KTH VETENSKAP OCH KONST

Oskar Klein centre

Manifestation of the jet photosphere during the prompt phase in GRBs

Felix Ryde
KTH Royal Institute of Technology
Stockholm

On behalf of the Fermi GBM and LAT teams

Bottom Line

1. **Band crisis**
   The Band function is not the *universal* GRB spectrum. What does it mean?

2. **Appearance of the photosphere**
   Blackbody, BB+nonthermal, broadened functions

3. **GRB jet properties are variable.**
   Lorentz factor decreases over individual pulses while the flow nozzle increase

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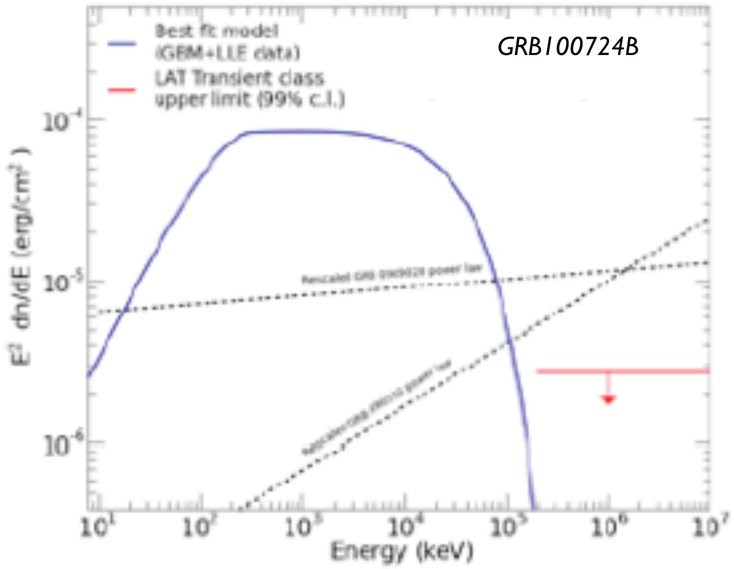
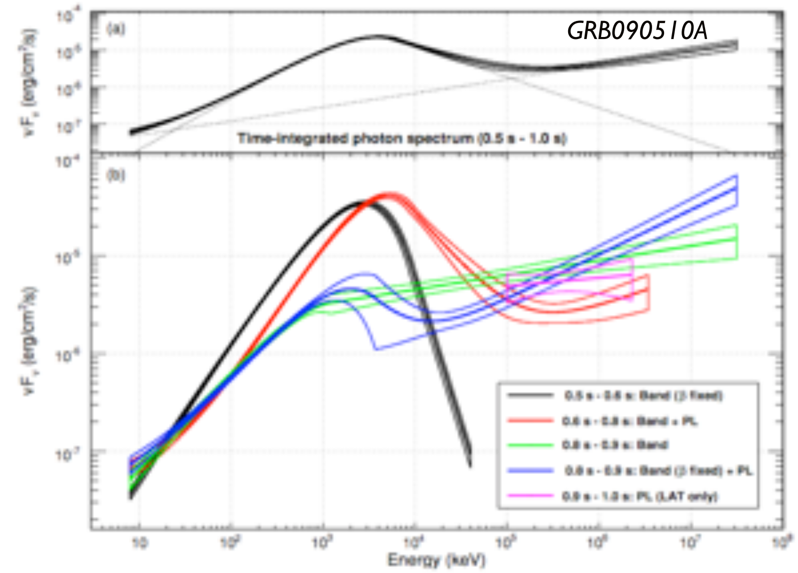
Spectral shapes of Fermi GRBs

The most well-observed bursts, i.e. most fluent and within the LAT FoV

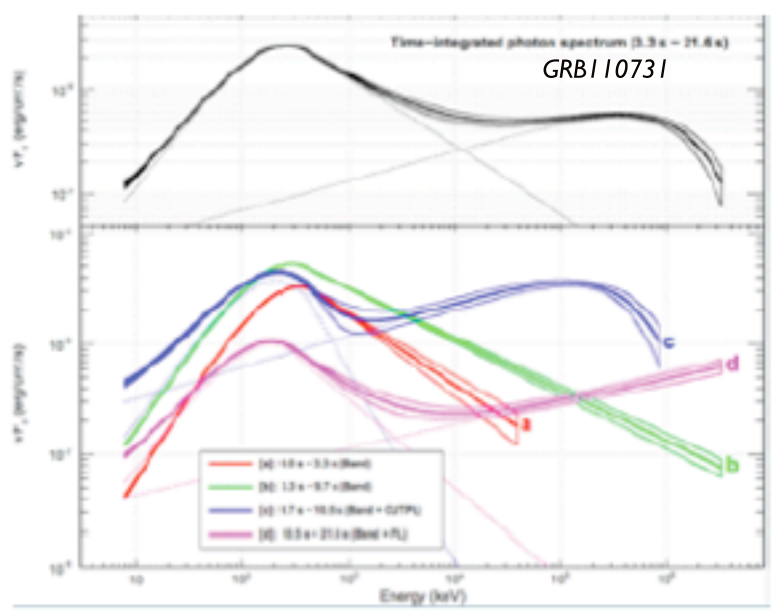
Exponential cut off



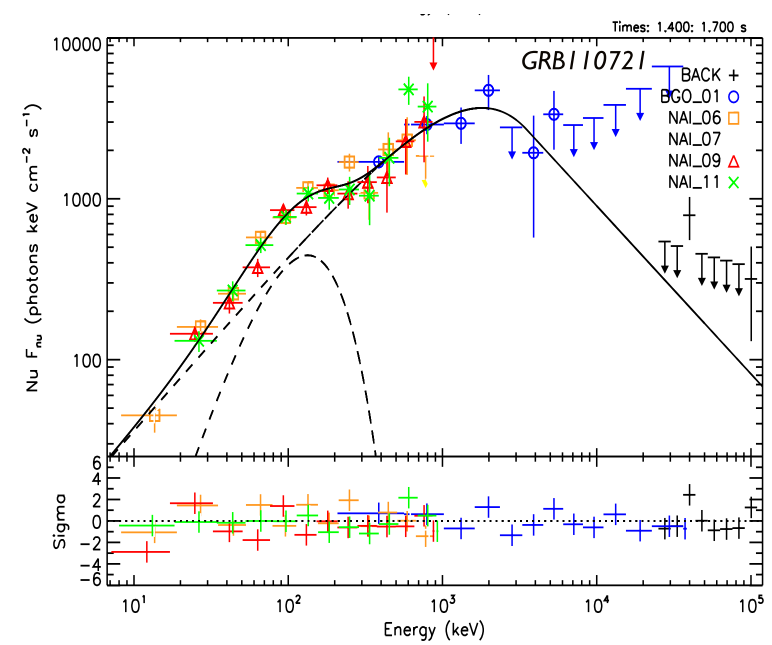
Additional power law



Additional p-l with cut off



Double humped spectra



Statistically highly significant deviations from the Band function

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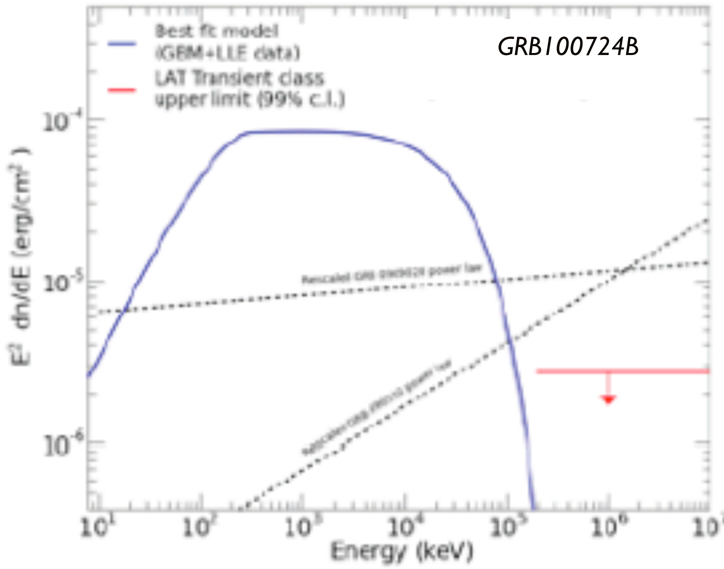

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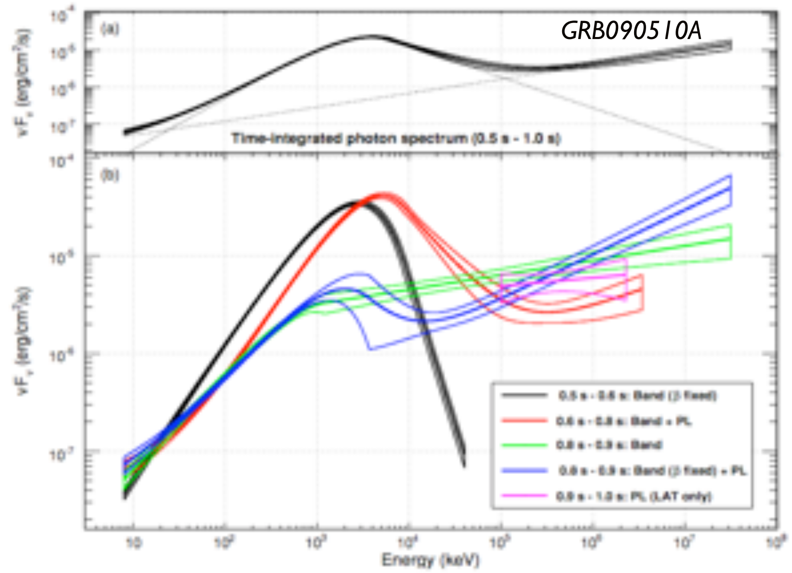

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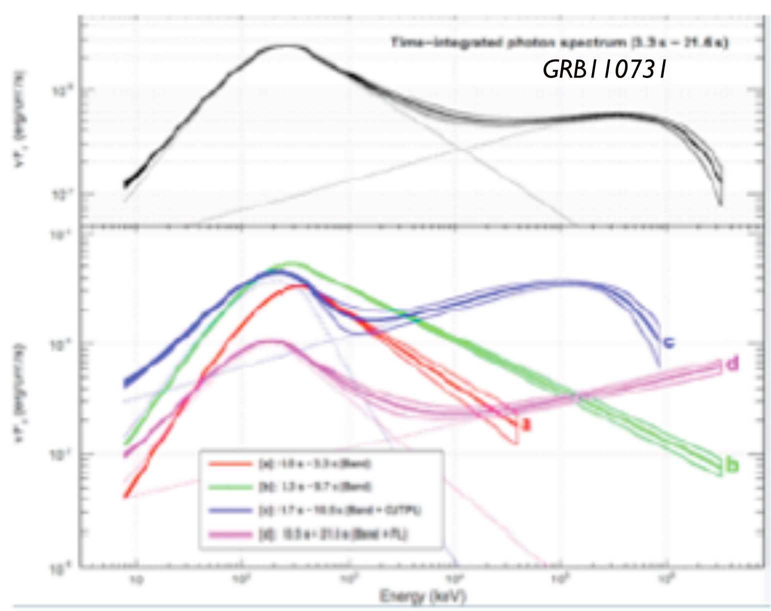

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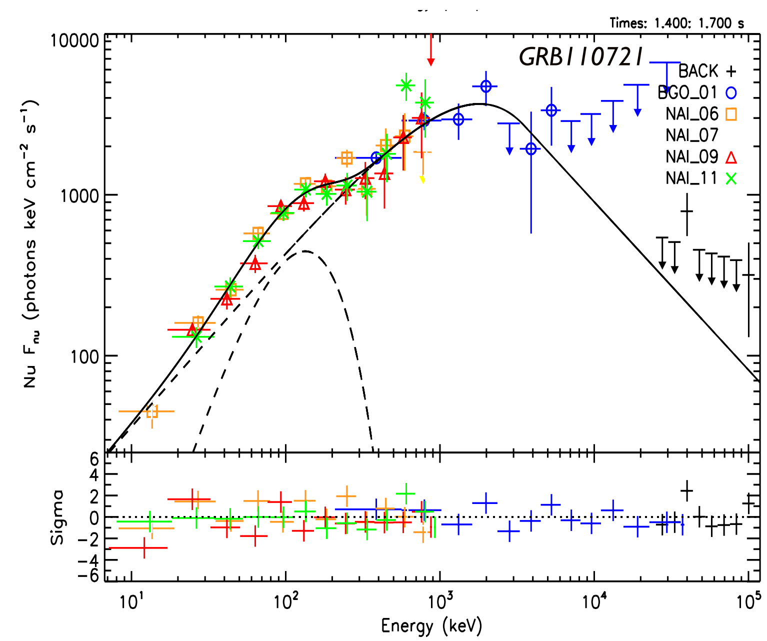

Statistically highly significant deviations from the Band function

"Band Model Crisis"

GBM+LAT joint spectral fits during "GBM" time window

THE BEST SPECTRAL MODEL FOR THE GRB DURING THE GBM INTERVAL, ORDERED BY FLUENCE

	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
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090328	817^{-33}_{+34}	Band	64.6
100116A	638^{-25}_{+26}	Band	26.6

Tetsted models:
- Band function
- Comptonized (cutoff p-l)
- Additional power laws
- Cut-offs

(Possible photospheric component not included in the catalogue)

Ackermann et al. 2013, ApJS, 209, 11

The phenomenological Band model, implemented for BATSE GRB observations up to a few MeV, does *not* seem to describe bright or well-observed LAT-detected GRBs sufficiently.

McEnery's talk

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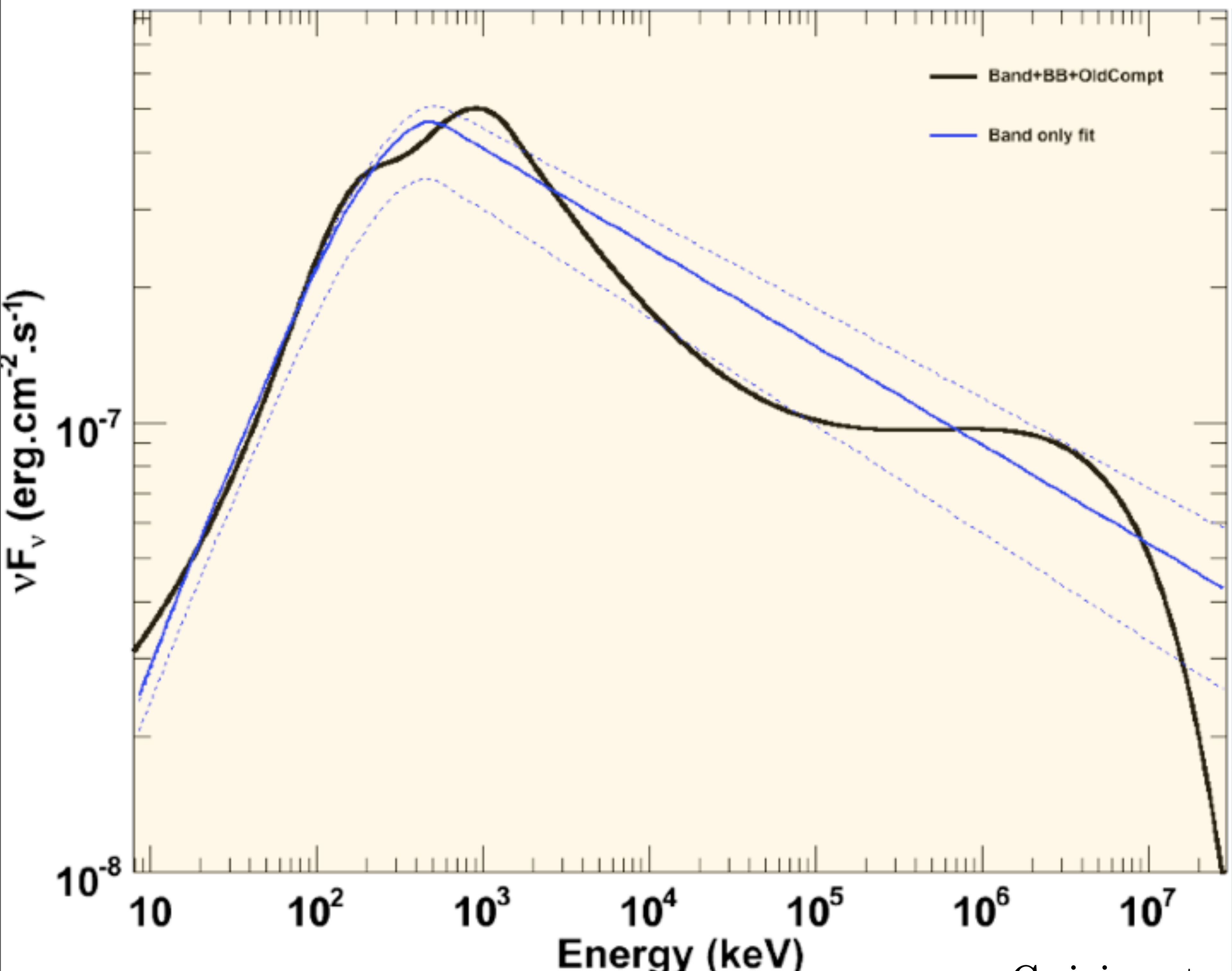
Band function is not a universal form of GRB spectra

McEnery's talk

Extrapolating the *Band* function from LOW to HIGH energy is really a BAD idea!

Which spectral fit is the correct one?

GRB080916c



- Single emission zone?
- Multiple emission zones?
- Emission mechanism?

Guiriec et al. (2012; Marcel Grossman)

Band function is not a universal form of GRB spectra

Solution: Fit theoretical models directly to the data!
Examples: Titarchuck et al. 2012, Burgess et al. 2013

A theoretical model should, after convolution with the response, fit a Band function. Model deviations from a Band function is thus possible!

In Burgess et al. 2013 it was showed that synchrotron emission spectra that are fitted with a Band function has α values centered around -0.81 ± 0.1 and not the expected -2/3.

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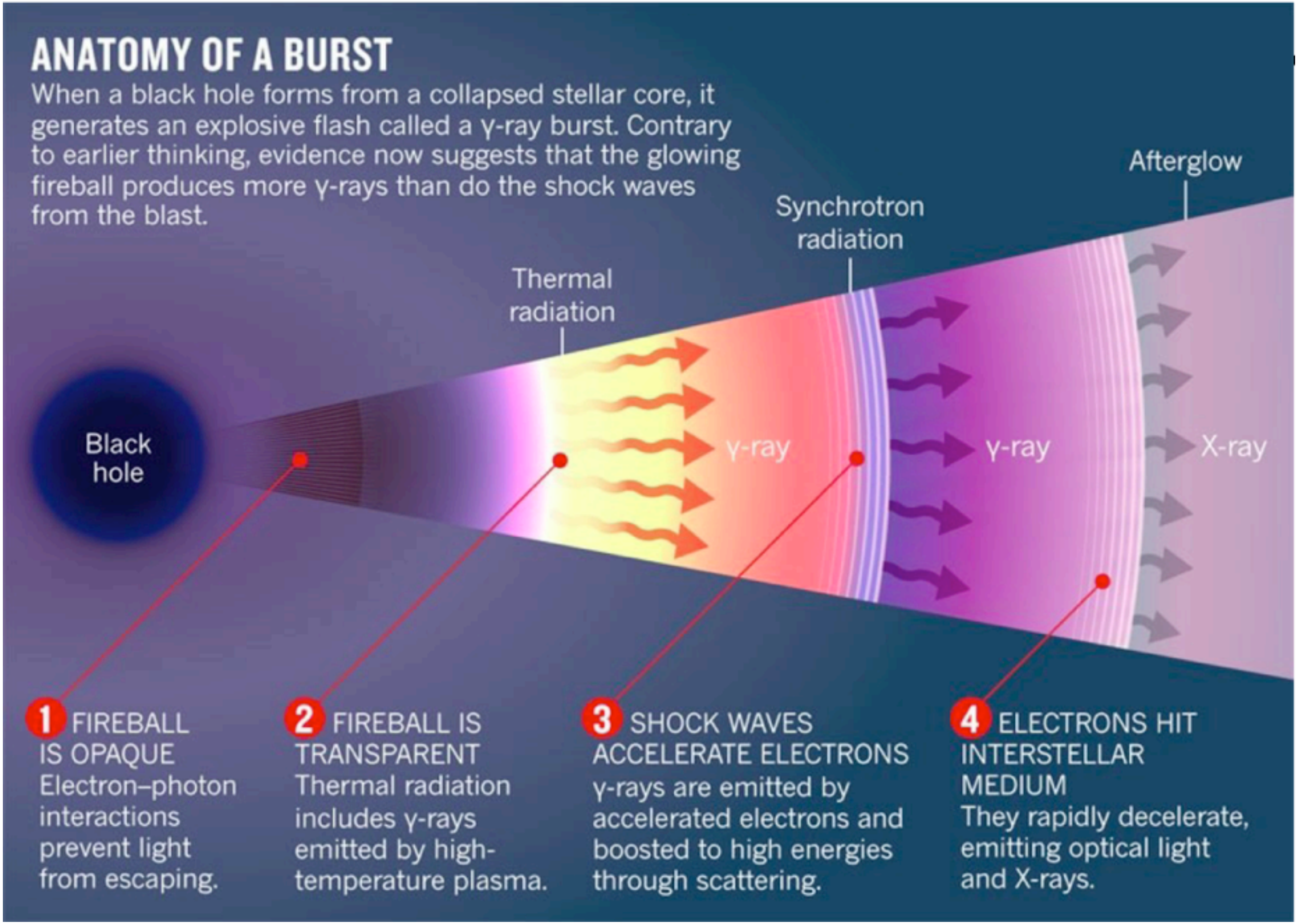
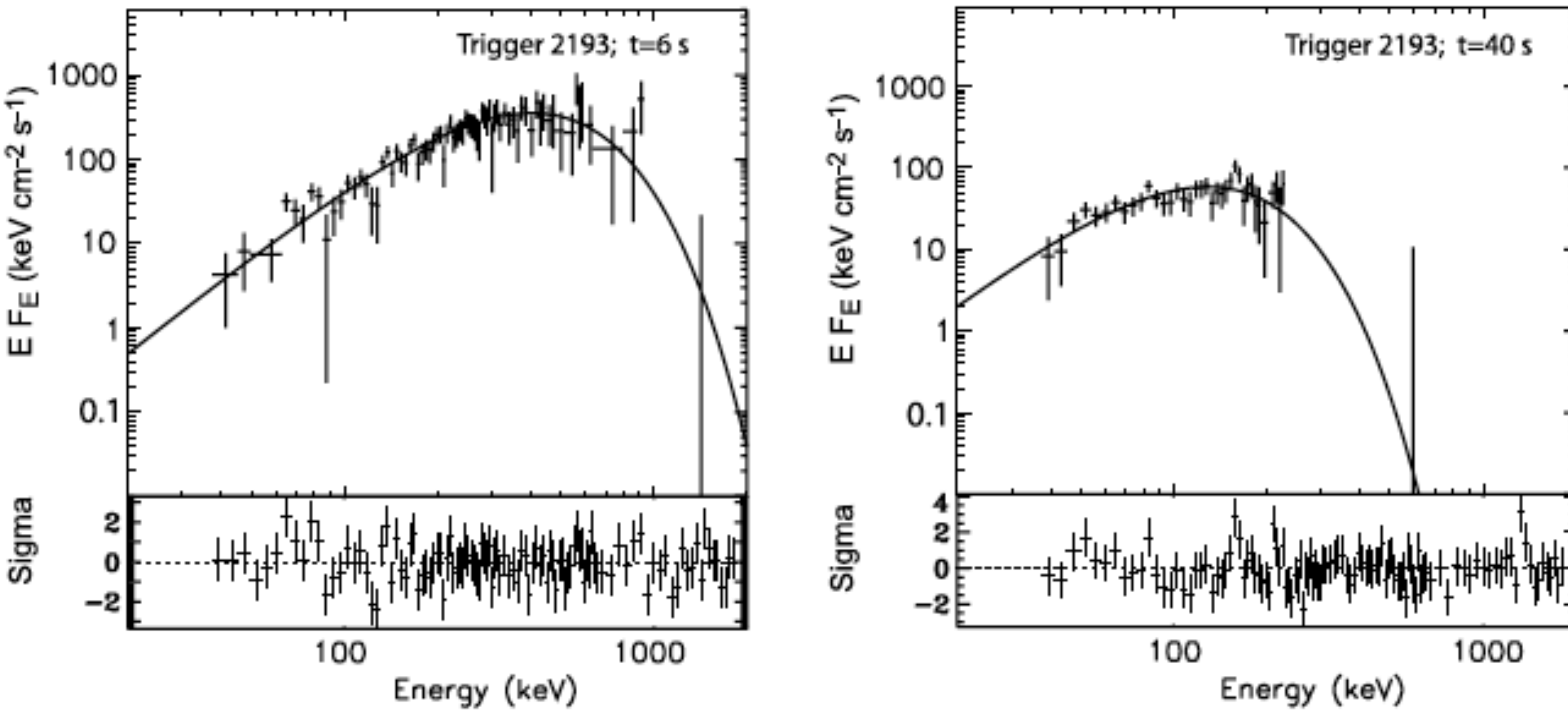
Basic framework: the fireball model



I. Single Planck function bursts

GRB930214



Ryde 2004

Spectra from temporally resolved pulses observed by BATSE over the energy range 20-2000 keV.

CGRO BATSE: 6 observed bursts

- **Ryde (2004):** Blackbody through out the pulse
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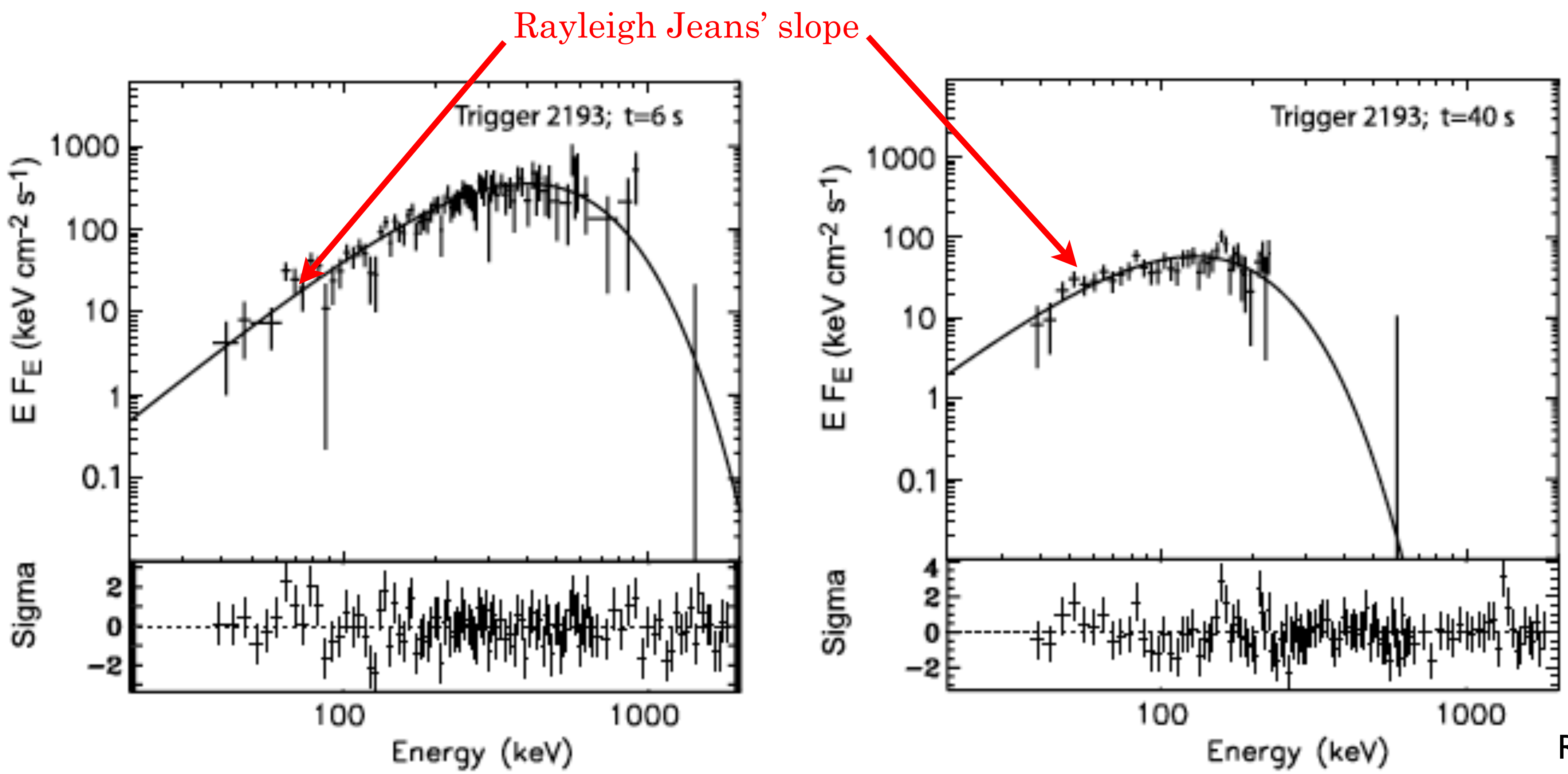

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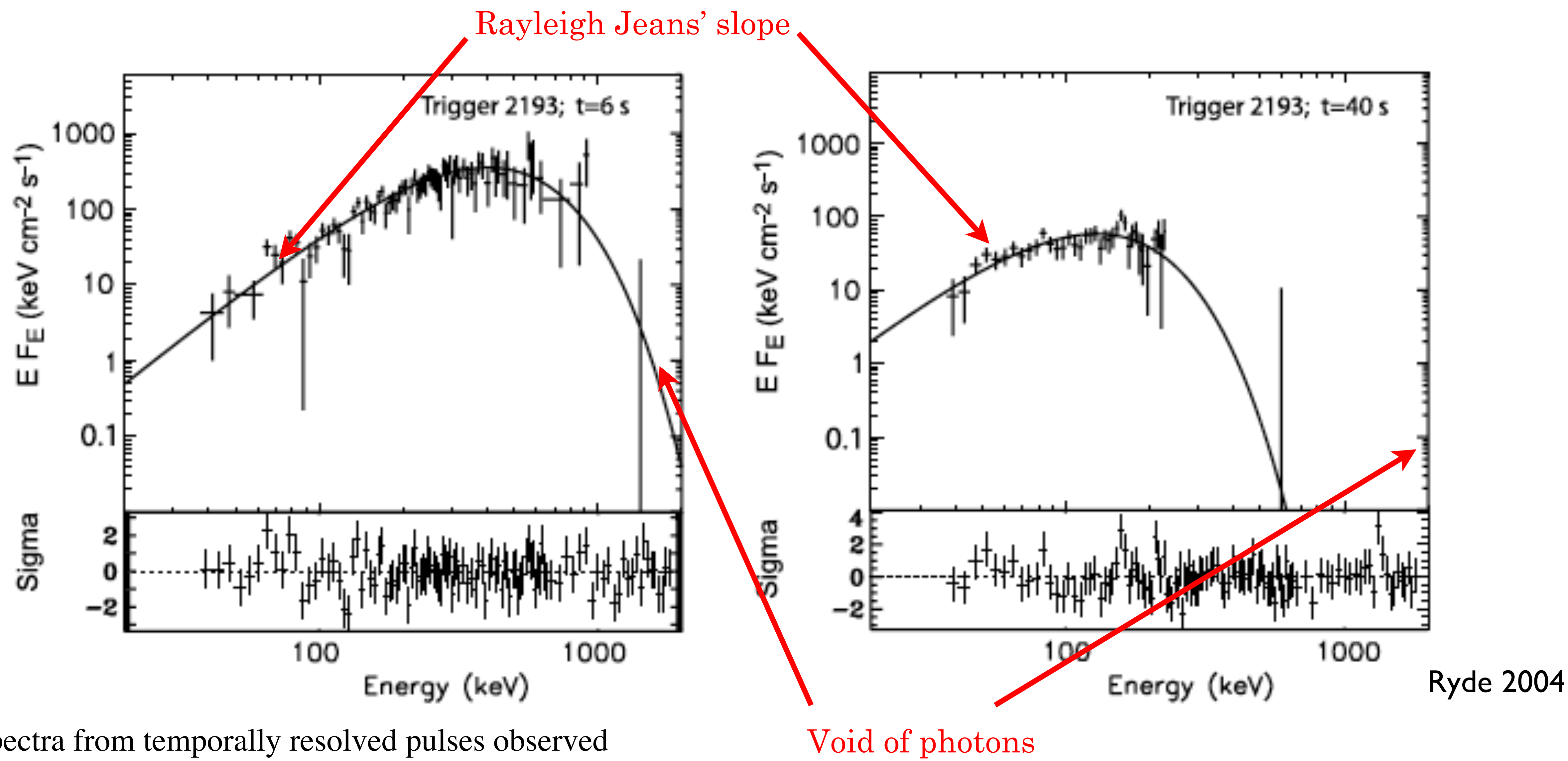

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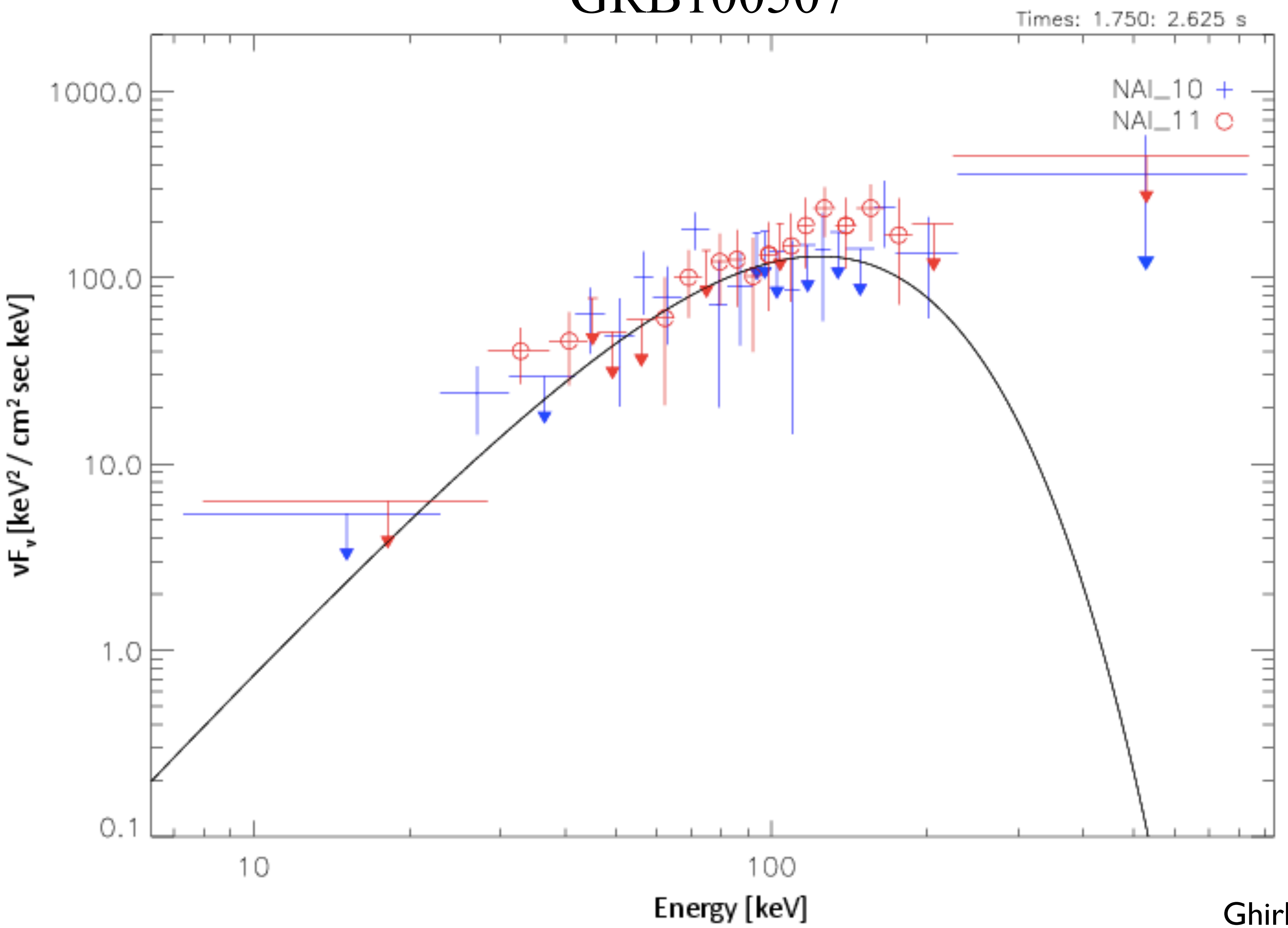
Fermi Gamma Ray Space Telescope

GRB100507



Ghirlanda et al. 2013

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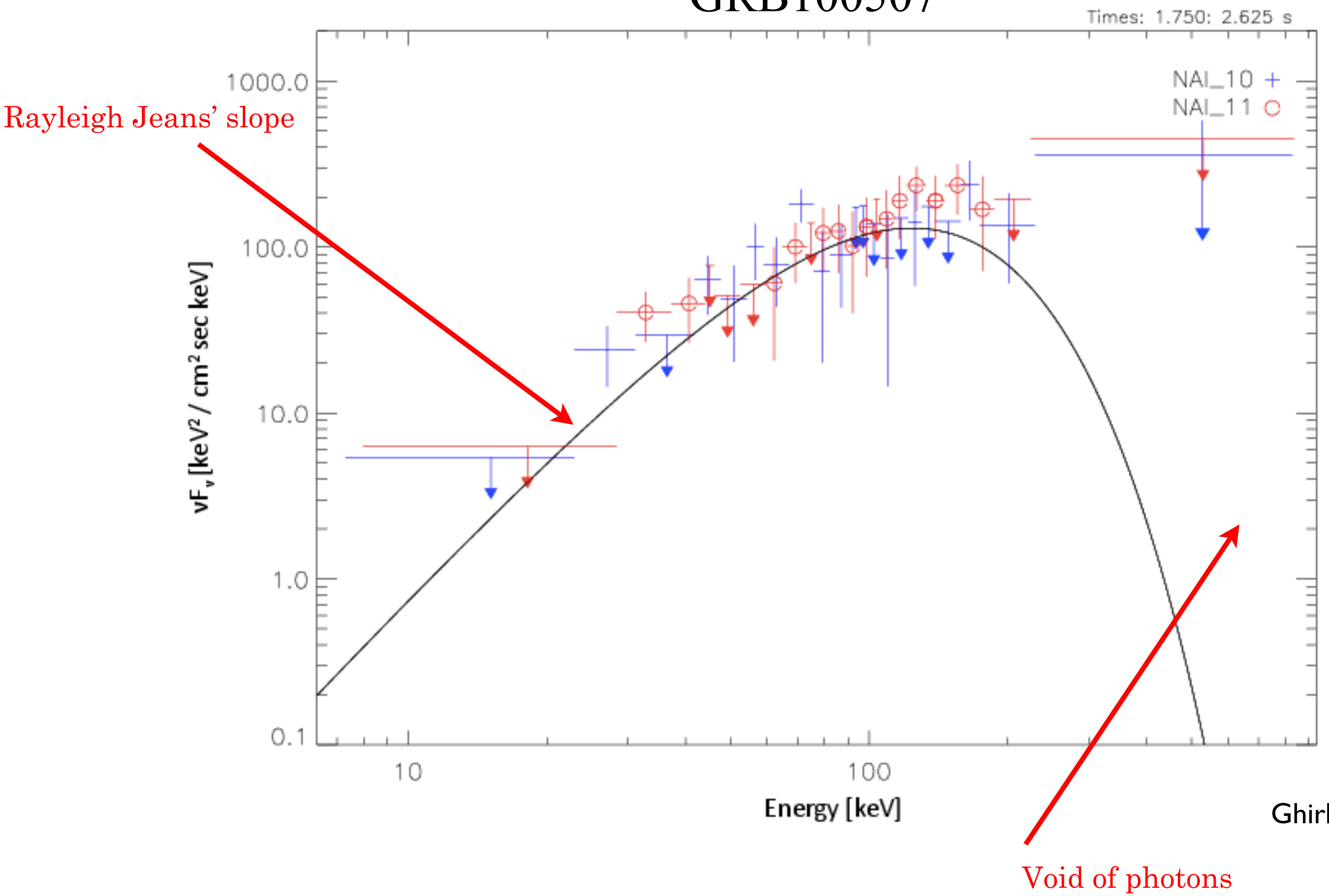
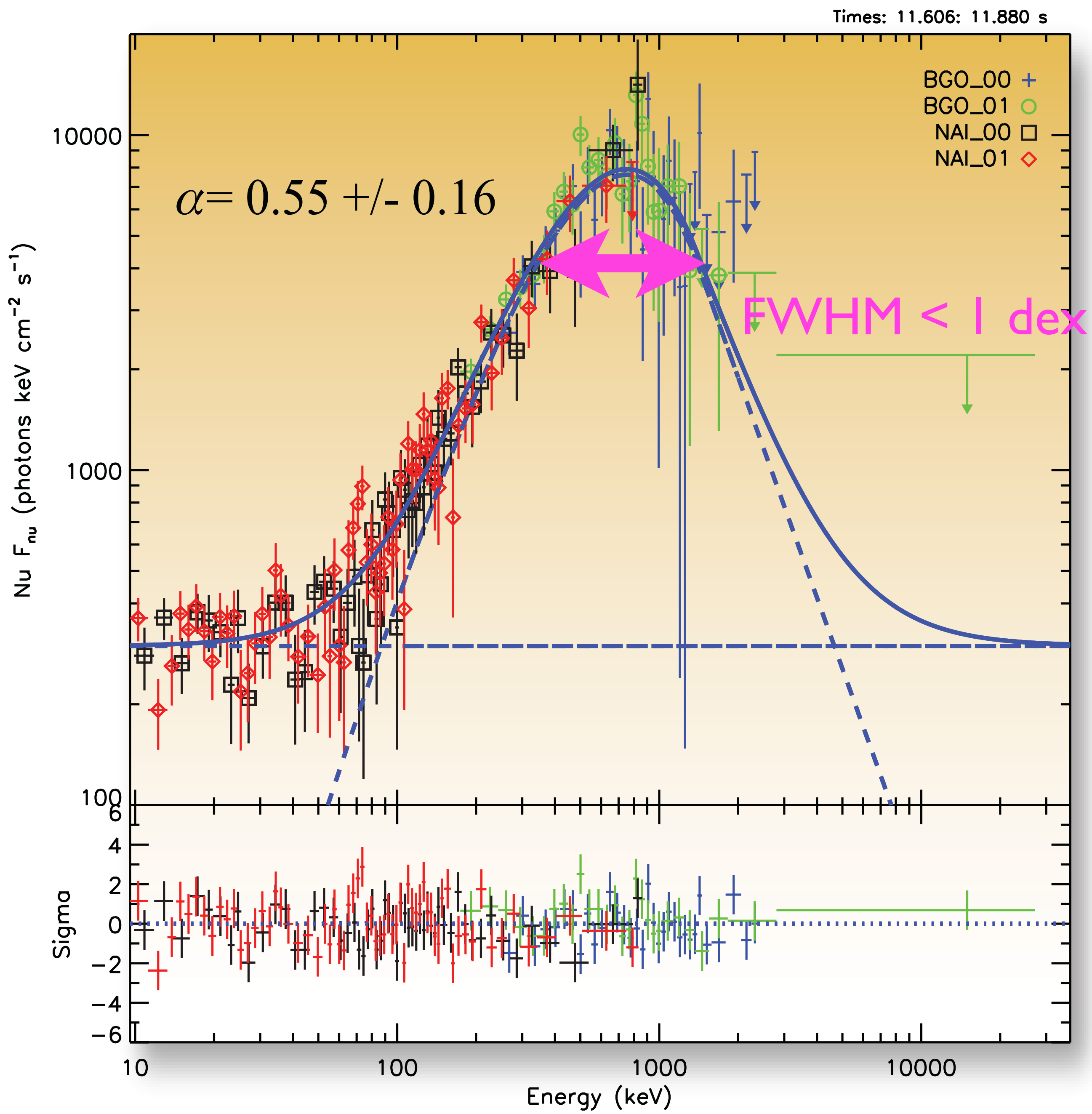


Ghirlanda et al. 2013

GRB090902B

Abdo et al. (2009), Ryde et al. (2010) Zhang et al. (2010)

Time resolved spectrum (11.608-11.880 s)



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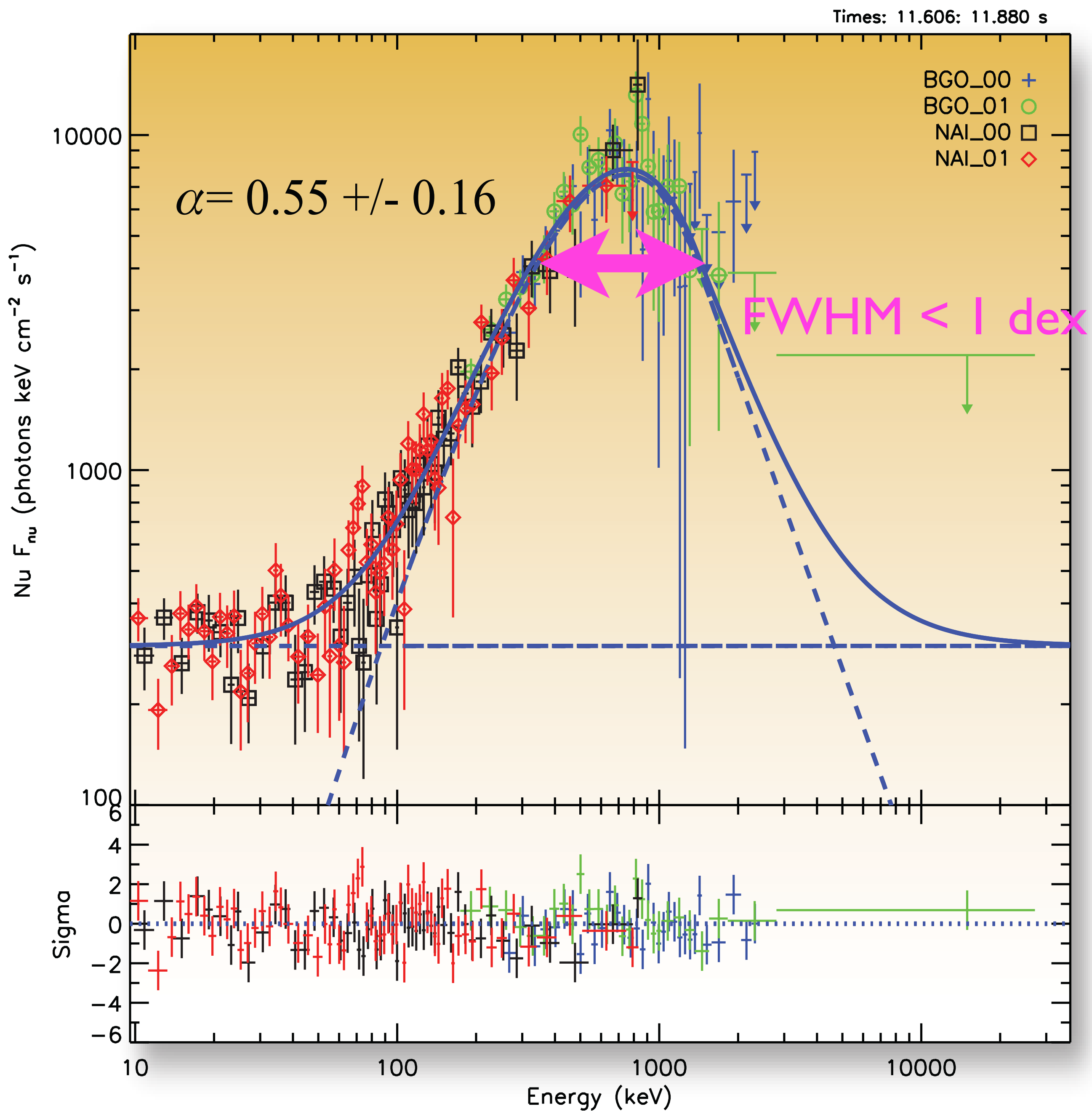

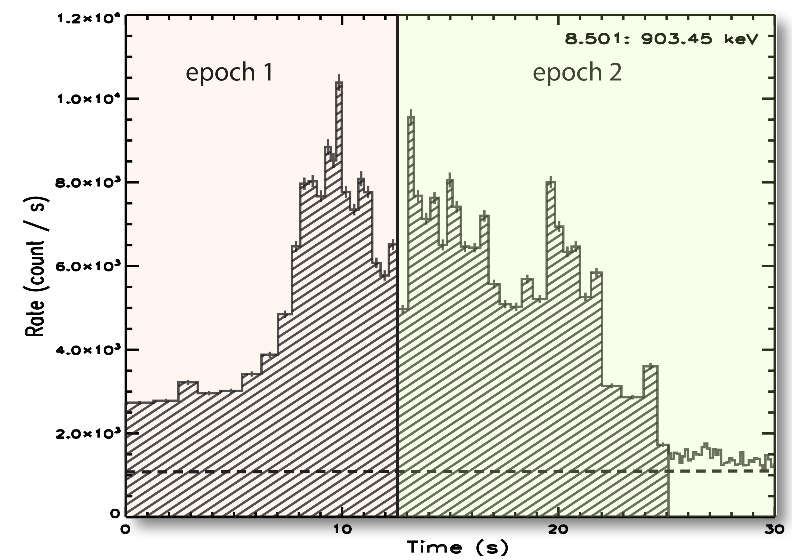

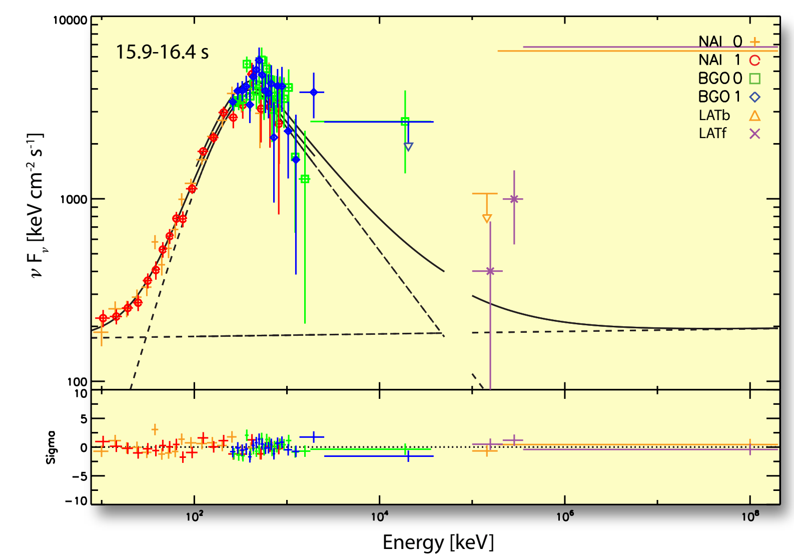

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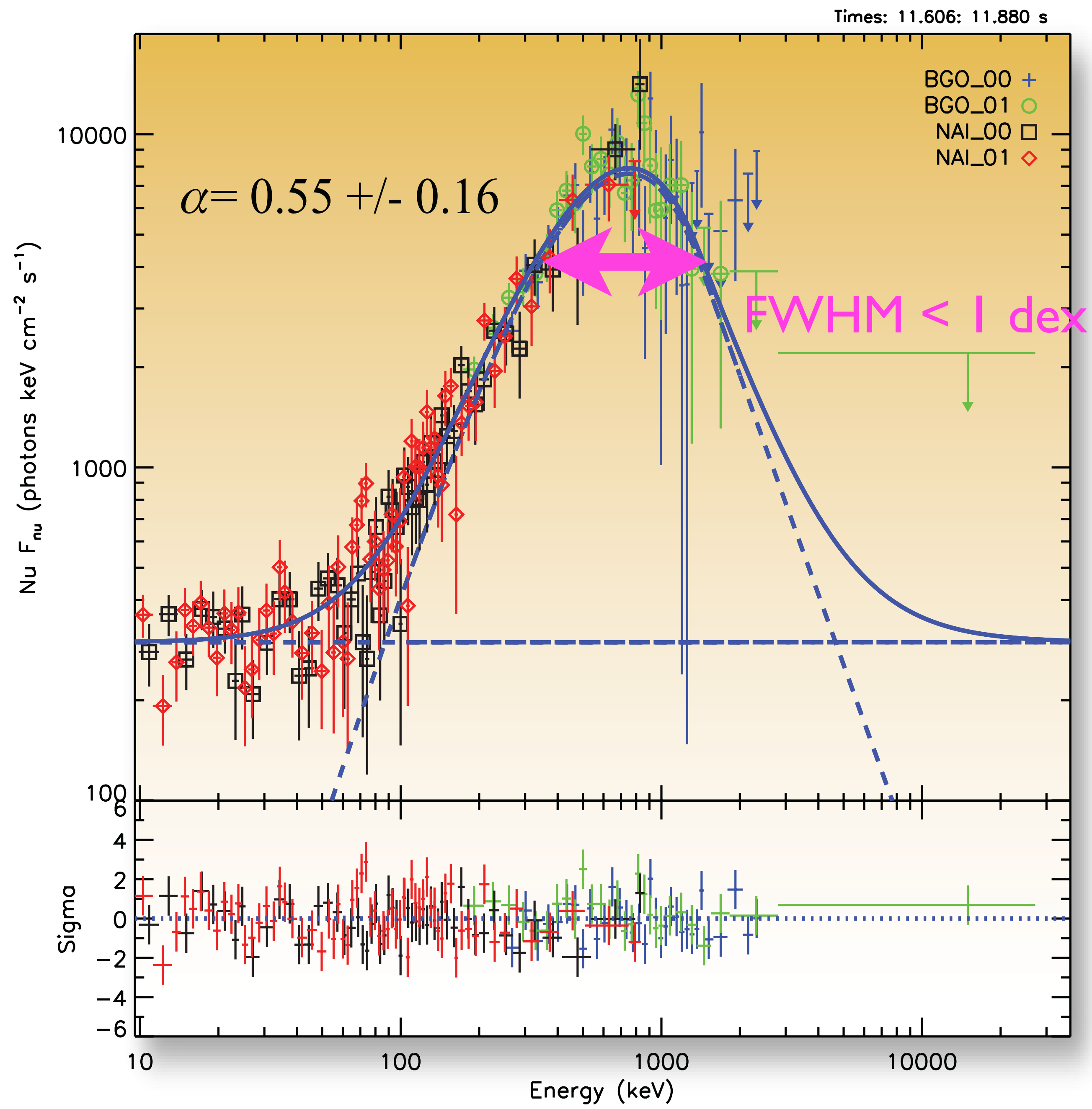
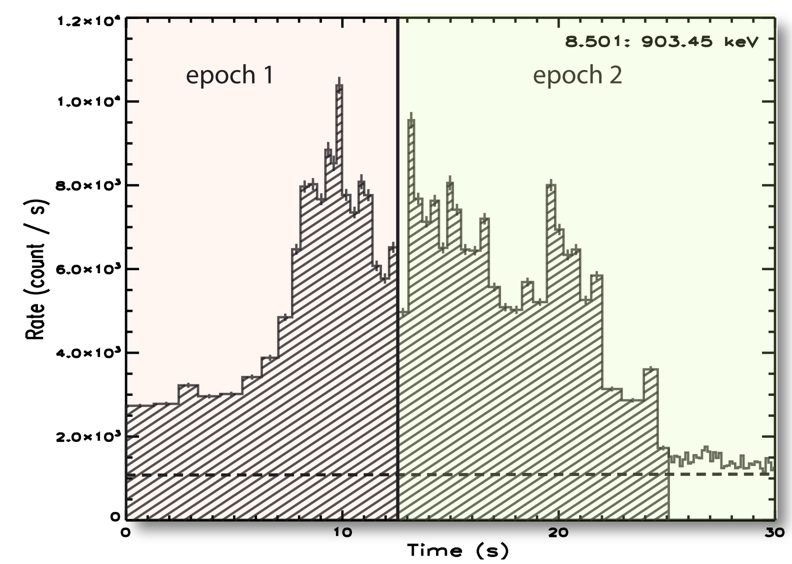
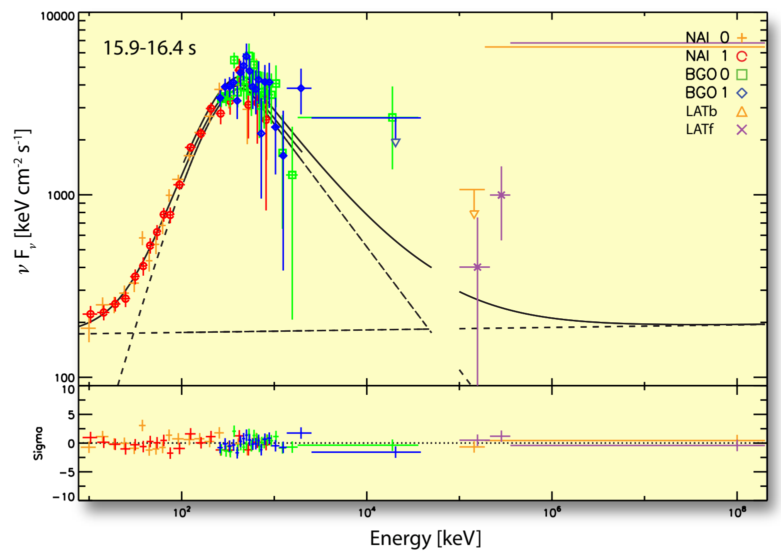


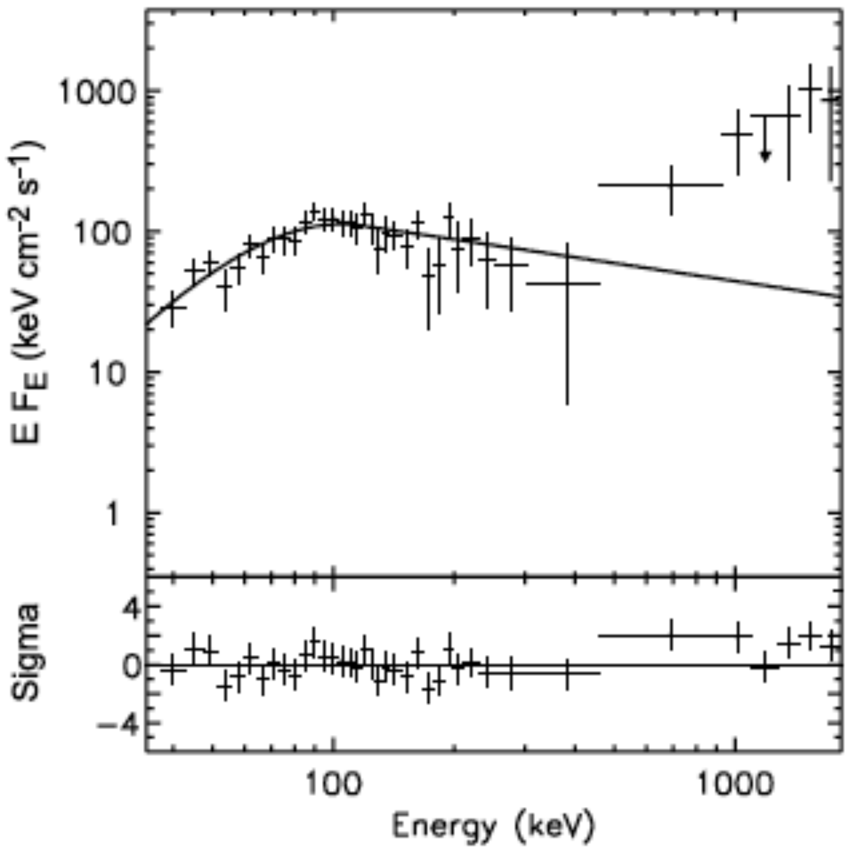




Observations of a Planck spectrum means that the spectrum was formed while the outflow was photon dominated (below the saturation radius) or that dissipation ended during the Planck or Wien part of the flow (Beloborodov 2011)

II. Blackbody + additional component

Band only



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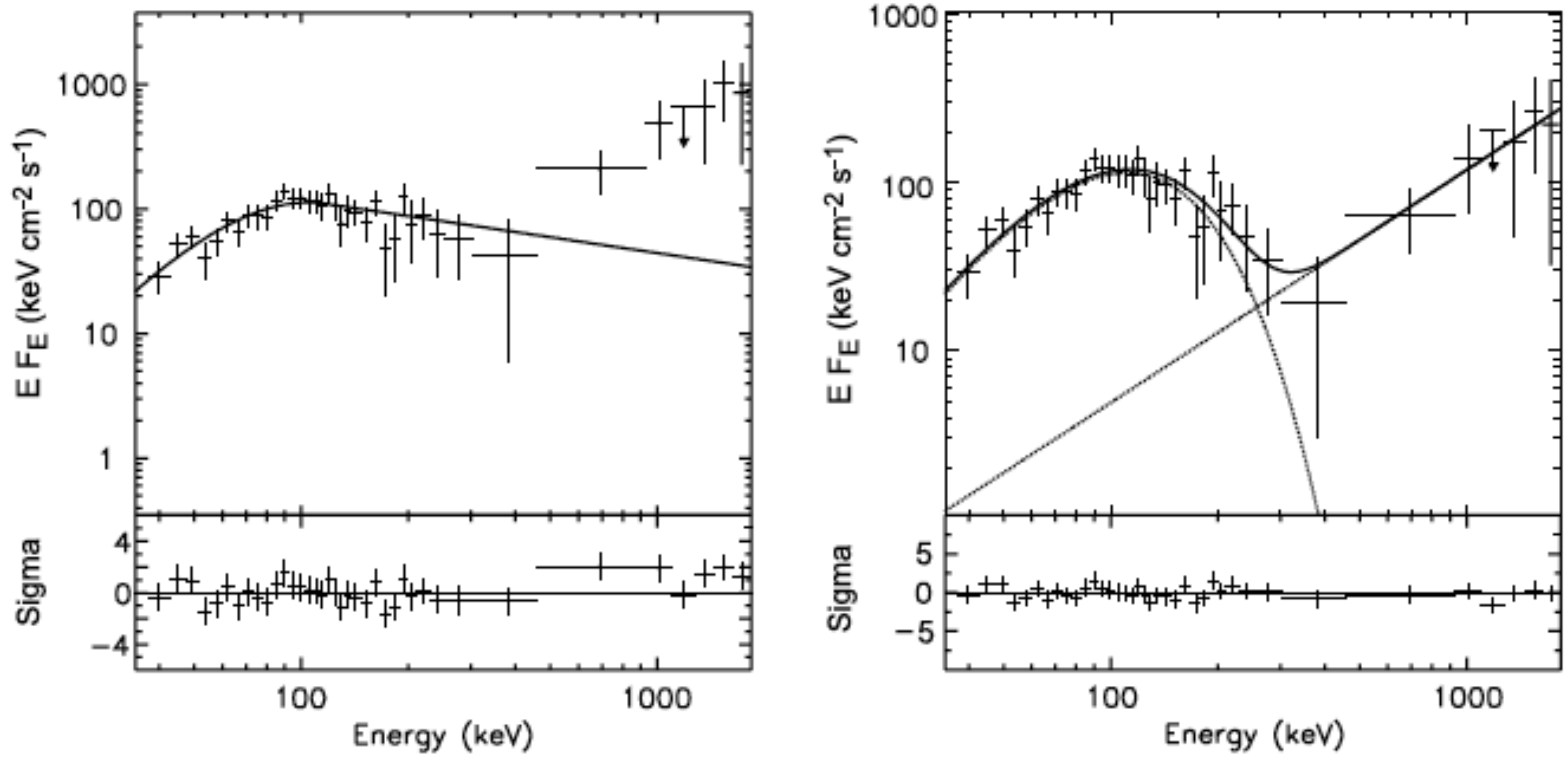

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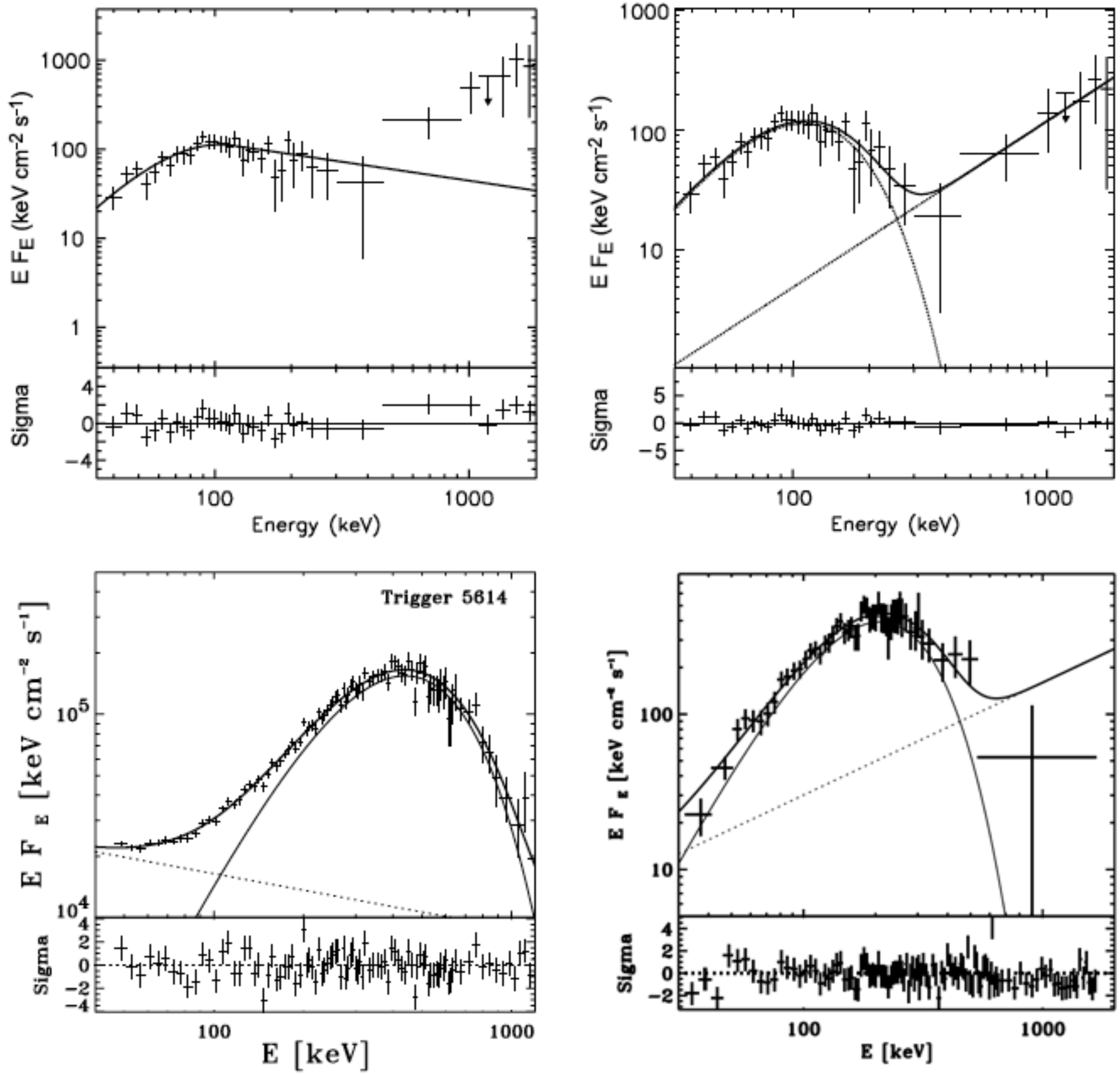


Ryde 2005

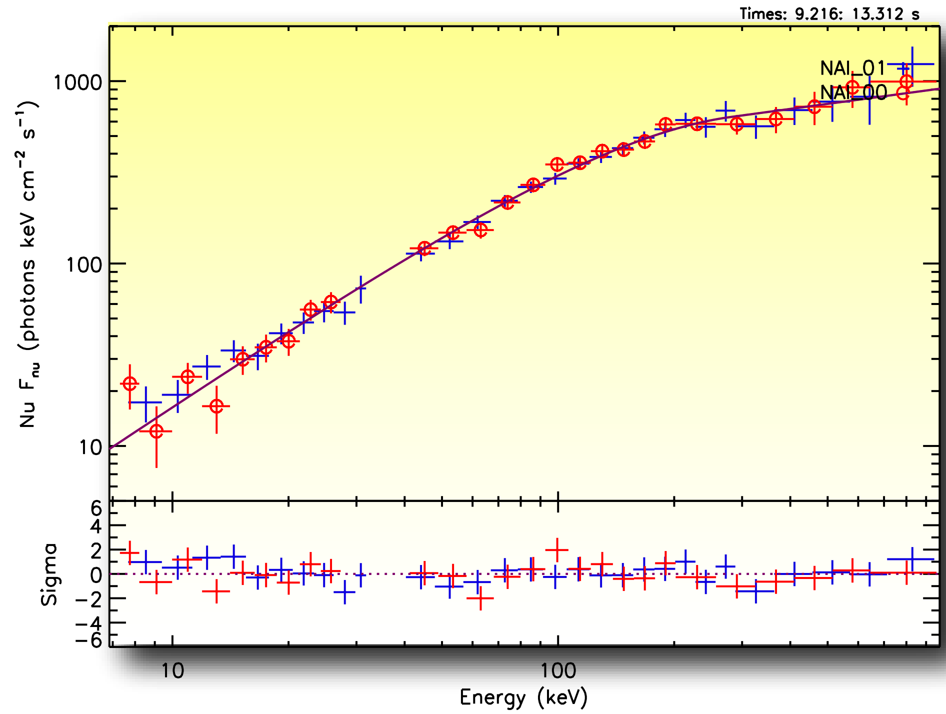
Photosphere in GRB100724B

Guiriec+10

Limiting the band width to 8 keV - 1500 keV (Comparing the BATSE fits)

Band model

NaI
Band



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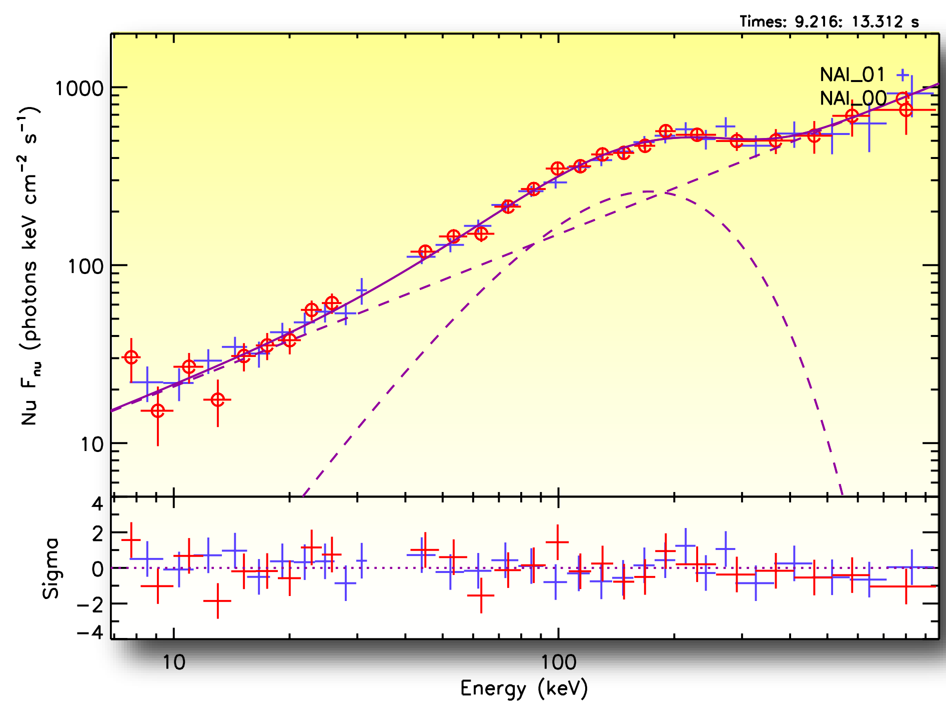
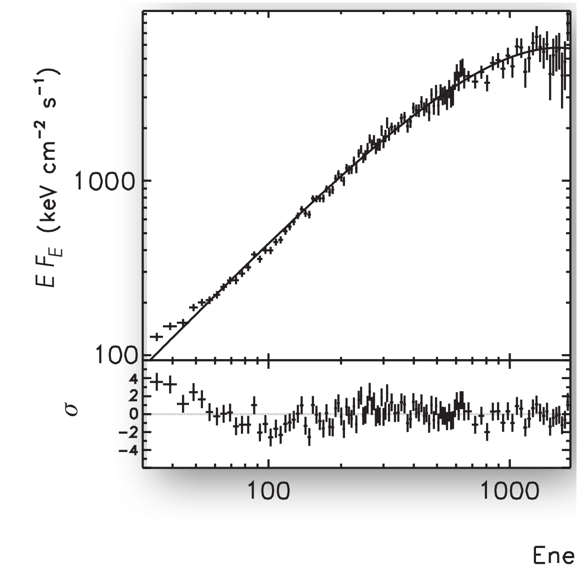
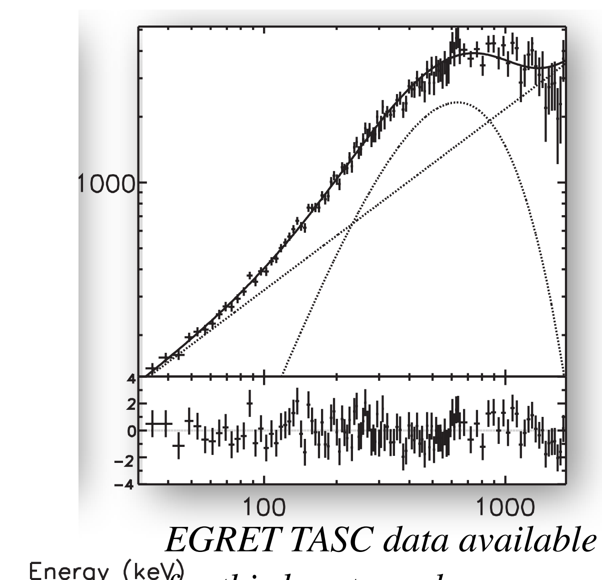


CGRO BATSE fits of GRB981021
(Ryde & Pe'er 2009)





EGRET TASC data available for this burst; peak energy = 1600 keV

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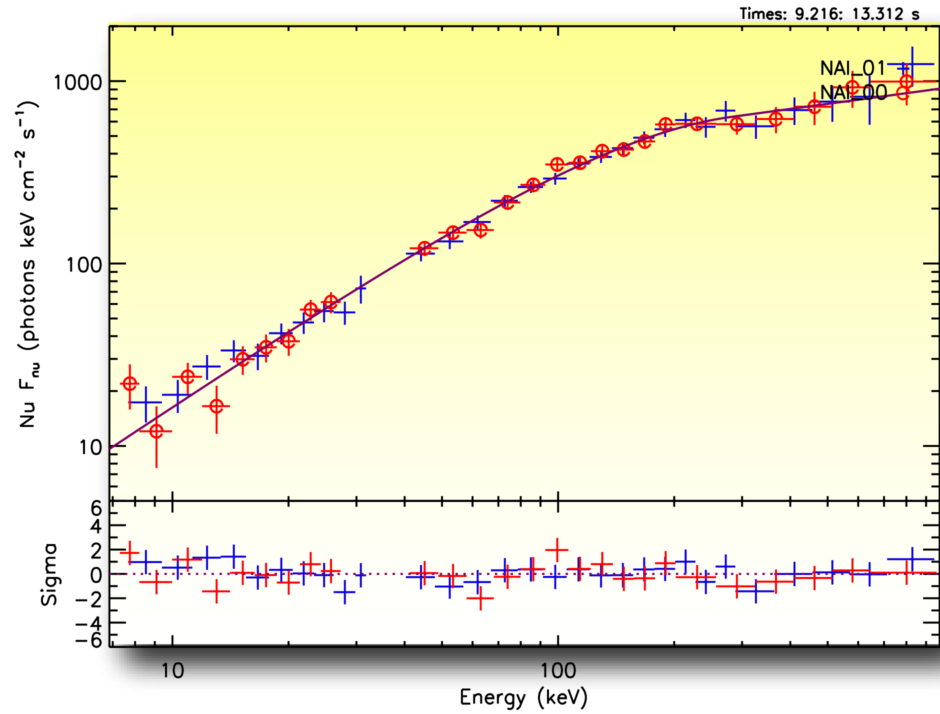

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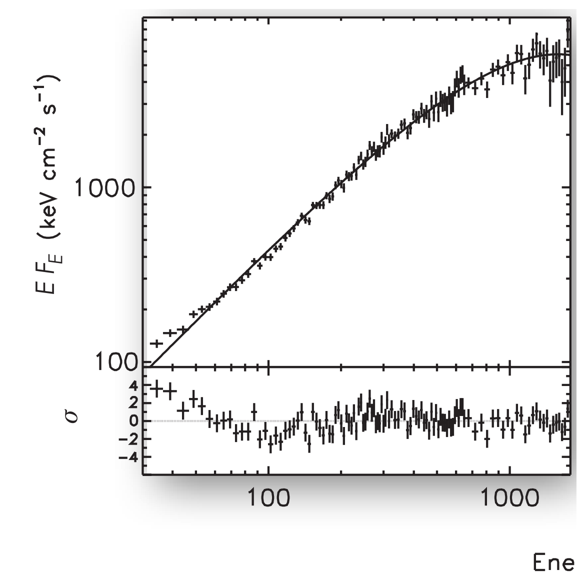
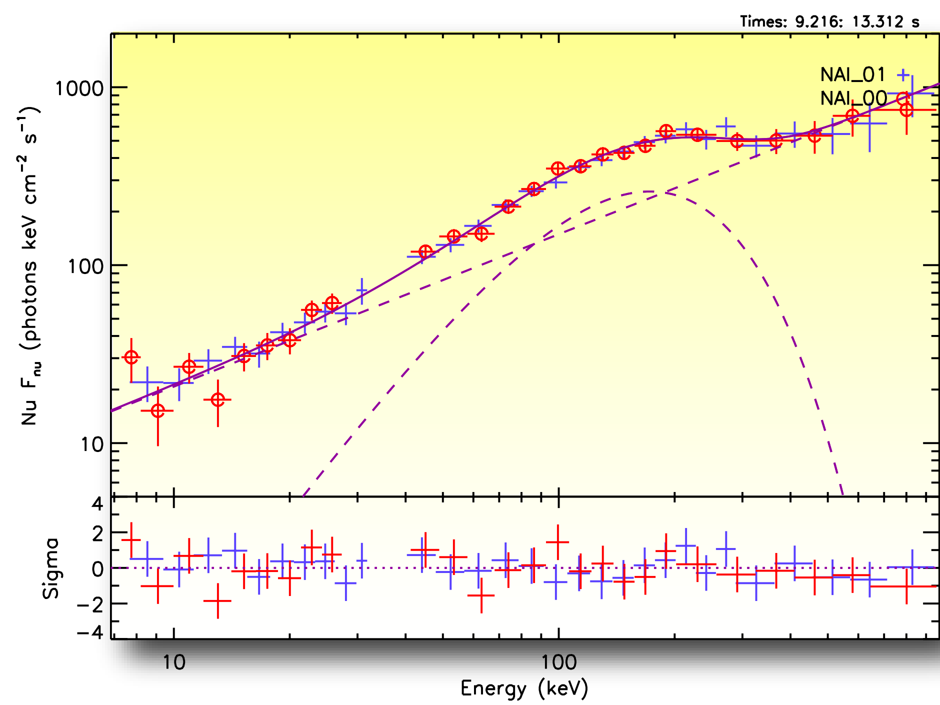
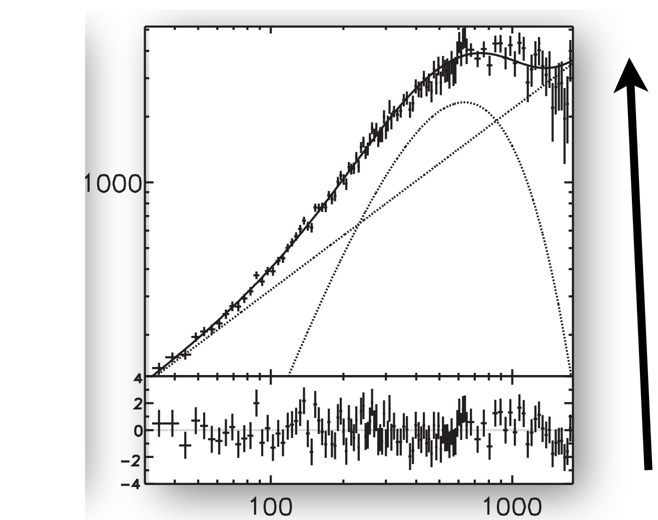


BB+pl model

NaI
BB+pl





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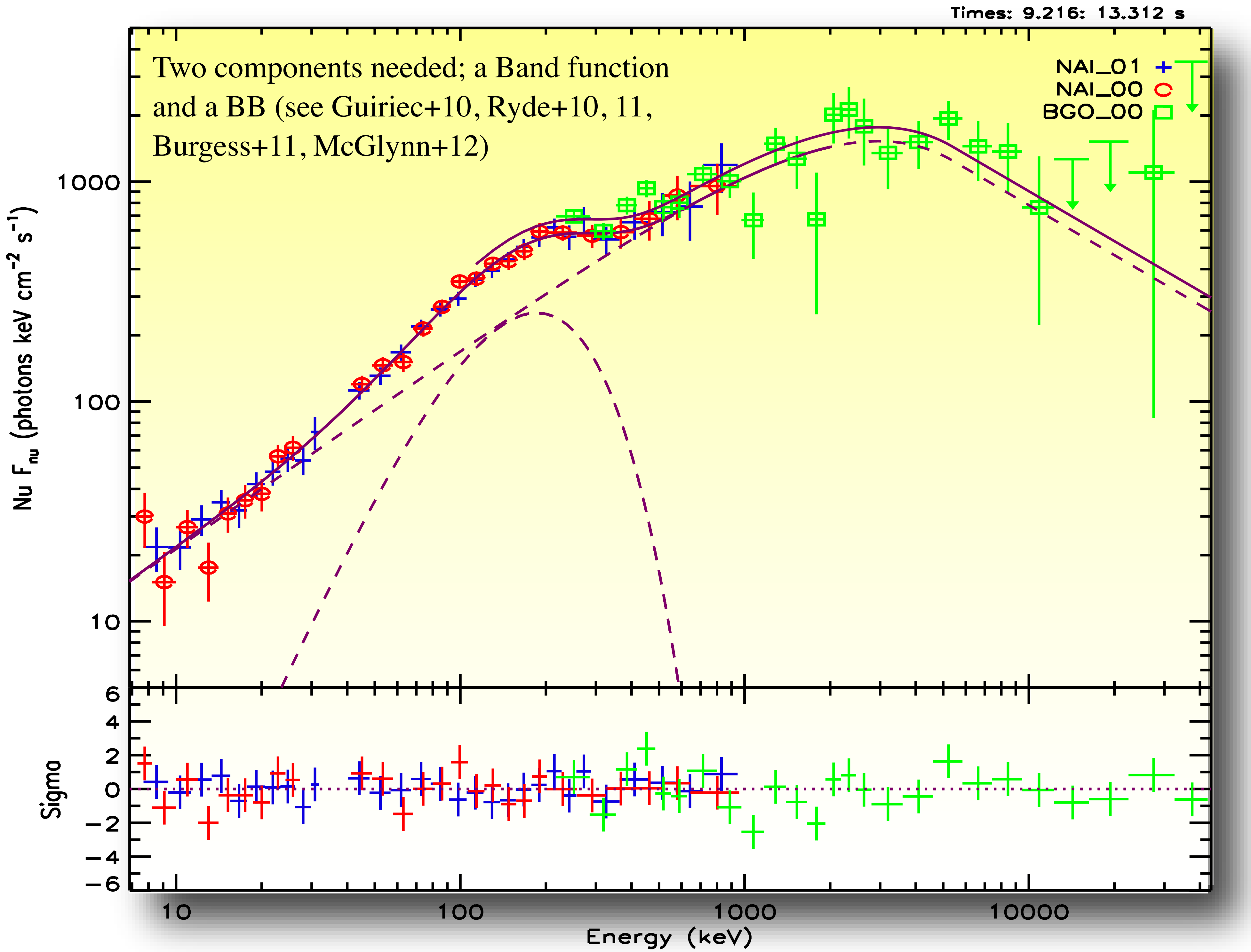

of GRB981021

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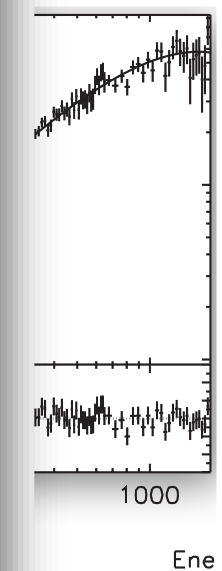

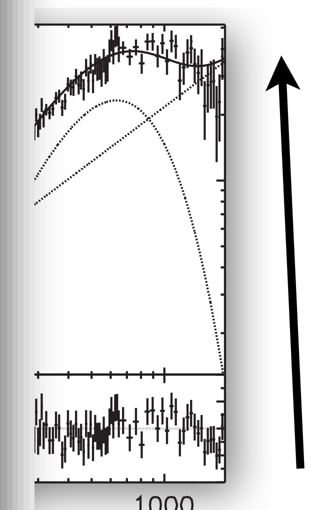

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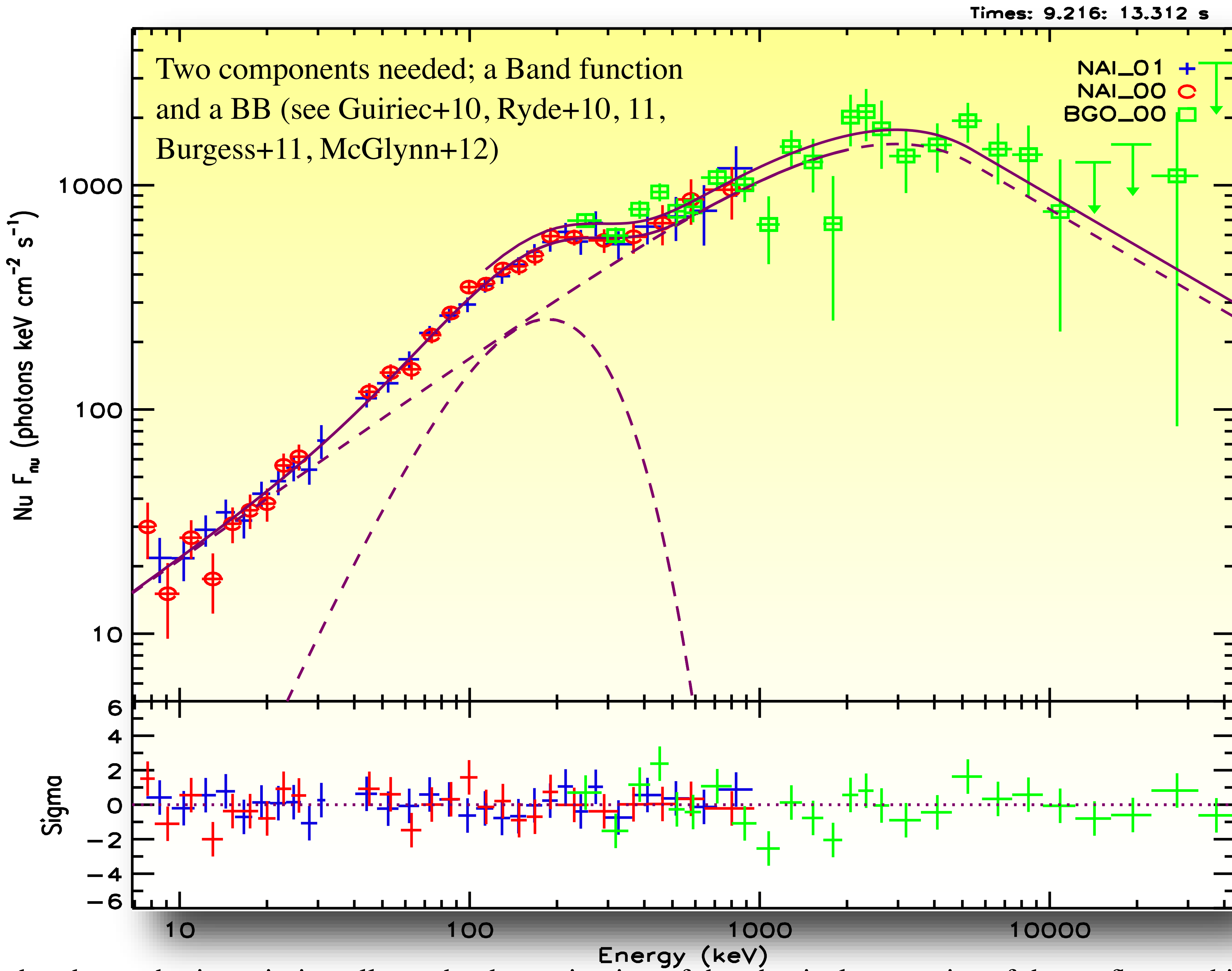

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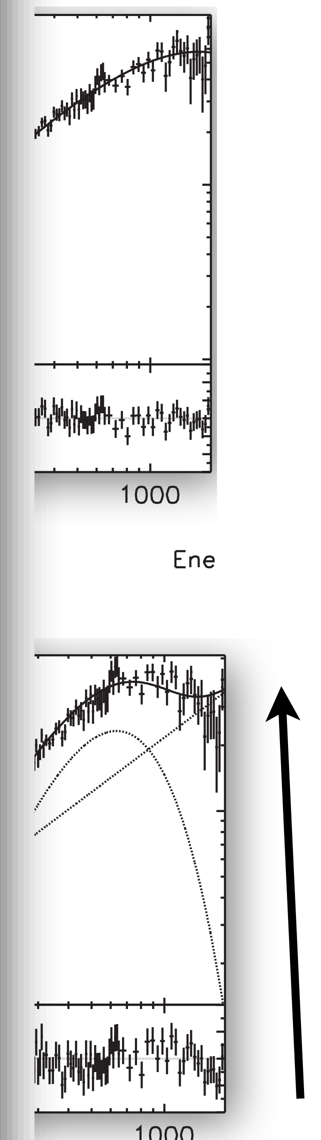

data available

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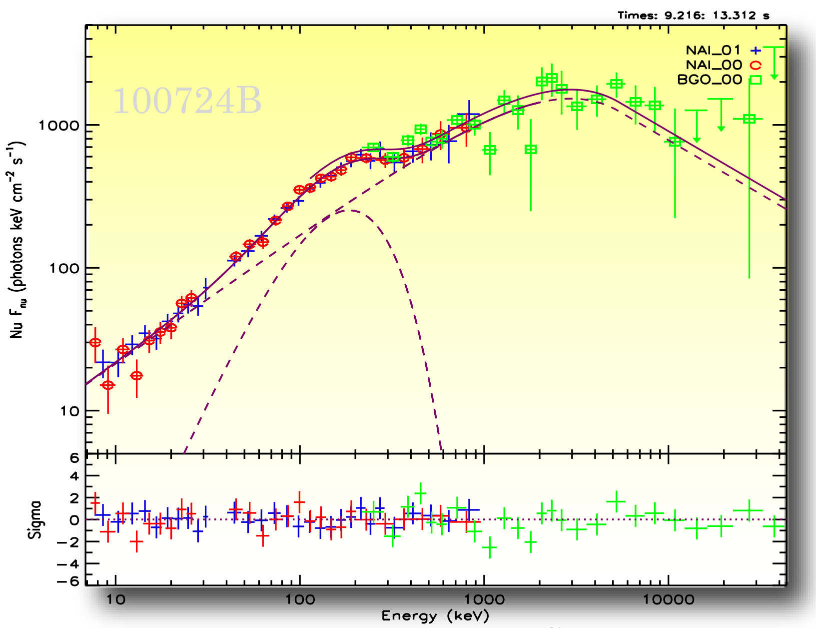
Having identified the photospheric emission allows the determination of the physical properties of the outflow and its photosphere Pe'er+07), Daigne+07.

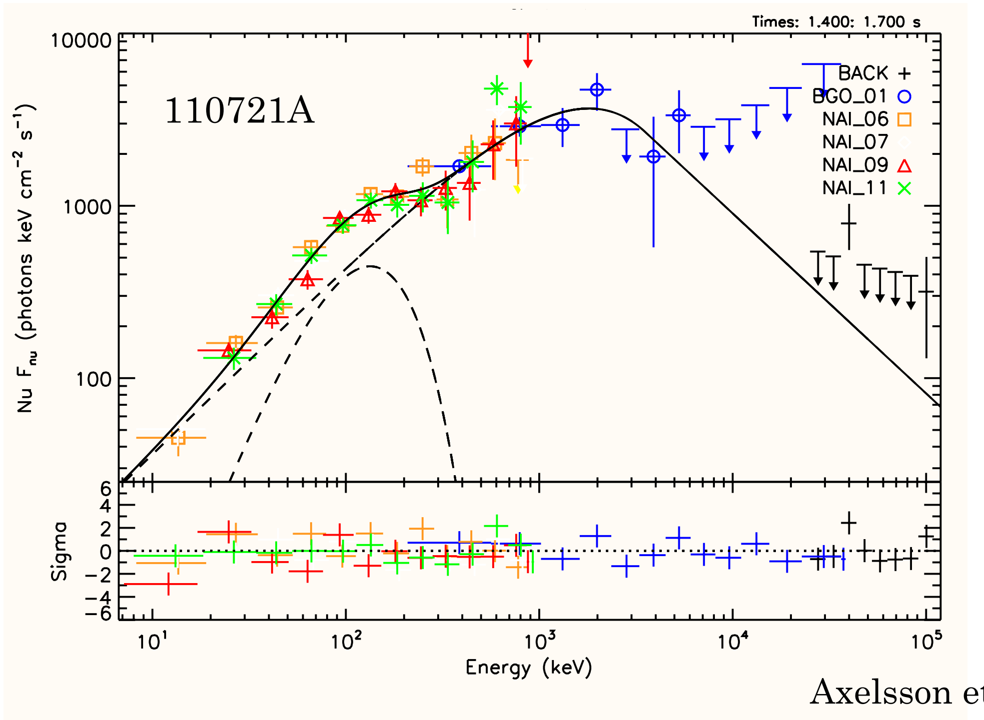
In this case we find that the bulk Lorentz factor $\Gamma \sim 325$ and photospheric radius $R_{ph} \simeq 5.6 \times 10^{11}$ cm

Examples of multi-peaked spectra observed by *Fermi*:

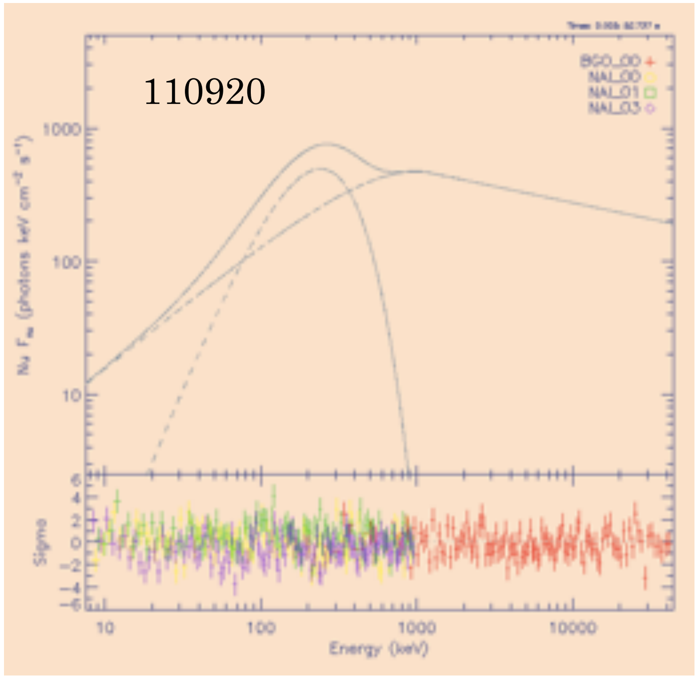
The photospheric component is modelled by a Planck function.
Is expected to be broadened to some extent.



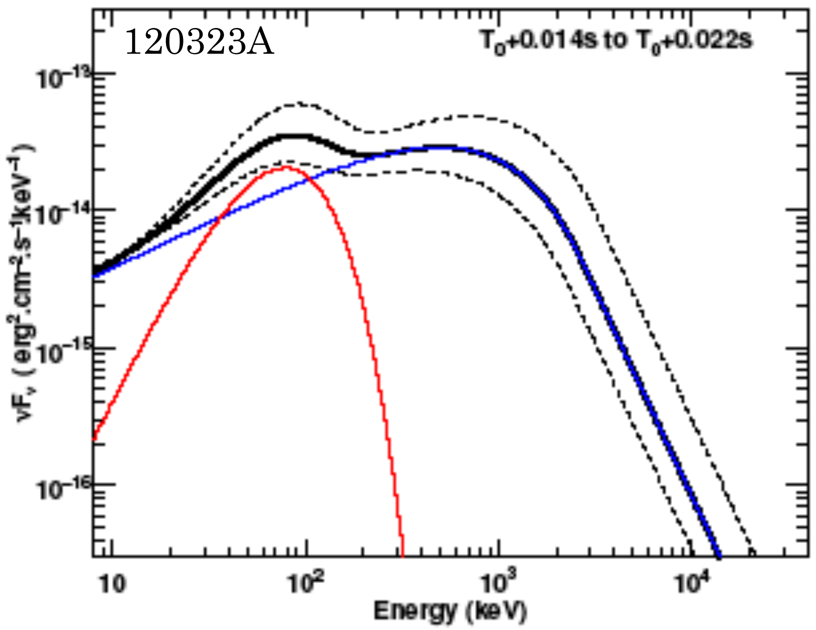
Guiriec et al. 2011



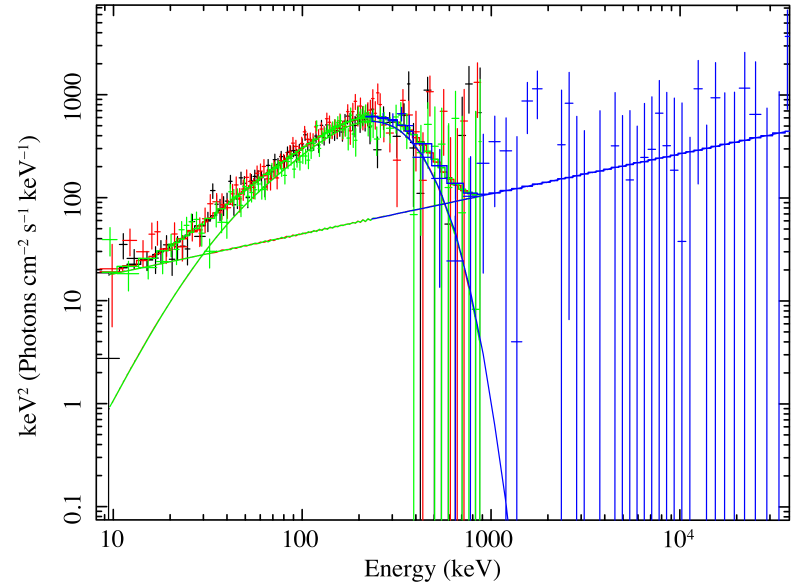
Axelsson et al. 2012



McGlynn et al. 2012



Guiriec et al. 2013

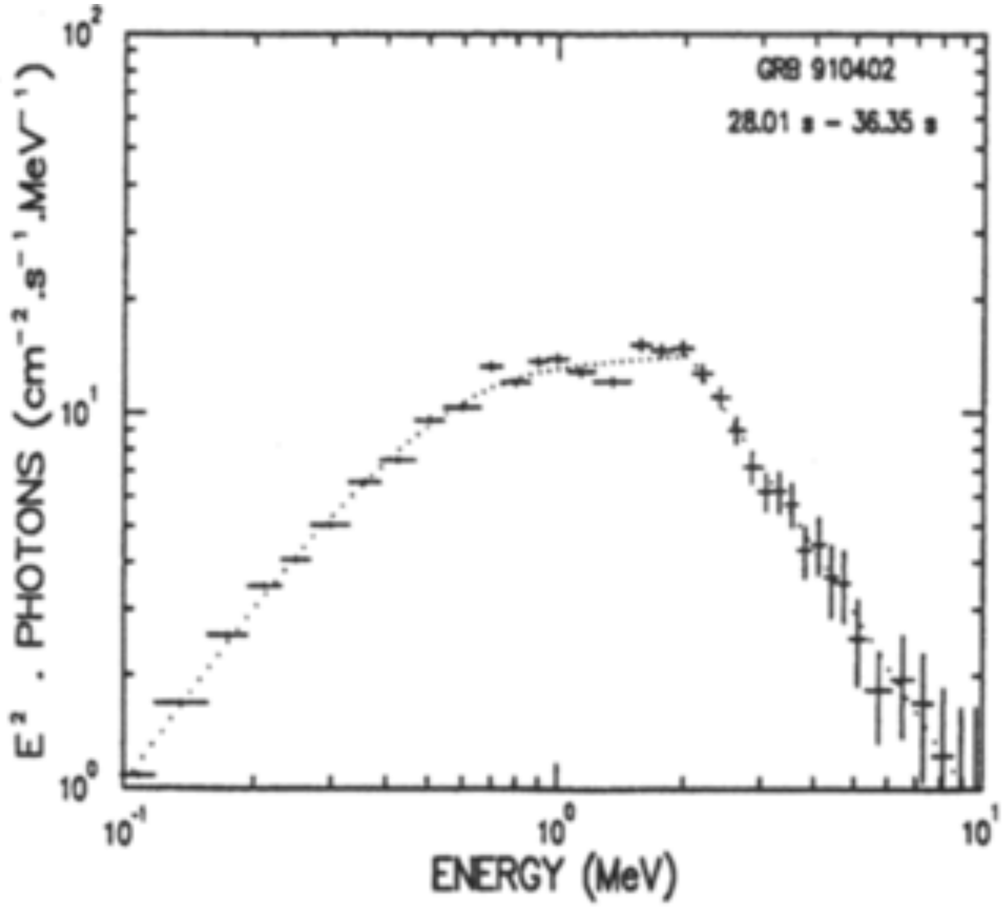


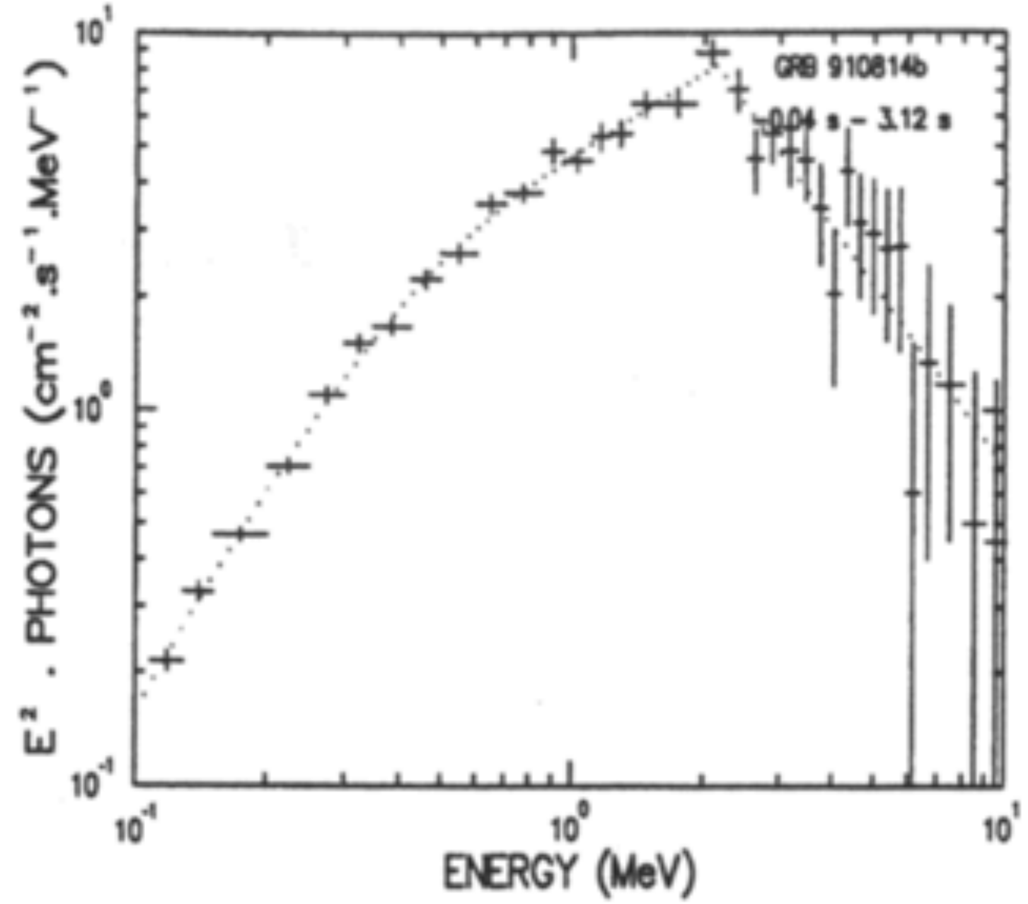
Iyyani et al. 2014

Two component spectra: Blackbody component typically 5-10% of total flux.
But many cases with 40-60 %.

Examples of multi-peaked spectra observed by *Fermi*:

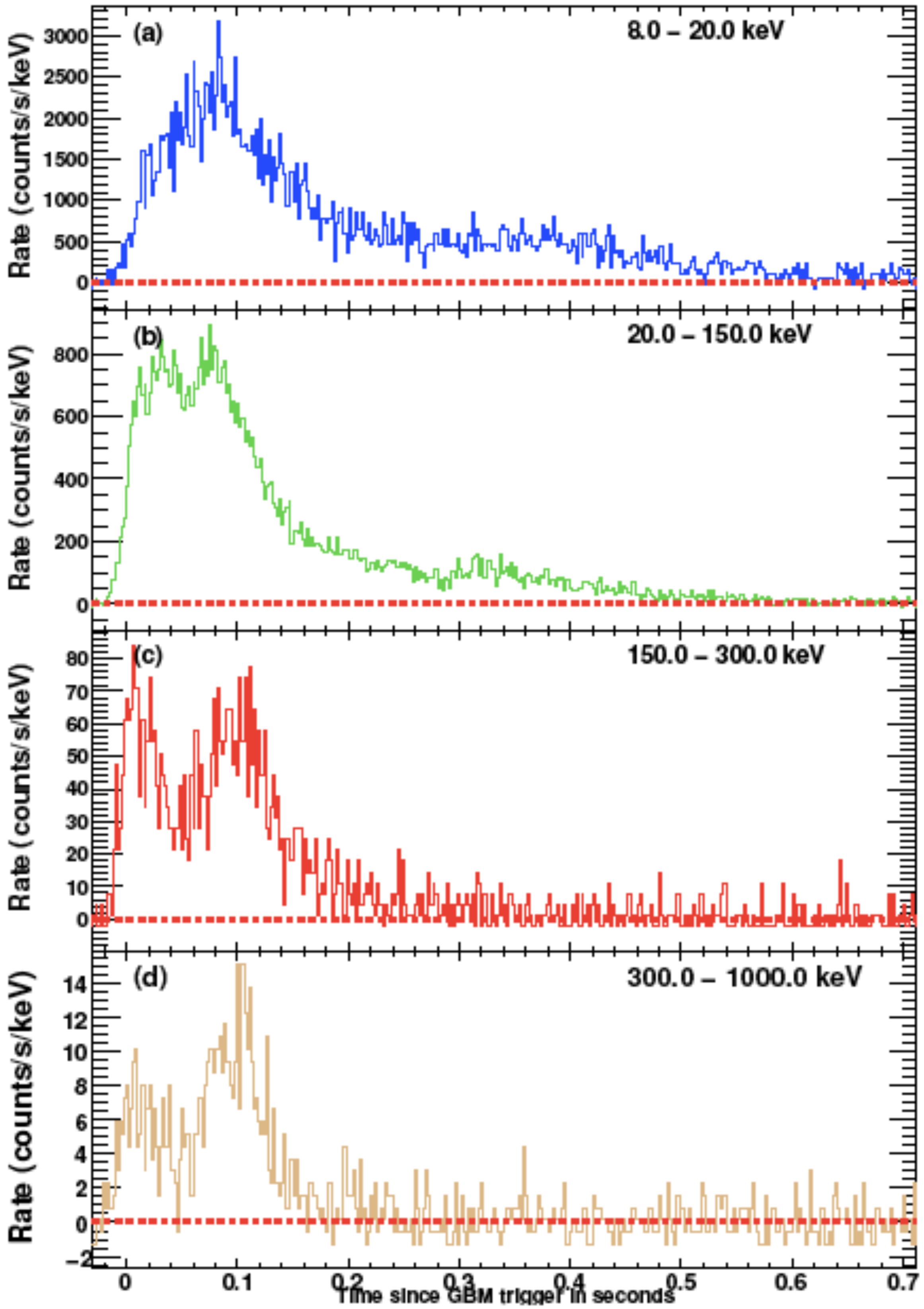
PHEBUS/Fregate





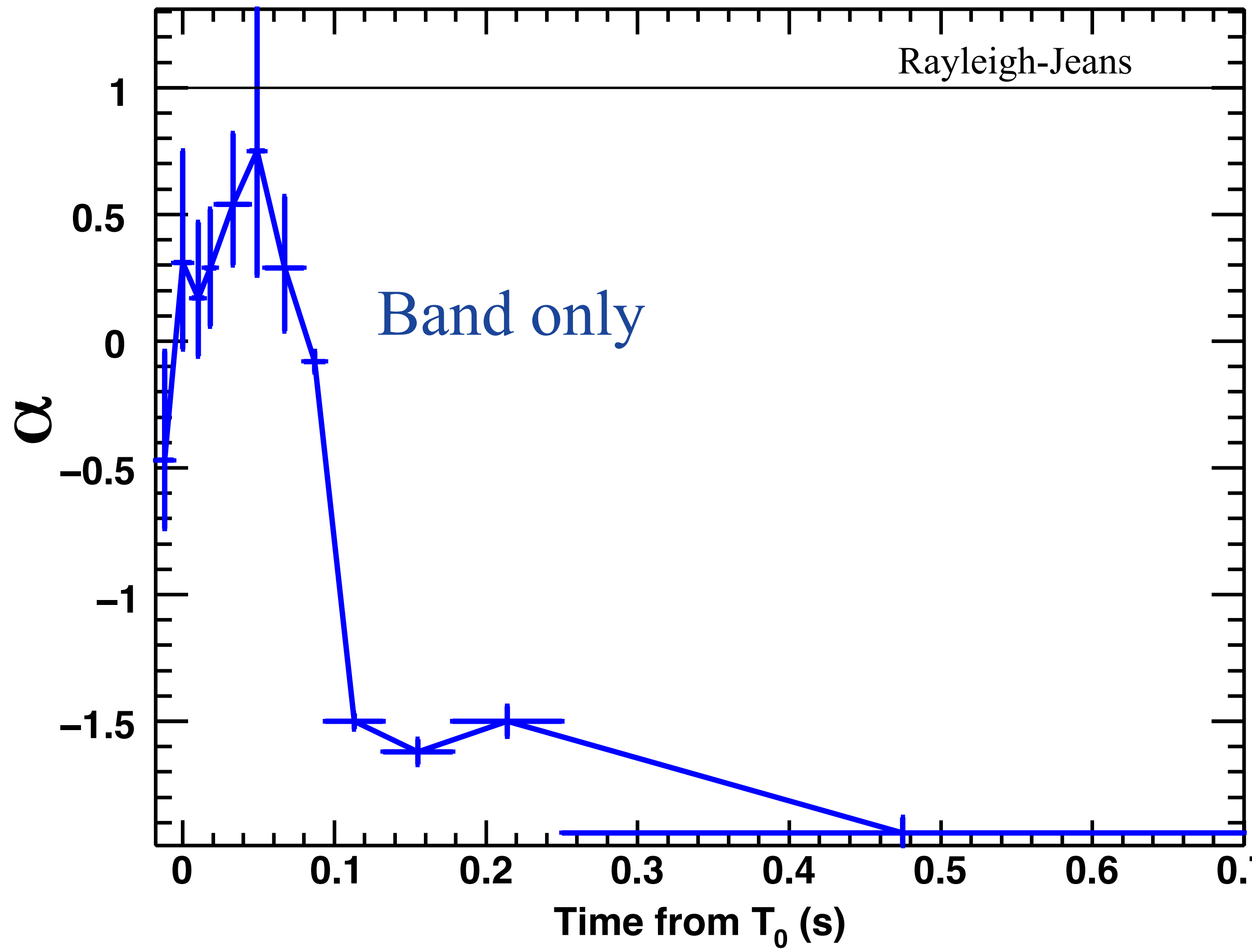
Barat et al. 2000

Multiple components in the *short* burst GRB120323A



One of the strongest bursts seen in the GBM

Low energy spectral index of the Band function



Guiriec et al. 2013

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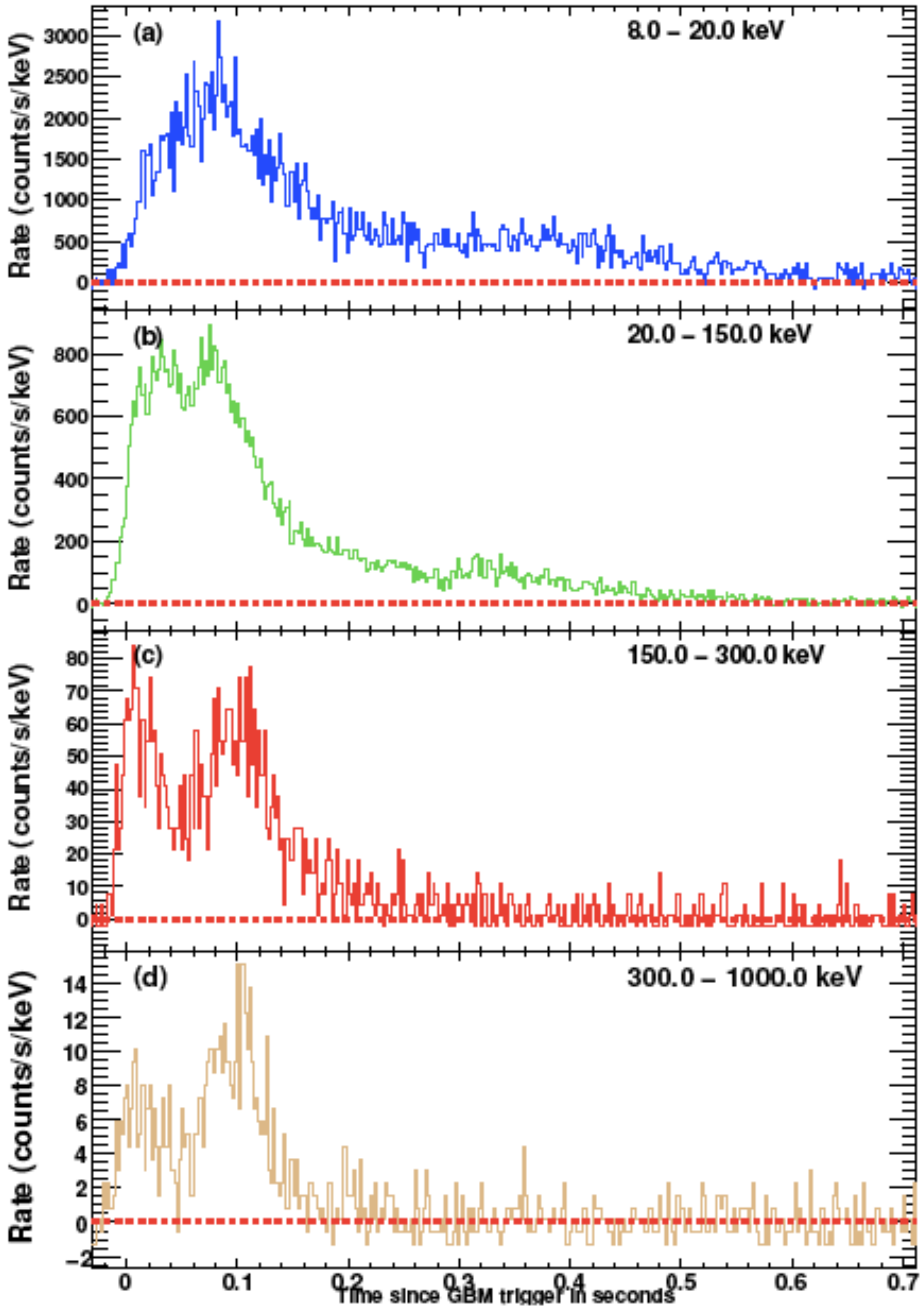

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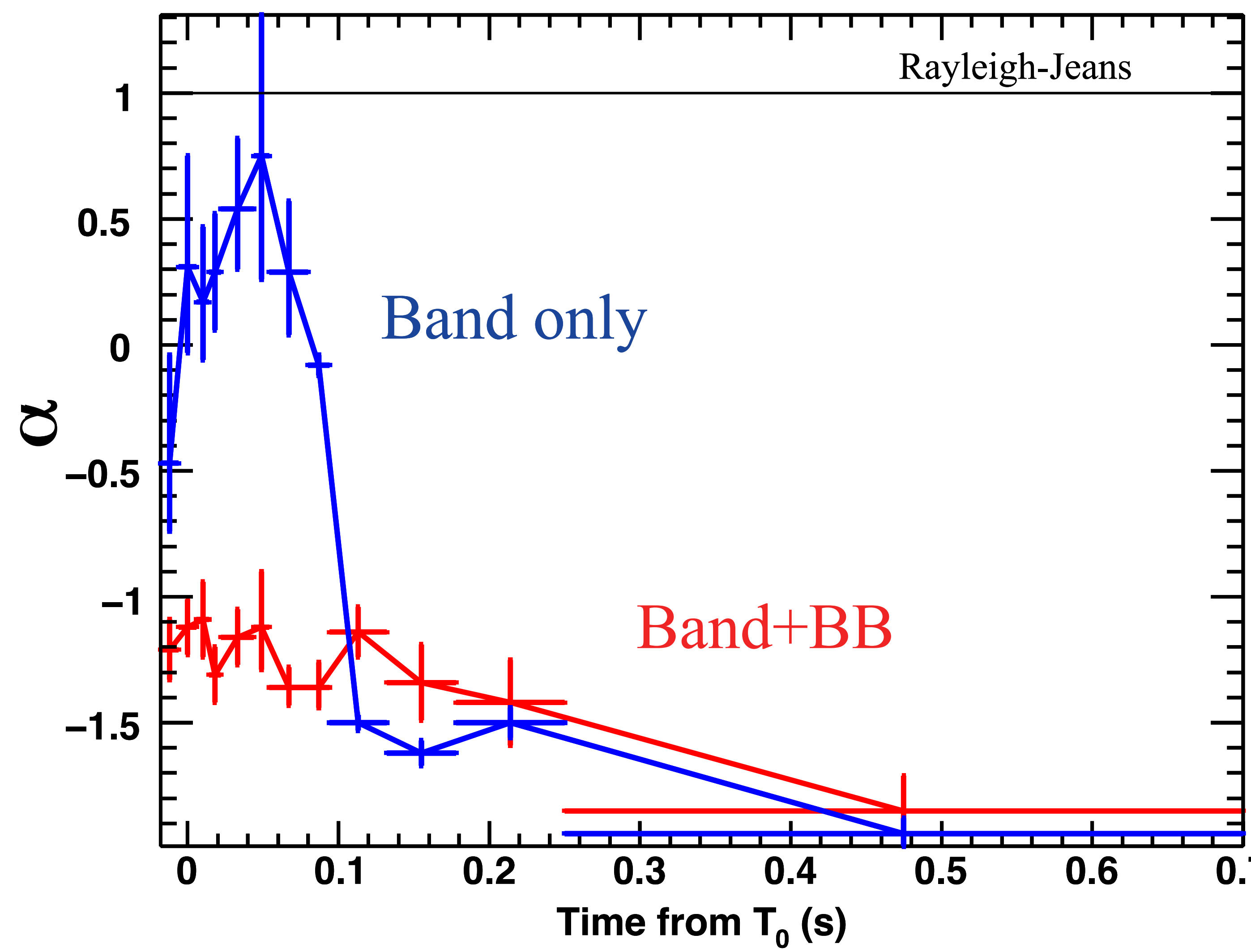
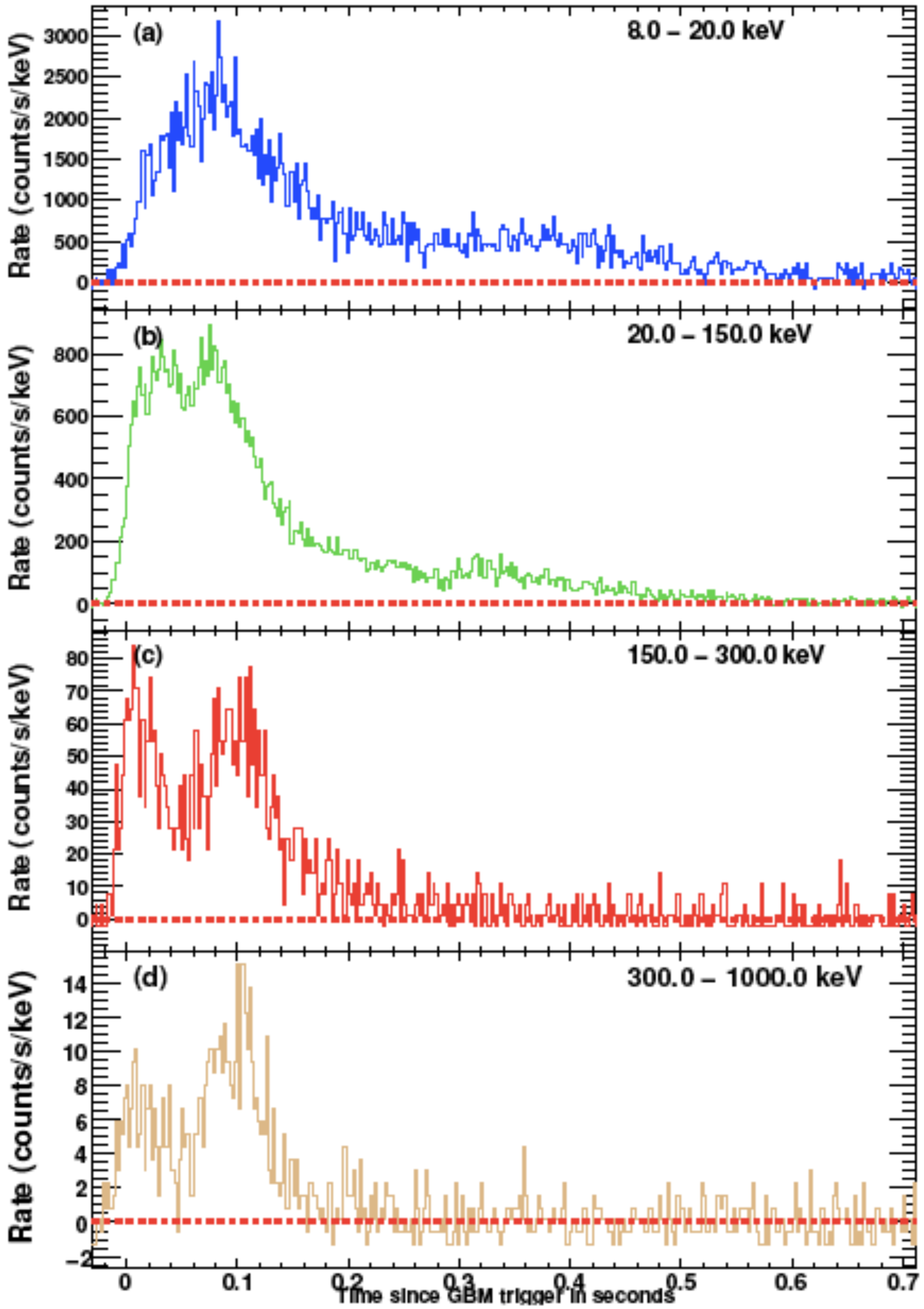


Guiriec et al. 2013

Multiple components in the *short* burst GRB120323A



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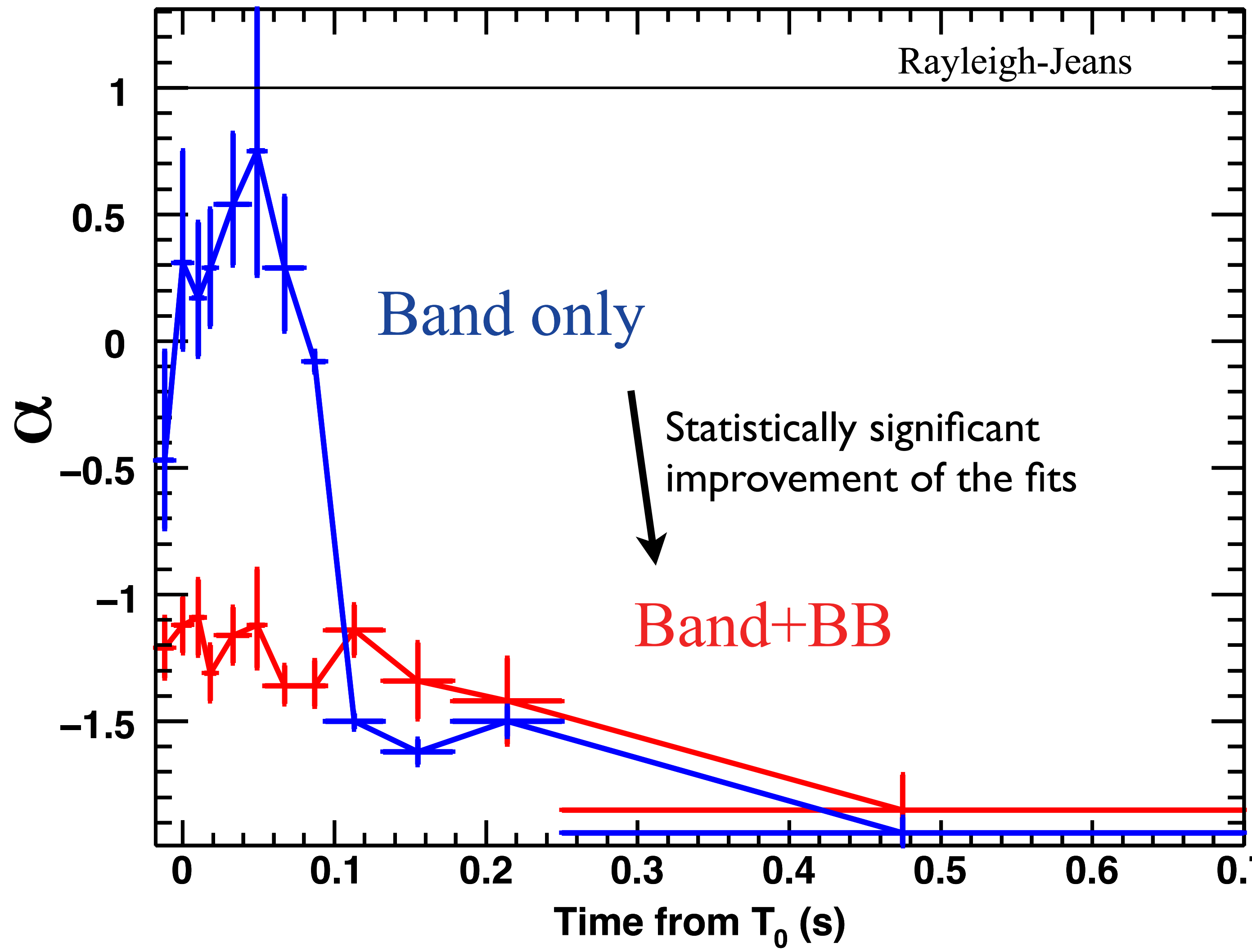

Guiriec et al. 2013

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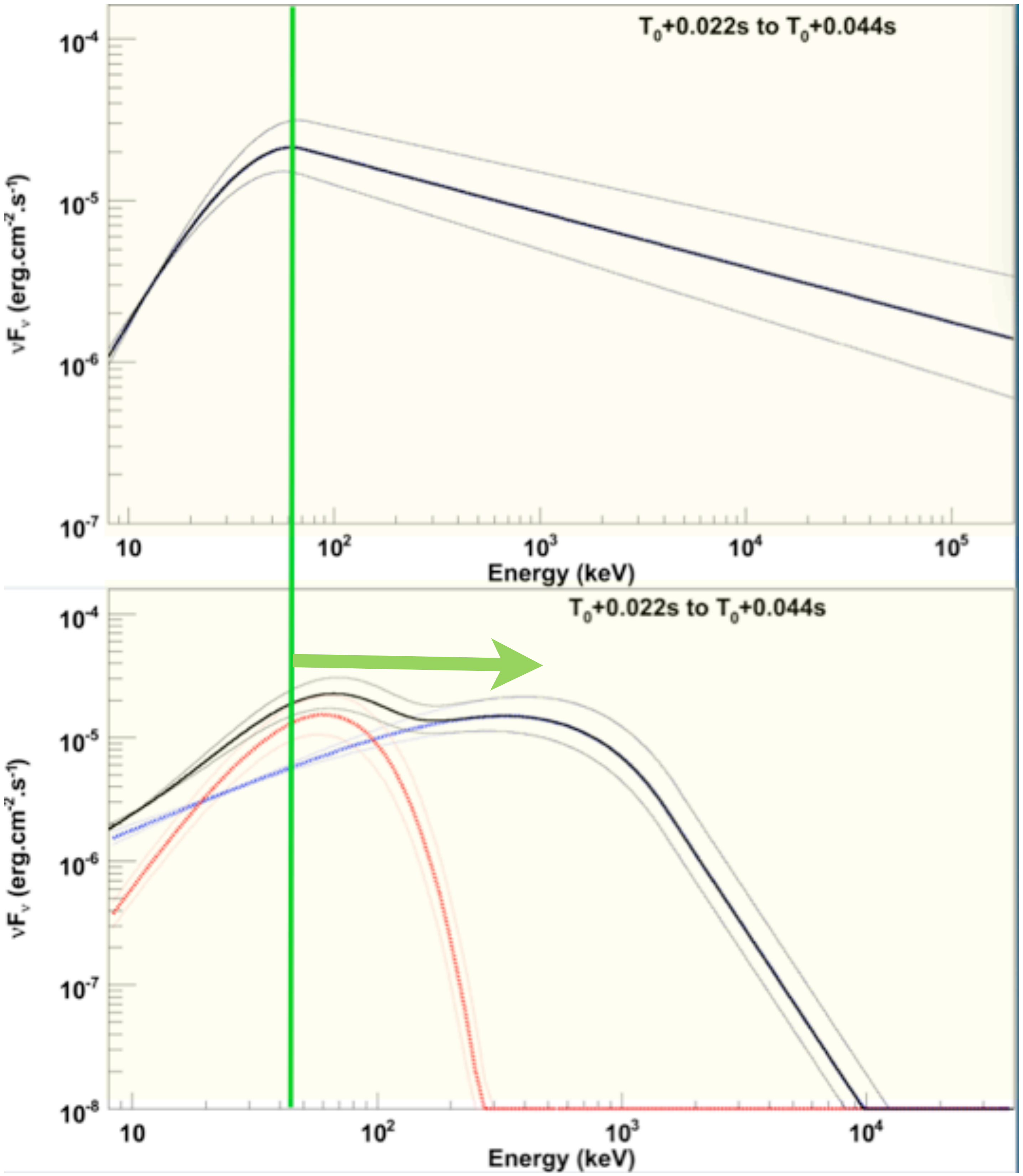


Changes the interpretations!

1. Change in Epeak
2. Change in alpha (synchrotron?)
3. Change in emission zones

Guiriec et al. 2013

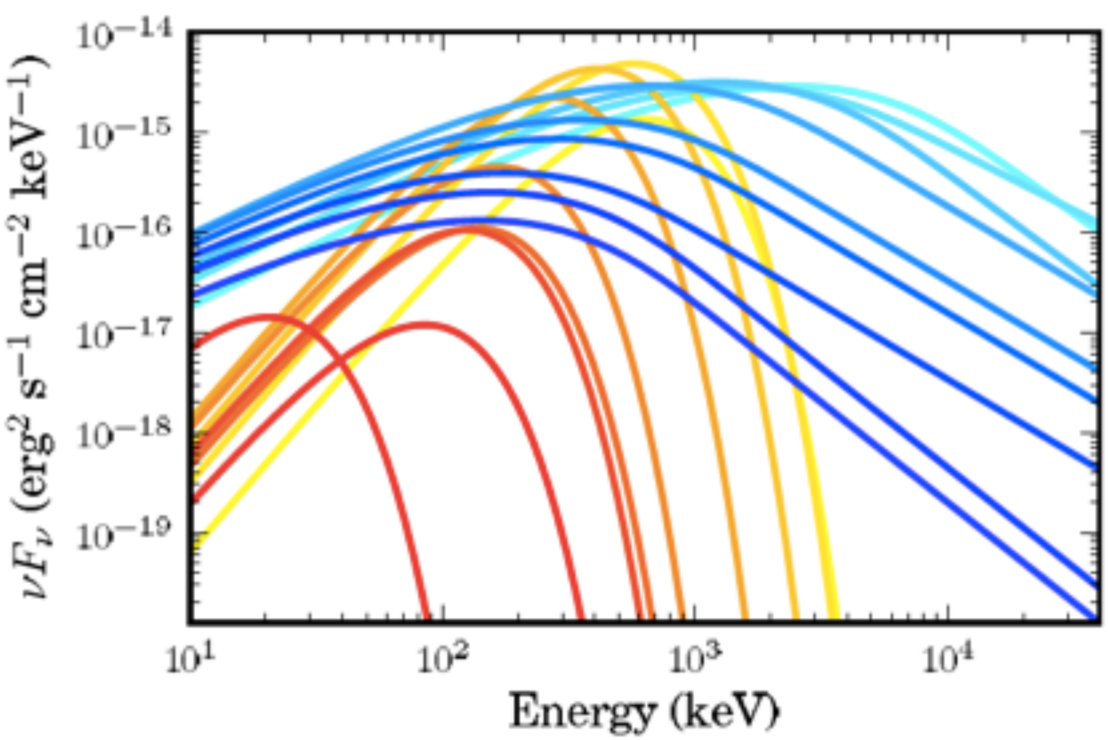
Omitting the Band function

The best procedure is to fit a *physical* model directly to the data:

Burgess et al. (2013) fit a *synchrotron spectrum* from a distribution of electrons in addition to a *Planck spectrum* (modelling the photosphere) in 8 well separated pulses.

- In all cases the fits are the same of better than the Band function.
- In 5 of these a BB is statistically required.

GRB081224A



Burgess et al. (2013)

- Temporal behaviour of BB and synch are different
- Slow-cooling synchrotron spectrum: the electrons must undergo continuous acceleration (magnetic reconnection events or second-order stochastic acceleration, MHD).

Bottom Line

1. **Band crisis**
   The band function is not the *universal* GRB spectrum. What does it mean?

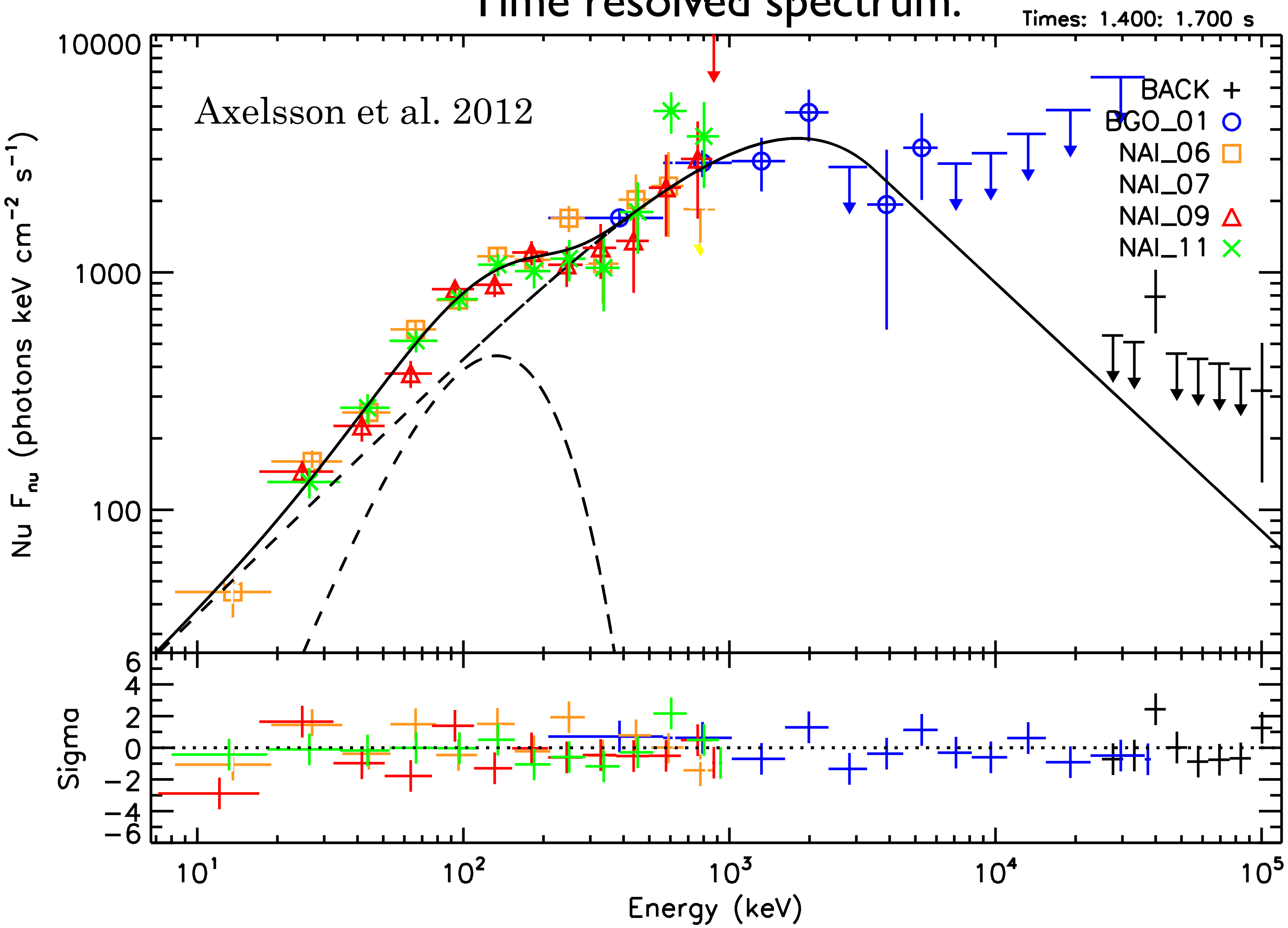
2. **Appearance of the photosphere**
   Blackbody, BB+nonthermal, broadened functions

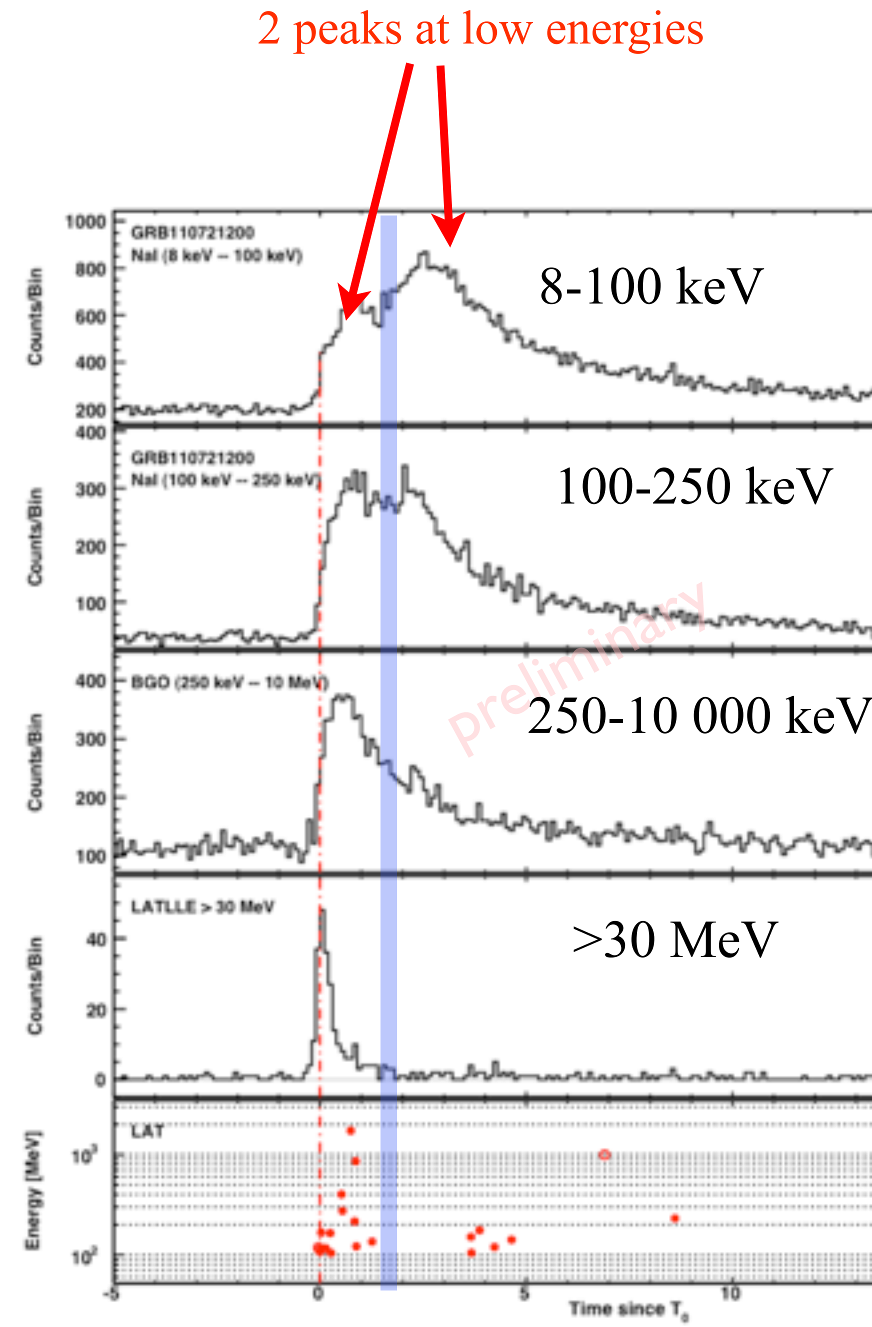
3. **GRB jet properties are variable.**
   Lorentz factor decreases over individual pulses while the flow nozzle increase

GRB110721A

- One of the ten strongest bursts: $876 \pm 28 \times 10^{-7}$ erg/cm^{-2}
- Best model BB+Band: < 5 sigma detection of an extra component

Time resolved spectrum:

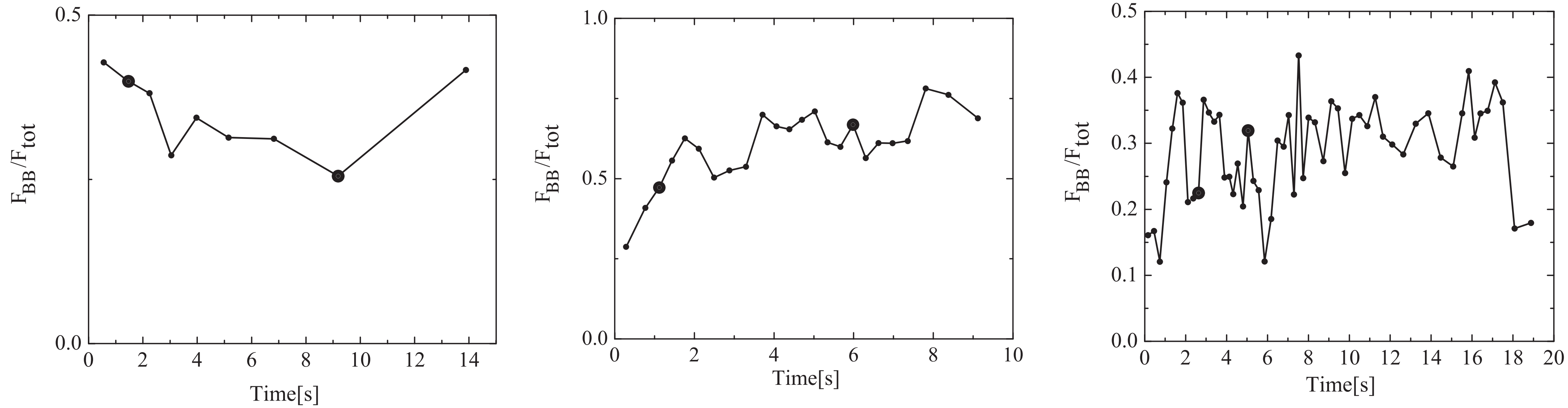




The thermal and nonthermal emission do not track each other.

Flux ratio = $\frac{F_{\rm BB}}{F_{\rm NT}}$

CGRO BATSE typically constant:



Ryde & Pe'er 2009

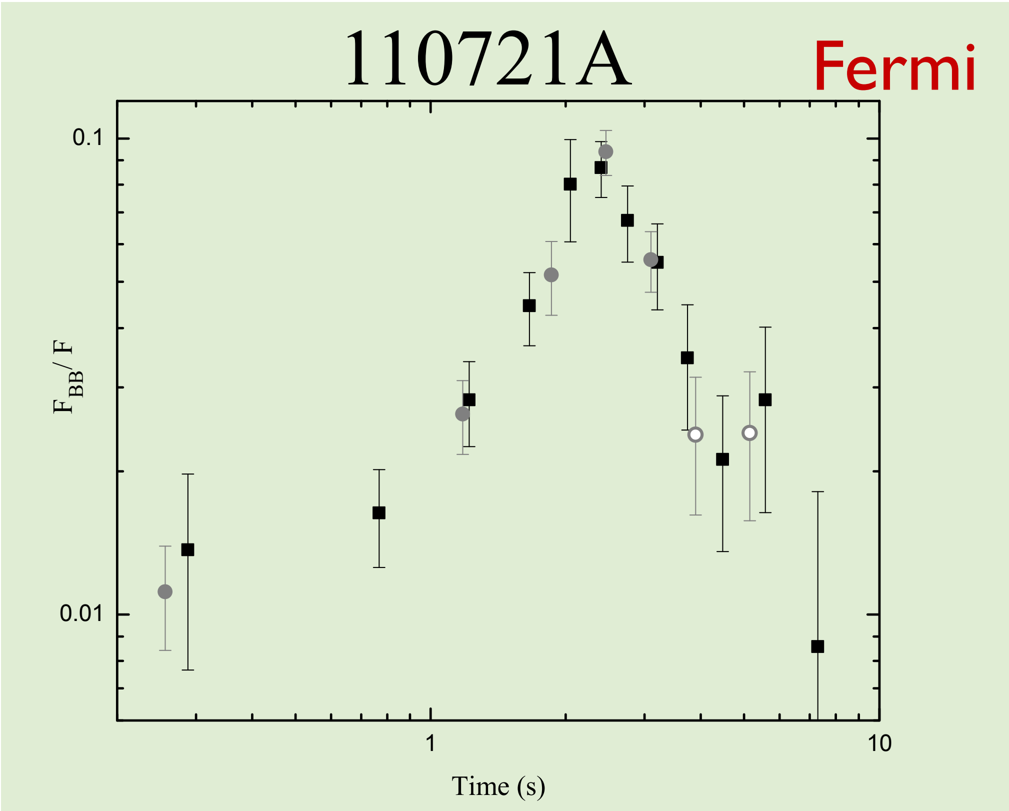
But in GRB 110721A

$\frac{F_{\rm BB}}{F_{\rm NT}}$ has a distinct pulse shape

- Varying adiabatic losses

$$\epsilon_{\rm ad} = \left(\frac{r_{\rm ph}}{r_{\rm s}}\right)^{-2/3} = \frac{F_{\rm BB}}{F_{\rm NT}}$$

- Varying photon starvation (Beloborodov 2012)
- Varying radiative efficiency
  (Should though be high since luminous burst; Cenko et al. 2010, Nemmen et al. 2012)



Iyyani et al. 2013

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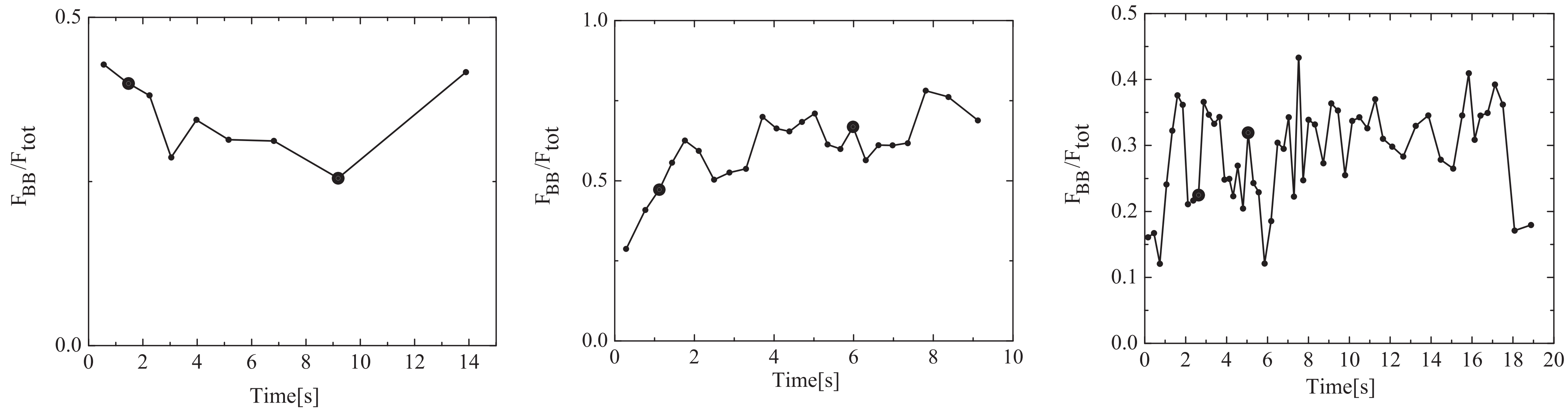

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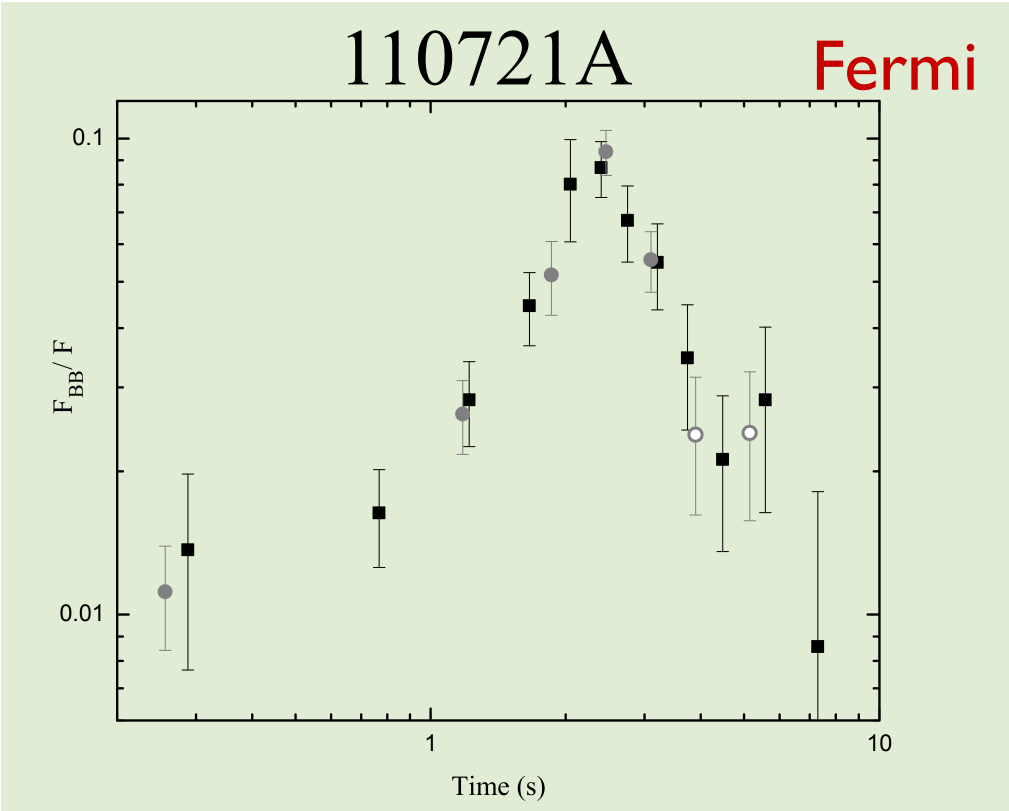
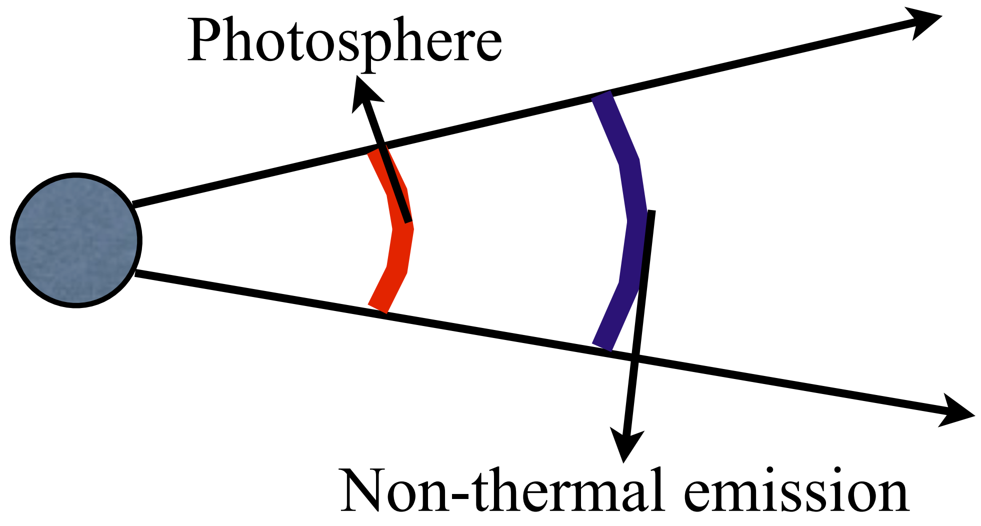
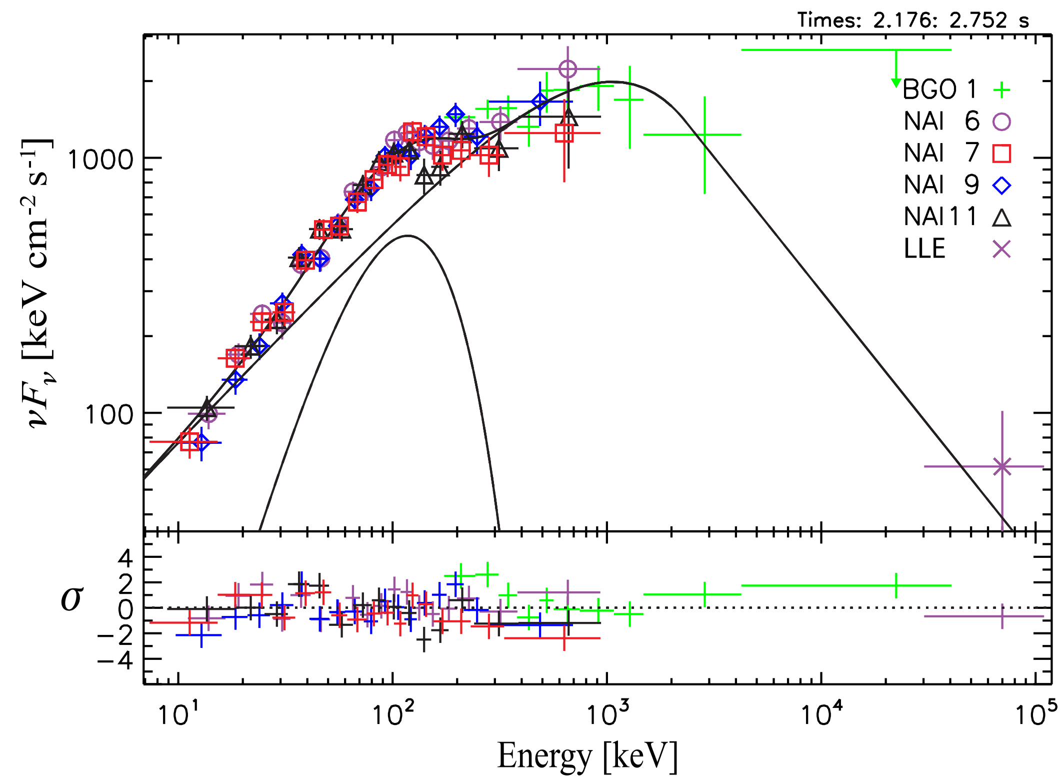


Iyyani et al. 2013

Photosphere model: 2 Emission zone - model





Photosphere
(No dissipation below) → Thermal component - Planck function (BB)

Above photosphere
(Optically thin) → Non-thermal component - Band function
synchrotron, ICMART...

2 zone emission, various realisations

If below the saturation radius - strong black body
If above saturation radius - adiabatic cooling

$$\left(\frac{r_{\rm ph}}{r_{\rm s}}\right)^{-2/3} = \frac{F_{\rm BB}}{F_{\rm NT}},$$

Assumptions

- The shortest observable variability time is given by $r_{ph}/2\Gamma c^2 \sim 0.2$ ms ($r_{ph} = 10^{12}$ cm & $\Gamma = 300$). But, the observed variation timescale is much longer than the time bins (0.1 s) used in spectral analysis. Light curve traces the activity of the central engine. In each time bin, the flow is assumed to be quasi- static.

- Flow is thermally and adiabatically accelerated beyond r_0: $r_{ph} > r_s$

- What we see is the baryonic photosphere (no subphotospheric dissipation, and no photon starvation).

- Emission is dominanted by the line-of-sight emission.

- Observed part of the flow is approximately spherical.

Using BB: Outflow parameters calculations

Translation of the observables to jet quantities
Pe'er, Ryde et al. (2007)

$$F \quad \Gamma$$
$$F_{BB} \longrightarrow r_{ph}$$
$$T \quad r_o \ (r_s)$$

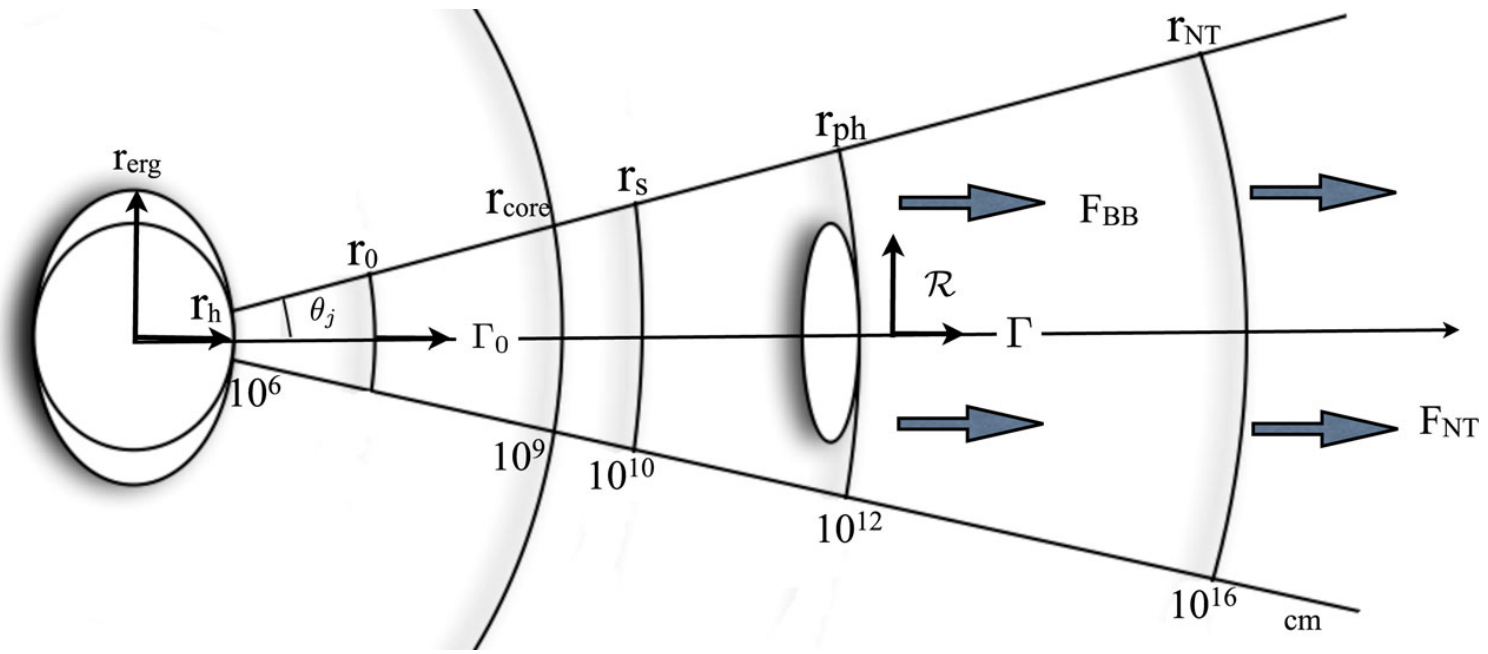
(Unknowns efficiencies, magnetisation, distance)

F = total observed flux
F_{BB} = BB flux
T = temperature

BB normalisation, $\mathcal{R} \equiv \left(\frac{F_{\rm BB}}{\sigma_{\rm SB} T^4} \right)^{1/2} \propto r_{\rm ph}/\,\Gamma$

Also depend on unknowns

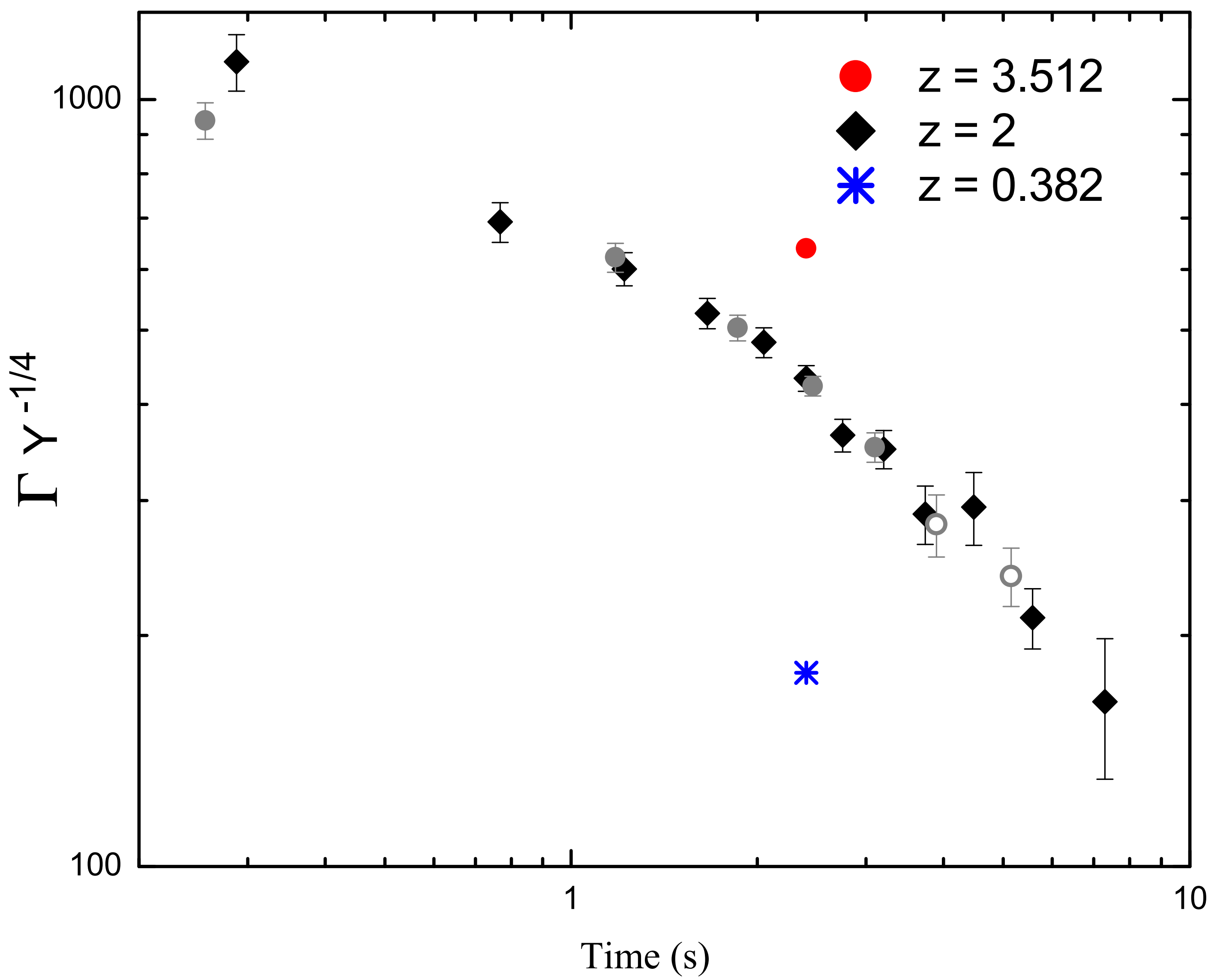
Y = inverse of the fraction of the total energy of the burst in observed γ- rays.
ε_{BB} = fraction of the fireball luminosity thermalised at r_0.



If the flow is magnetised: Weak dependences on the magnetisation parameter σ (Hascöet et al.2013).

Results: • Lorentz factor, Γ

$$\Gamma \propto (F/\mathcal{R})^{1/4} Y^{1/4}$$



Γ decreases monotonously with time

$\Gamma \sim 1000 \longrightarrow 100$

Implications

* Challenge for simplest internal shock model.

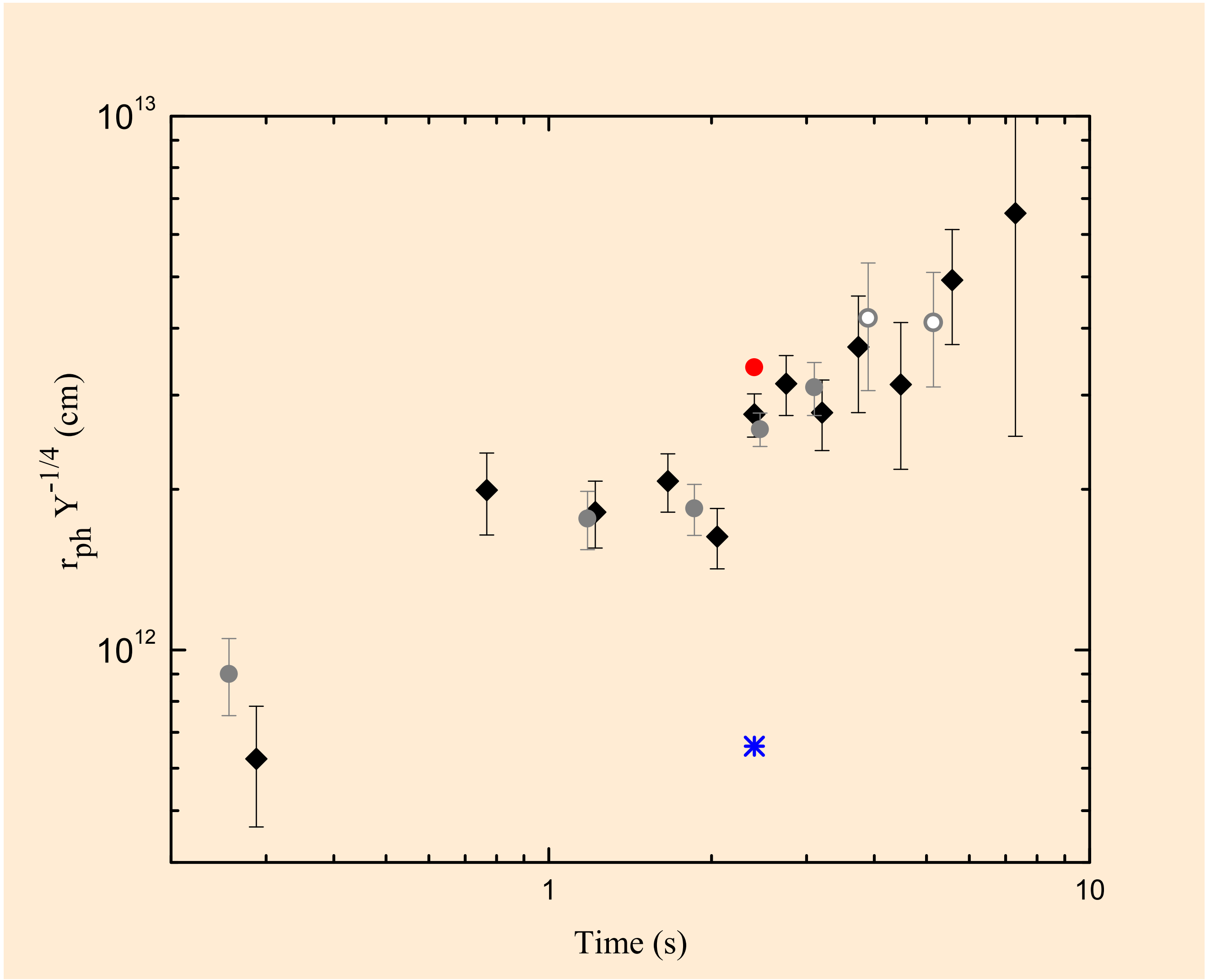
* Challenge for the magnetar model of GRB central engine.

$\mathcal{R}$

* Decreasing Γ : Increase in baryon pollution as accretion disk stabilises.

- # Photospheric radius, r_{ph}

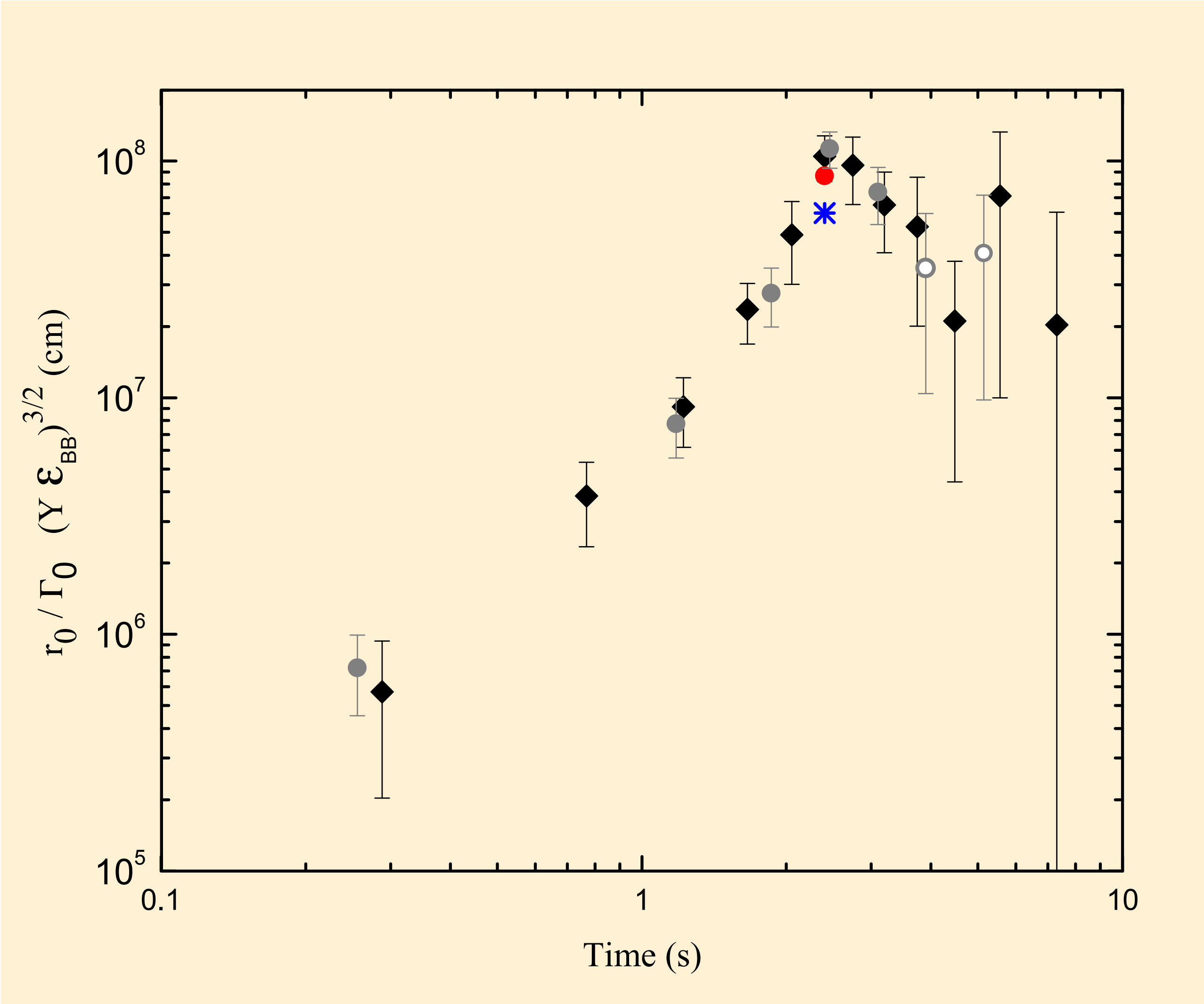
$$r_{\rm ph} \propto F^{1/4} \mathcal{R}^{3/4} Y^{1/4}$$



r_{ph} increases with time but moderate variation in comparison to other parameters

• Nozzle radius, r_0

$$\frac{r_0}{\Gamma_0} = 10^8\mathrm{cm}\left(\frac{\mathcal{R}}{10^{-18}}\right)\left(\frac{F_{\rm BB}/F}{0.07}\right)^{3/2}(\epsilon_{\rm BB}\,Y)^{-3/2}.$$



At t = 2.6 s the value reaches its peak.

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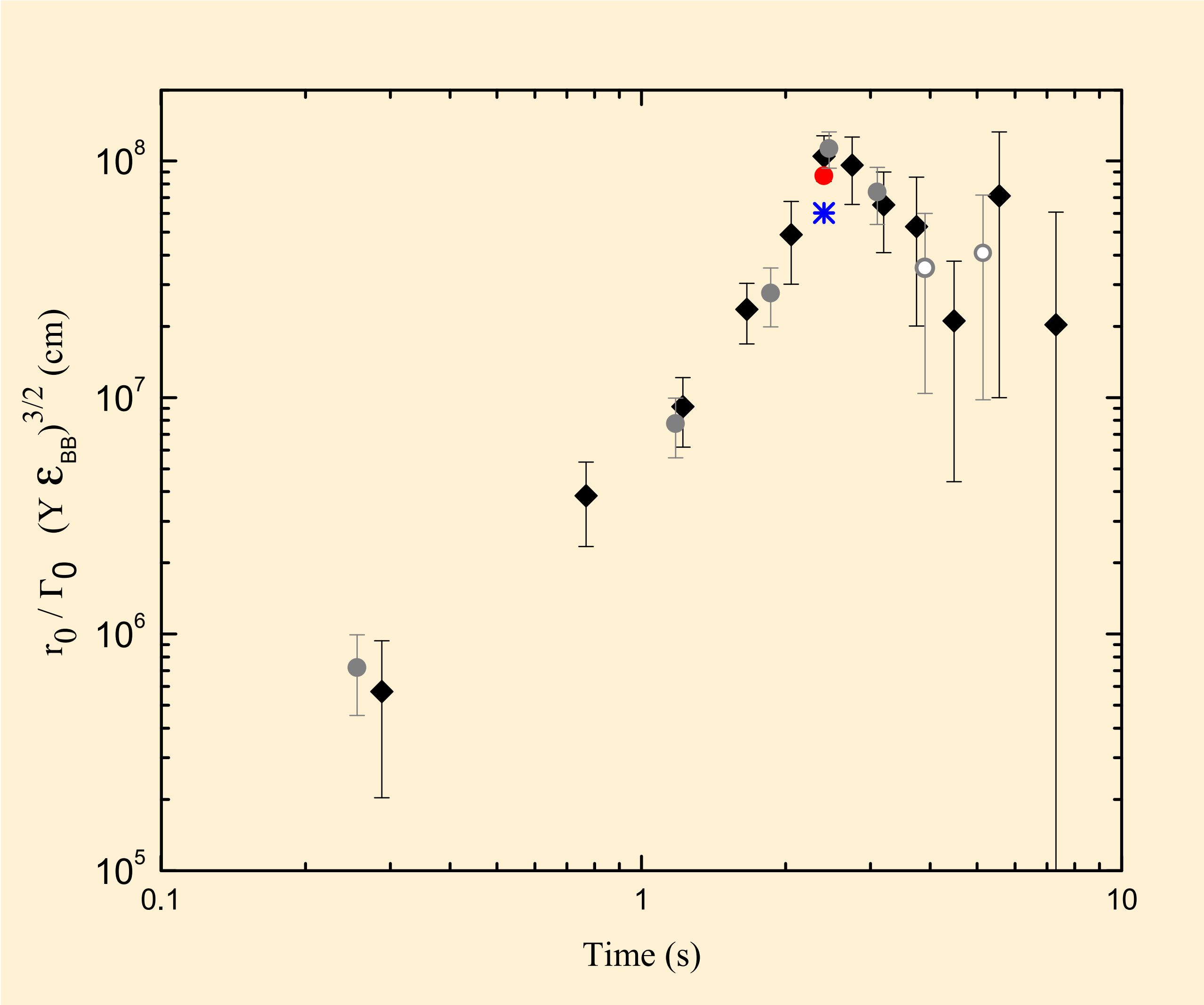

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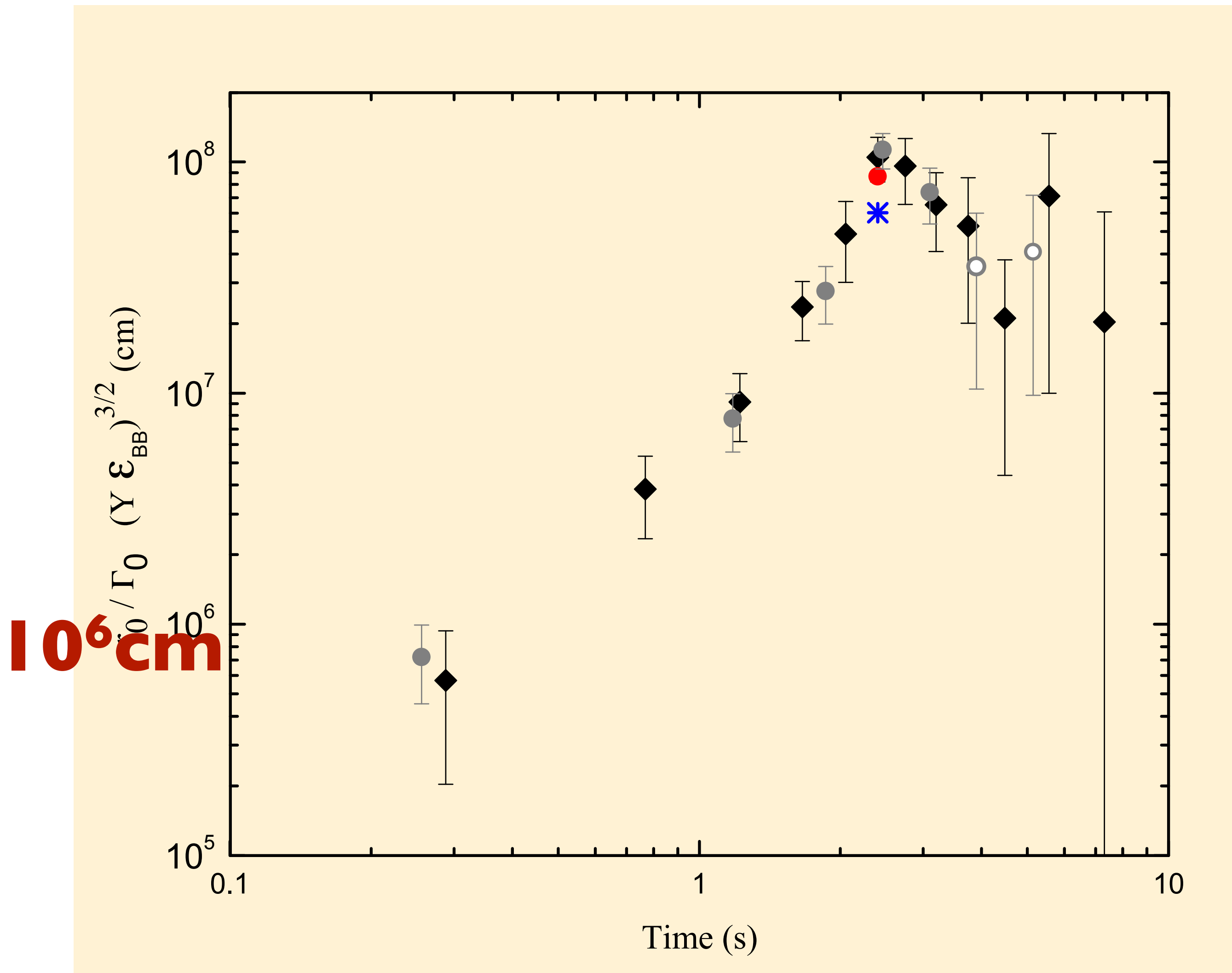

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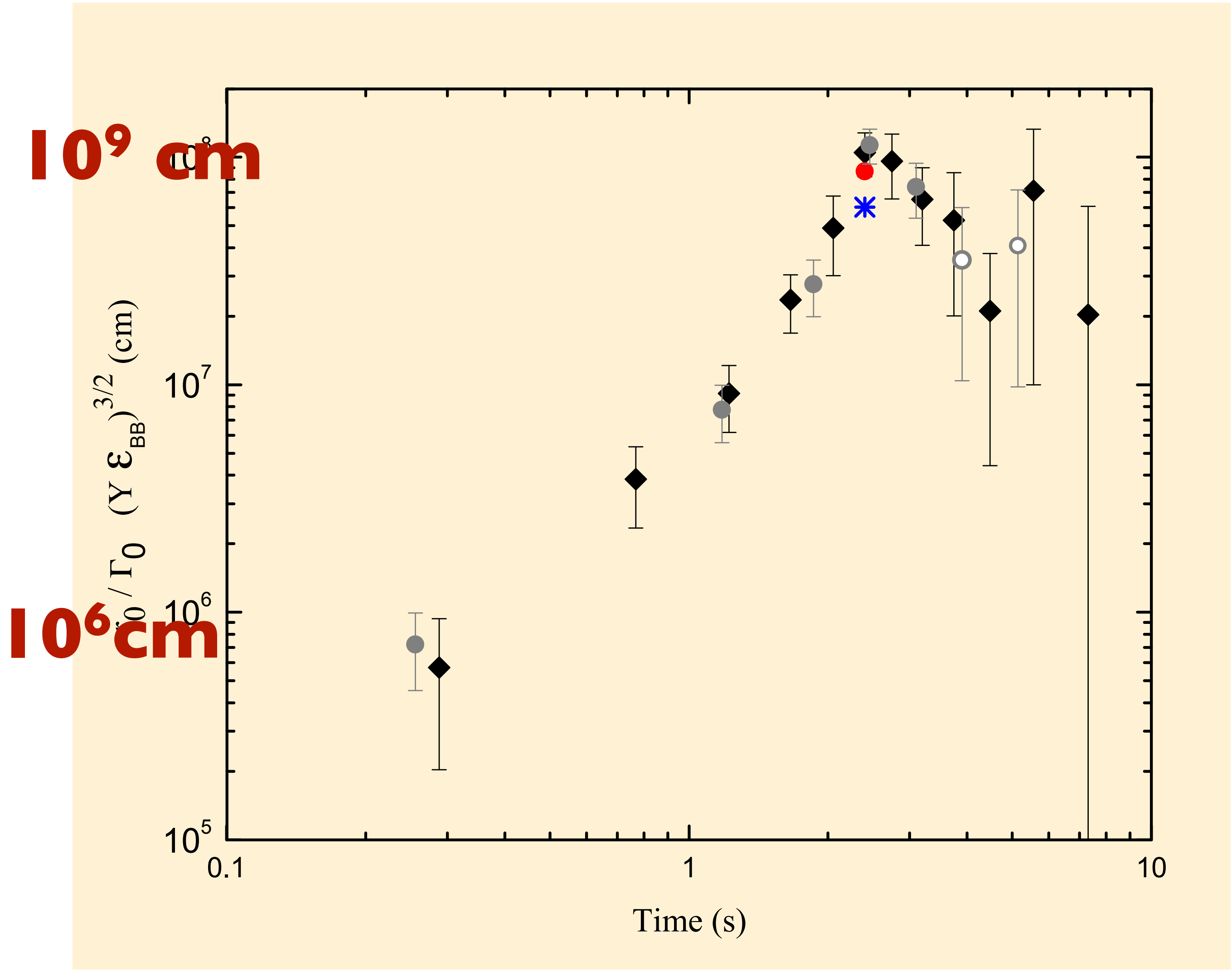

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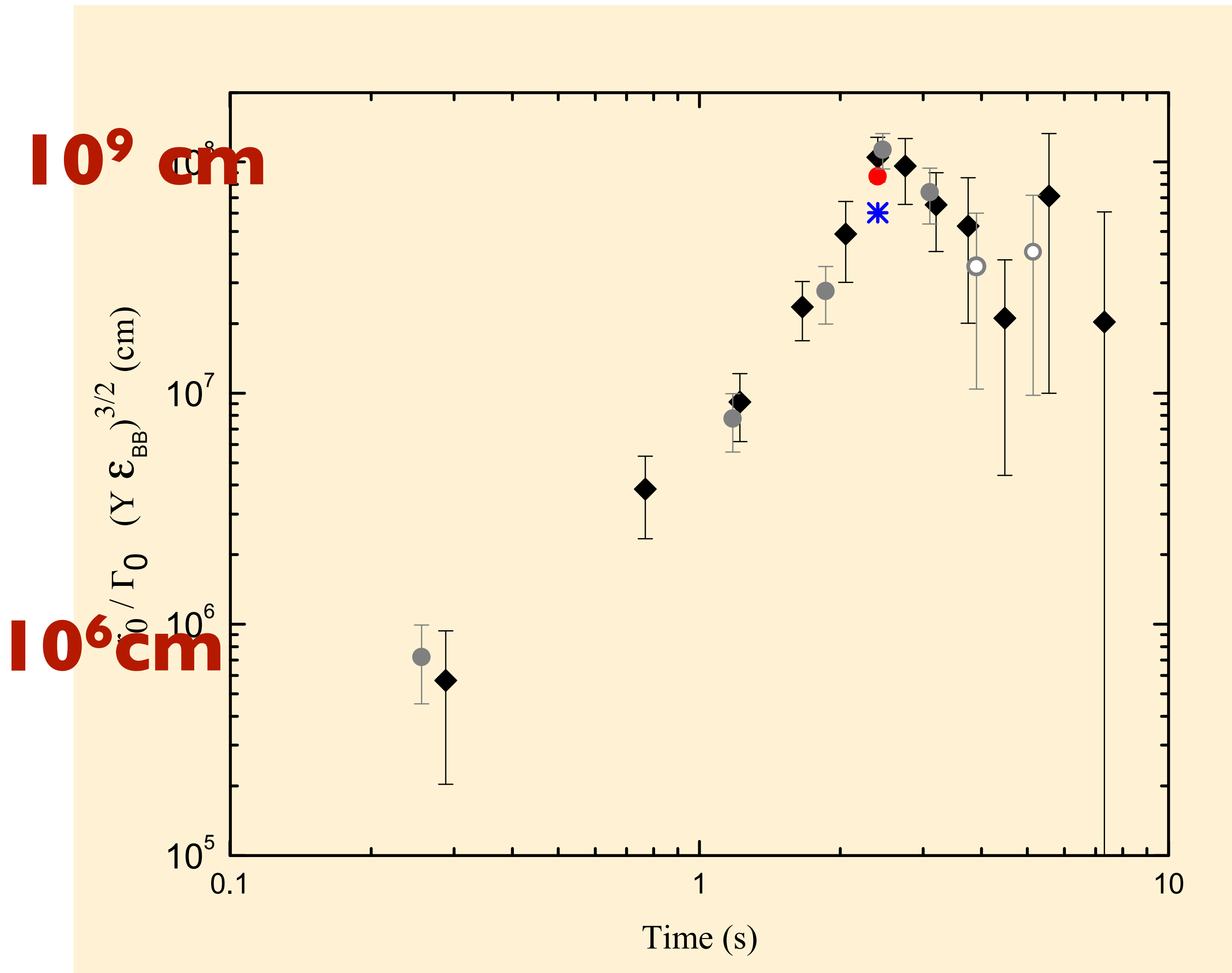

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The core of
the Wolf- Rayet progenitor star
(Woosley & Weaver 1995,Thompson et al. 2007).

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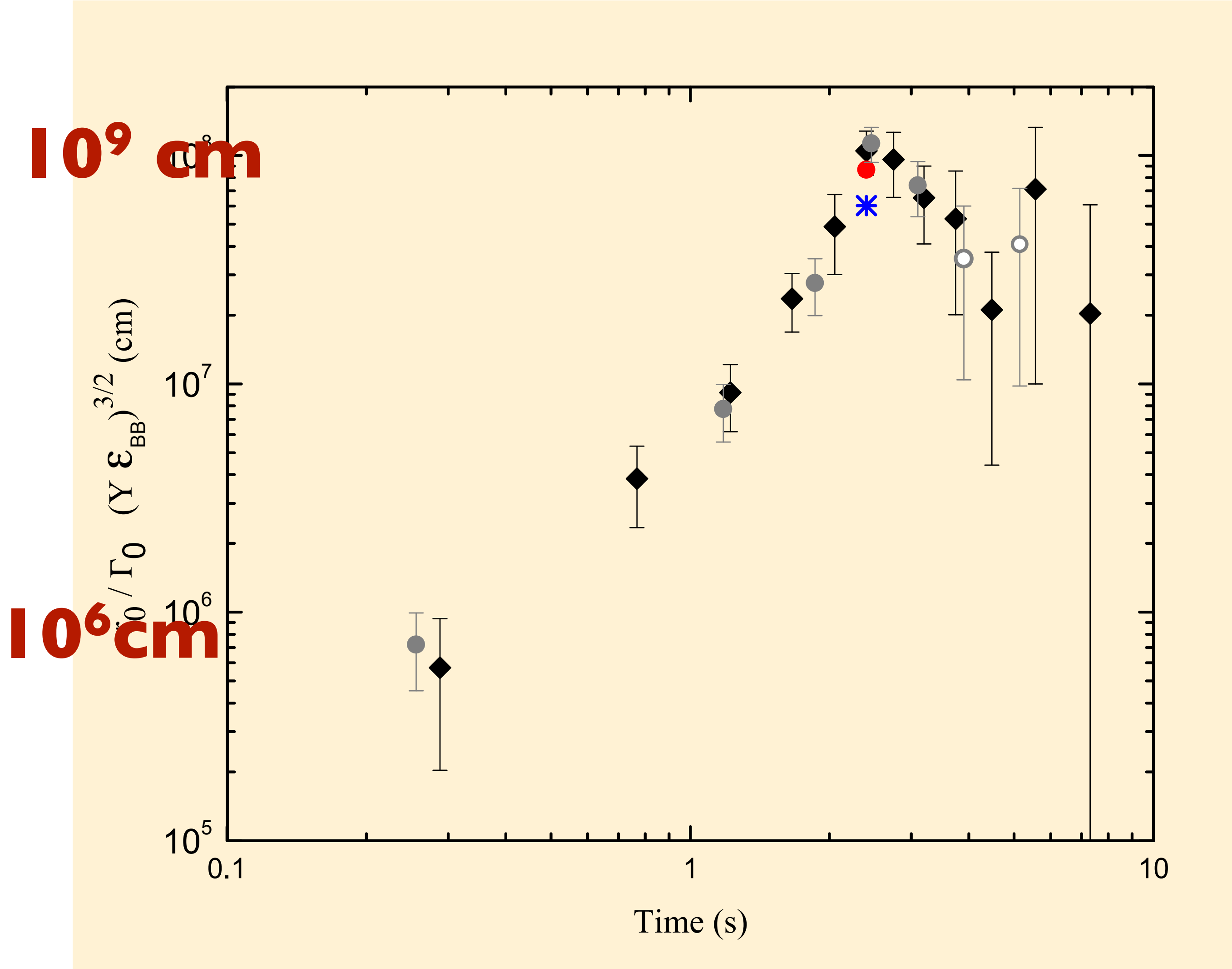

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The core of
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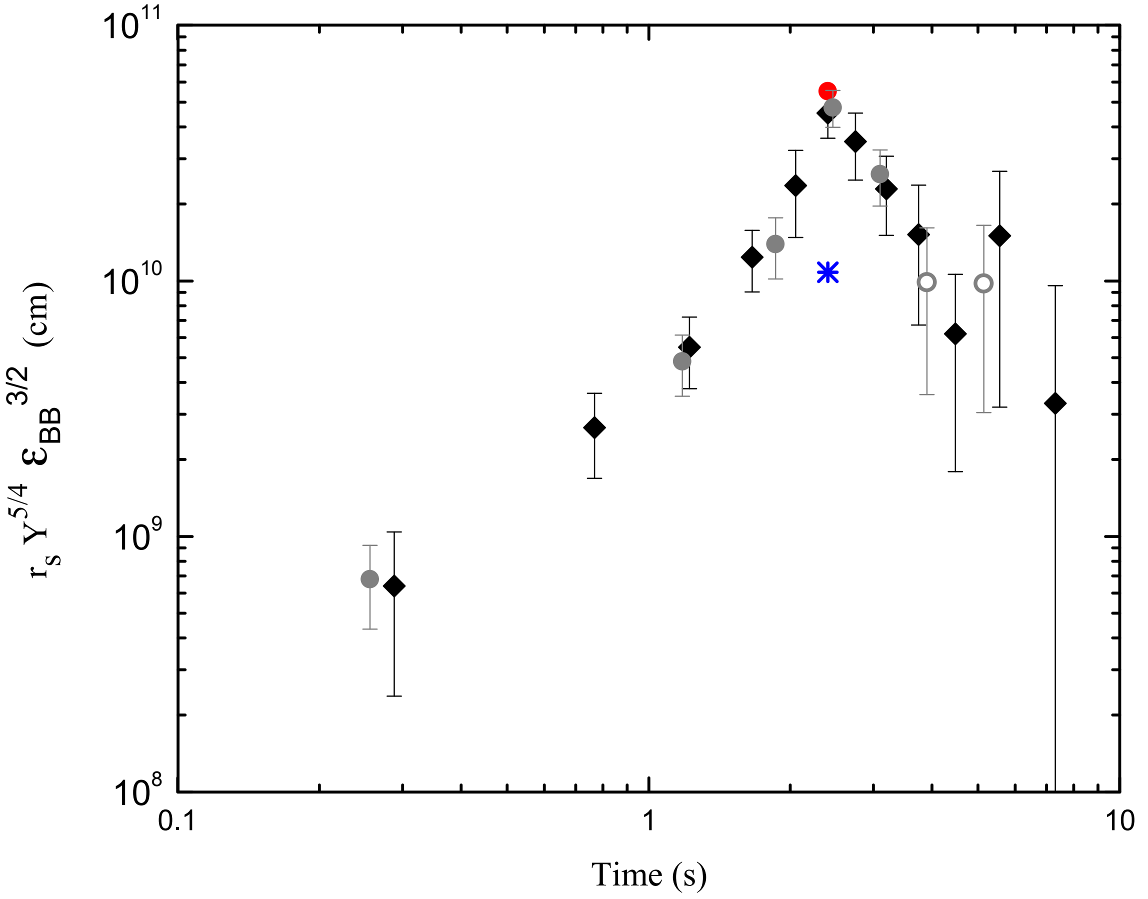
(Woosley & Weaver 1995,Thompson et al. 2007).

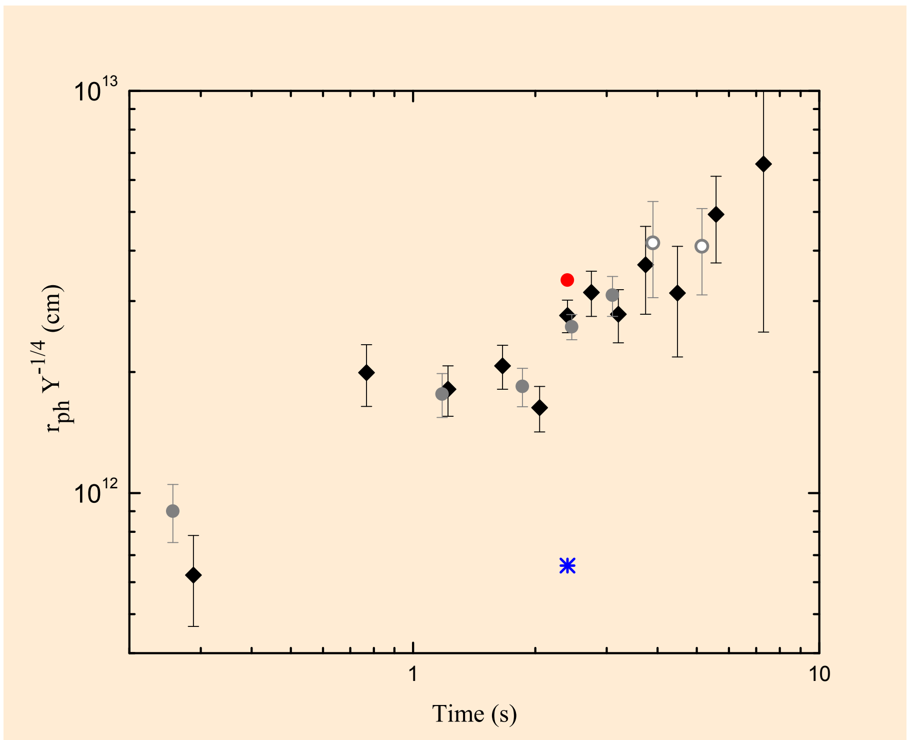
As the jet drills through the progenitor star oblique shocks prevents it from accelerating strongly

• Saturation radius, r_s

$$r_s = \Gamma\, r_0$$



Photospheric radius, r_{ph}



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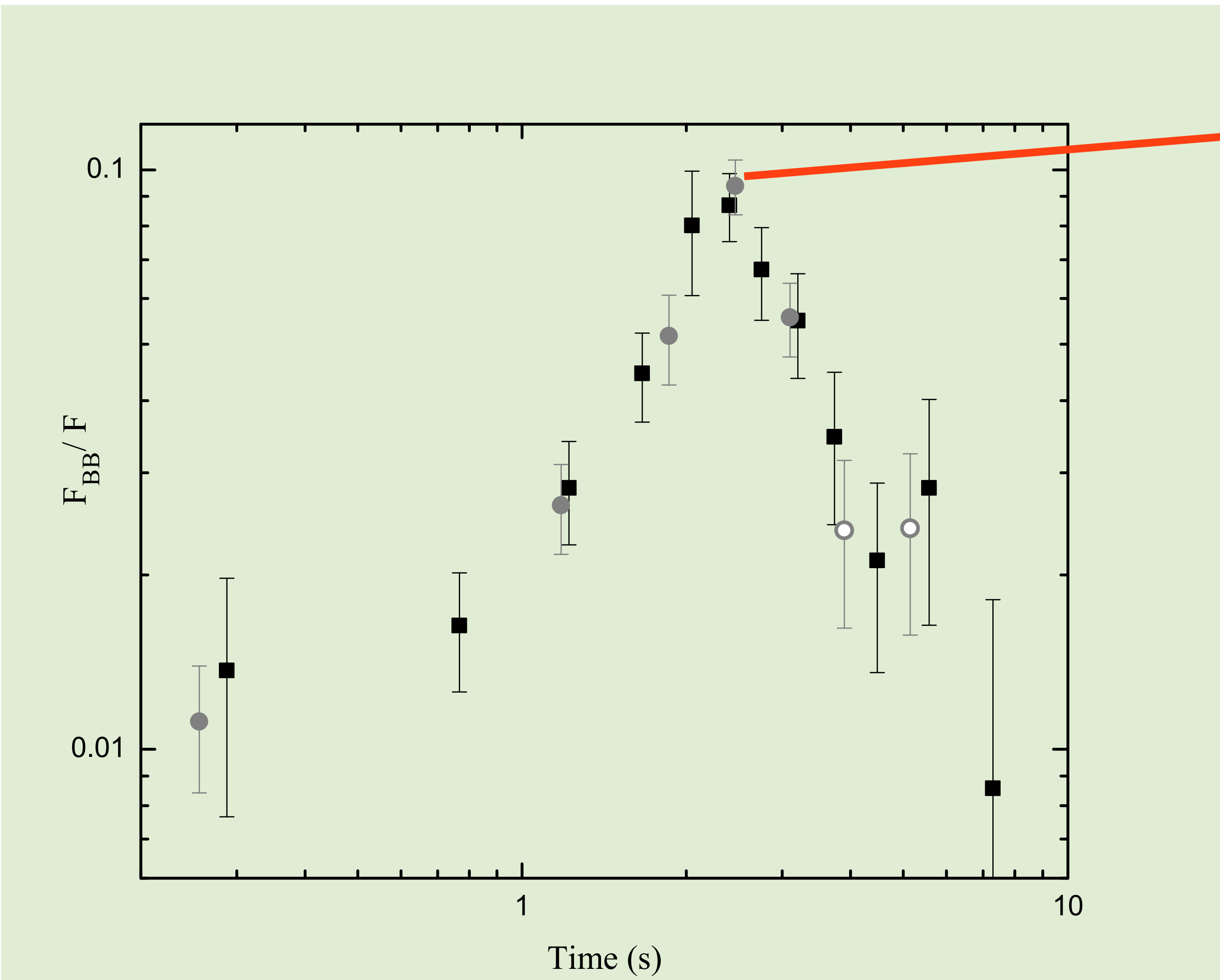
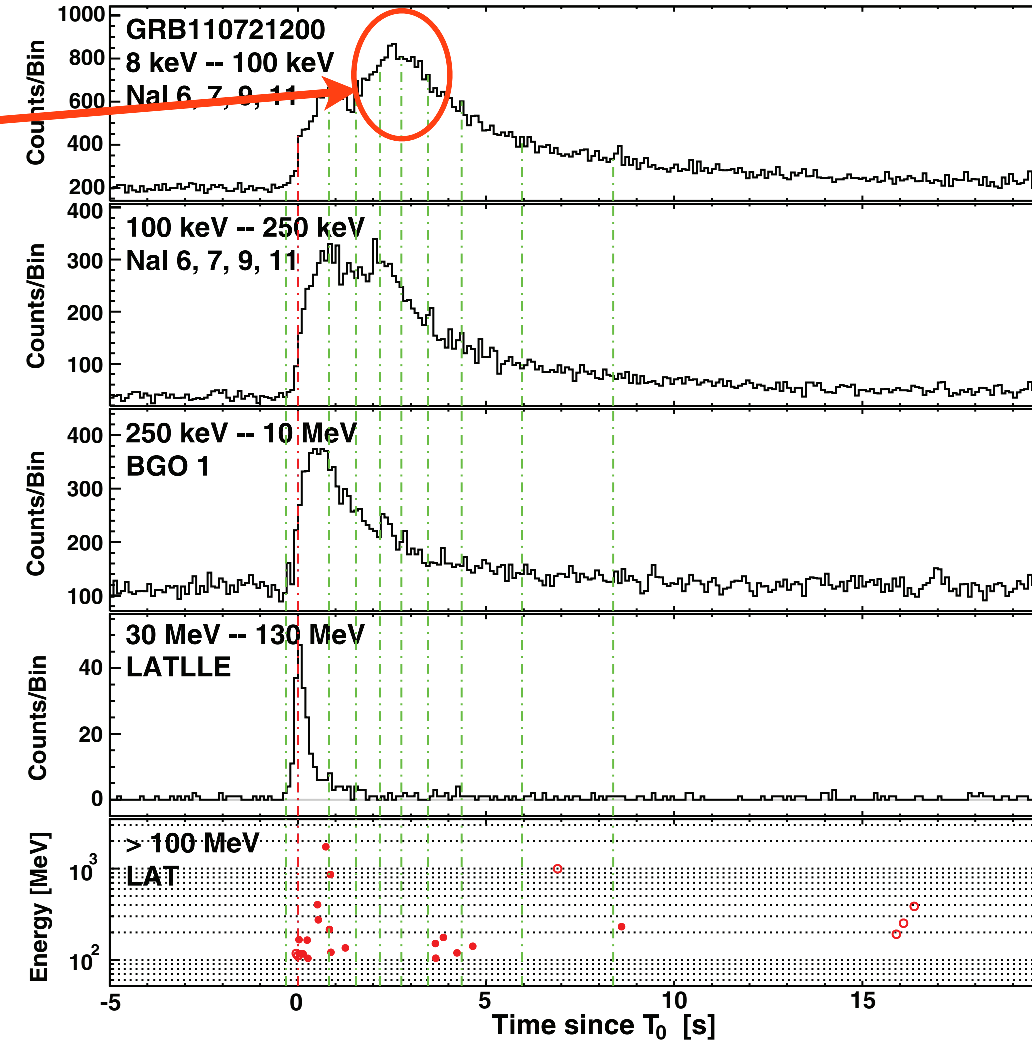


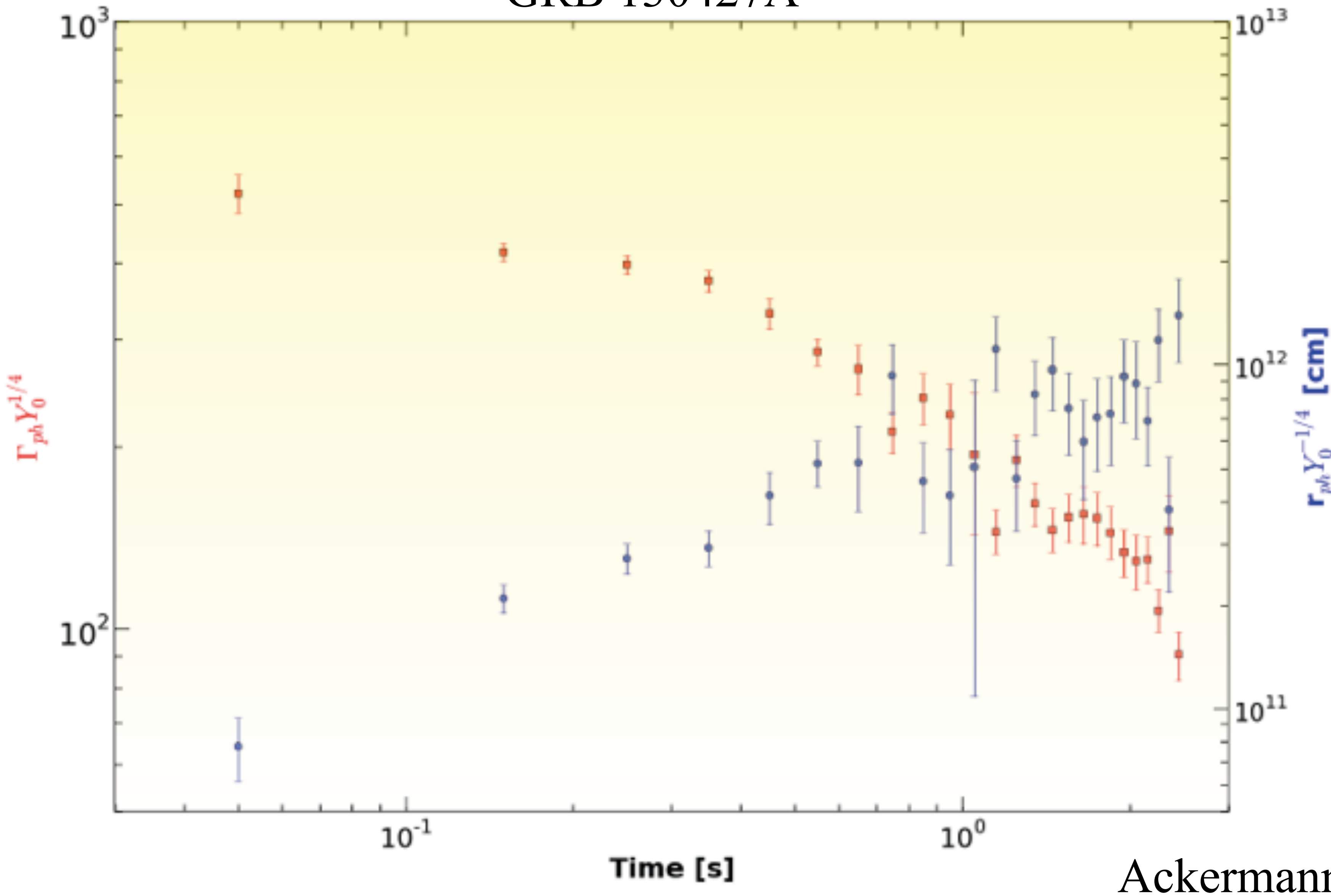


Axelsson et al.2012

Adiabatic loss is minimum when r_s is closest to r_{ph} and F_{BB} becomes dominant resulting in a thermal pulse.

More Fermi bursts:

GRB 130427A

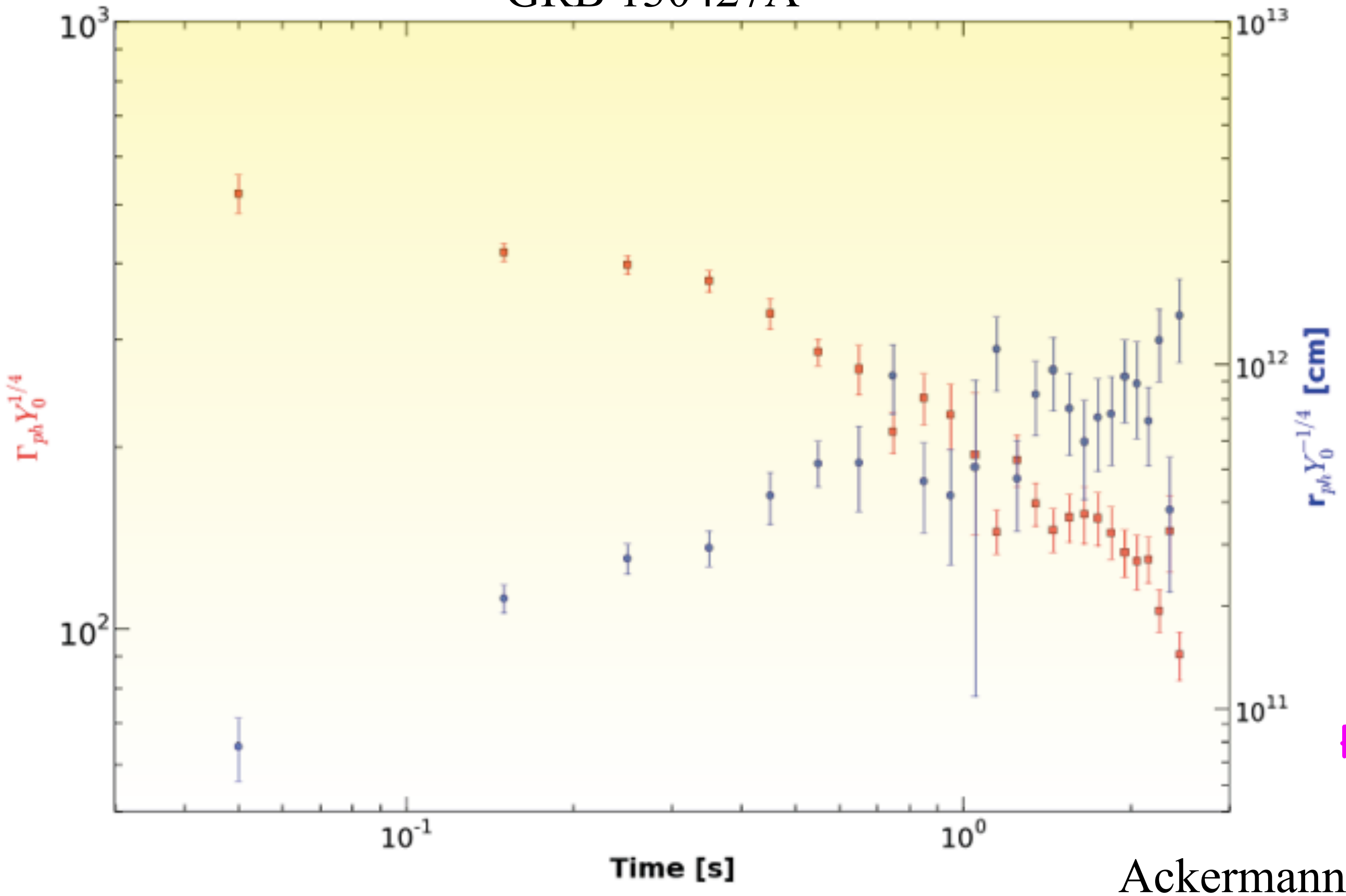


Preece's talk

Ackermann et al. 2013

More Fermi bursts:

GRB 130427A



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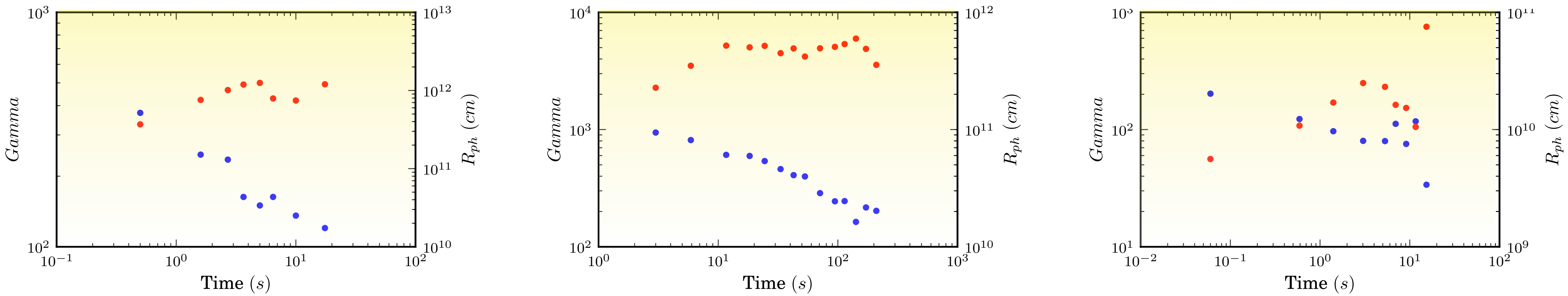
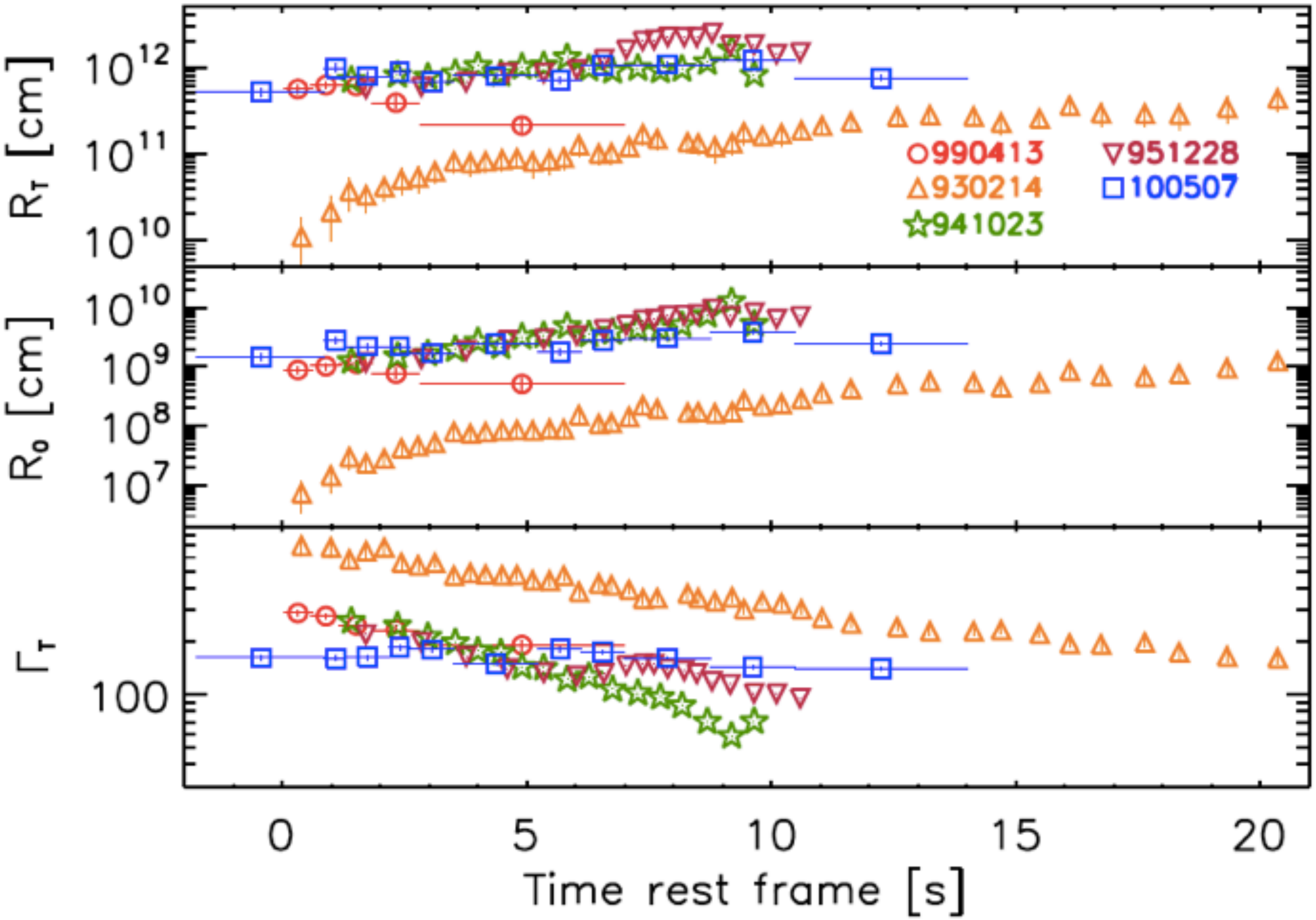


Burgess in prep. (2013)

Jet parameters for BATSE bursts and for GRB 100507



r_o generally increases and lies in between 10^7 and 10^{10}cm

Γ typically decreases

Ghirlanda et al. 2013

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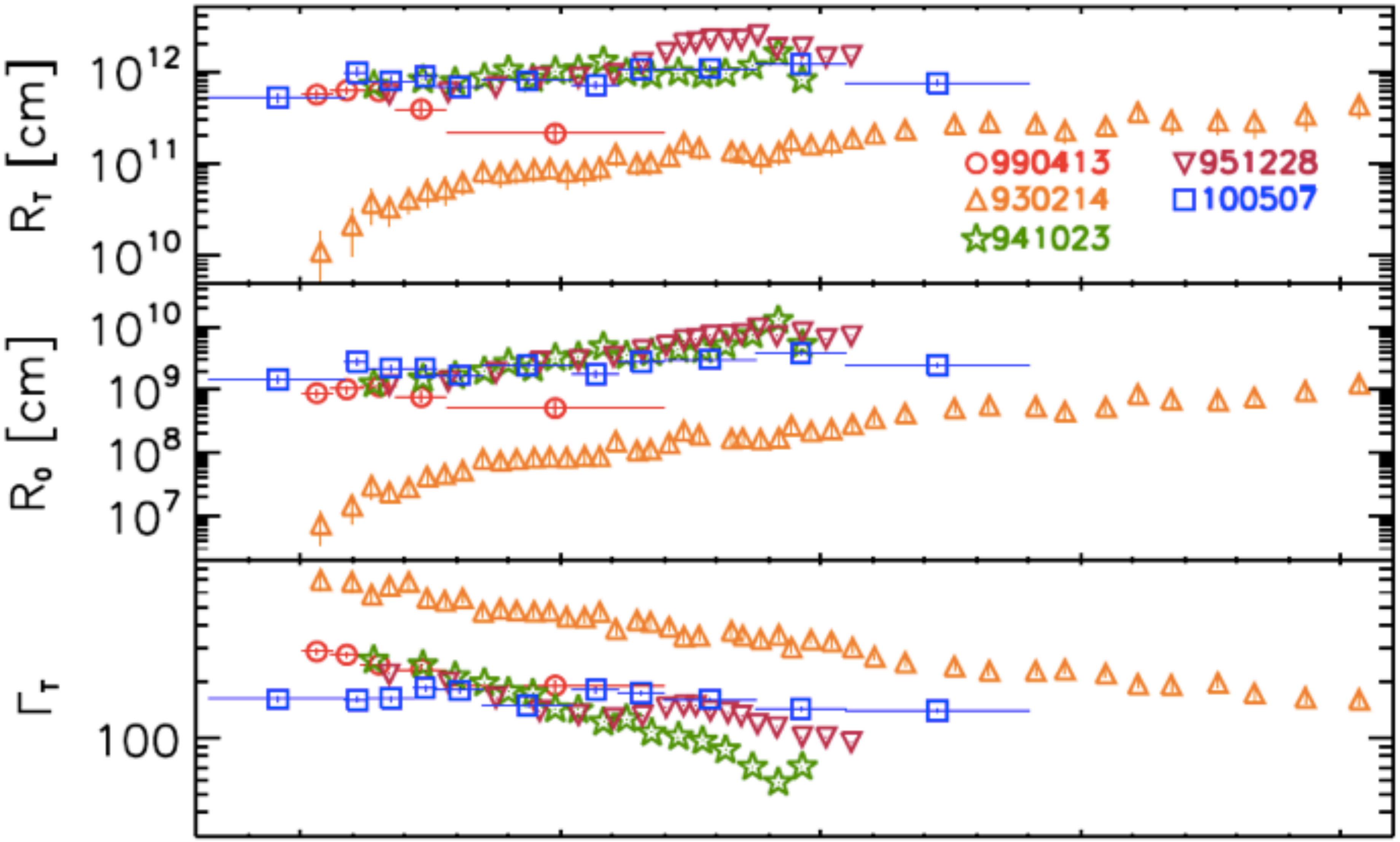

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Ghirlanda et al. 2013

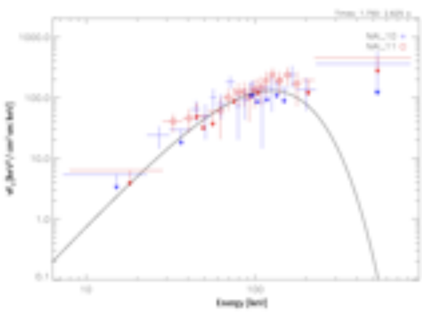
- Alternative interpretations:
  (i) Varying efficiency
  (ii) High latitude emission
  (iii) Varying photon starvation

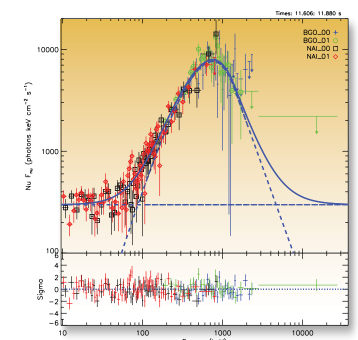
Conlusions

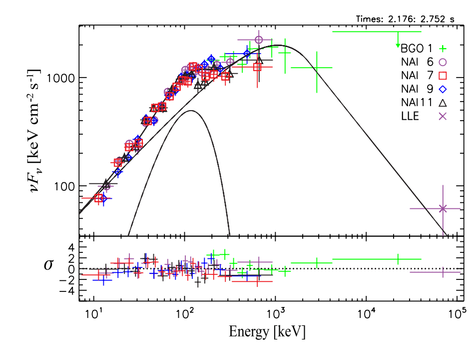
1. *Band function is not the universal spectral shape.* More complex spectra are needed with multiple components: photospheric emission, cut offs, and additional power laws

2. *Observational appearance of the photosphere:*

Planck spectrum - Broadened functions - BB+nonthermal







3. *GRB jet properties are variable.* Over individual pulses Γ decreases, while r_0, and r_{sat} increase. This causes the F_{BB} and F_{tot} to have different temporal profiles