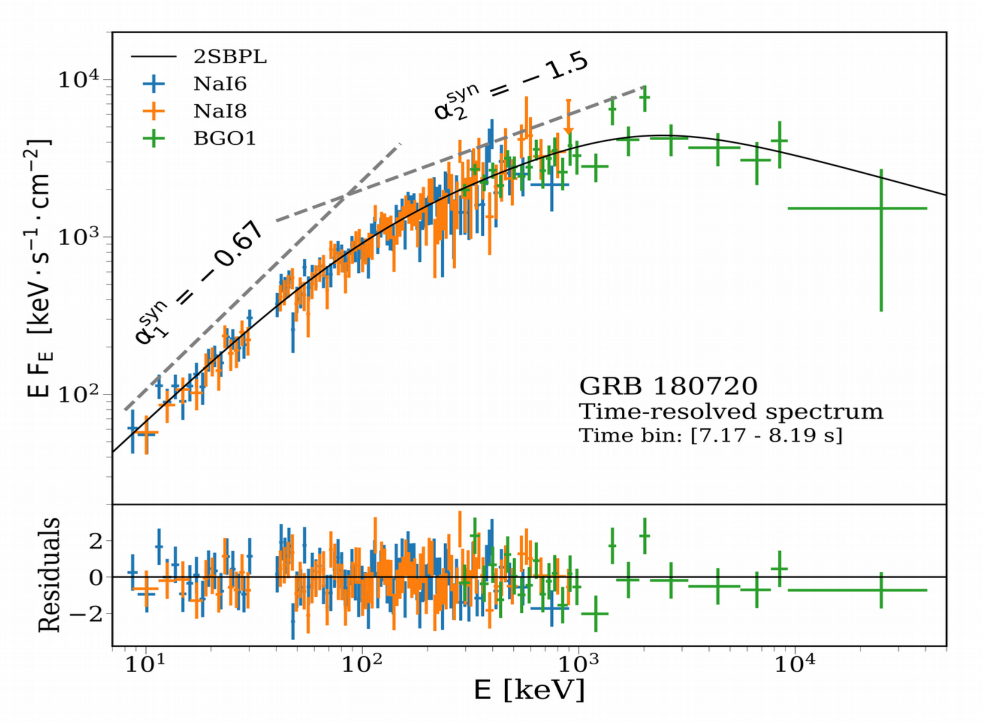
Synchrotron indices



DISTRIBUTION OF THE SPECTRAL INDICES
from the time-resolved analysis

Selection of the candidates

Ravasio, Ghirlanda, Nava & Ghisellini, 2019, A&A, 625, A60



We selected the brightest events in the Fermi/GBM Catalogue

10 LONG BRIGHTEST GRBs (over 2194 long GRBs detected by GBM)

10 SHORT BRIGHTEST GRBs (over 439 short GRBs detected by GBM)

Results of the time-resolved spectral analysis

10 LONG GRBs

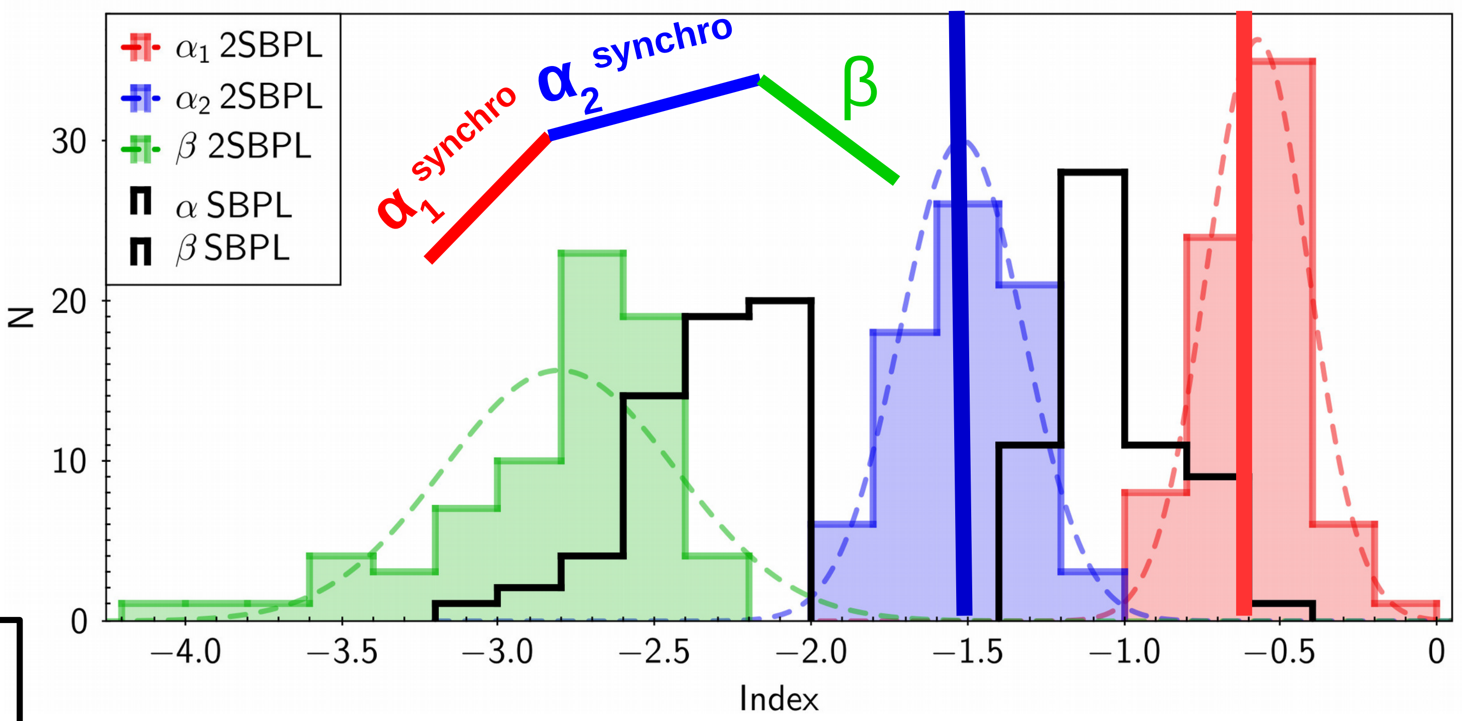
↓

BREAK FOUND IN 8/10 GRBs

In most of the time resolved spectra (139/199, **∼ 70%**) the best fit model is the 2SBPL function

$\langle\alpha_1\rangle = -0.58\ (0.16)$

$\langle\alpha_2\rangle = -1.52\ (0.20)$



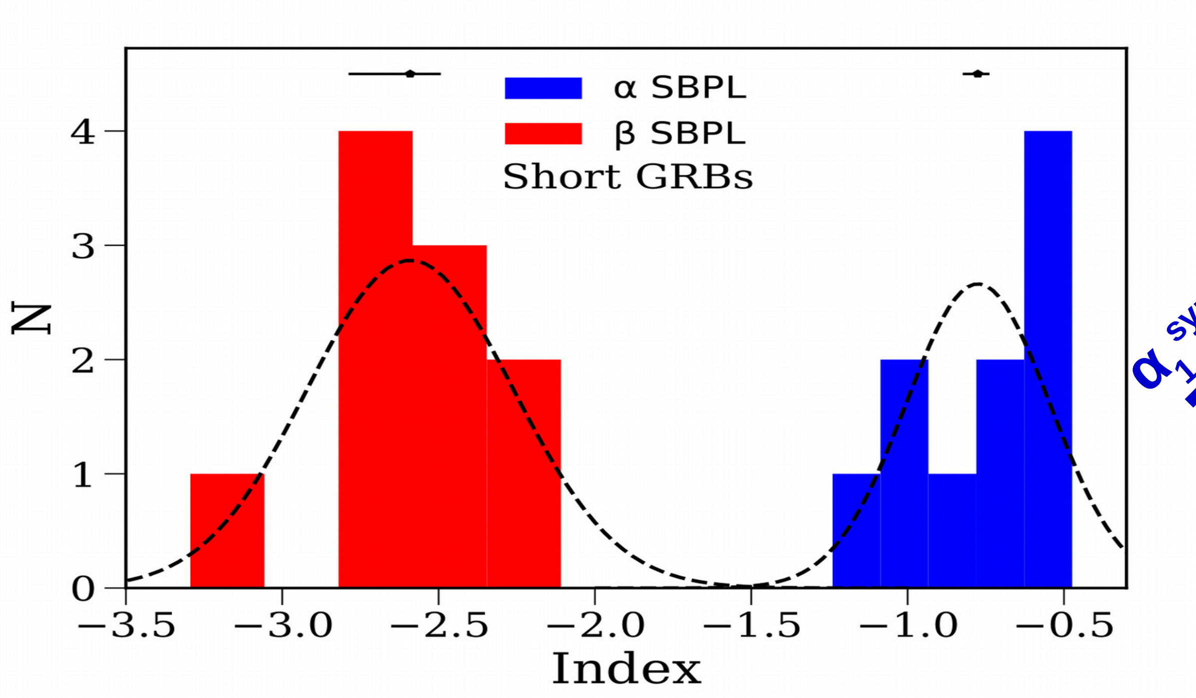
Single break function → $\langle\alpha\rangle = -1.02\ (0.19)$

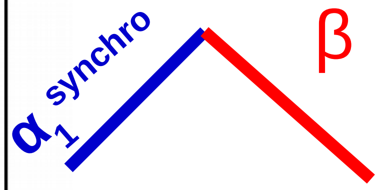
Results of the time-resolved spectral analysis

10 SHORT GRBs

NO BREAK!

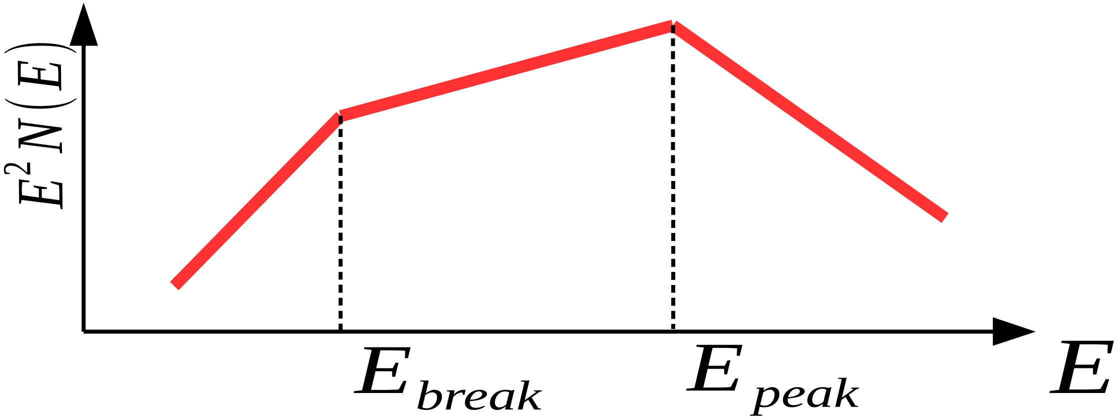
<α> = −0.78 (0.23)





- **It seems to exist only one component below the peak energy**
- **Consistent within 1σ with the synchrotron value α= -2/3**

Theoretical implications

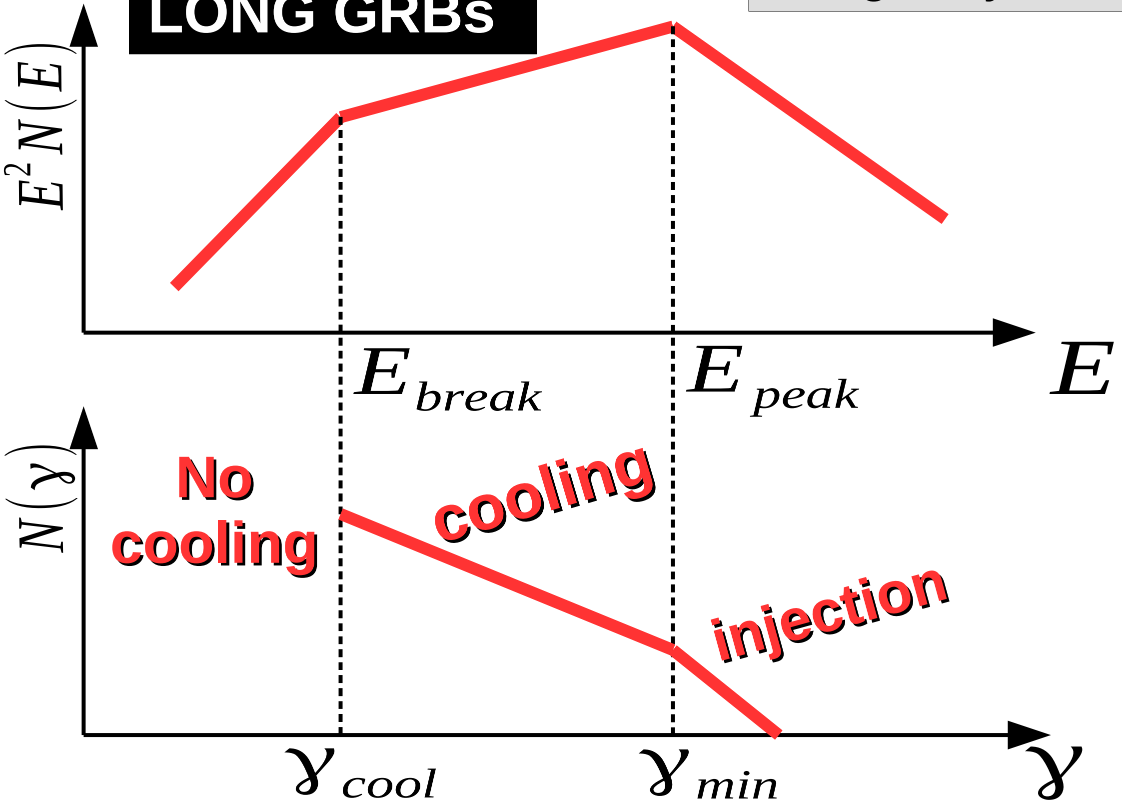


Theoretical implications

LONG GRBs

Marginally fast cooling regime

(Kumar & McMahon 2008, Daigne 2011, Beniamini & Piran 2013)



E_{break} → synchrotron cooling frequency

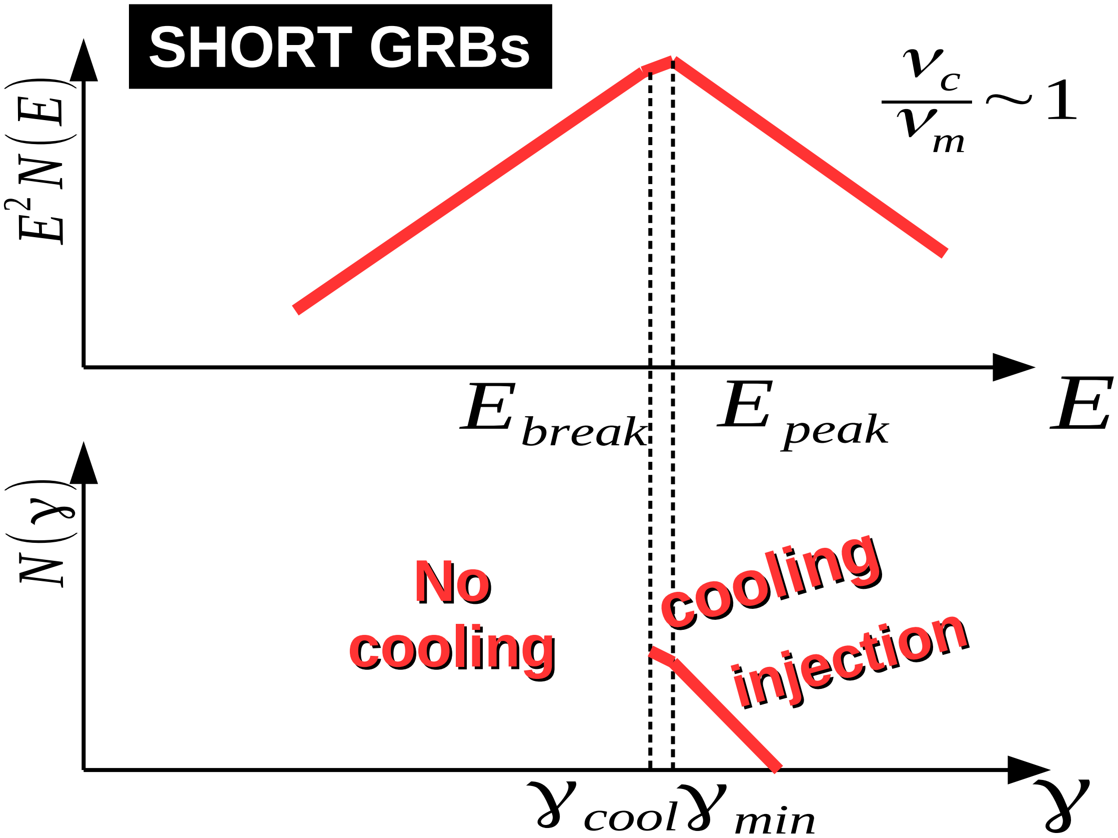
$$t_{cool}^{obs} = \frac{6\pi m_e c}{\sigma_T \gamma_e B^2}\frac{1+z}{\Gamma} \sim 1\,s$$

$$\gamma_e^2 \sim \frac{1+z}{\Gamma}\frac{2\pi m_e c}{e B}\nu_{syn}$$

At the emitting region

$$\boxed{B \sim 10\,\Gamma_2^{-1/3}\,\nu_{syn,100\,keV}^{-1/3}\,Gauss}$$

Theoretical implications



$$\frac{\nu_c}{\nu_m} \sim 1$$

E_{break} → synchrotron cooling frequency

$$t_{cool}^{obs} = \frac{6\pi m_e c}{\sigma_T \gamma_e B^2} \frac{1+z}{\Gamma} \sim 1\, s$$

$$\gamma_e^2 \sim \frac{1+z}{\Gamma} \frac{2\pi m_e c}{e B} \nu_{syn}$$

At the emitting region

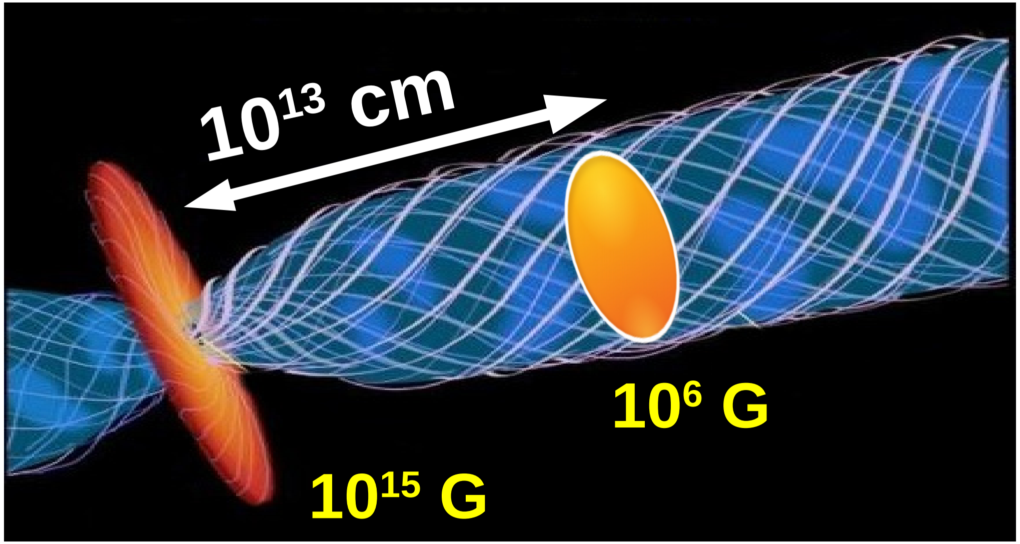
$$\boxed{B < 10\, \Gamma_2^{-1/3} \nu_{syn,100\, keV}^{-1/3}\ Gauss}$$

Theoretical implications

E_{break} frequency → synchrotron cooling

B ~ 10 Gauss ✗

GRB Standard Model:



Theoretical implications

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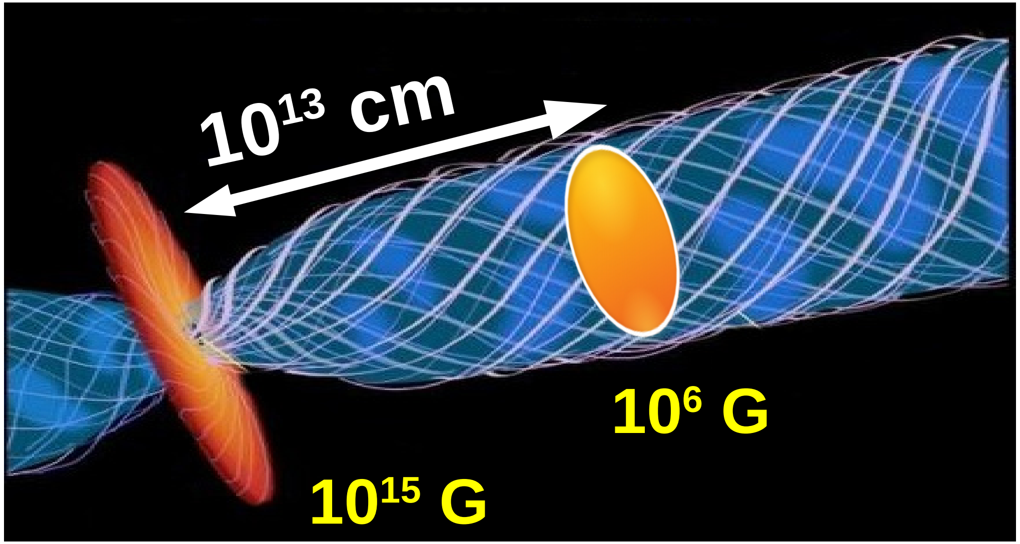
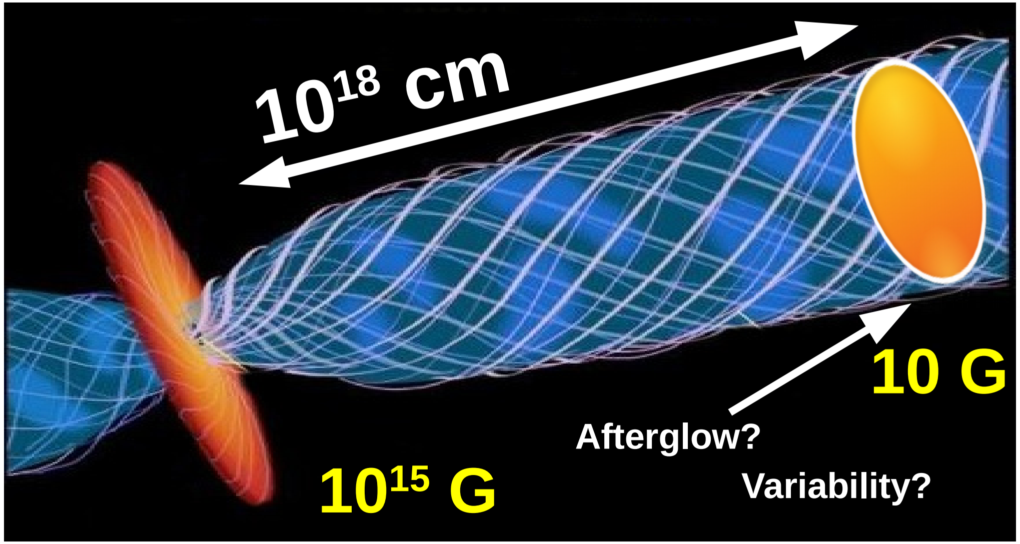
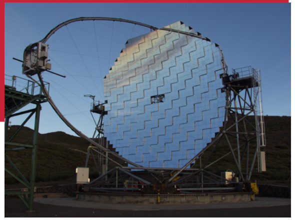
GRB Standard Model:





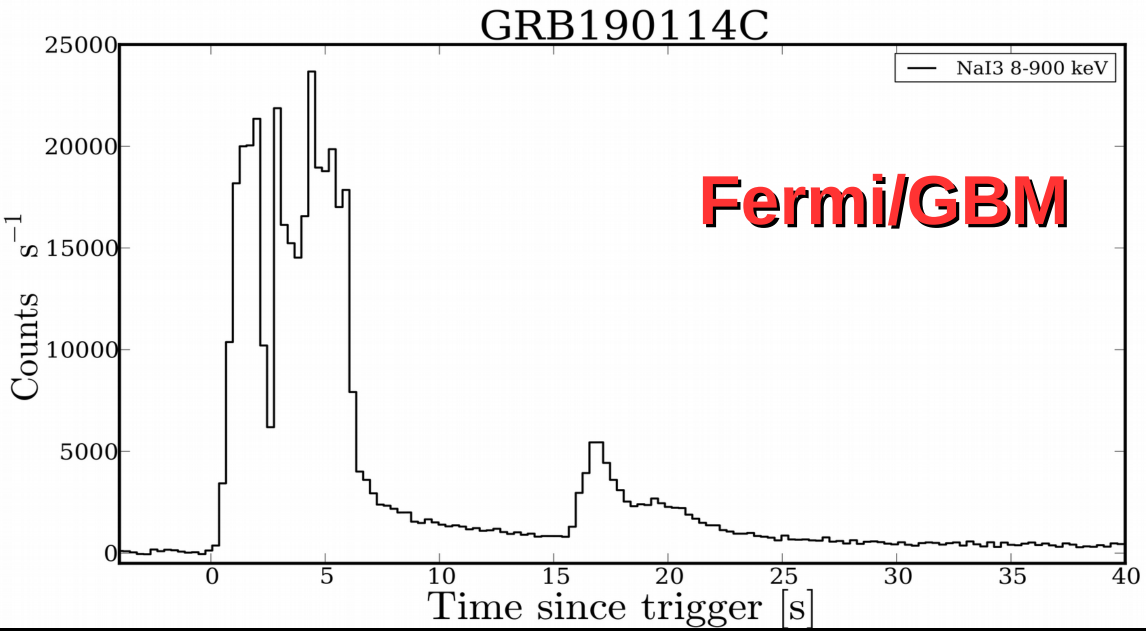
GRB 190114C: the first GRB detected at VHE



Mirzoyan et al. GCN #23701: **MAGIC detects the GRB 190114C in the TeV energy domain**

Hamburg et al. GCN #23707: **GRB 190114C: Fermi GBM detection**

- Preliminary spectral analysis shows a strong statistical preference for an **extra power-law component**

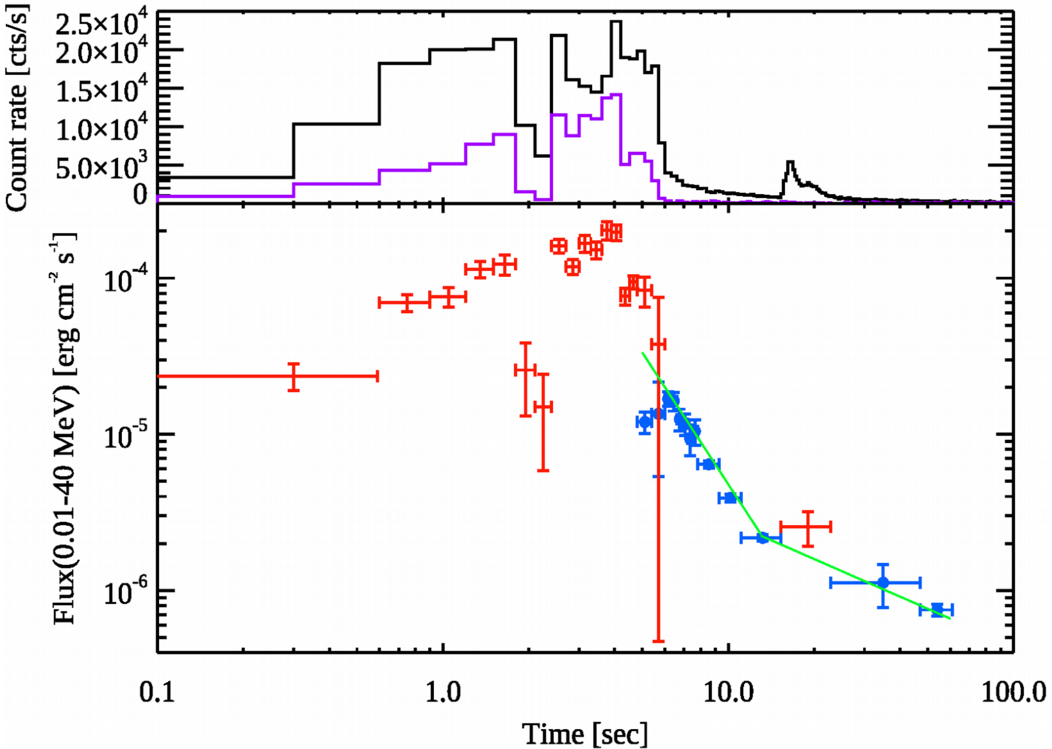


We analyze its spectral evolution detected by Fermi/GBM between 10 keV and 40 MeV

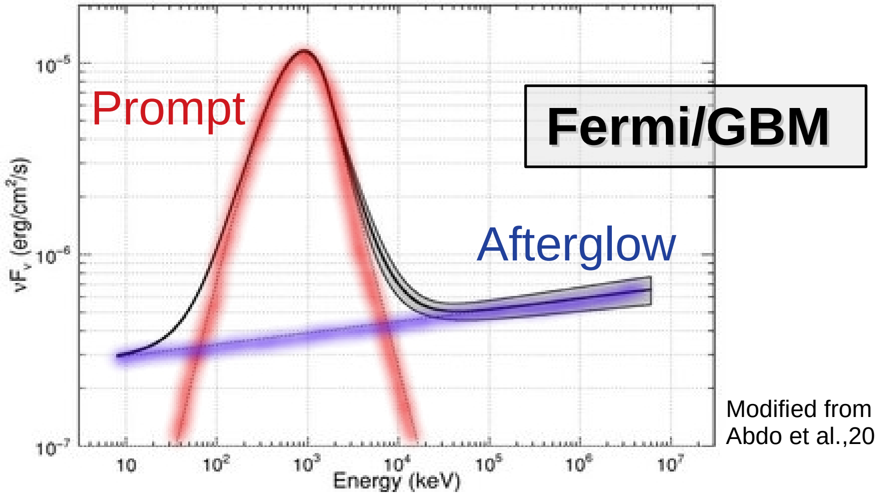
- **T90= 116 s**
- **z = 0.42**
  (Selsing et al. 2019)

Spectral analysis of GRB 190114C

Ravasio M.E., Oganesyan G., et al., 2019, A&A



Evidence of compresence of **prompt** and **afterglow** in the GBM energy range

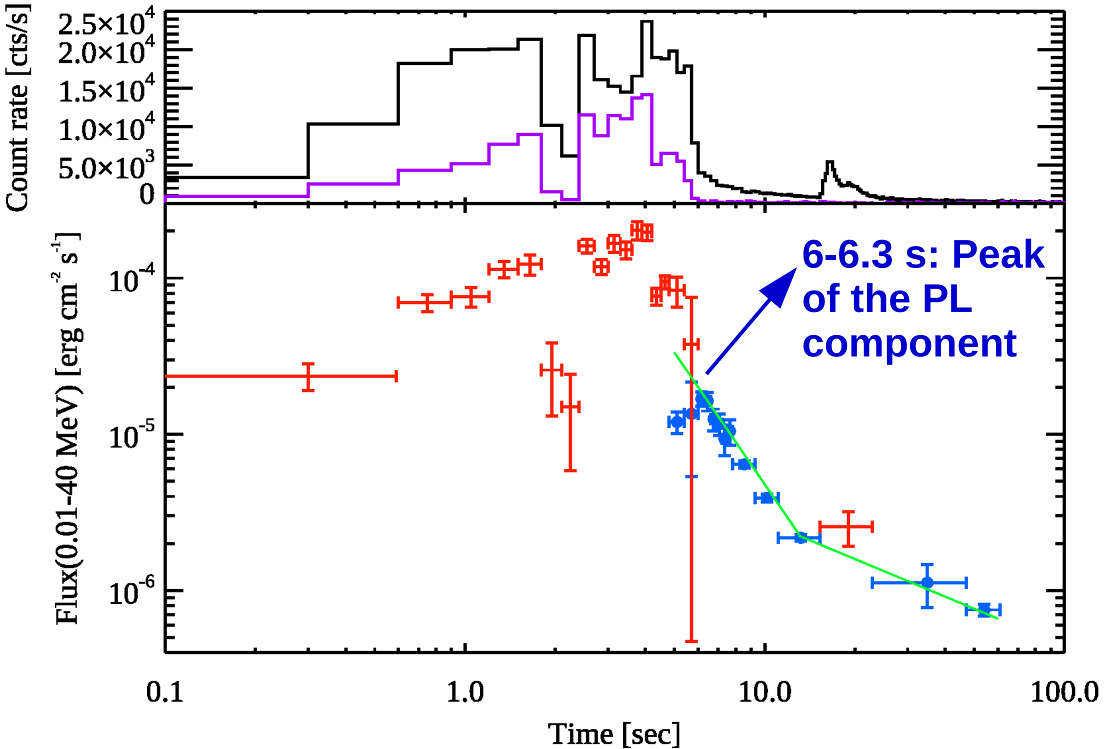


Modified from Abdo et al.,2009

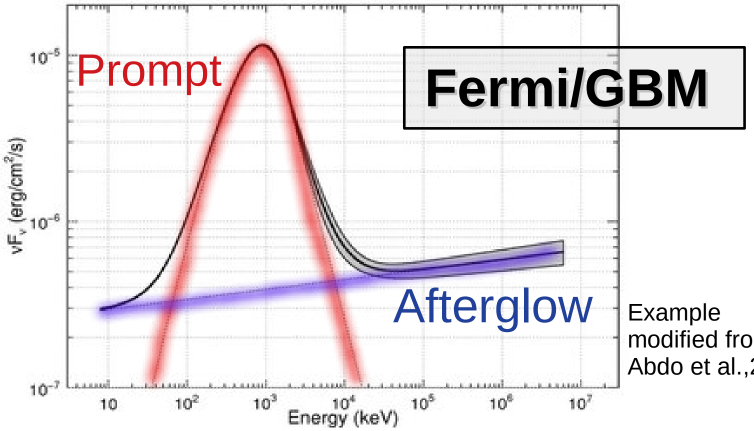
- The first 4 s of the burst show a **typical prompt emission spectrum**, fit by a standard fitting function with typical parameters
- Starting from 4 s post-trigger, we find an additional non-thermal component, fit by a **power-law with spectral index** $\Gamma_{PL} \sim -2$ peaking at 6 s

Spectral analysis of GRB 190114C

Ravasio M.E., Oganesyan G., et al., 2019, A&A



6-6.3 s: Peak of the PL component



Example modified from Abdo et al.,2009

Estimate of the bulk Lorentz factor Γ_0 **from the peak of the afterglow lightcurve** (using equation from Nava et al., 2013):

$$\Gamma_0 \sim 700$$

Homogeneous medium with density $n_0 = 1\,cm^{-3}$

$$\Gamma_0 \sim 130$$

Wind medium with: $\dot{M}_w = 10^{-5} M / yr$ $v_w = 10^2 km/s$

Evidence of compresence of **prompt** and **afterglow** in the GBM energy range

Summary

- ☑ **At last, GRBs spectra → synchrotron!**

Synchrotron model found to fit well single-pulsed Fermi GRBs spectra by Burgess et al. 2018

- ☒ **Identifying E_{break} as the synchrotron cooling frequency → B ~ 10 Gauss**

(marginally fast cooling regime)

(1) Ravasio et al., 2018, *Consistency with synchrotron emission in the bright GRB 160625B observed by Fermi*, Astronomy & Astrophysics
(2) Ravasio et al., 2019, *Evidence of two spectral breaks in the prompt emission of Gamma Ray Bursts*, Astronomy & Astrophysics
(3) Ravasio et al., 2019, *GRB 190114C: from prompt to afterglow?*, Astronomy & Astrophysics

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- 🛠 **Next step: Find the reason why!**

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- ✓ **At last, GRBs spectra ⟶ synchrotron!**

Synchrotron model found to fit well single-pulsed Fermi GRBs spectra by Burgess et al. 2018

- ✗ **Identifying E_{break} as the synchrotron cooling frequency ⟶ B ~ 10 Gauss**

(marginally fast cooling regime)

- 🛠 **Next step: Find the reason why!**

GRB 190114C

- **Evidence of compresence of both prompt and afterglow in the GBM energy range**
- **Estimate of bulk Lorentz factor Γ_0 (150 – 700) from the peak in the afterglow lightcurve**
- **Waiting for the MAGIC spectrum to give crucial information about the origin of the entire high energy spectrum!**

(1) Ravasio et al., 2018, *Consistency with synchrotron emission in the bright GRB 160625B observed by Fermi*, Astronomy & Astrophysics
(2) Ravasio et al., 2019, *Evidence of two spectral breaks in the prompt emission of Gamma Ray Bursts*, Astronomy & Astrophysics
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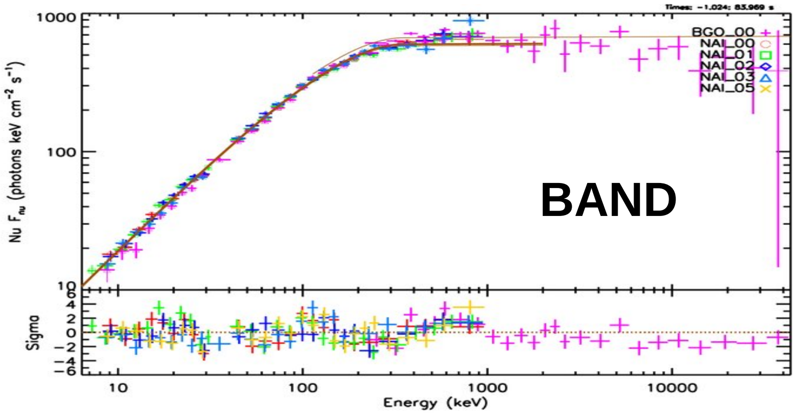
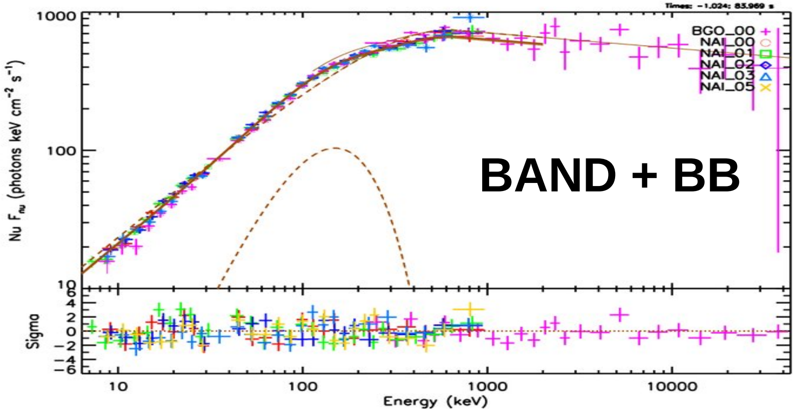
Thanks for your attention!

Back-up slides

Multi-component models: example of the addition of a blackbody





The spectrum could be a **combination of thermal and non-thermal emission**

Physically motivated as the emission from the fireball photosphere, demonstrated to be present in few cases (Ghirlanda et al., 2003)

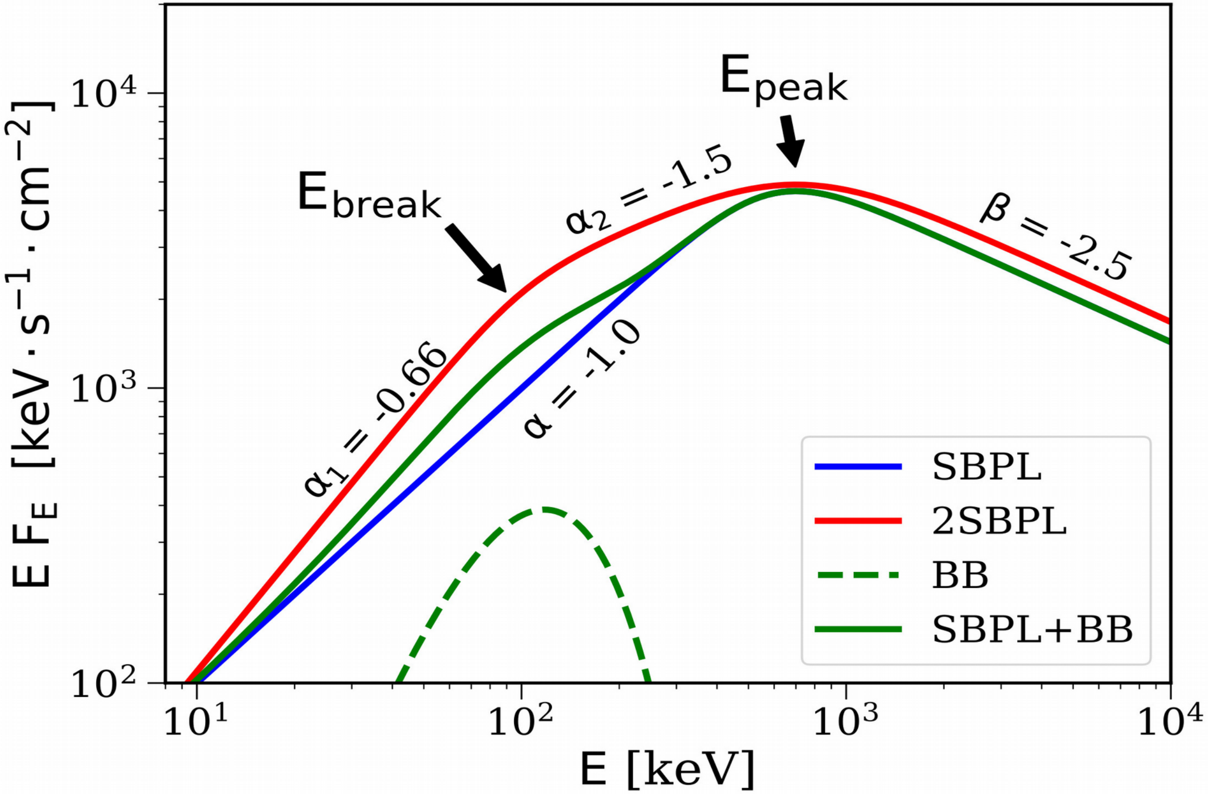
The addition of a blackbody (BB) can produce a **hardening** of the low energy part of the spectrum

→ **The addition of a BB has been widely used in literature**

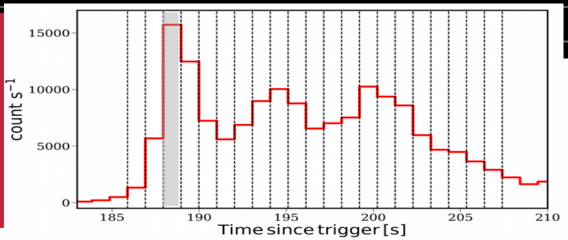
(Ryde et al. 2010, Guiriec et al. 2011,2013,2015, 2016, 2017)

E.g. from Guiriec et al. 2011

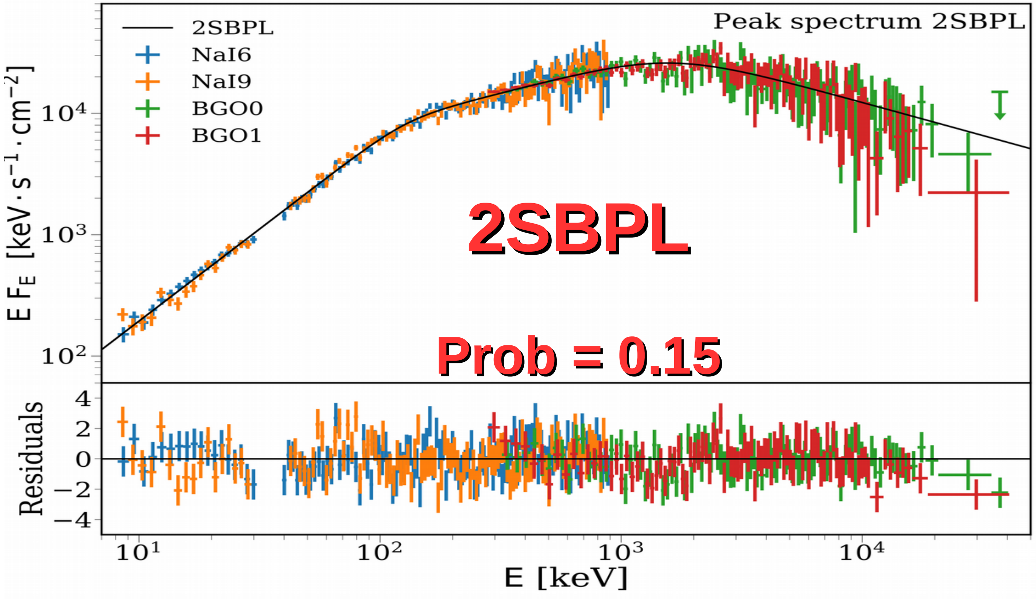
Comparison of the fitting functions



GRB160625B
Time-resolved analysis

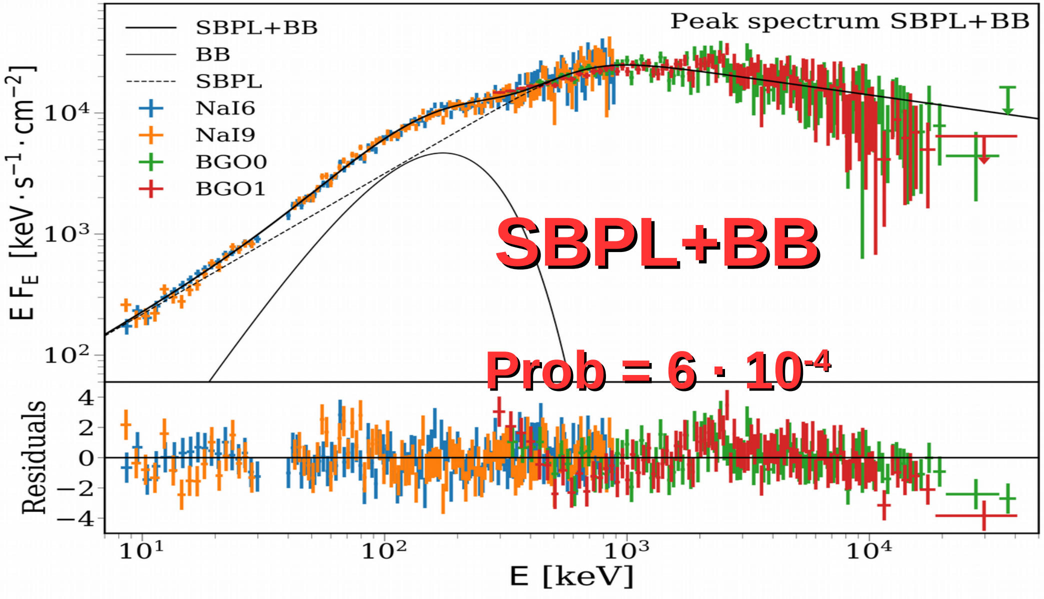


Comparison between competing models:
One- vs Two-Component



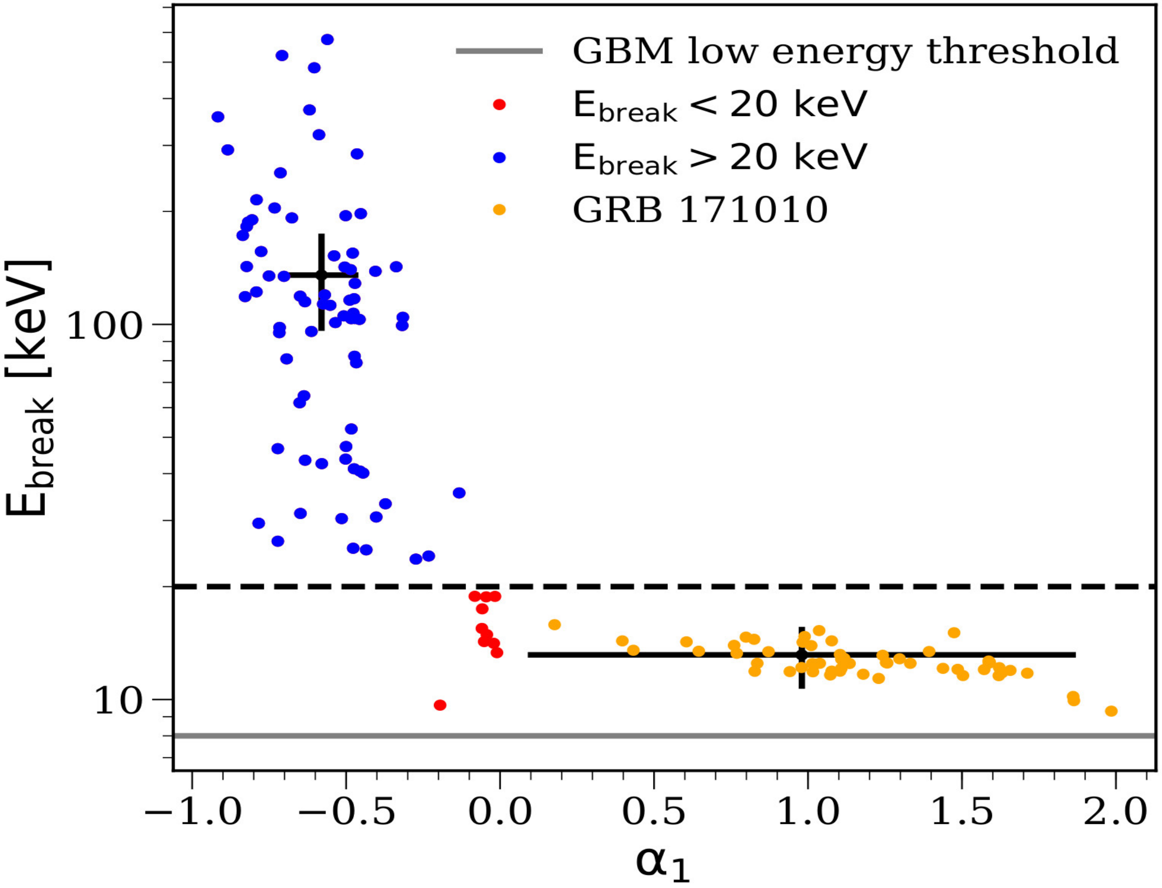
2SBPL

Prob = 0.15



SBPL+BB

Prob = $6 \cdot 10^{-4}$


GBM low energy threshold
$E_{break} < 20$ keV
$E_{break} > 20$ keV
GRB 171010
E_{break} [keV]
100
10
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
α_1

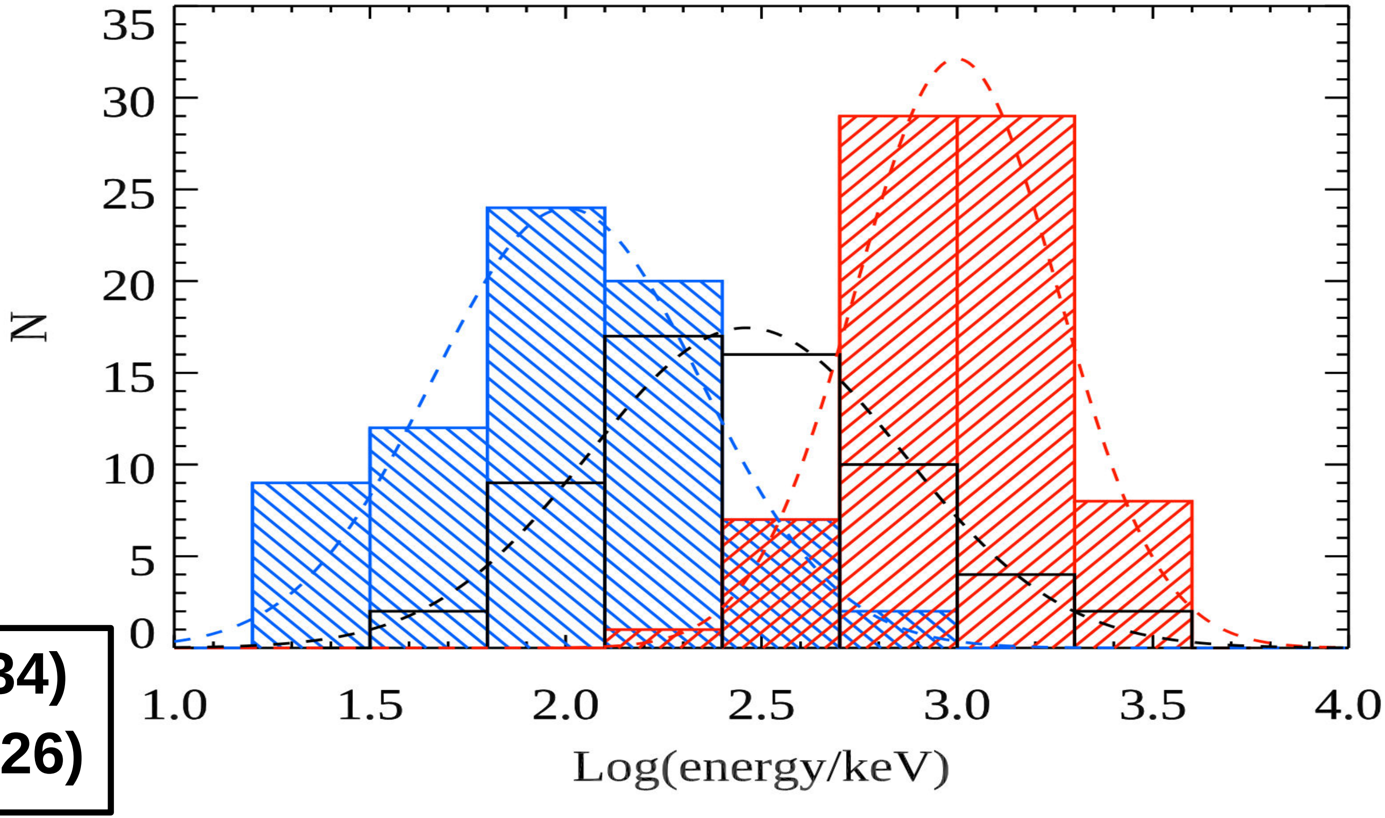
Results of the time-resolved spectral analysis

10 LONG GRBs

BREAK FOUND IN 8/10 GRBs

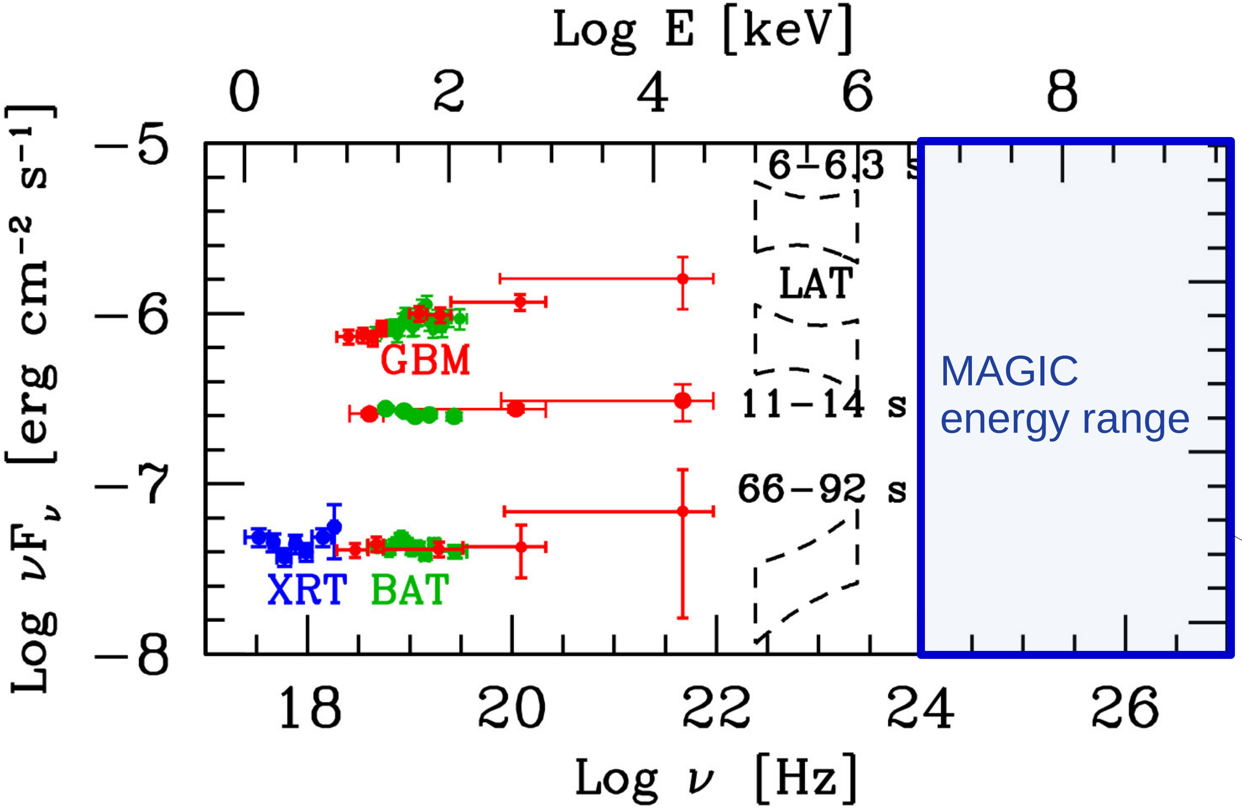
$\langle \log(E_{break/keV}) \rangle = 2.00\ (0.34)$

$\langle \log(E_{peak/keV}) \rangle = 3.00\ (0.26)$



Single break function → $\langle \log(E_{peak/keV}) \rangle = 2.46\ (0.40)$

SED of GRB190114C



Ravasio et al., 2019, A&A

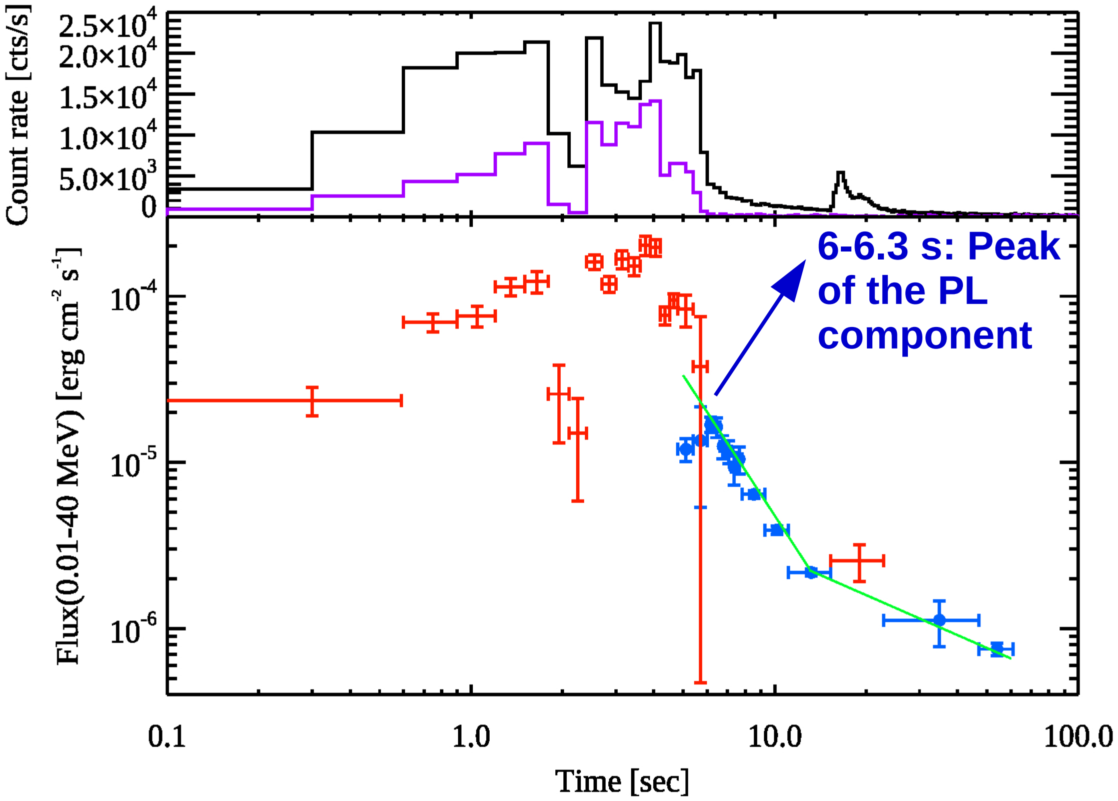
- The power-law **spectral slope** that we find in the GBM data is remarkably similar to that found in the LAT spectrum*
- The **spectral energy distribution** obtained from XRT+BAT+GBM+LAT data seems to be consistent with a single emission component

Therefore the MAGIC spectrum will give crucial information about the origin of the entire high energy spectrum

* LAT data taken from Wang et al., 2019

Spectral analysis of GRB 190114C

Ravasio M.E., Oganesyan G., et al., 2019, A&A



We interpret this power-law component as due to the **afterglow emission of the burst, deriving an estimate of the bulk Lorentz factor** Γ_0 , that depends on (from Nava et al., 2013):

- **afterglow onset** $t_p = 6\, s$
- blast wave kinetic energy E_k
- density of the circumburst medium n_0

$$\Gamma_0 \sim 700$$

Homogeneous medium with density $n_0 = 1\, cm^{-3}$

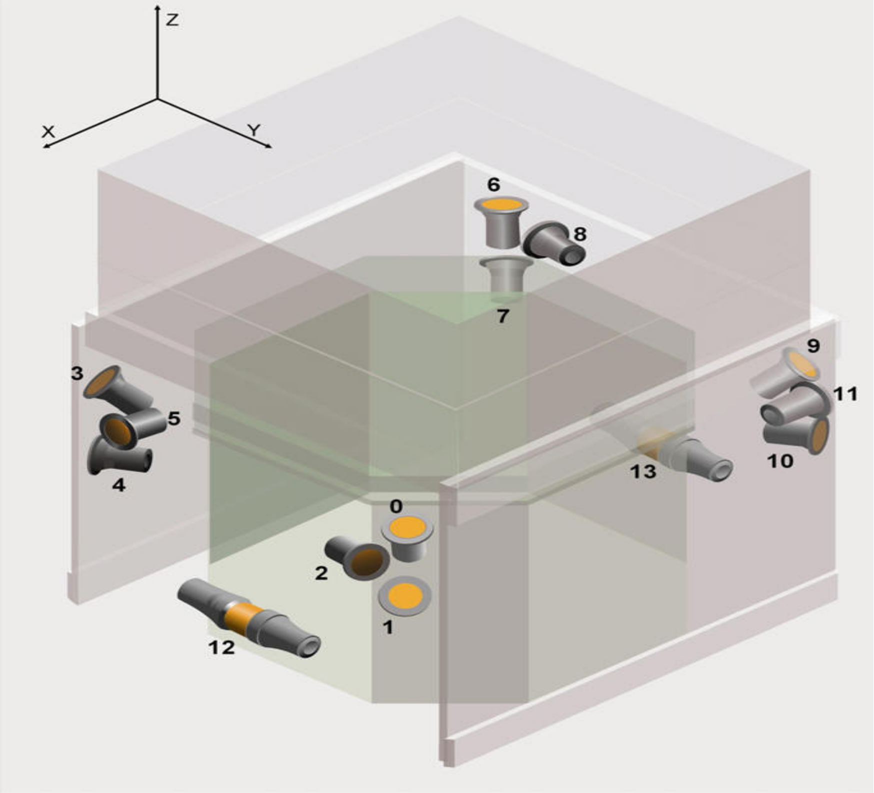
$$\Gamma_0 \sim 130$$

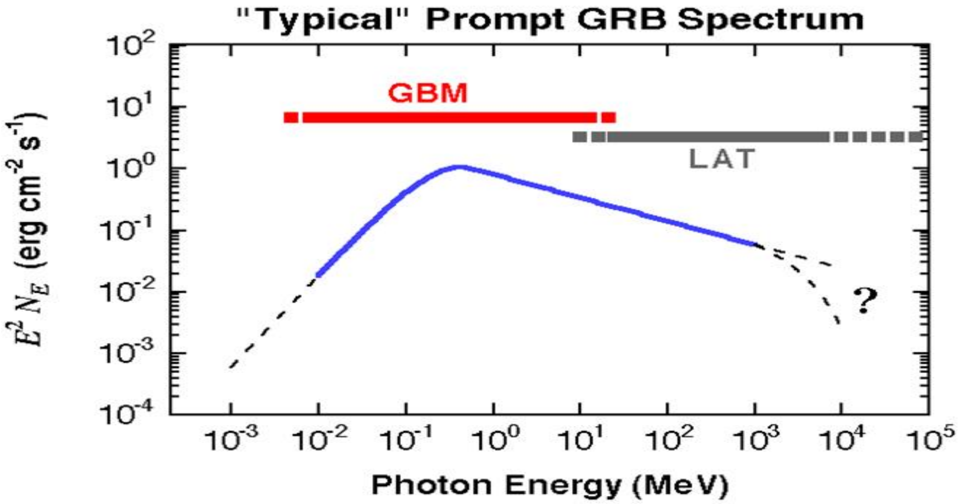
Wind medium with:

$\dot{M}_w = 10^{-5} M / yr$

$v_w = 10^2 km / s$

Fermi/GBM


Z
X
Y
0
1
2
3
4
5
6
7
8
9
10
11
12
13


"Typical" Prompt GRB Spectrum
GBM
LAT
?
$E^2 N_E$ (erg cm^{-2} s^{-1})
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
Photon Energy (MeV)