Signature of the Photosphere in the GRB Prompt Emission

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Outline

- **Background**

- **Thermal and non-thermal components**

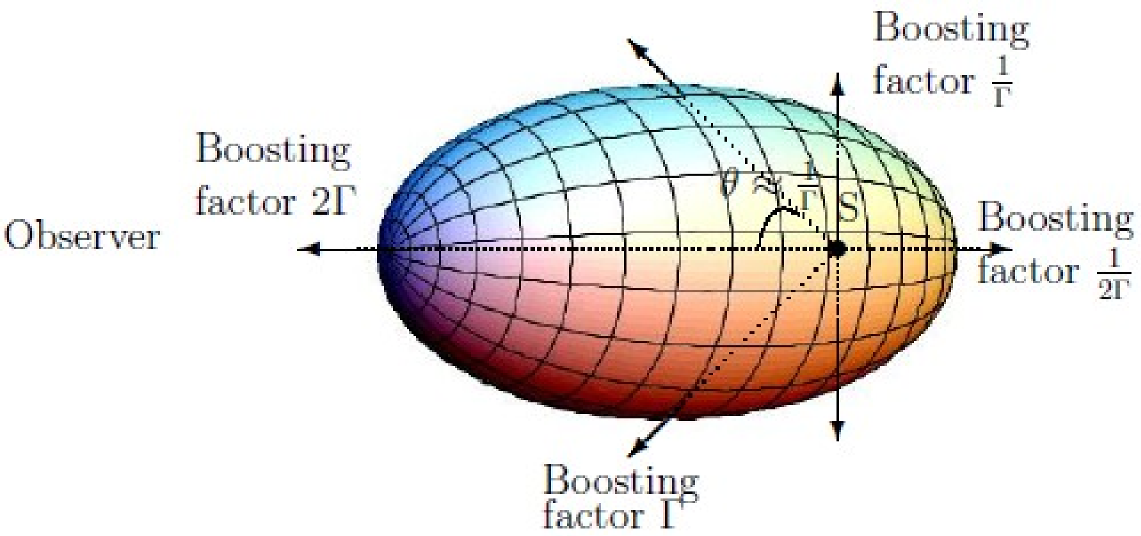
  - 2BBPL model: 090902B and 081221
  - Parametrized joint fit: 081221, 090618
  - A Spine-sheath Jet
  - Independent Detection
  - Predicting GeV emission

- **Conclusions and future works**

The Fireball Model

- Goodman (1986), Paczynski (1986) gave standard model even before the BATSE was launched

- If a high energy density is created at a point of space it will drive e-p plasma and radiation.

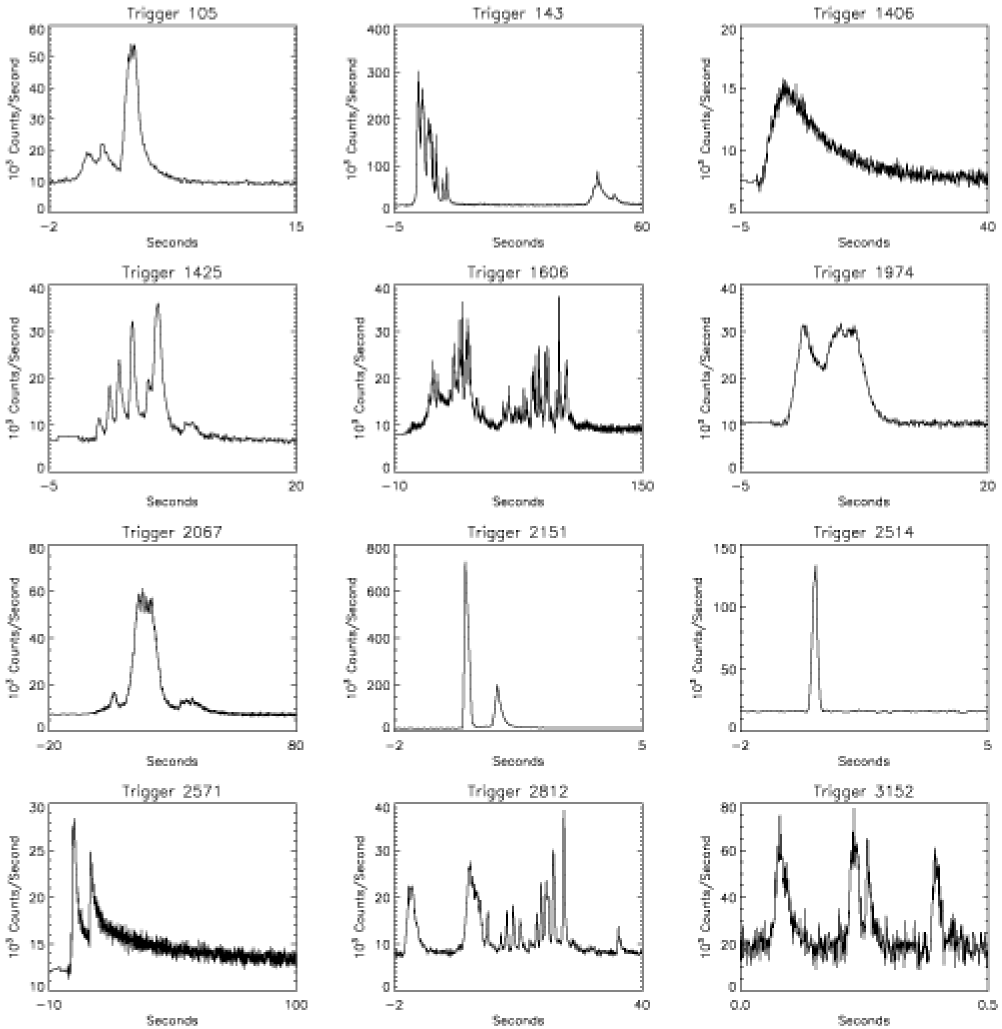


- The radiation will be thermalized before reaching the photosphere. Hence, the **spectrum** should be **blackbody** like. There will be boosting by Lorentz factor towards the observer, and the temperature should decrease due to adiabatic expansion

- The **light curve** is predicted as a simple **pulse**

Light Curve and Spectrum

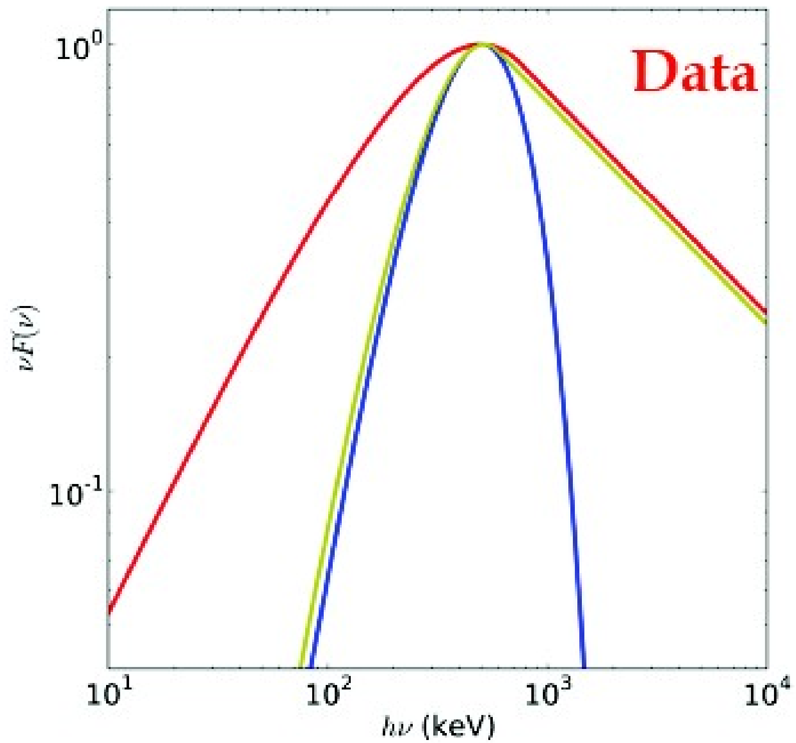
- **The zoo of GRB Light curves**



Credit: J.T. Bonnell (NASA/GSFC)

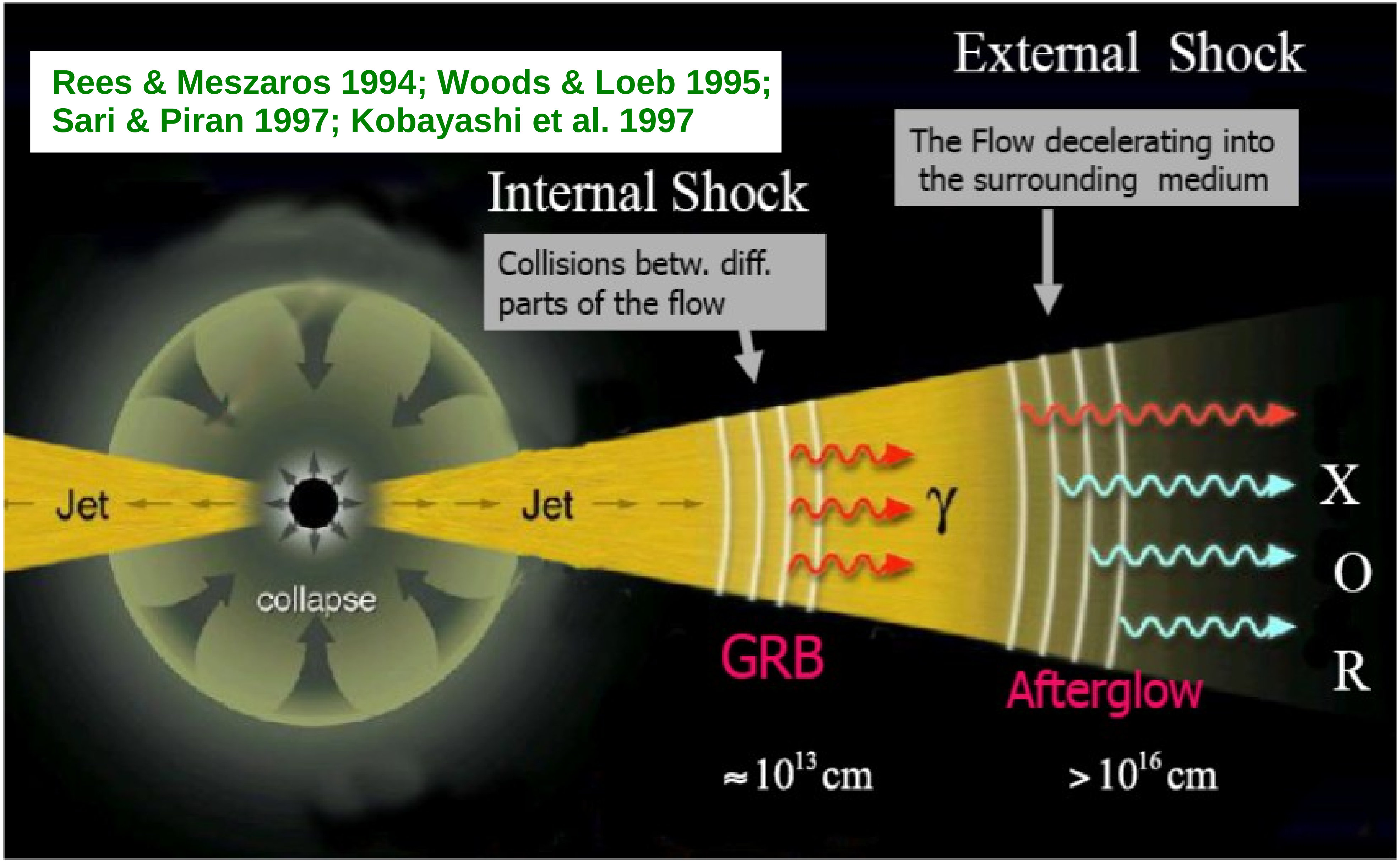
- **Single variant of spectrum**

Lazzati, GRB conference 2012, Munich



Blue: Blackbody (BB)
Green: Inverse Compton (IC)
Red: Data

Internal-External Shock

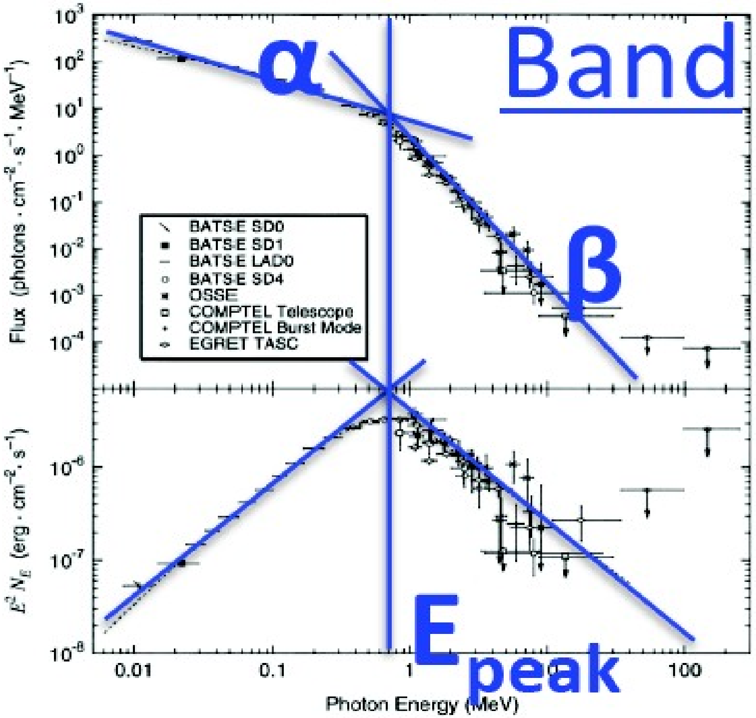


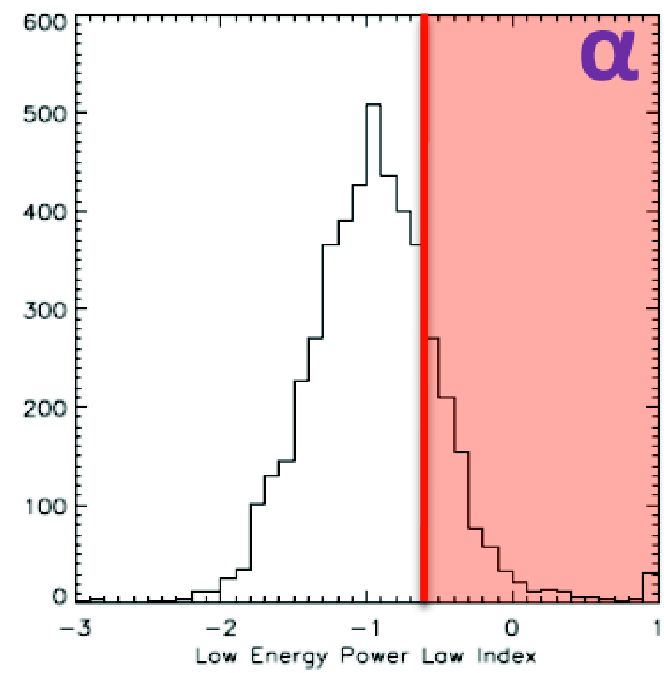
Band Model

- The internal shock produces relativistic electrons, which in their rest frame produce **synchrotron** emission. This model is phenomenologically represented by Band model --- two smoothly joined power-laws.

Four-parameter model of Band (Band et al. 1993)

$$I(E) = \begin{cases} A_b \left[\frac{E}{100}\right]^{\alpha} exp\left[\frac{-(2+\alpha)E}{E_{peak}}\right] \\ \text{if } E \leq [(\alpha-\beta)/(2+\alpha)]E_{peak} \\ \\ A_b \left[\frac{E}{100}\right]^{\beta} exp[\beta-\alpha]\left[\frac{(\alpha-\beta)E_{peak}}{100(2+\alpha)}\right]^{(\alpha-\beta)} \\ \text{otherwise} \end{cases}$$



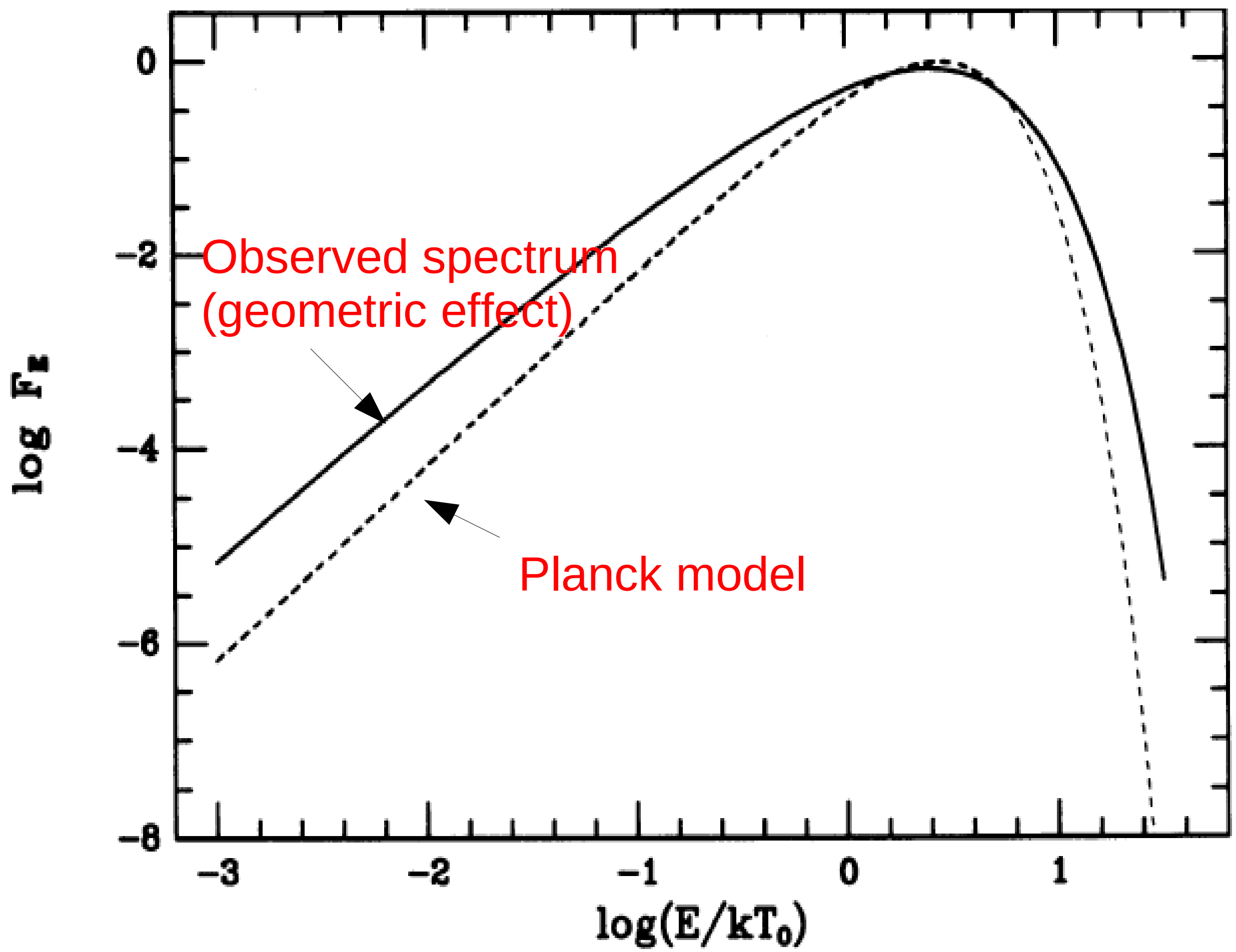


Issues in the Synchrotron Model

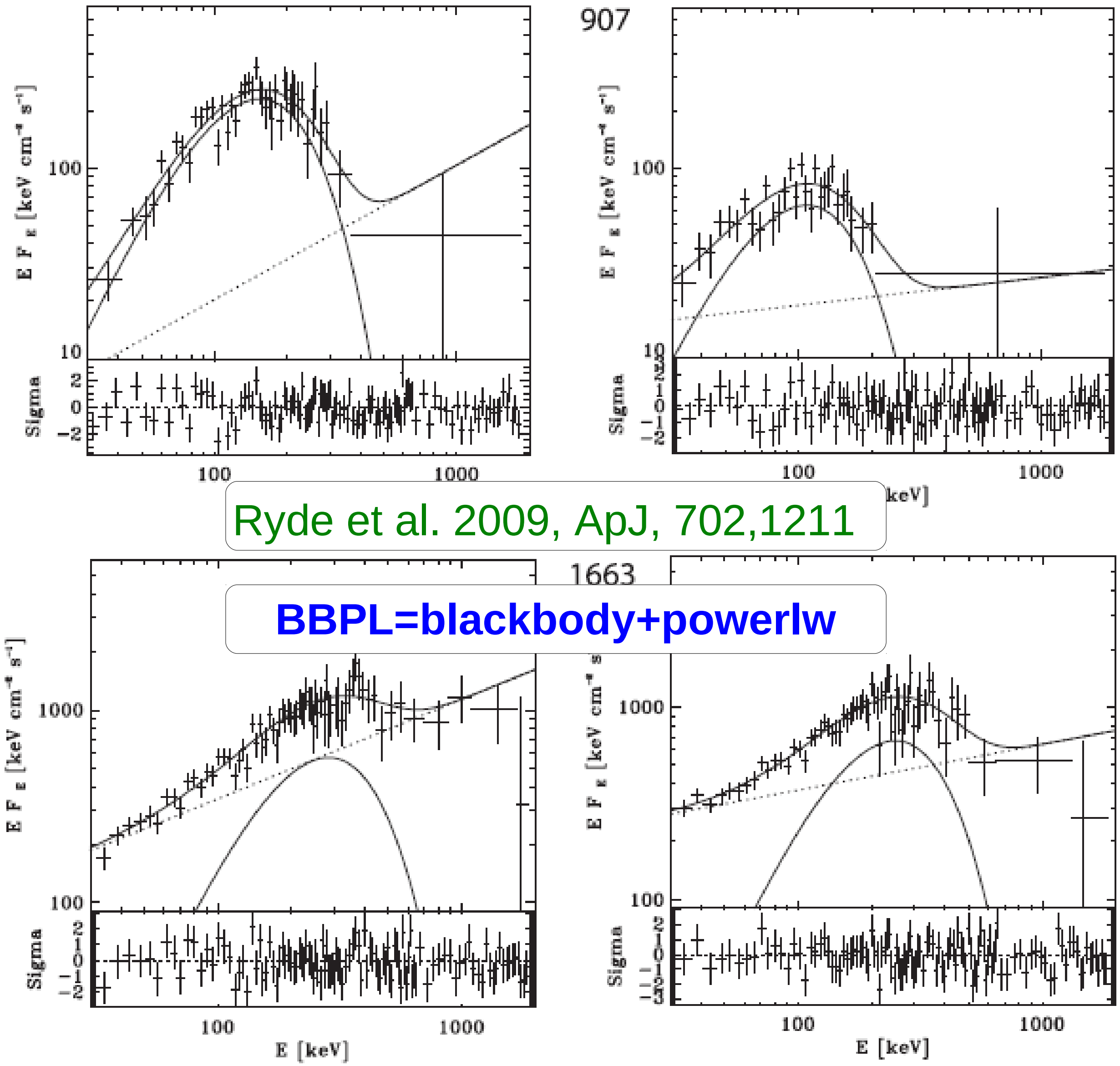
- Band model is a phenomenological model.
- Low energy index crosses the *"line of death"*
- The actual spectrum can be more complicated.
- IS model have its own problems: (i) efficiency is at most 20%, (ii) the situation of inner shell moving faster than the outer one is unstable (Waxman & Piran 1994, ApJL, 433, 85)

Back to Blackbody ?

- **Good news:** There are provisions in the original fireball model
- Once the photons go into the optically thin region, they are free to escape. With a reasonable guess work and assuming very high Lorentz factor, Goodman (1986) suggested broadening of the Planck spectrum
- But, this is still far from the actual observation

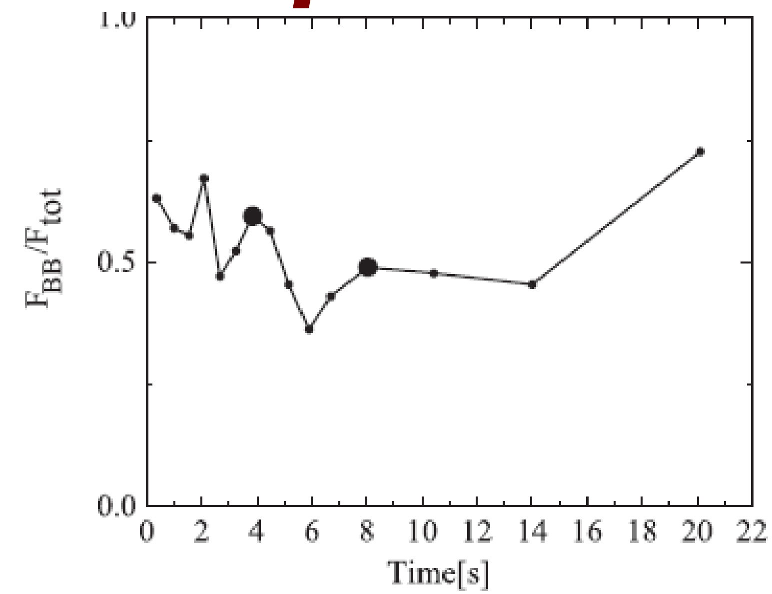


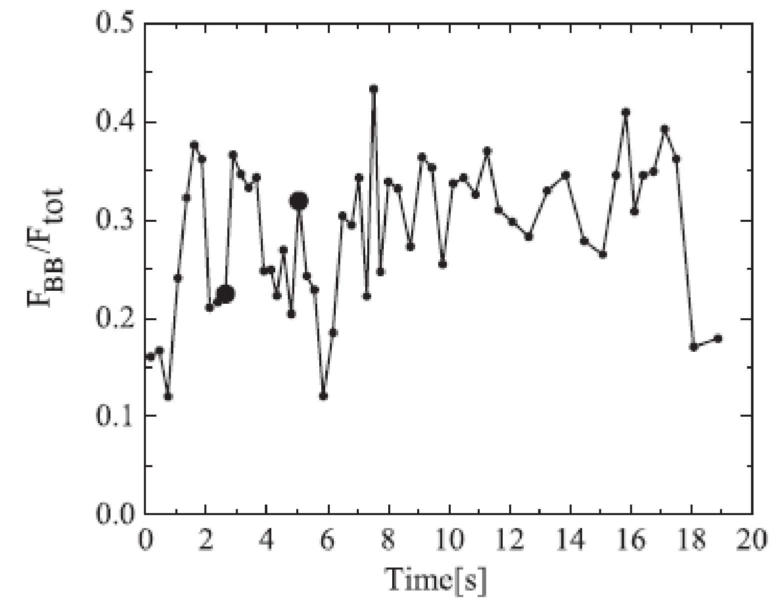
Time-resolved Spectrum



Ryde et al. 2009, ApJ, 702,1211

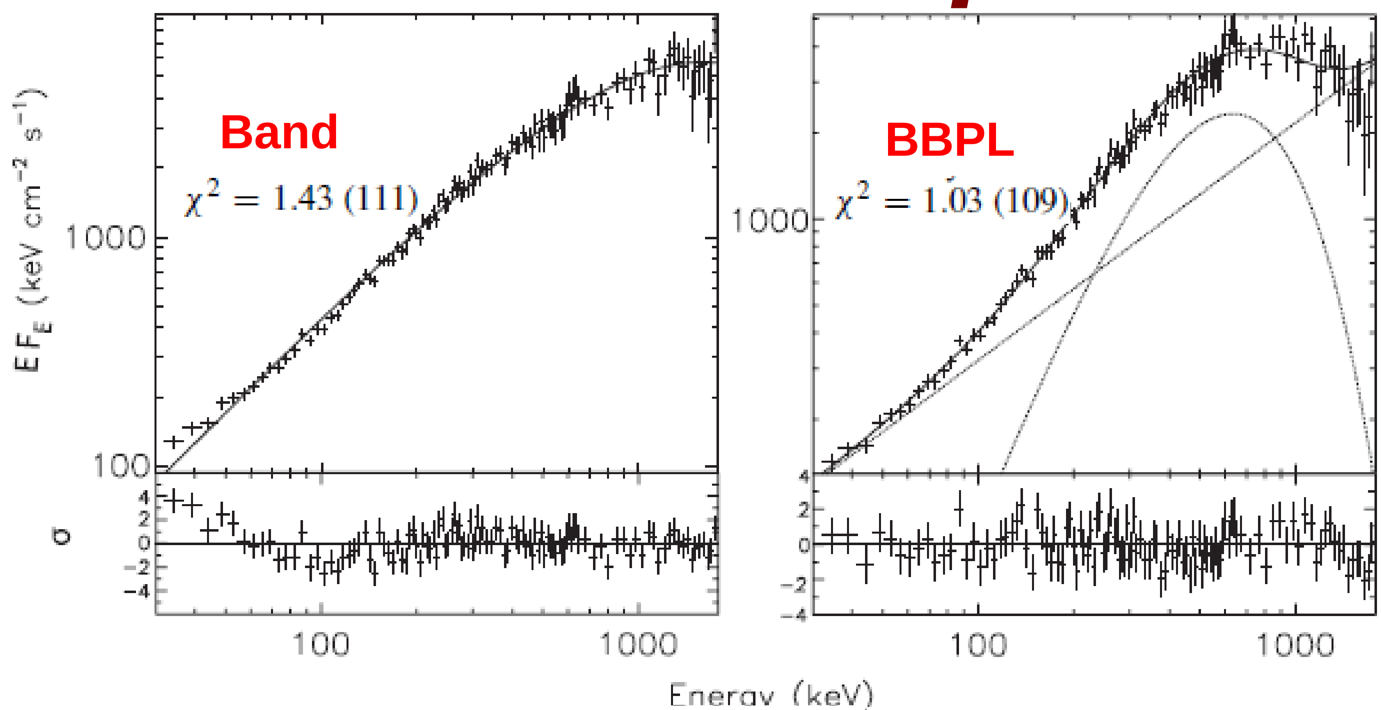
BBPL=blackbody+powerlw

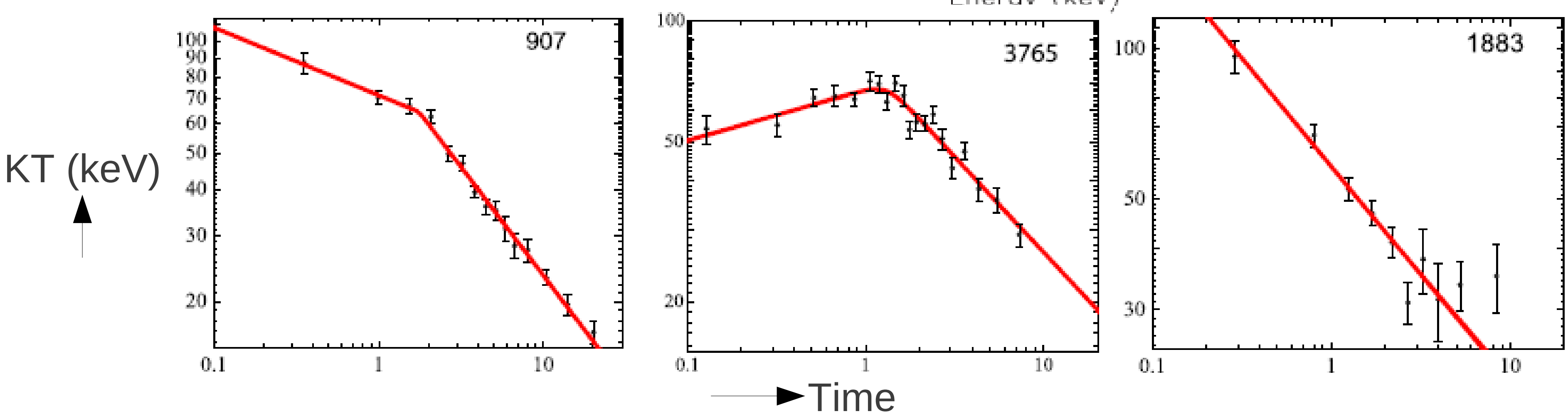




Time-resolved Spectrum

- BBPL sometimes is even better than Band model
- The kT evolves with time. This can be explained by the standard fireball model





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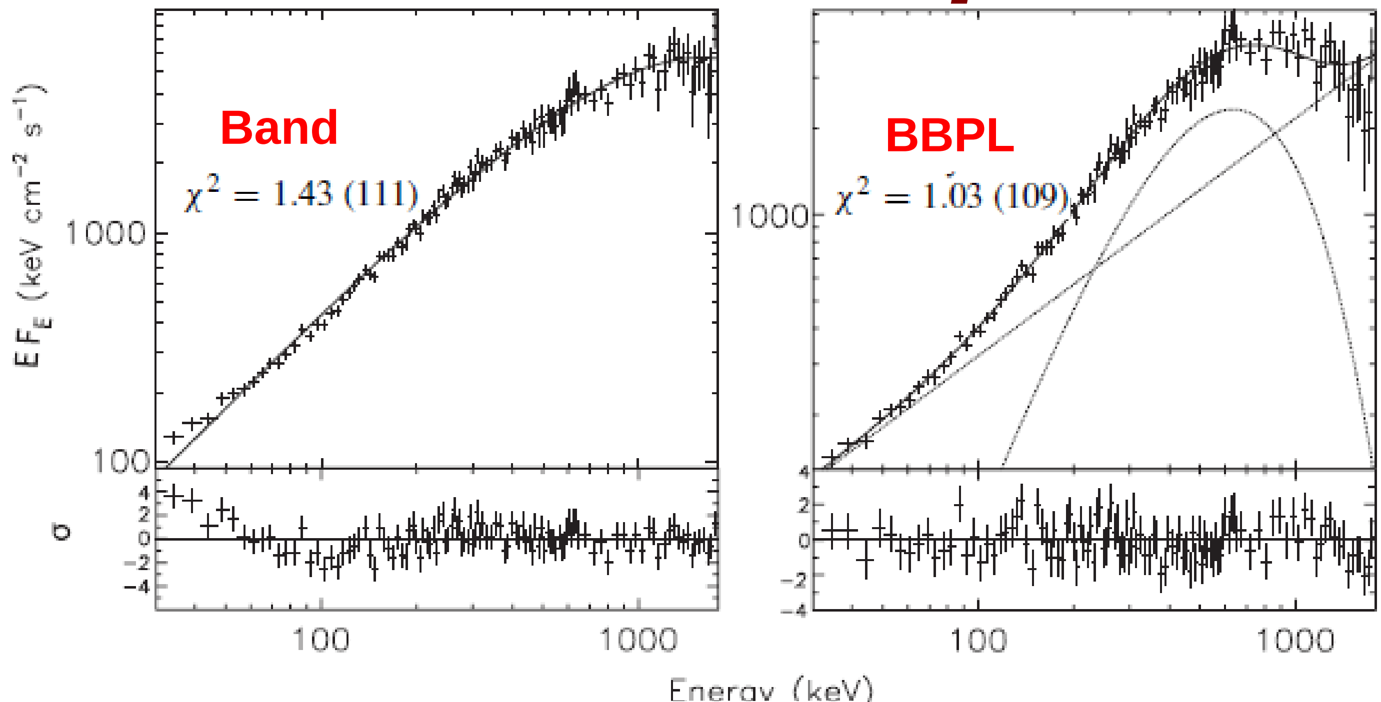
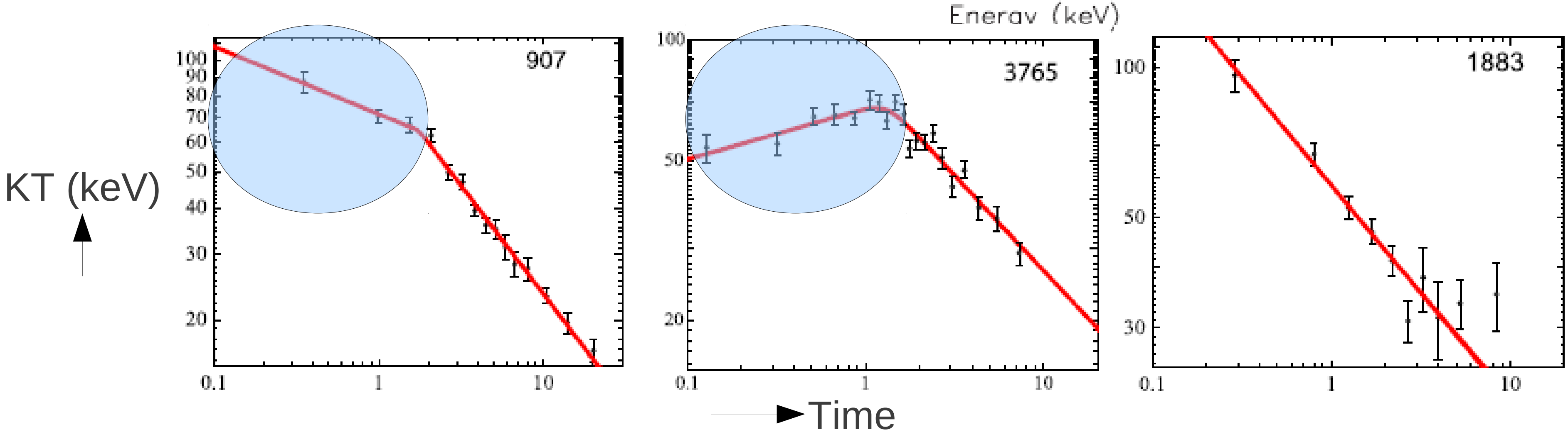
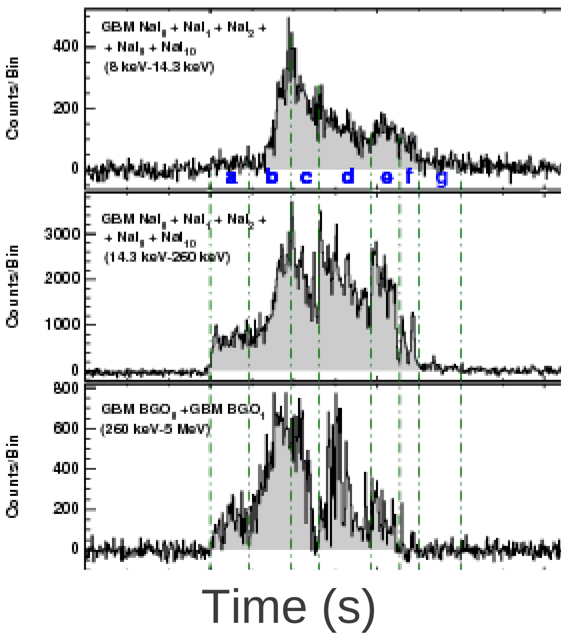
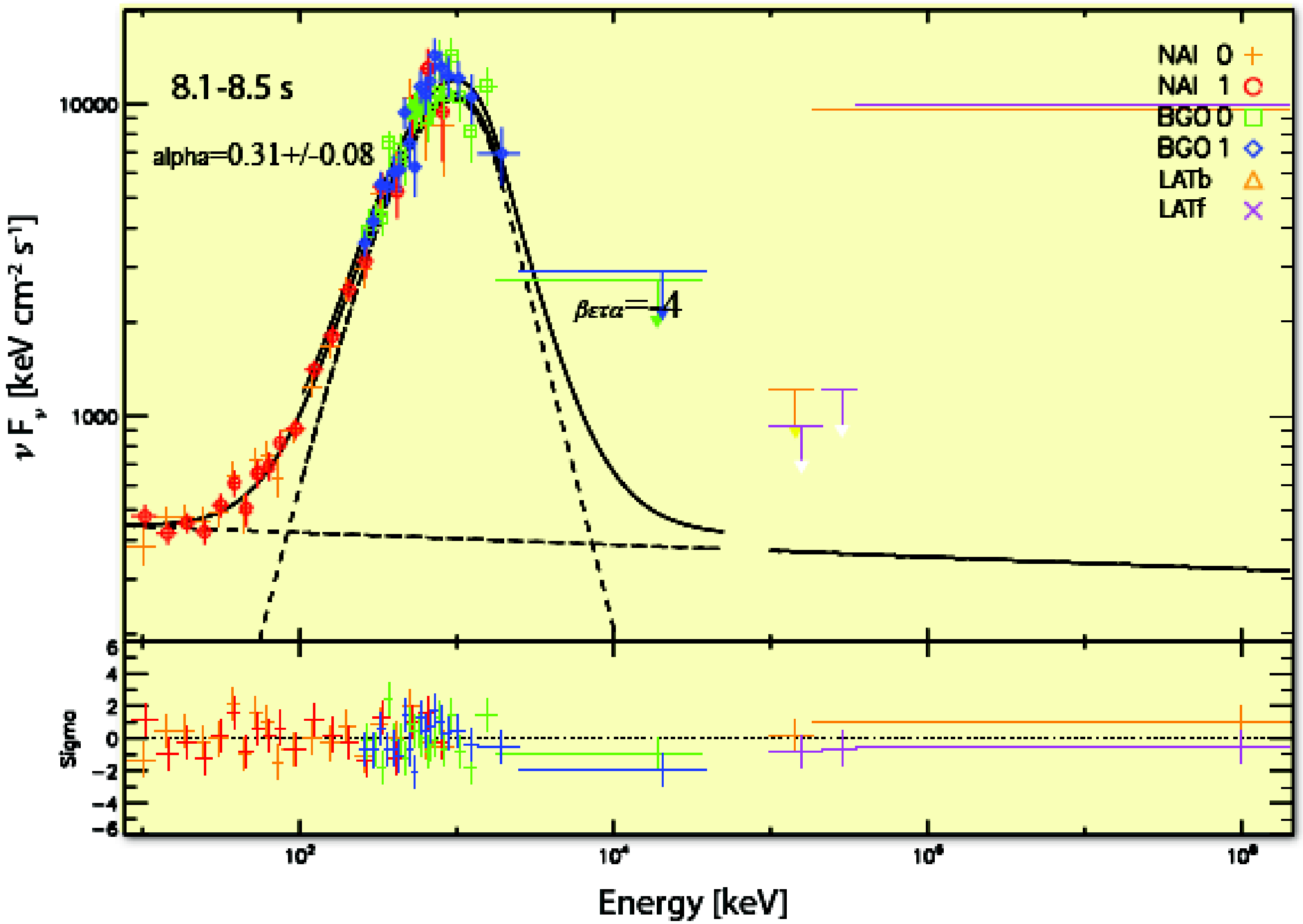




Various Other Possibilities

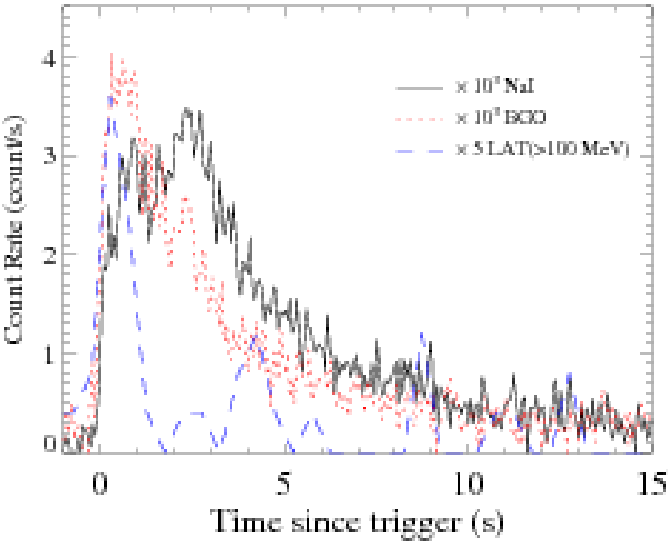


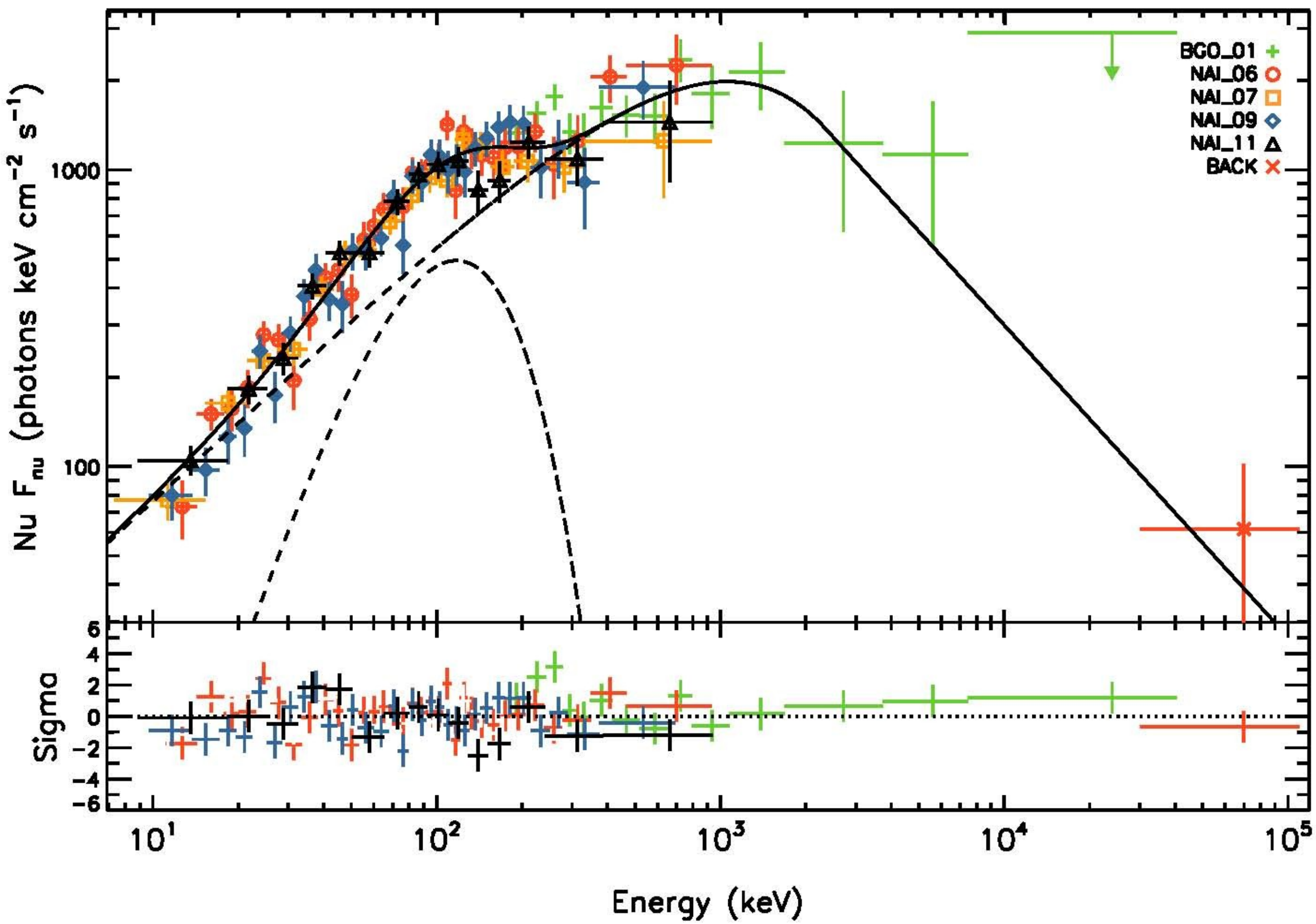


- **Subphotospheric dissipation ---** **Multicolour BB+PL (mBBPL)**

- Time resolved spectra of **GRB 090902B** (Ryde + 2010). The light curve **does not** contain a smooth or separable pulses. **For the same GRB Zhang et al. (2011) claim a BBPL fit for fine enough temporal bins.**

Various Other Possibilities

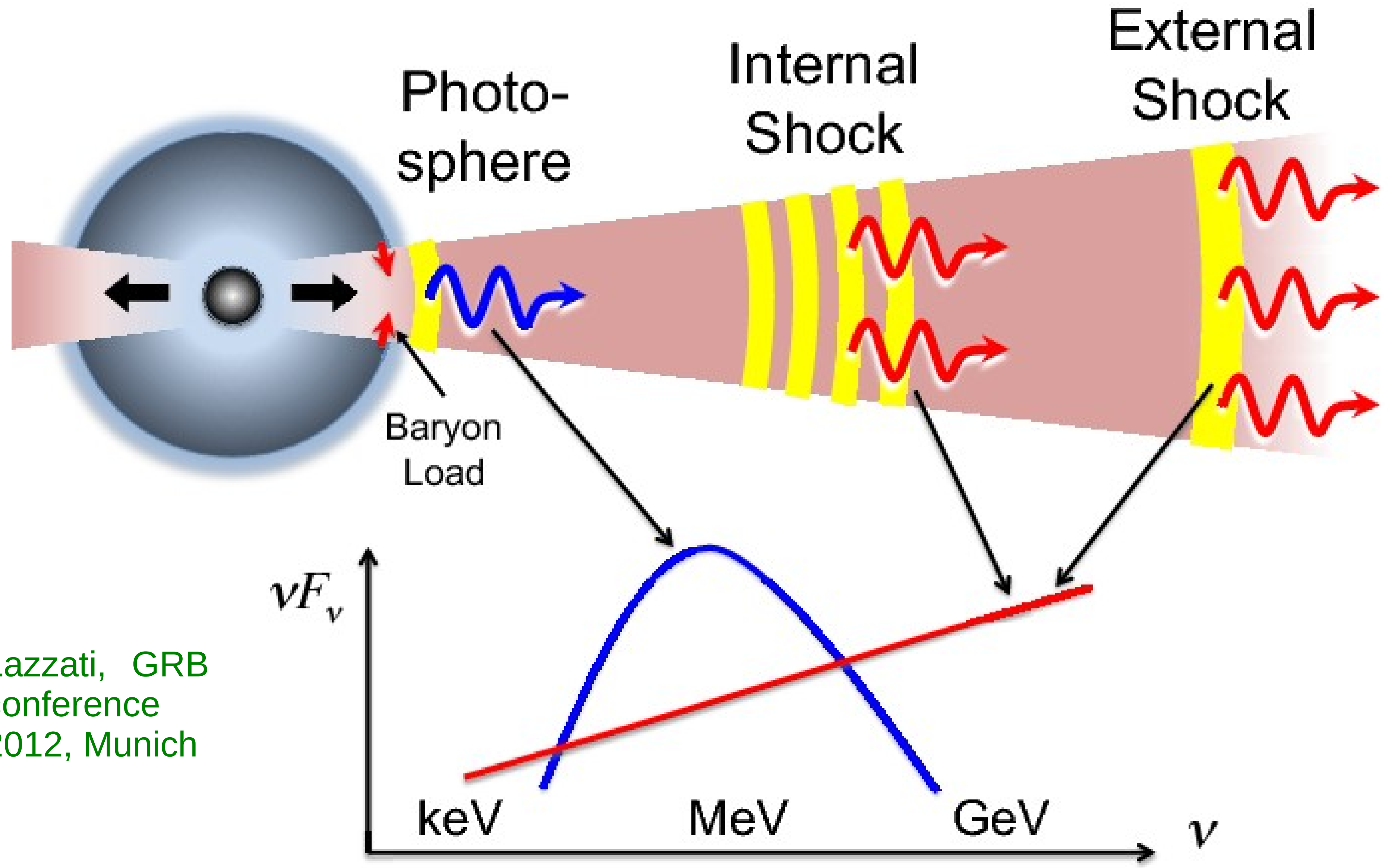




- **Double hump structure --- Band+BB**

- **GRB 110721A,** fitted with Band+BB model (Axelsson et al. 2011). One notices the double hump in the spectrum (Also see Guiriec et al. 2011; Ryde et al. 2010, 2011; Burgess et al. 2011, McGlynn et al. 2012).

The Final Picture?

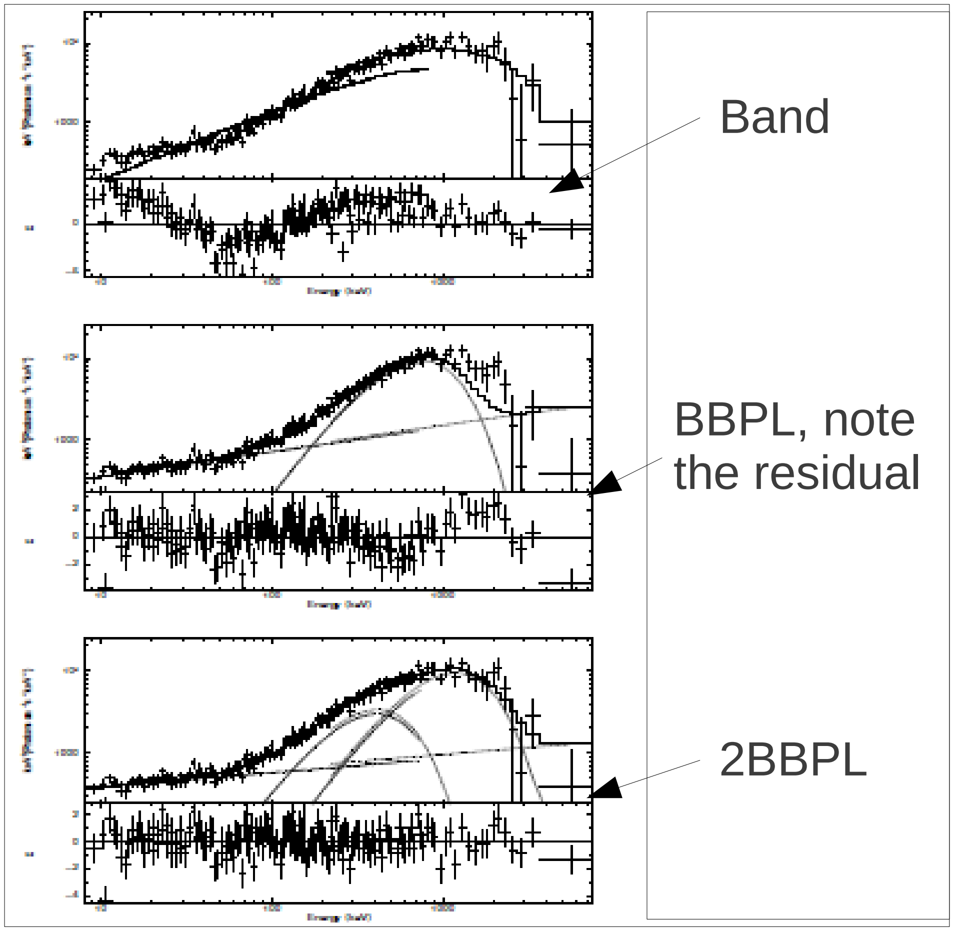


Lazzati, GRB conference 2012, Munich

The Model

I. GRB 090902B and GRB 081221

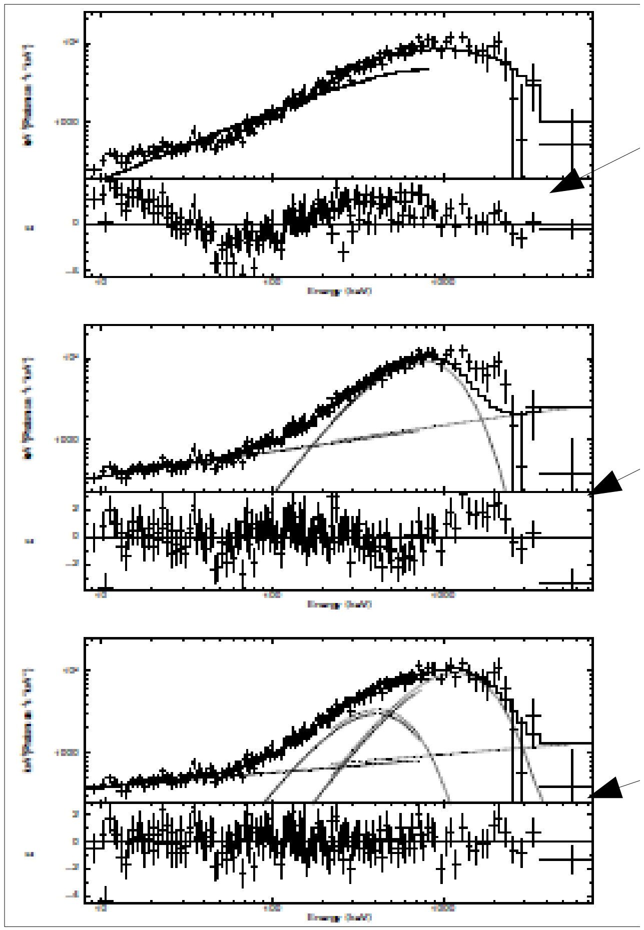
2BBPL Model: GRB 090902B

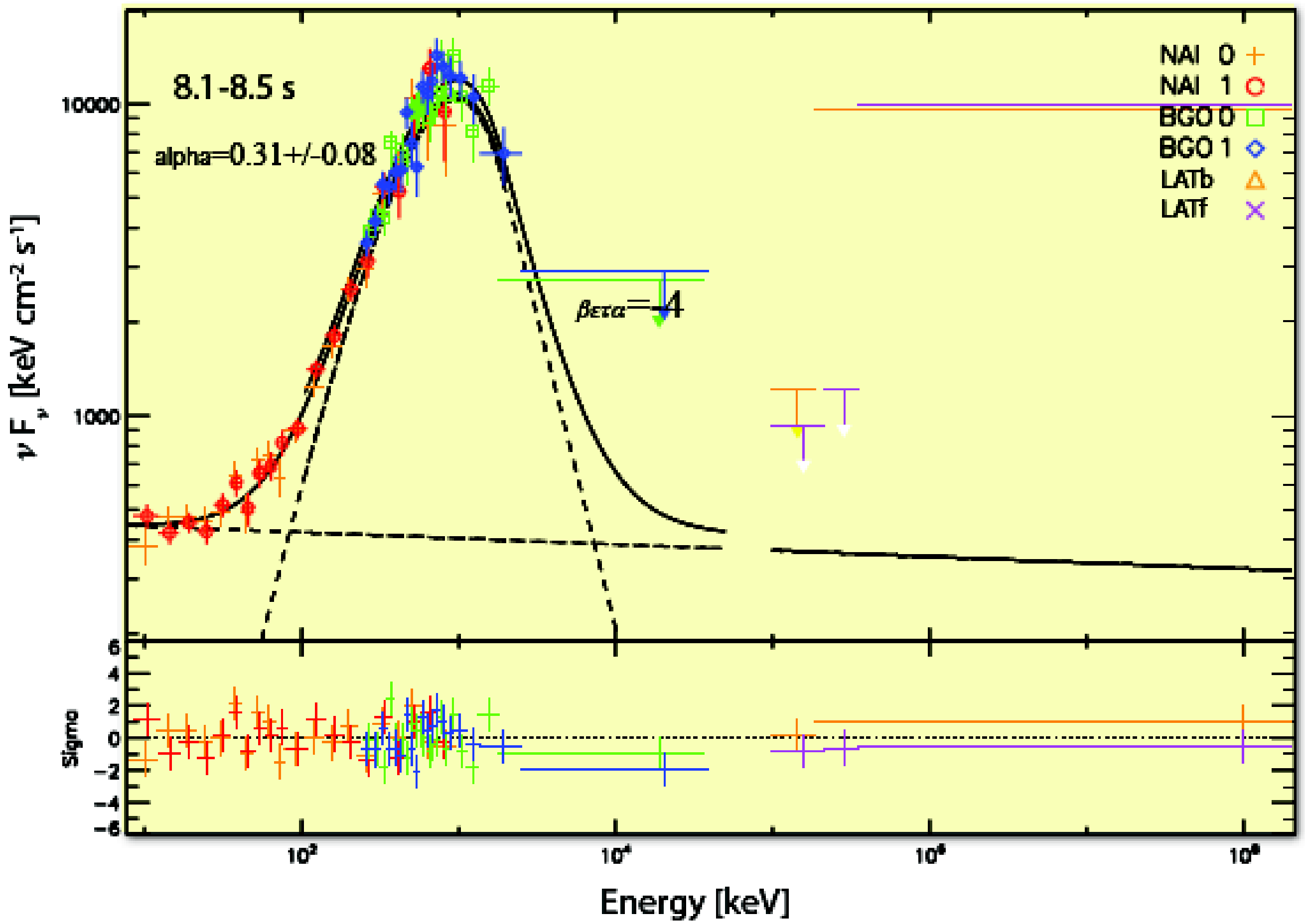


Rao, Basak, Bhattacharya et al. 2013

- Double hump is clearly visible in the residual of BBPL fit.
- mBBPL, as done by Ryde + (2010), takes a continuous temperature distribution over a disk. In contrast 2BBPL model is truly double hump.

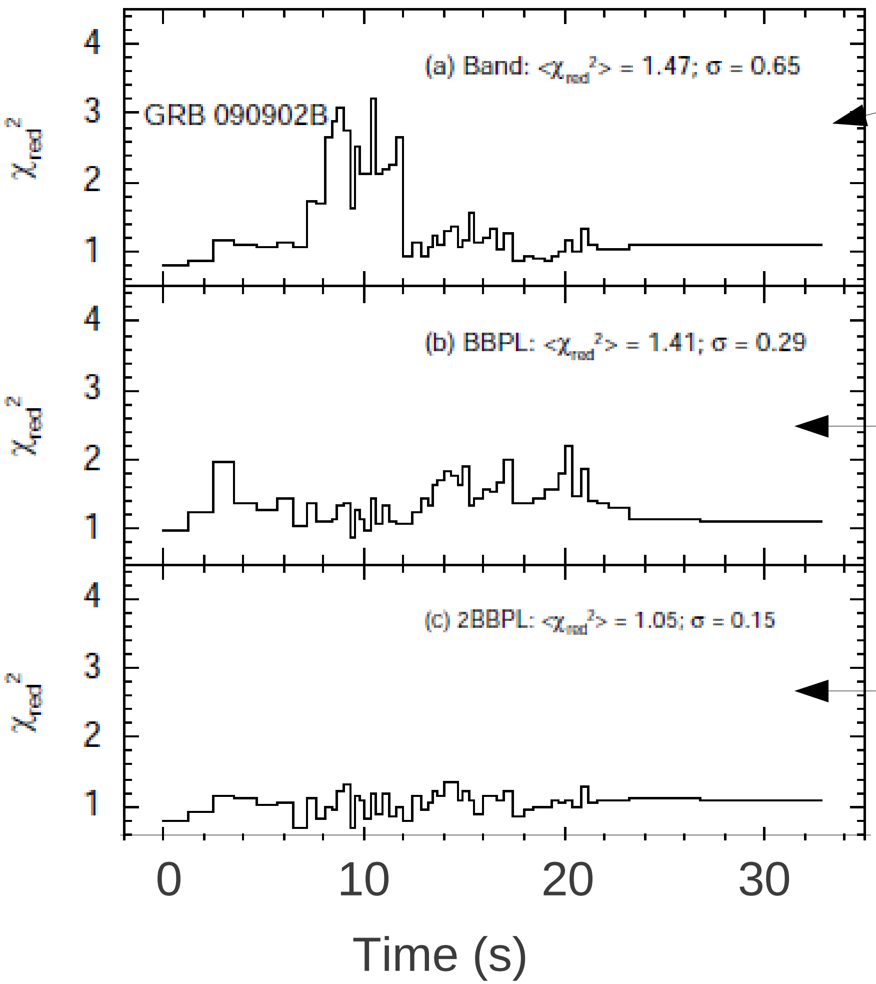
2BBPL Model: GRB 090902B





Rao, Basak, Bhattacharya et al. 2013

2BBPL Model: GRB 090902B



Band model

Rao, Basak, Bhattacharya et al. 2013

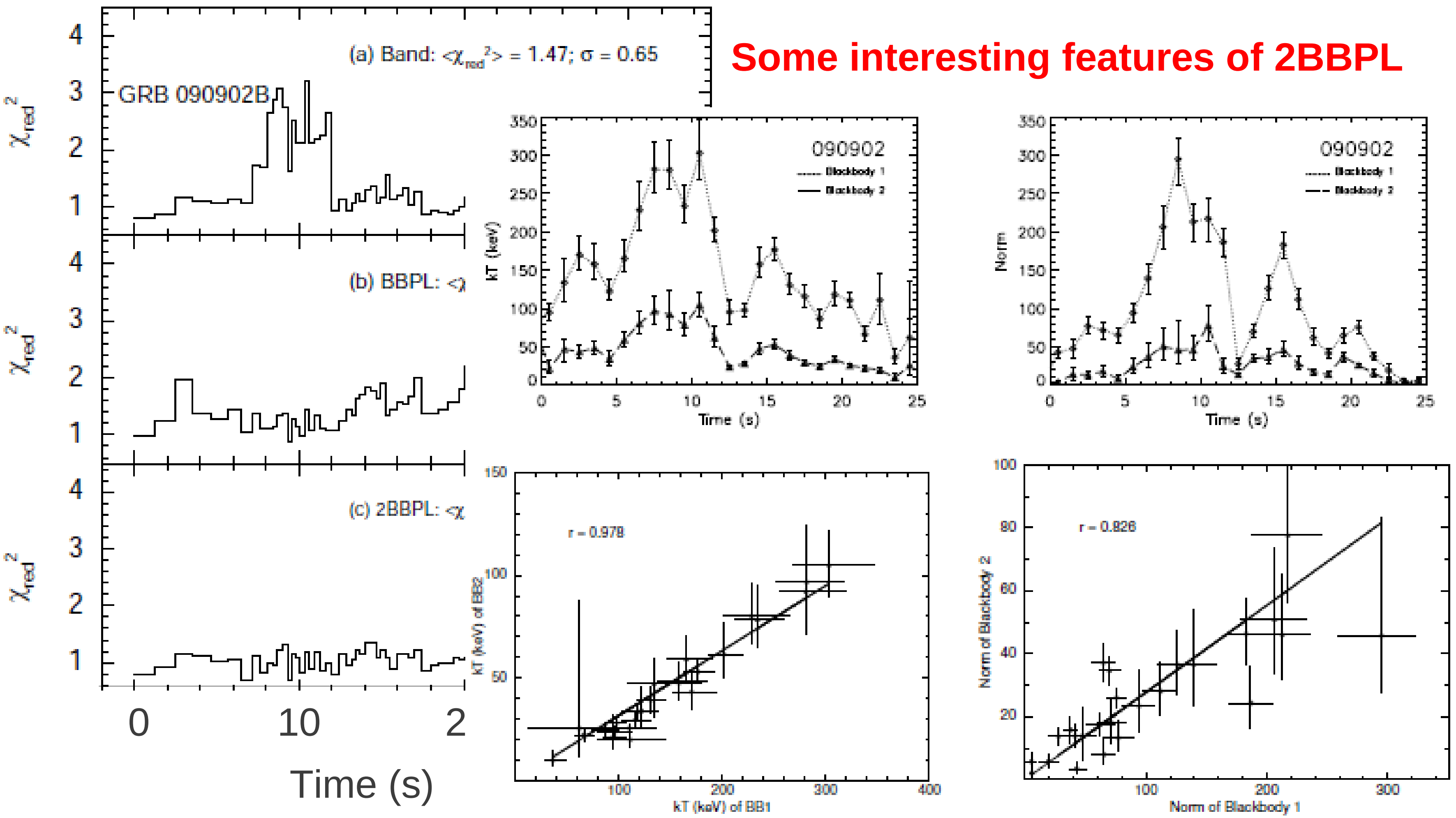
BBPL model

2BBPL model

2 BBs with a power-law

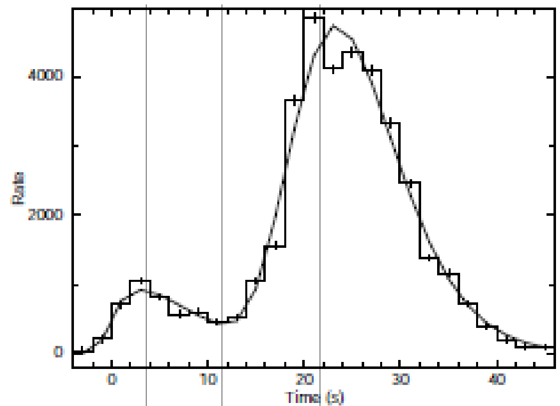
2BBPL Model: GRB 090902B

Some interesting features of 2BBPL

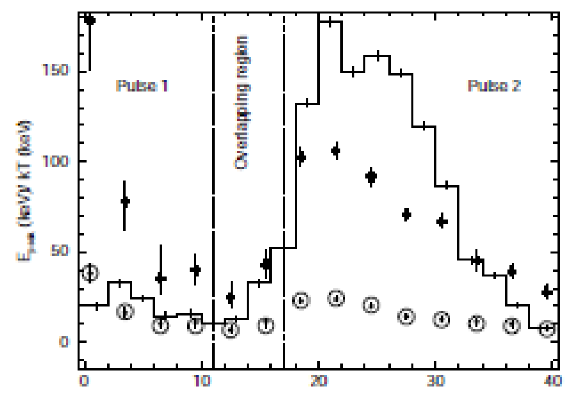


Case Study: GRB 081221

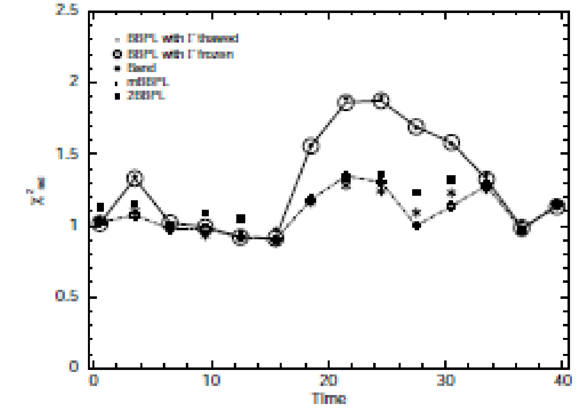
Basak & Rao 2013a, ApJ, 768, 187



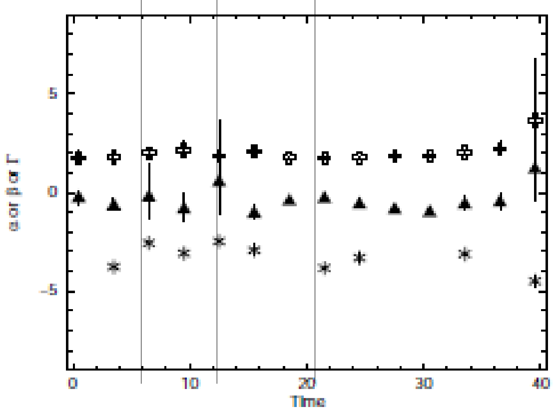
Light Curve



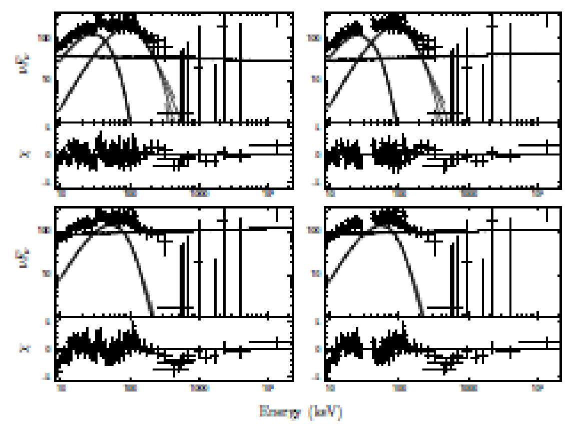
kT & peak energy evolution



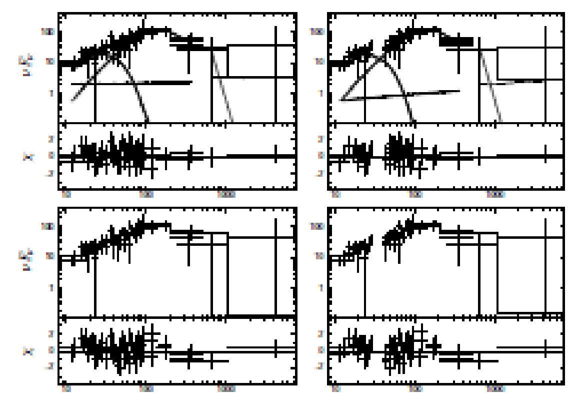
Chi squares



Parameter evolution

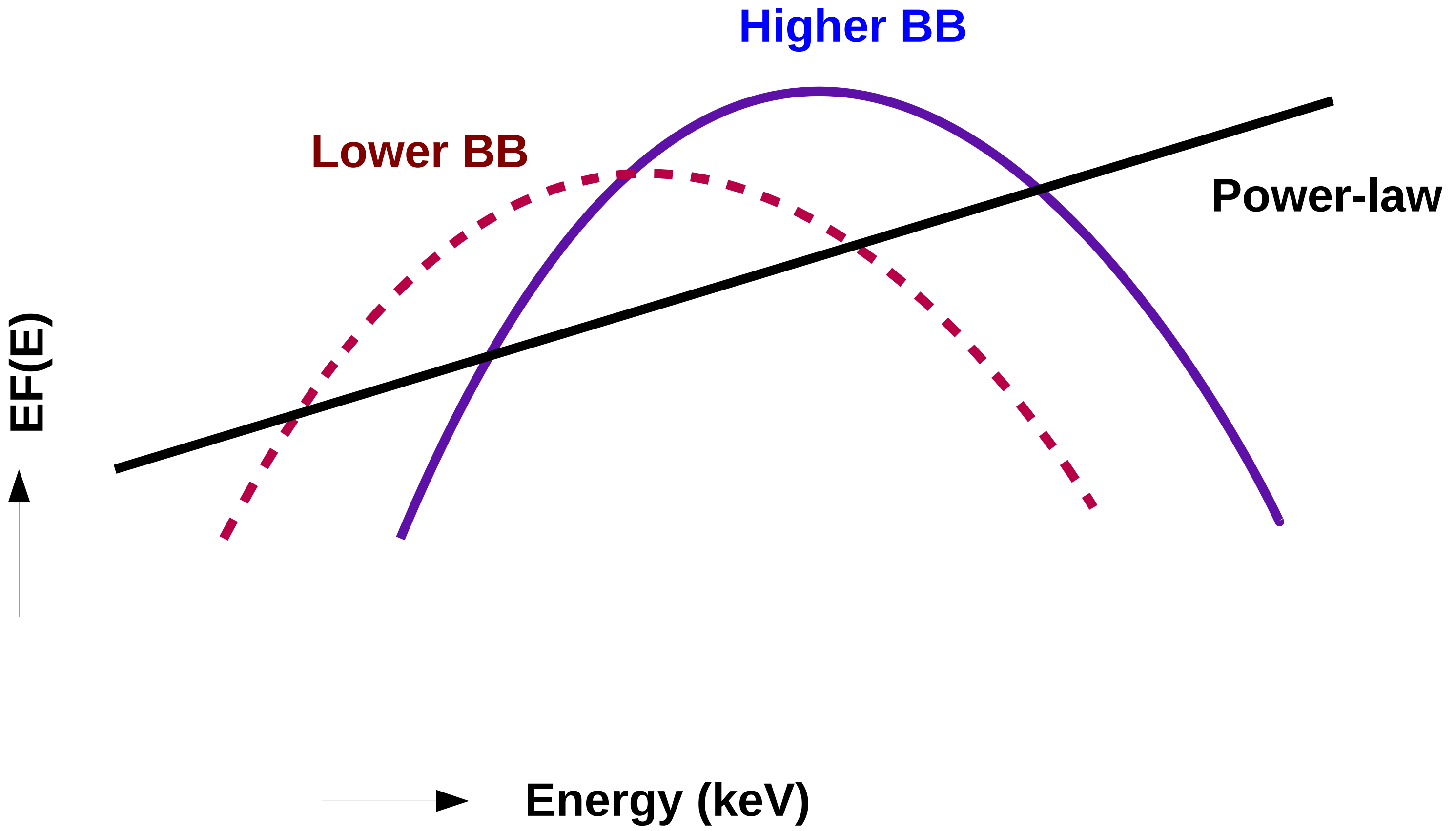


2BBPL and BBPL fit

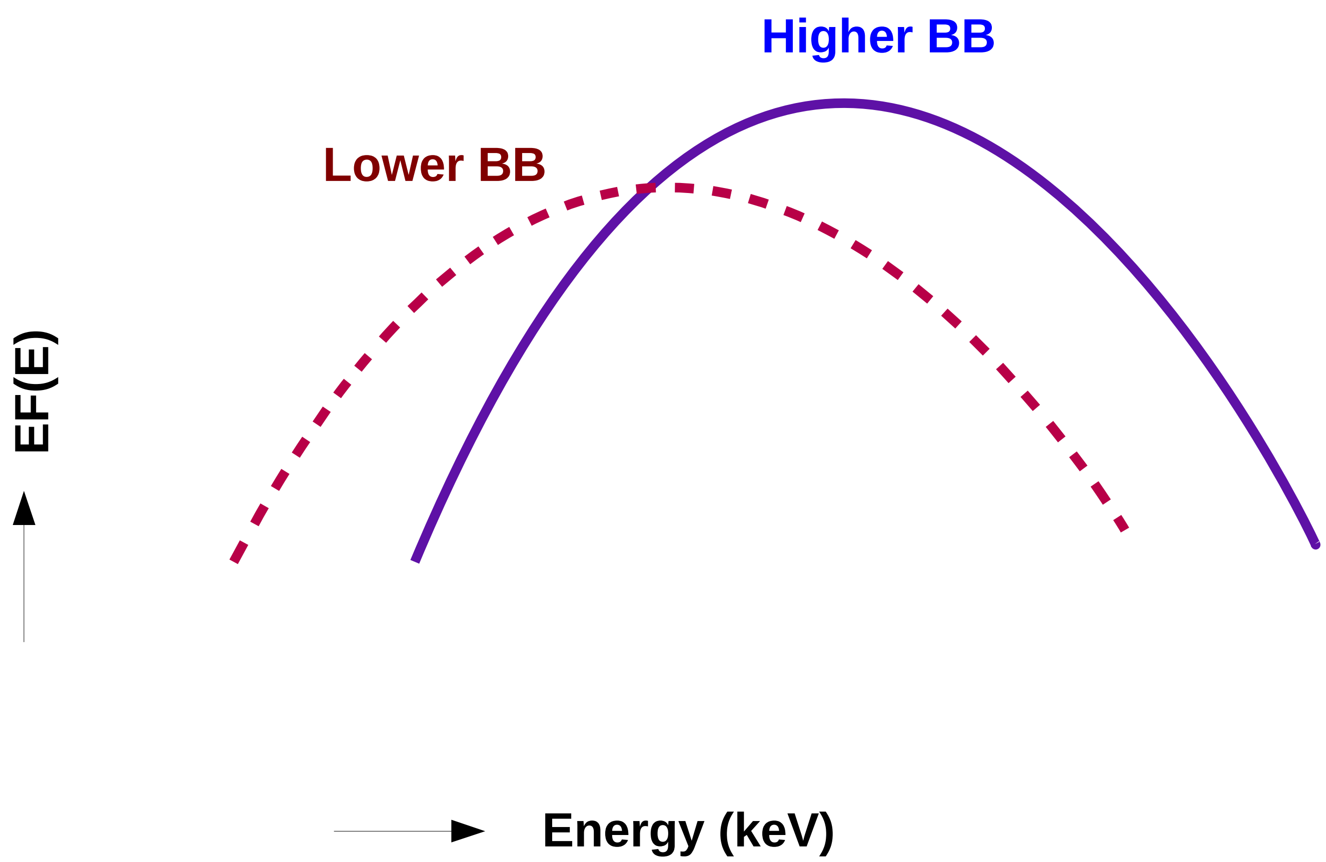


2BBPL and Band fit

Conclusion I

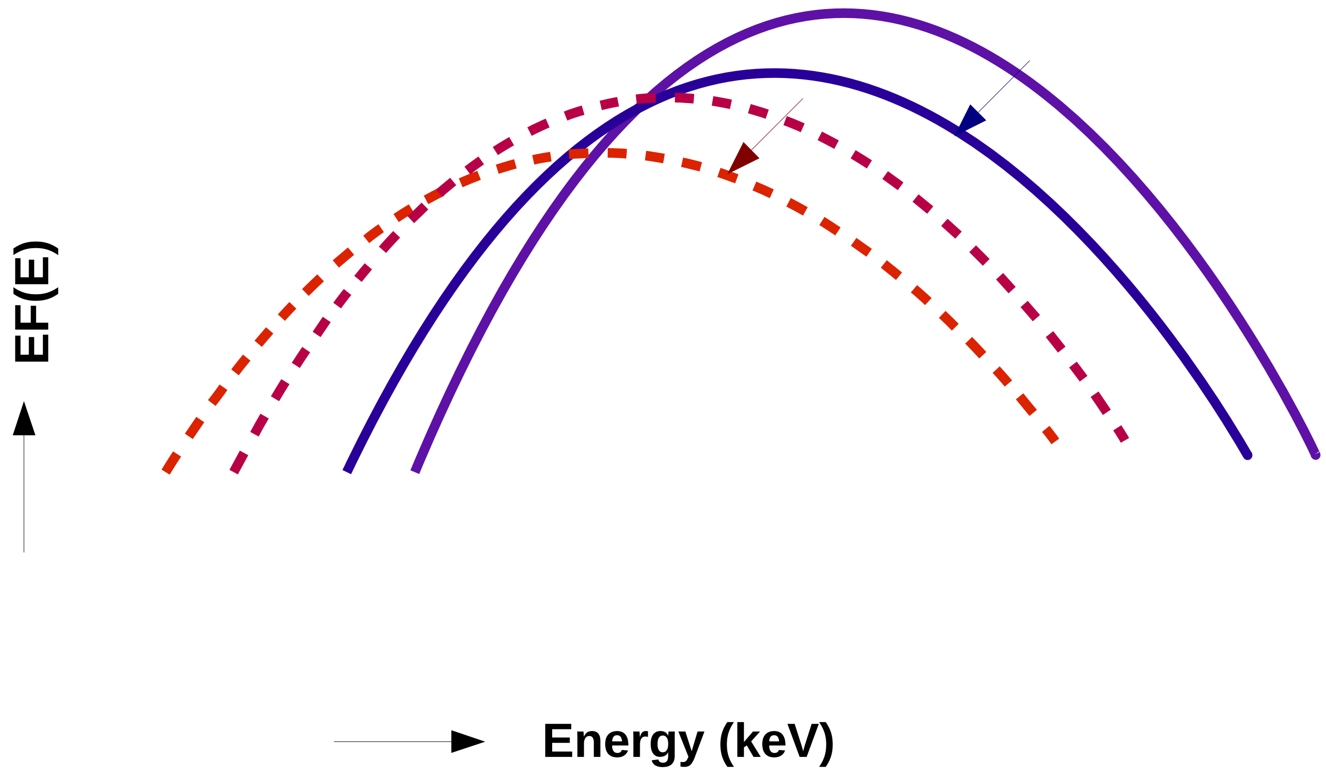


Conclusion I

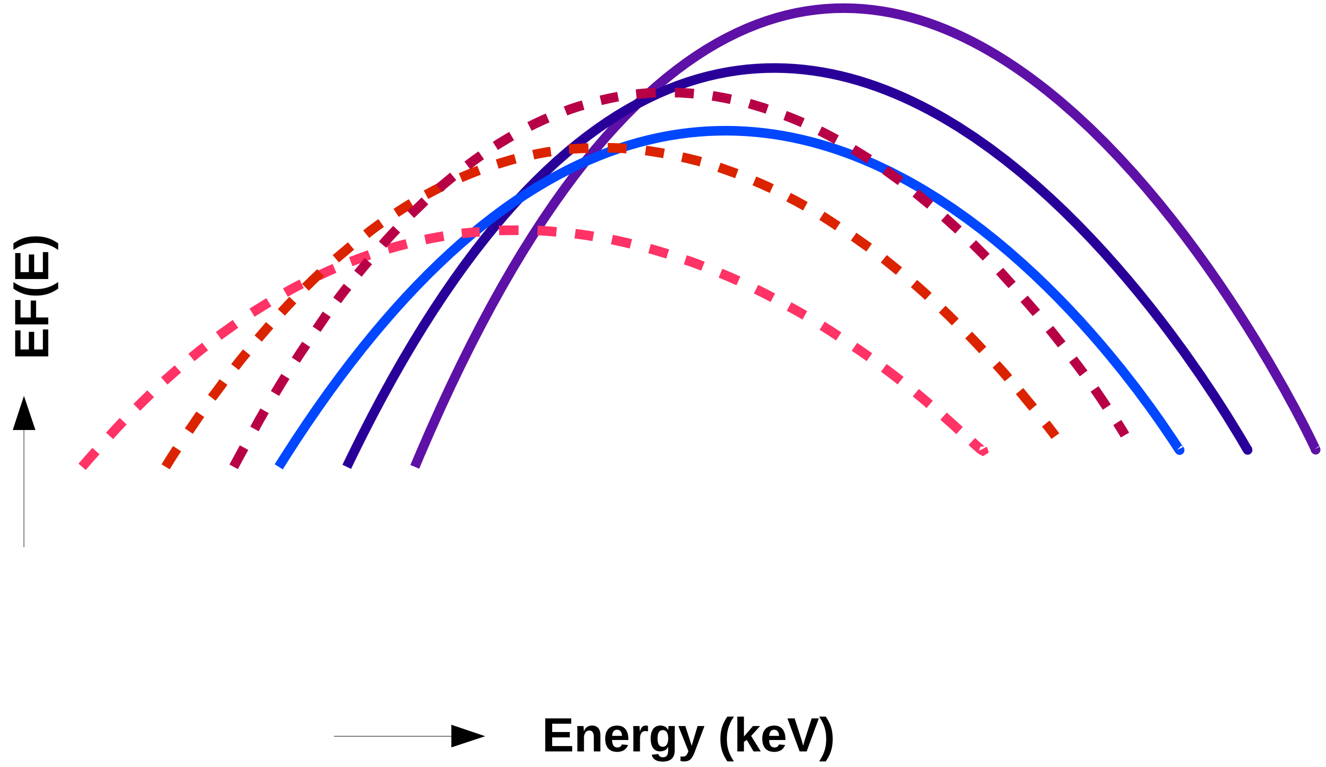


Conclusion I

At a later time:



Conclusion I



The Model

II. Parametrized Joint Fit

See poster P31 in the GRB conference

Choices of Spectral Models

Spectral models

Fully non-thermal

- Band model.

Thermal+non-thermal

- BBPL
- mBBPL
- 2BBPL

BBPL=Blackbody+powerlaw
mBBPL=Multicolor BB+PL
2BBPL=2BBs+PL

Choices of Spectral Models

Spectral models

Fully non-thermal

- Band model.

Thermal+non-thermal

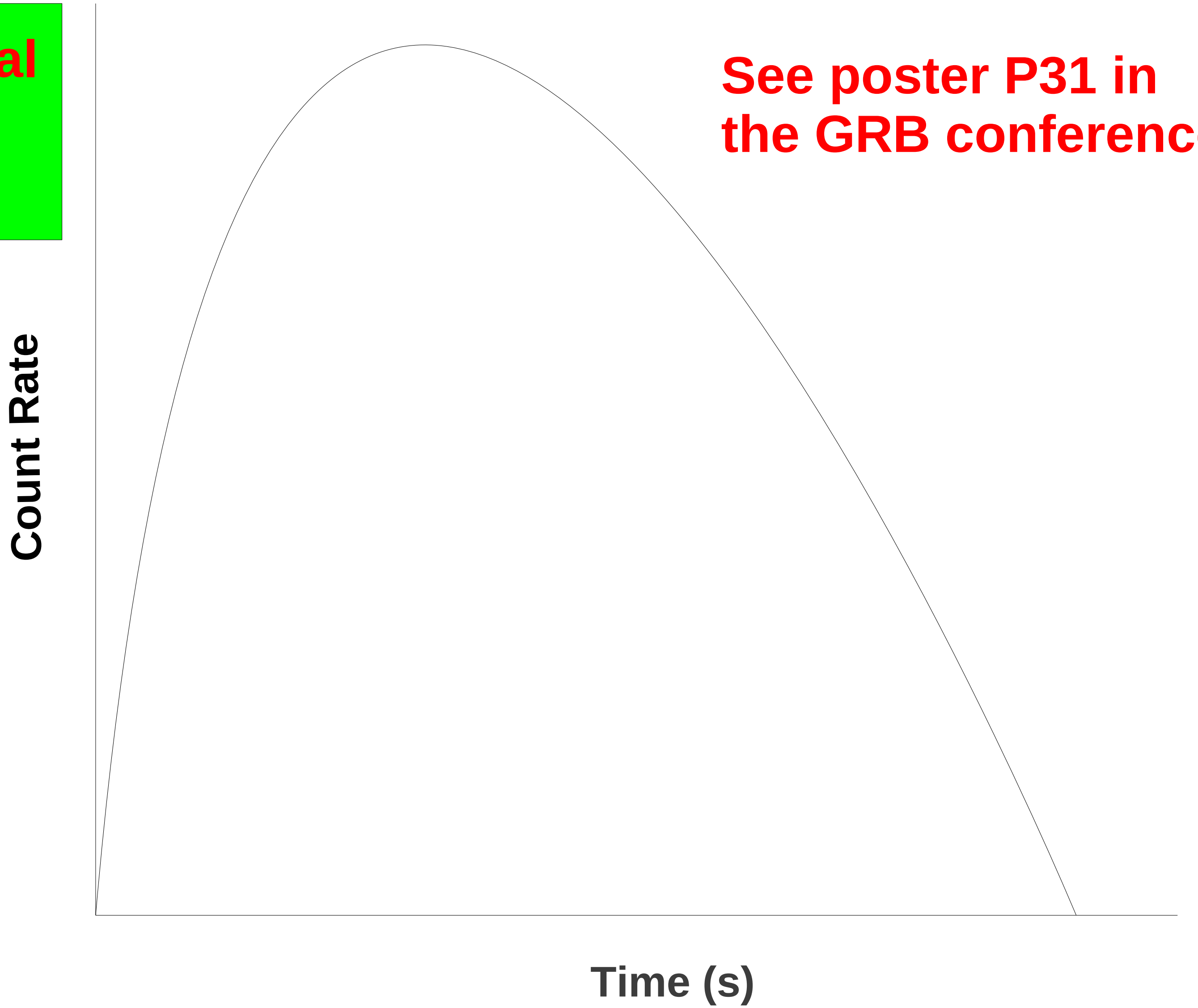
- BBPL
- mBBPL
- 2BBPL

- A proper choice of time bins
- Re-binning of spectral channels
- Parametrization of spectral model

Parametrized Joint Fit

Fully non-thermal

- Band model.



See poster P31 in the GRB conference

Parametrized Joint Fit

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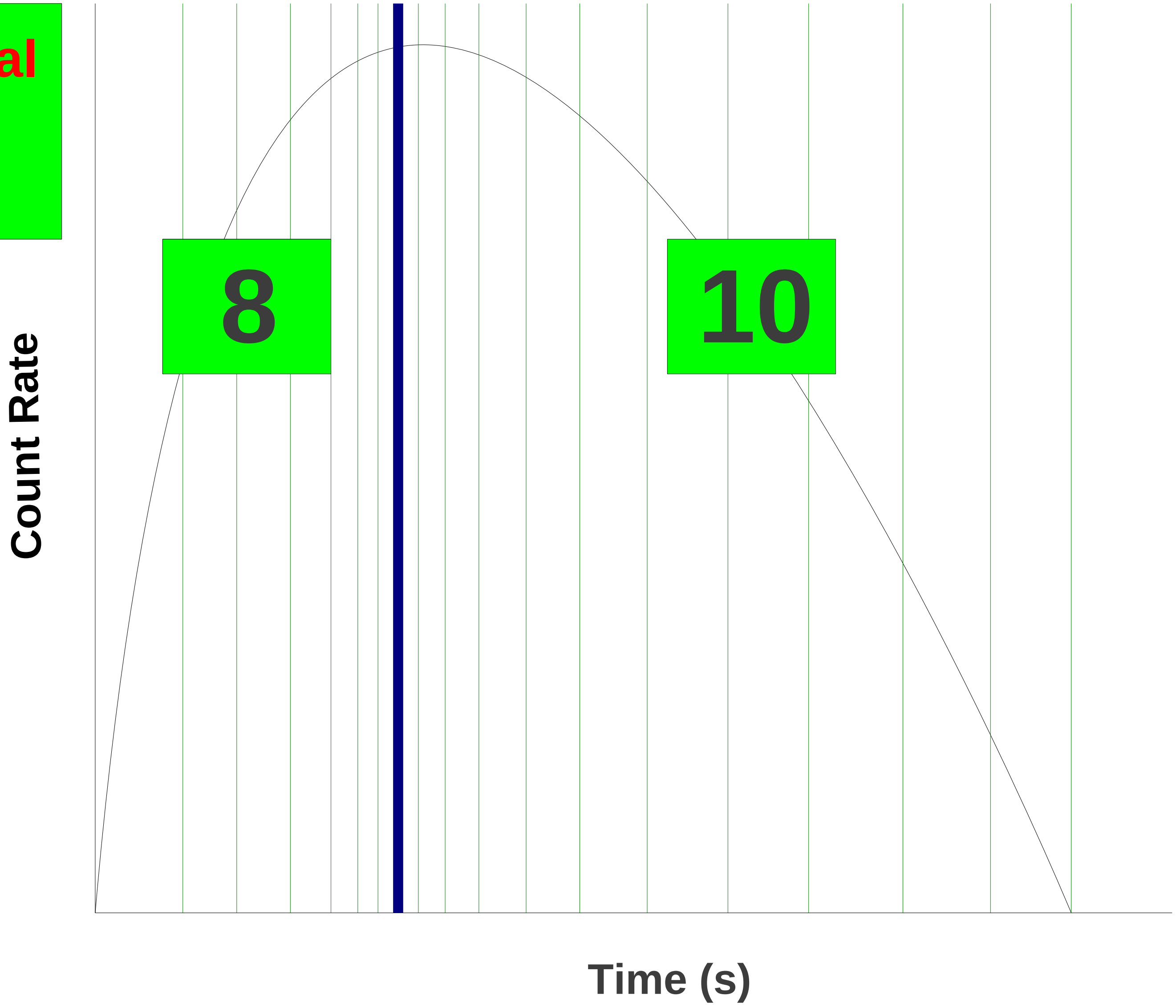


Time binning according to the count per bin. Notice the unequal bin size

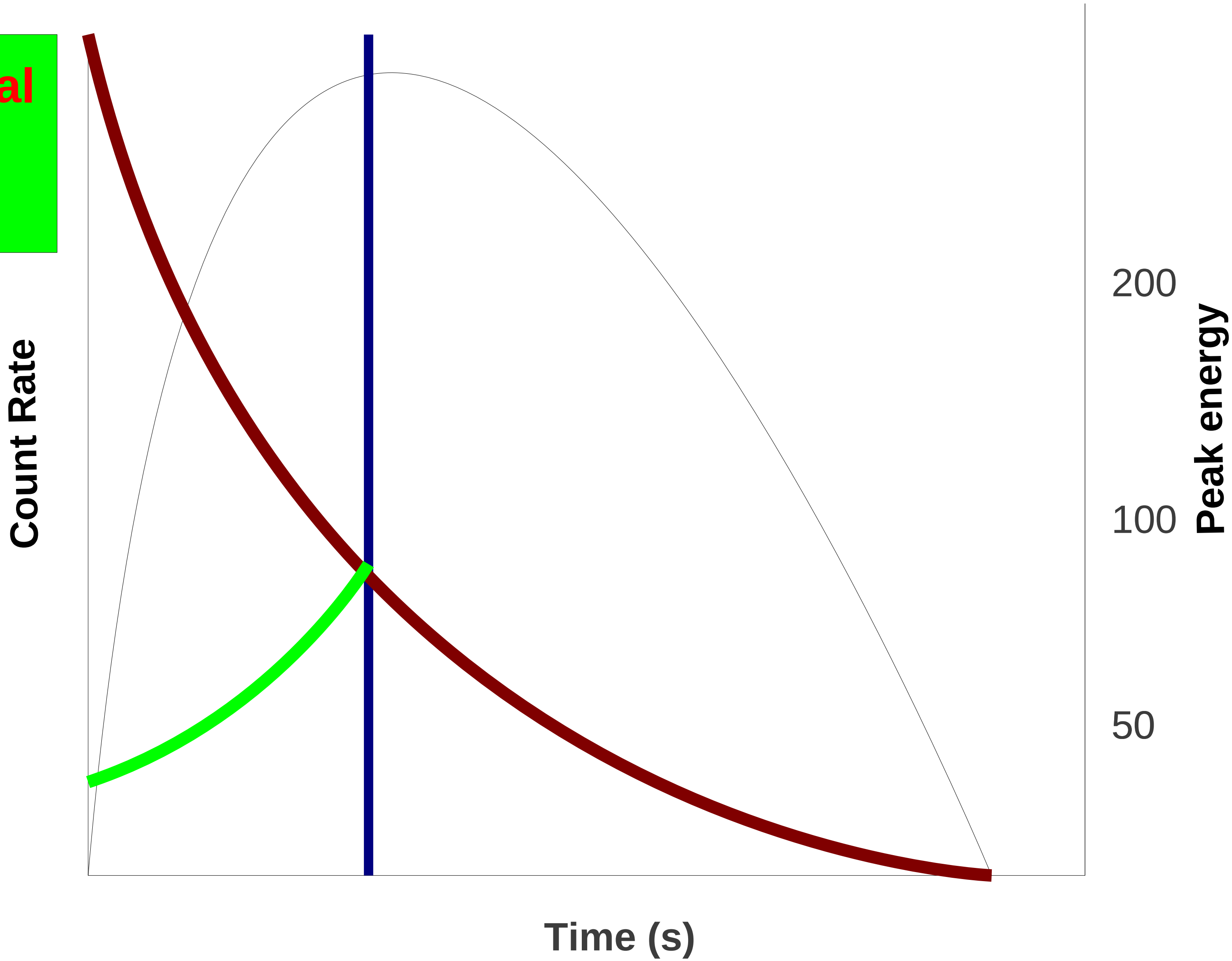
If a 4 parameter model (Band) is fitted at each bin, total **72** (18x4) parameters are required.

Parametrized Joint Fit

Fully non-thermal

- Band model.

Peak energy of the Band model varies smoothly with time



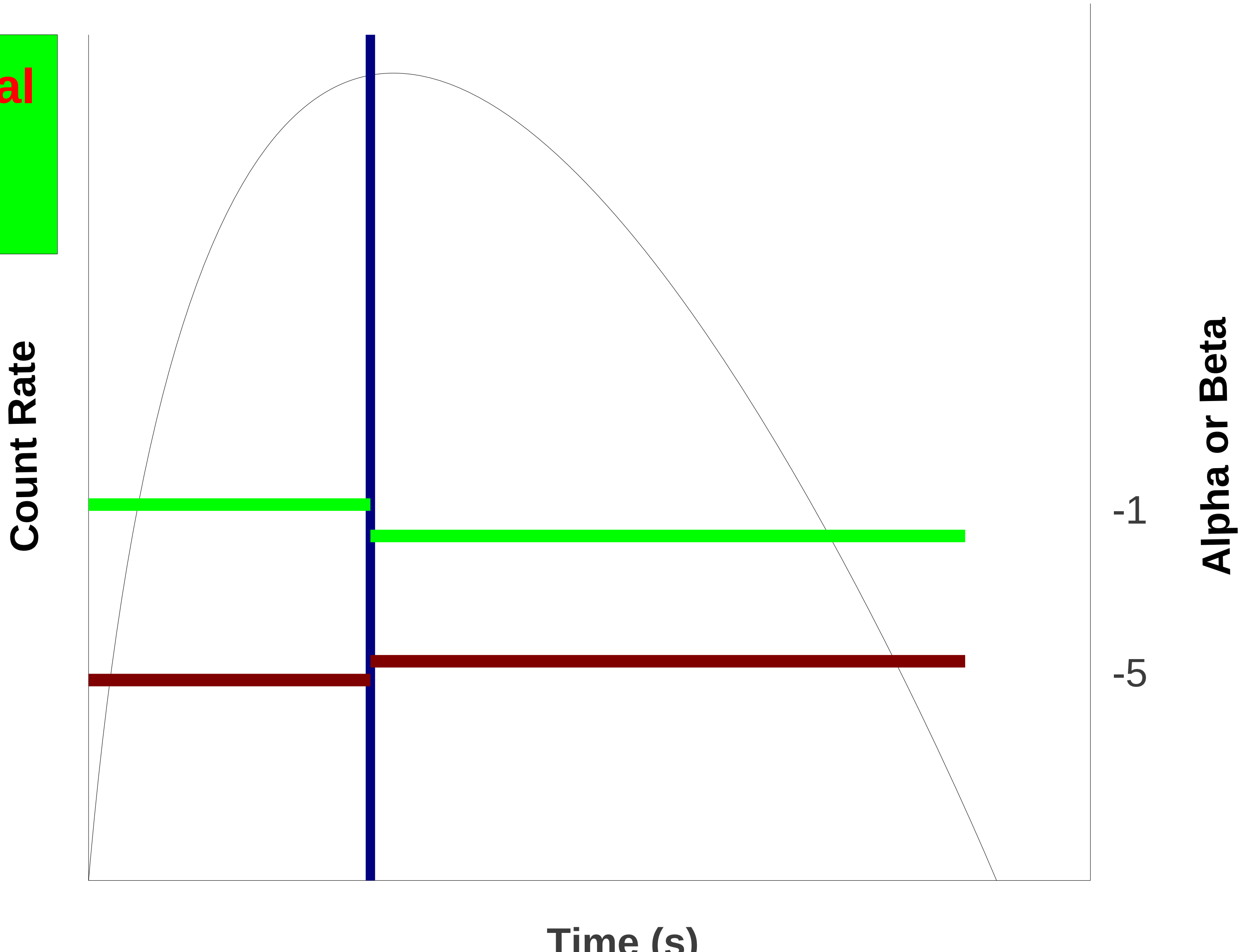
Parametrized Joint Fit

Fully non-thermal

- Band model.

Peak energy of the Band model varies smoothly with time

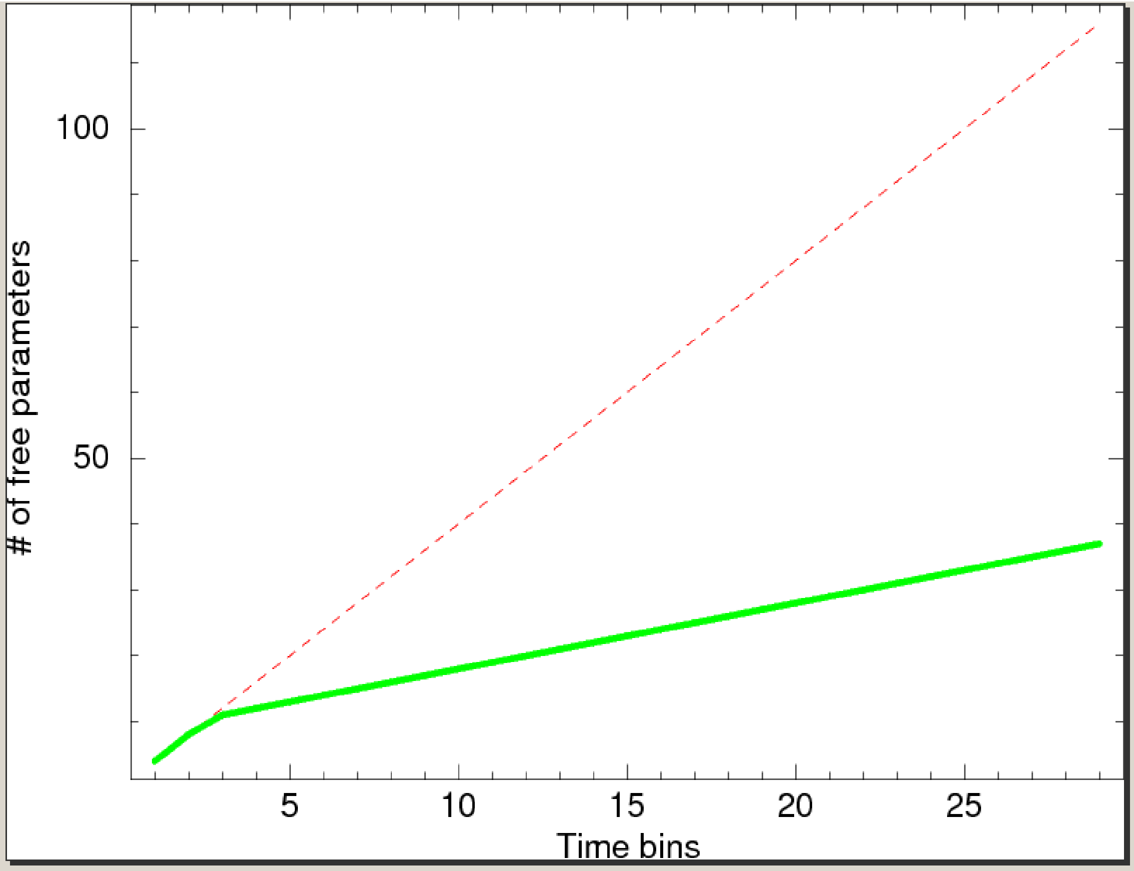
Photon indices remain more or less constant over a section



Parametrized Joint Fit

- Band model.

- **Perform a simultaneous fit, parametrizing the peak evolution and tying the photon indices.**

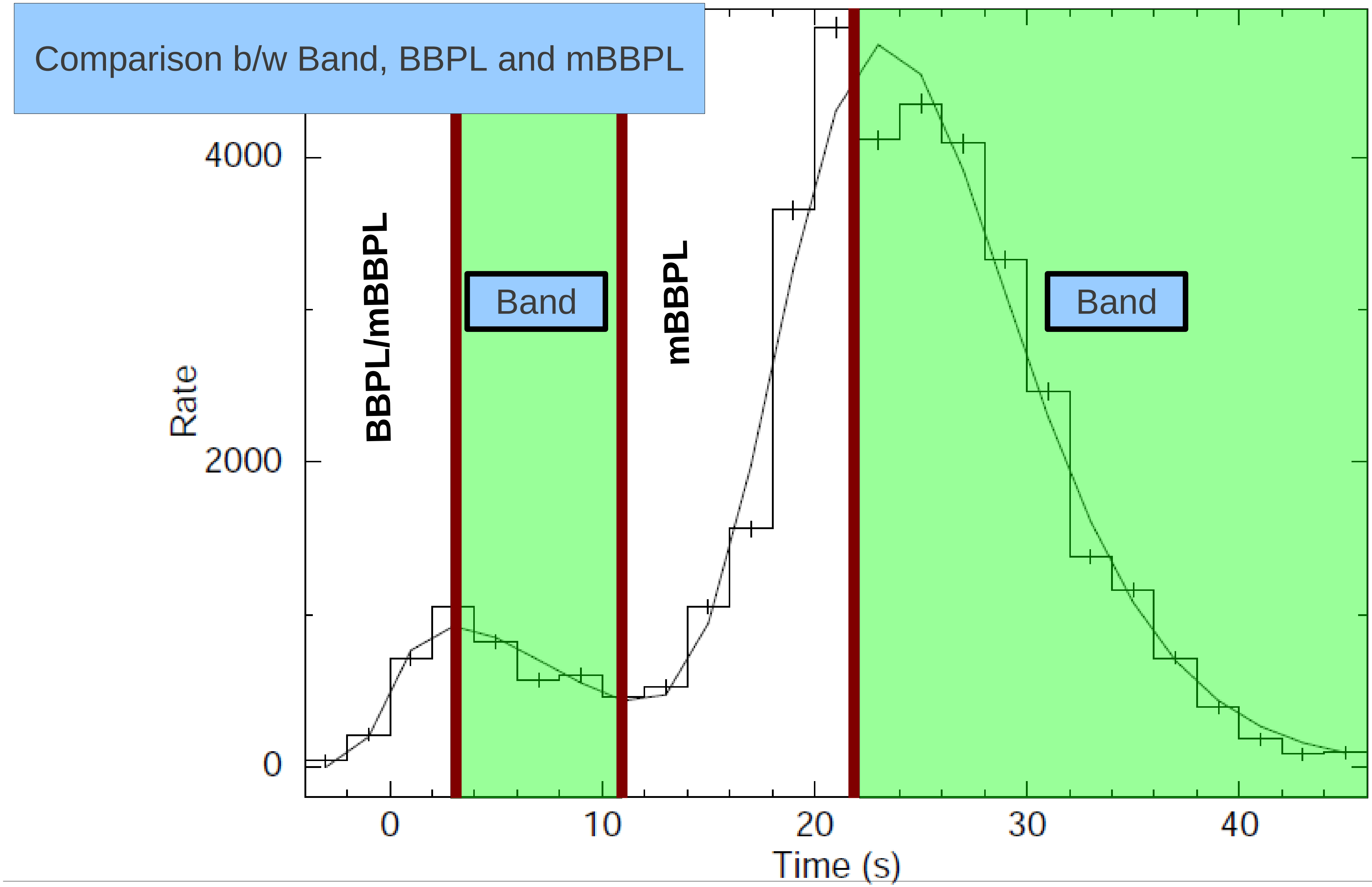


- **From 72 parameters, this will reduce to 26 parameters**

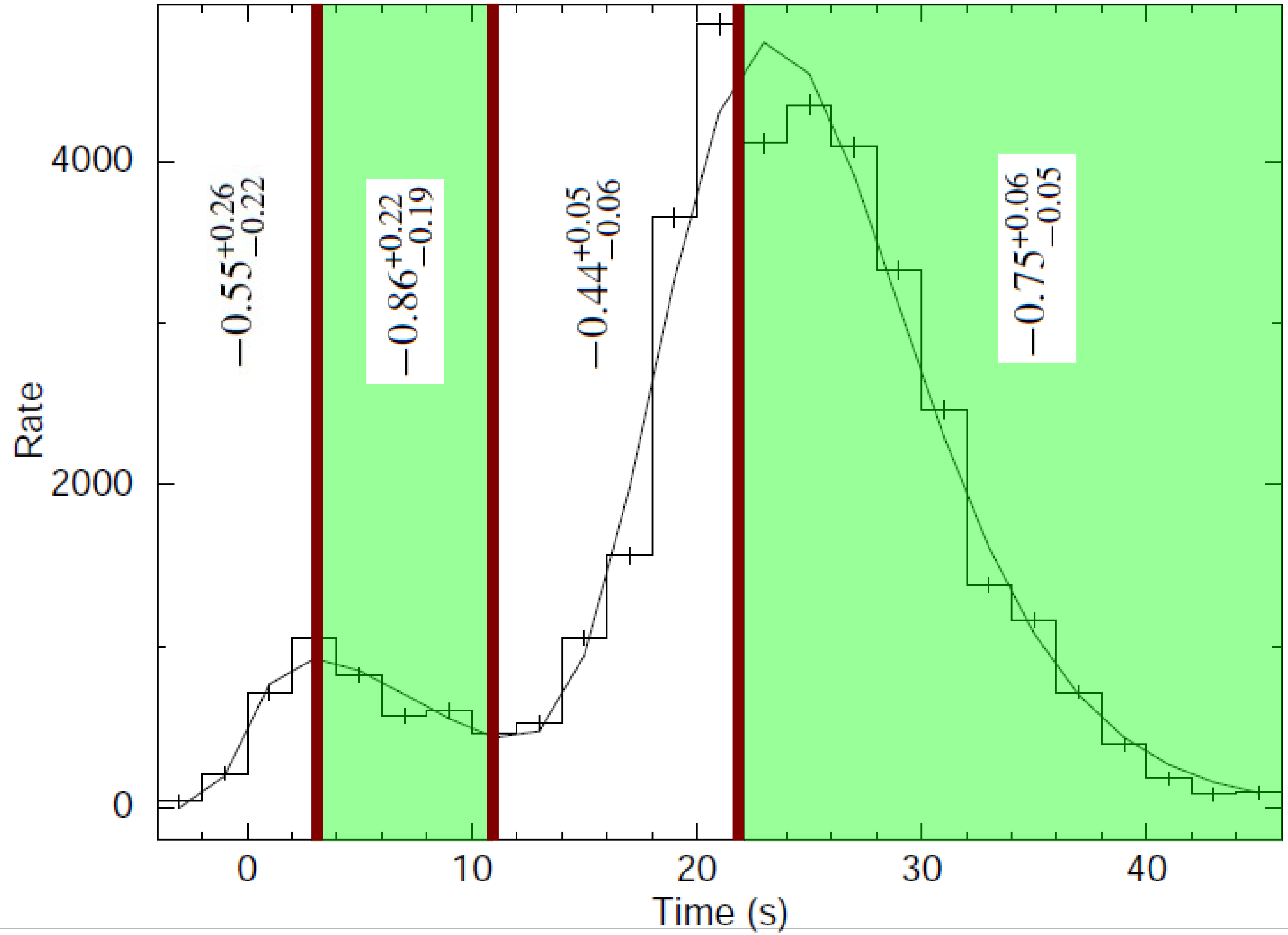
- **Similar treatment for other models**

- **For example, BBPL will have same no. Of parameters as Band. MBBPL will have one extra and 2BBPL will have two extra free parameters,**

Spectrum at different Regions



Values of Alpha



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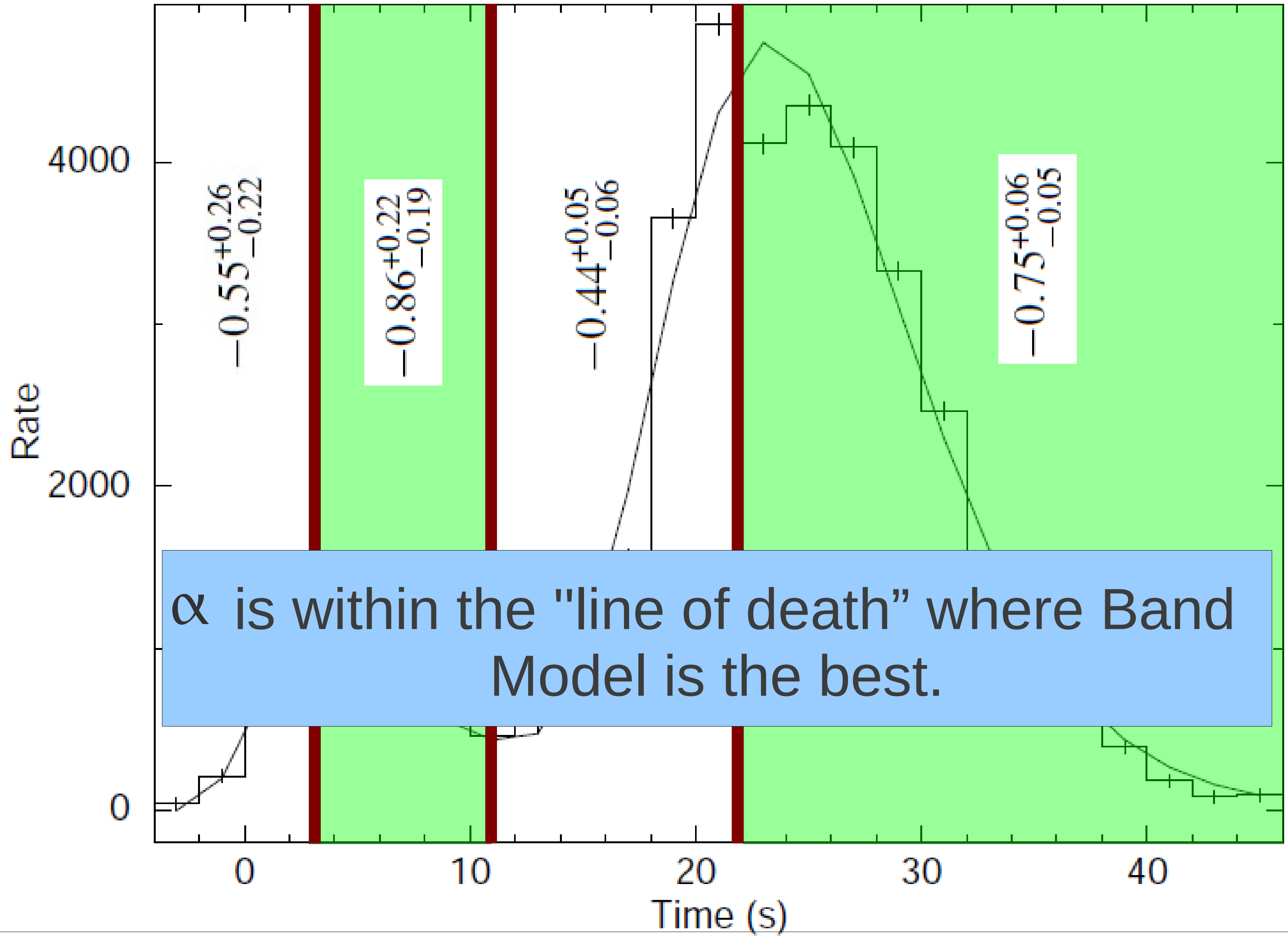


α is within the "line of death" where Band Model is the best.

Results: GRB 081221

Region	Model2/ Model1	p	σ	C.L.
Pulse1, Rising	BBPL/Band	0.38	0.87	61.5%
	mBBPL/Band	0.41	0.81	58.5%
	2BBPL/Band	0.30	1.04	70.2%
	2BBPL/BBPL	0.03	2.19	97.1%
Pulse1, Falling	Band/BBPL	0.30	1.03	69.9%
	mBBPL/BBPL	0.33	0.97	66.6%
	2BBPL/BBPL	1E-5	4.4	100%
	Band/2BBPL	0.48	0.70	51.9%
Pulse2, Rising	Band/BBPL	0.02	2.37	98.2%
	mBBPL/BBPL	0.01	2.55	98.9%
	2BBPL/BBPL	1E-20	9.29	100%
	2BBPL/Band	0.39	0.86	60.9%
Pulse2, Falling	Band/BBPL	1E-5	4.41	100%
	mBBPL/BBPL	8E-5	3.95	100%
	2BBPL/BBPL	2E-66	17.2	100%
	2BBPL/Band	0.30	1.03	69.7%
	2BBPL/mBBPL	0.16	1.39	83.5%

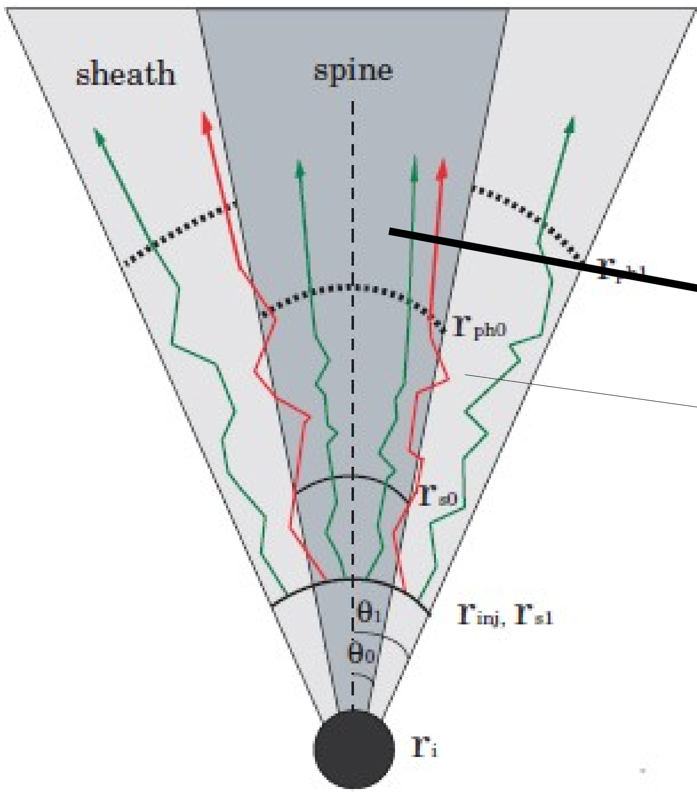
- In all cases 2BBPL is superior than BBPL. In all cases 2BBPL is comparable or **better** than Band. mBBPL is inferior than Band and 2BBPL
- In summary, 2BBPL is the best model
- Same results are obtained for two pulses of **GRB 090618**. These are the two brightest GRBs having separable pulses. It is unlikely that we can find better result in any other GRBs

Basak & Rao 2013a, ApJ, 768, 187

The Model

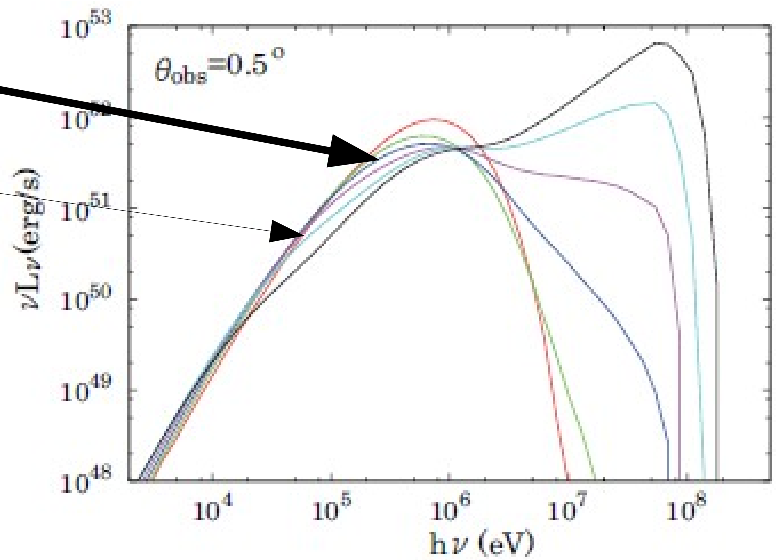
III. A Spine-sheath Jet

Origin of 2BBPL: Spine-sheath Jet



Ito, Nagataki, Ono et al. 2013

(Talk by H. Ito in GRB conf.)



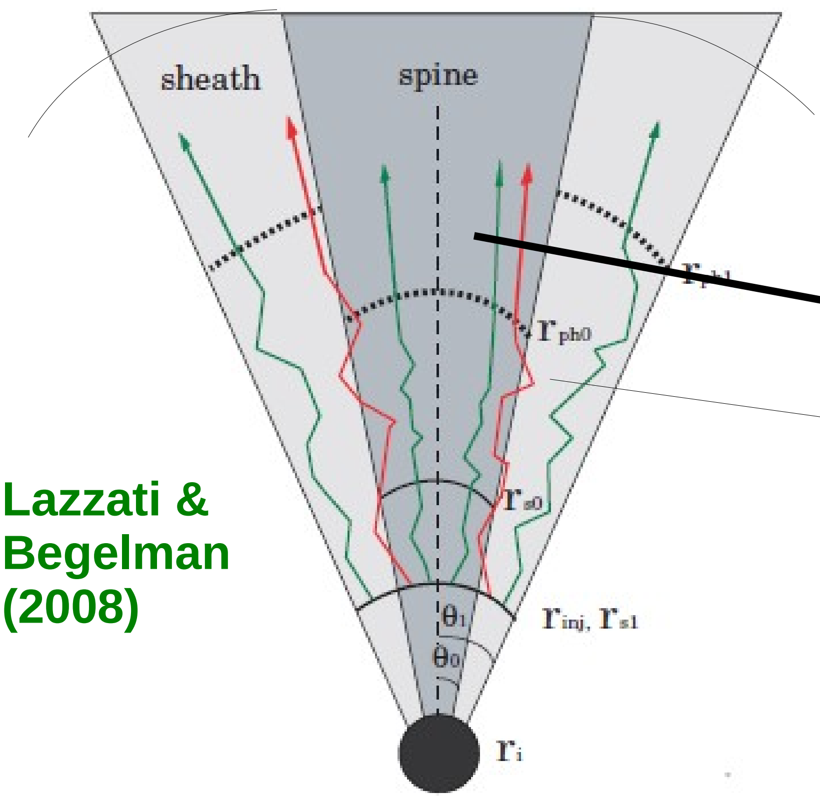
Peak of the spectrum,

$$E_p = r_i^{1/6} \eta^{8/3} L^{-5/12}$$

Peak luminosity,

$$L_p = r_i^{2/3} \eta^{8/3} L^{1/3}$$

Origin of 2BBPL: Spine-sheath Jet



Lazzati & Begelman (2008)

Ito, Nagataki, Ono et al. 2013

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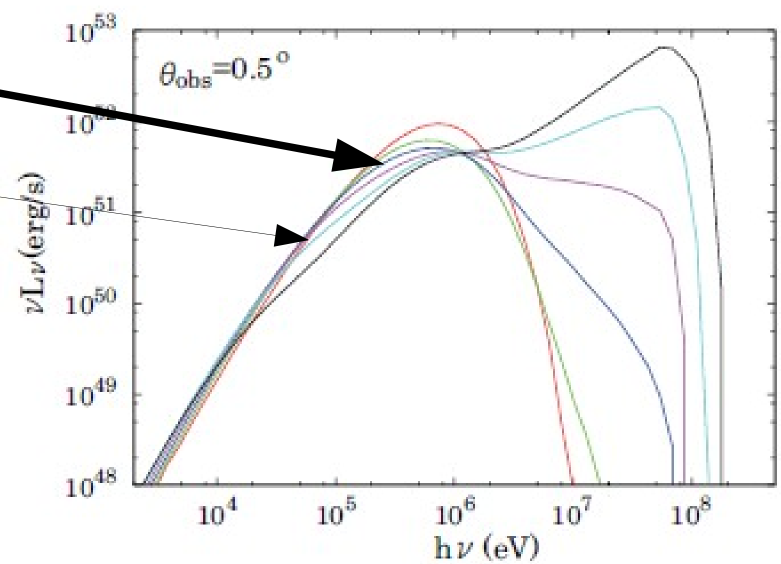

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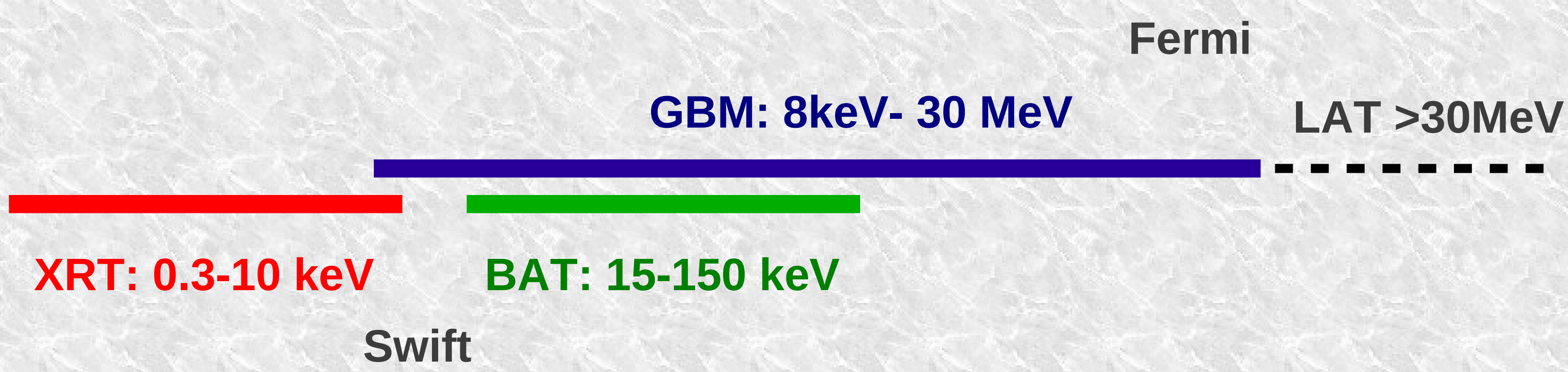
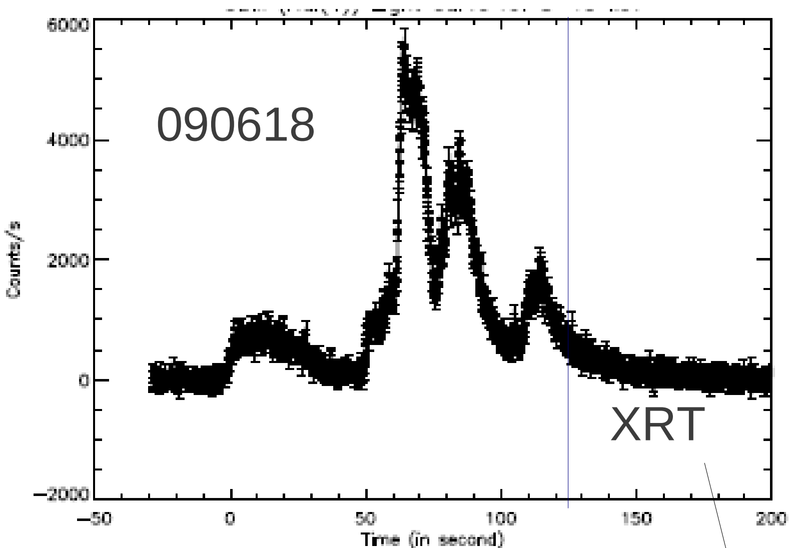
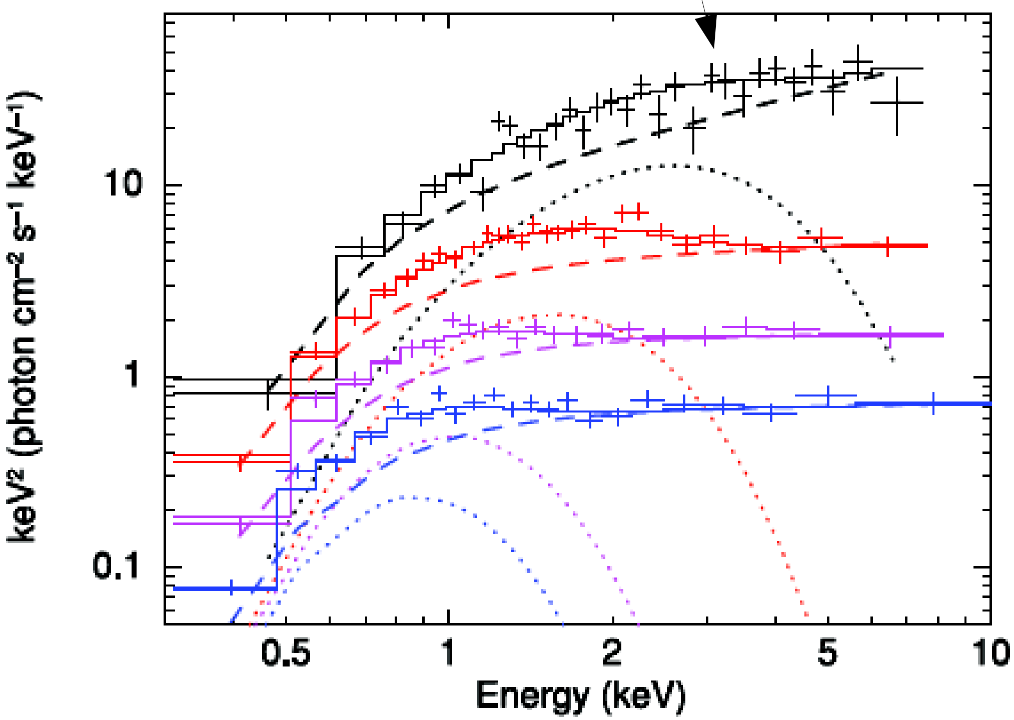
The Model

IV. Independent Observation

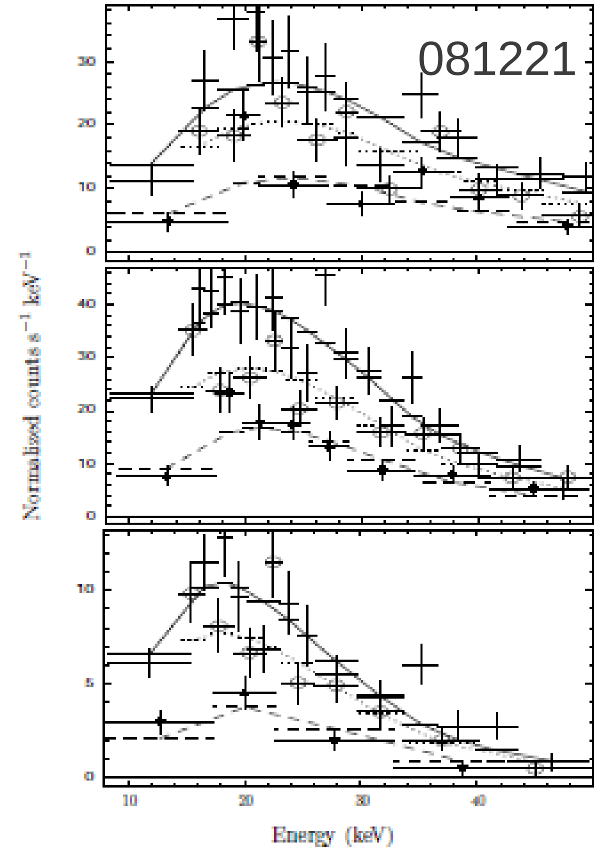


XRT Observation of the Second BB





Page et al. (2011)



Basak & Rao 2013a, ApJ, 768, 187

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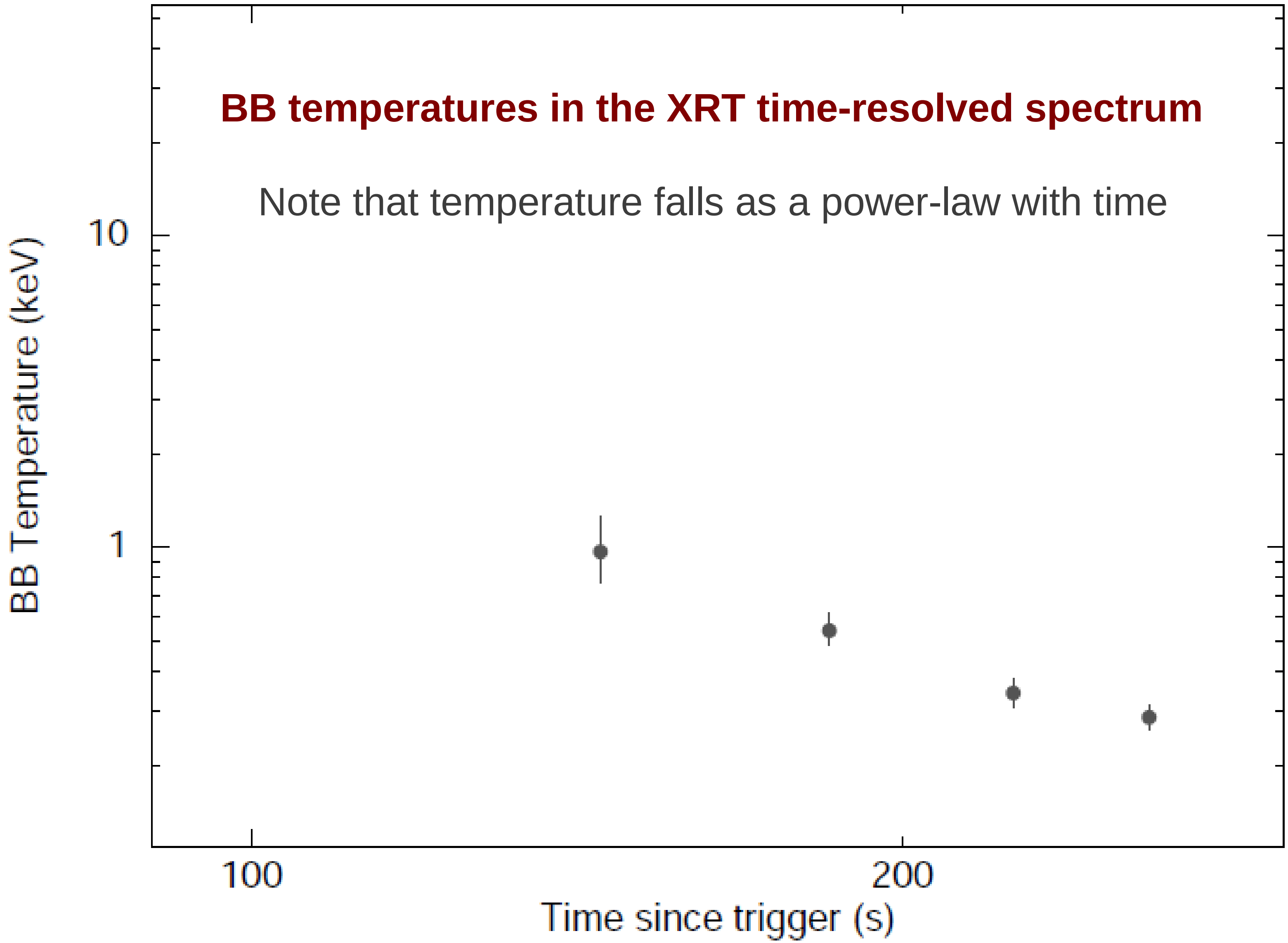

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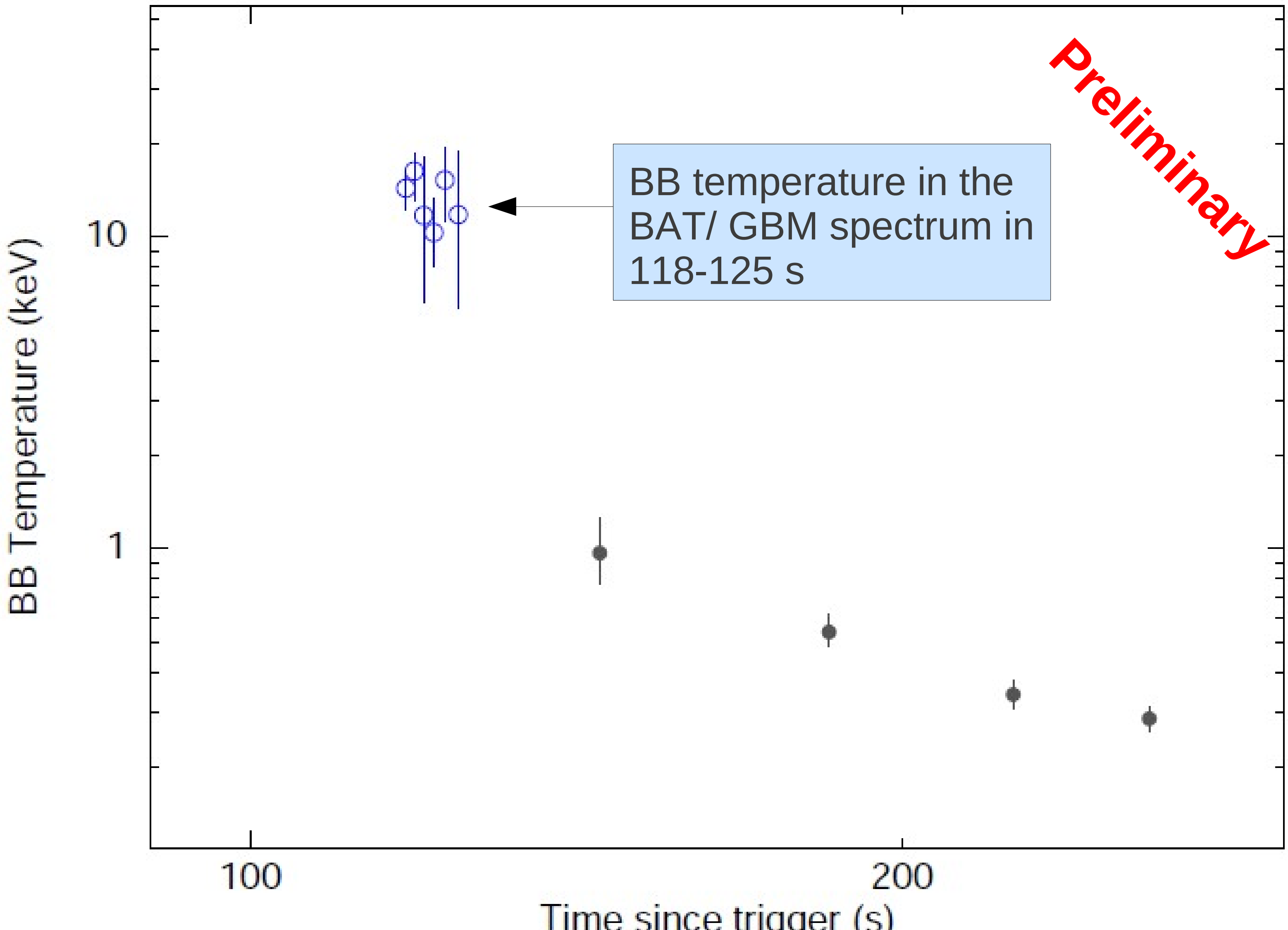
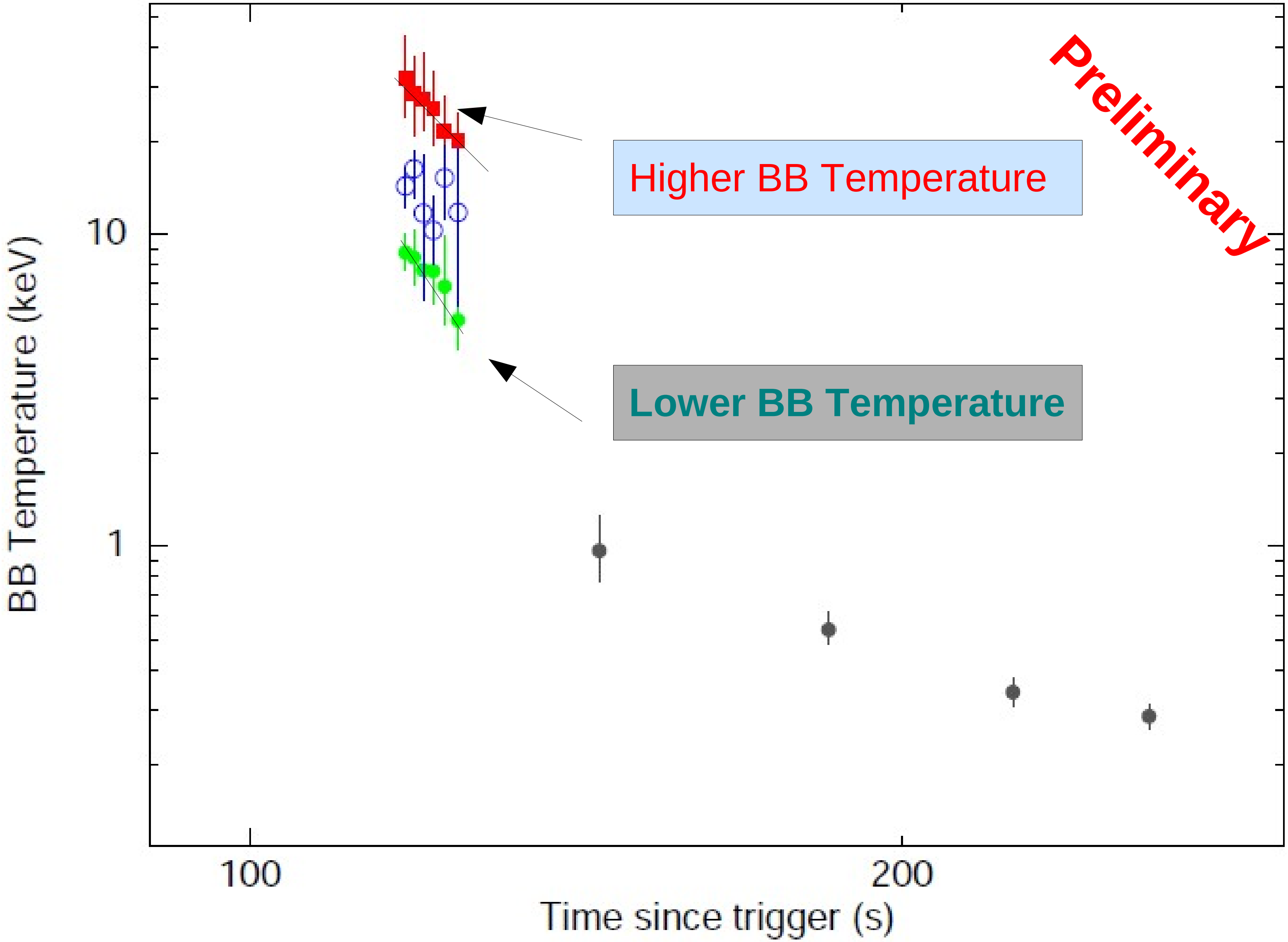


XRT Observation of the Second BB



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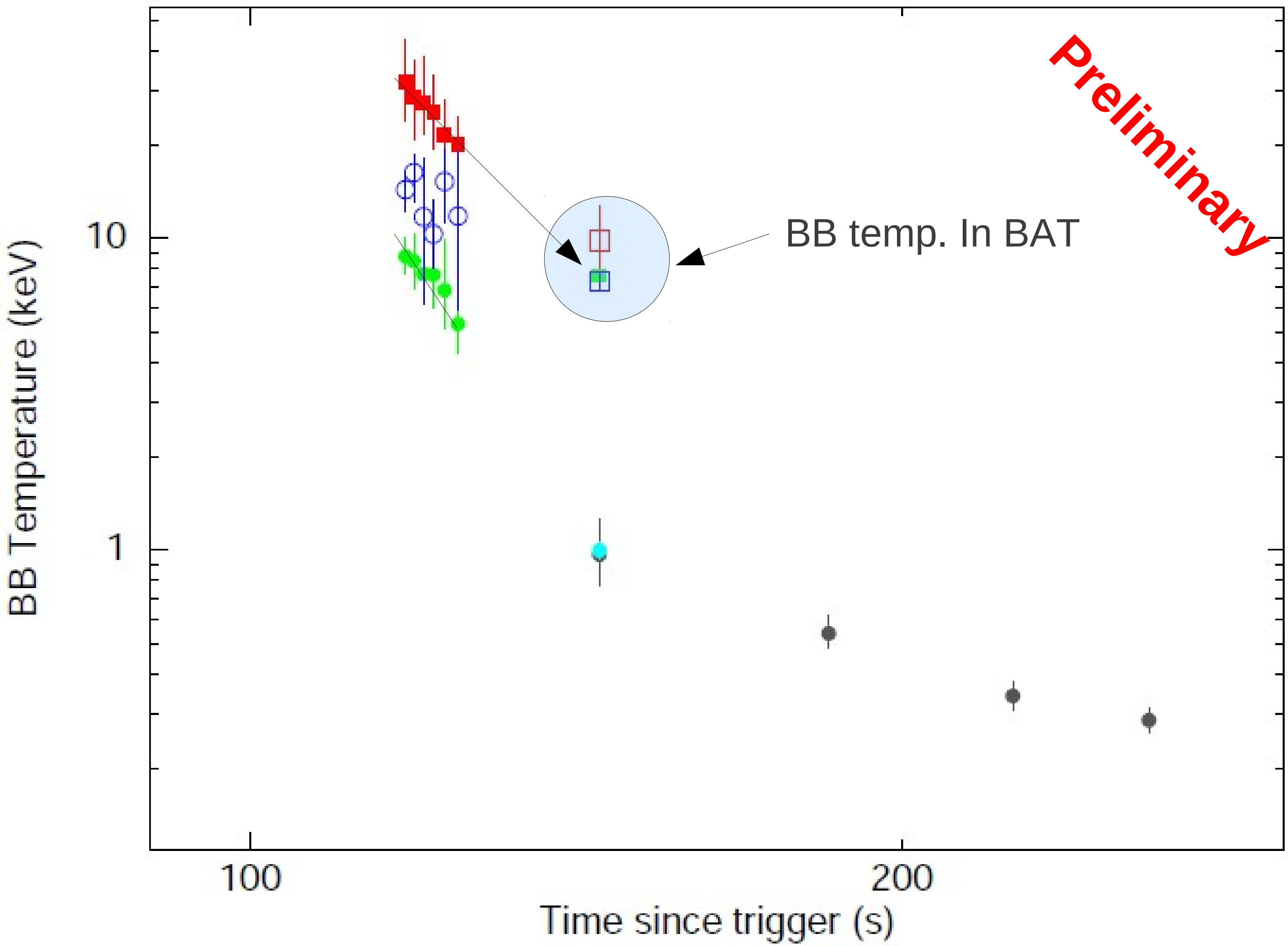

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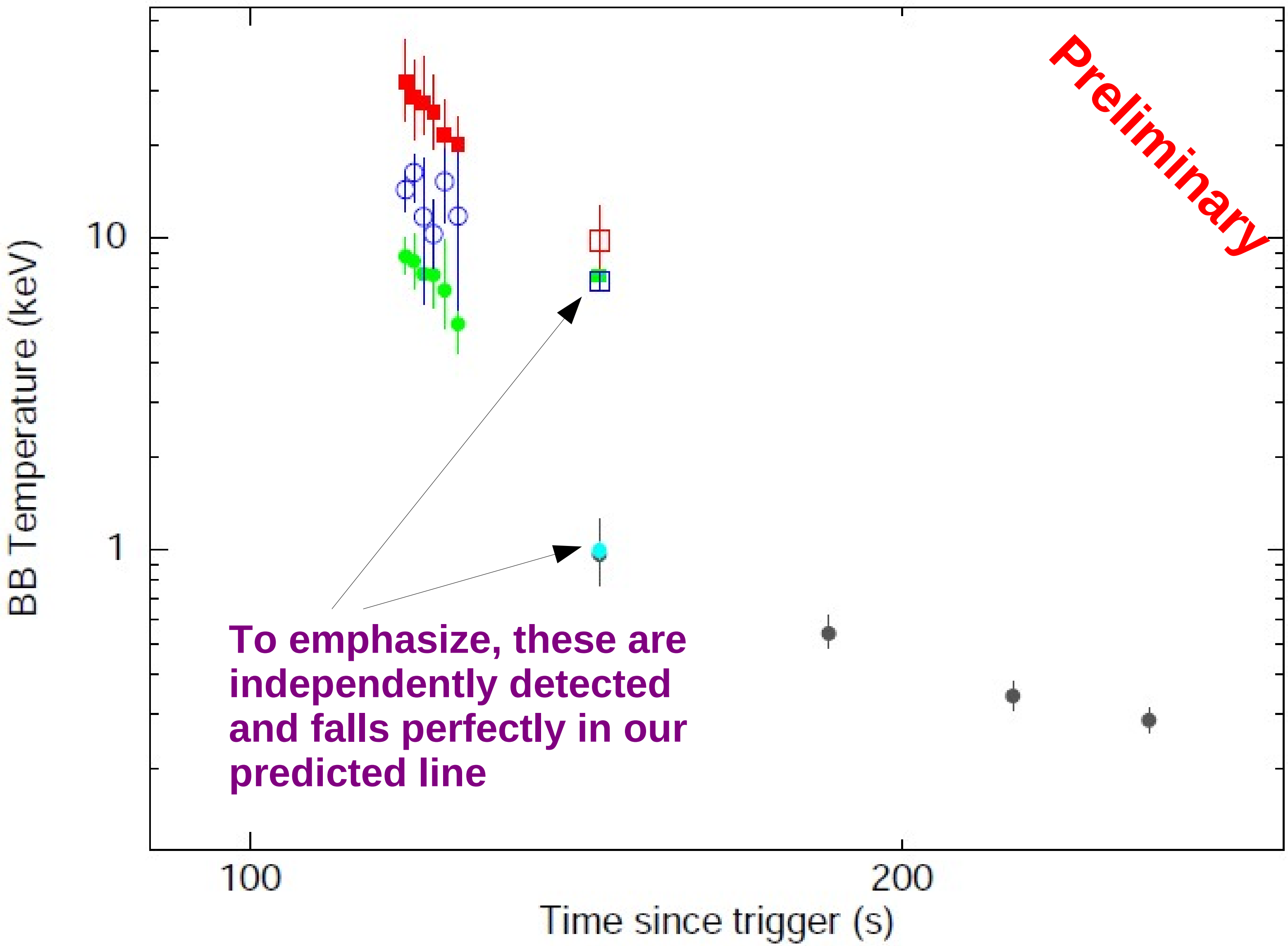


The Model

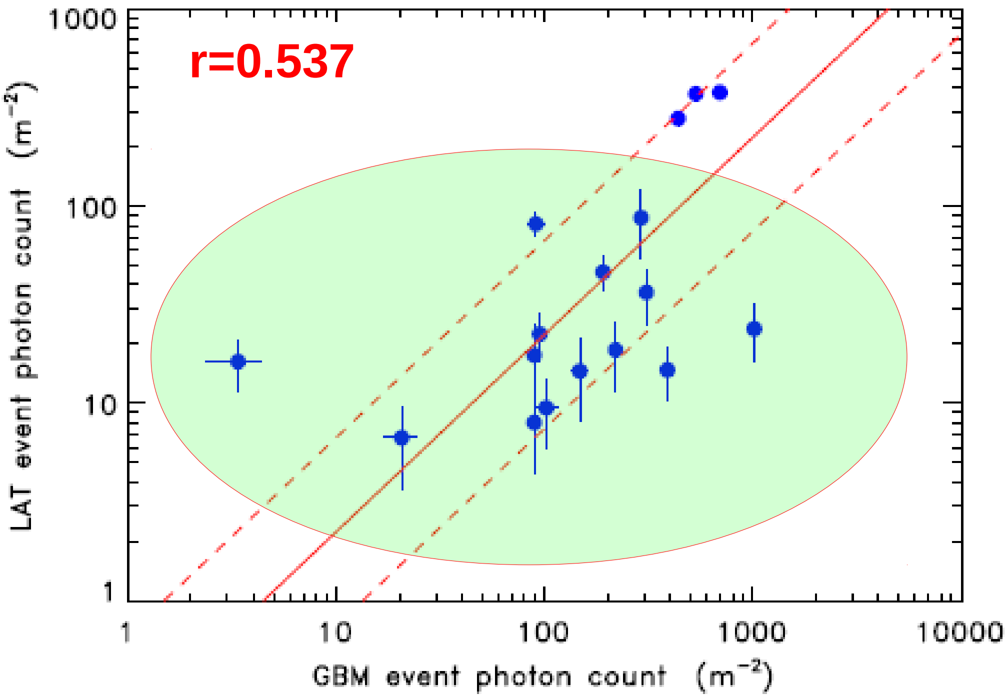
V. Predicting GeV emission

Predicting GeV Emission

- First detection: GRB 940217 (Hurley et al. 1994), observed by CGRO/EGRET, 90 minutes after the CGRO/BATSE detection.

- Features: (a) Delayed onset, (b) longer lasting, (c) late time power-law temporal evolution, (d) spectrum: either an extrapolation of Band or significantly different component (most notable for bright cases)

- **Problems:** (1) No unified spectral model found for MeV-GeV data (e.g., Zhang et al. 2011 found five combinations) (2) Very weak MeV-GeV correlation to draw inferences



Zheng et al. 2012

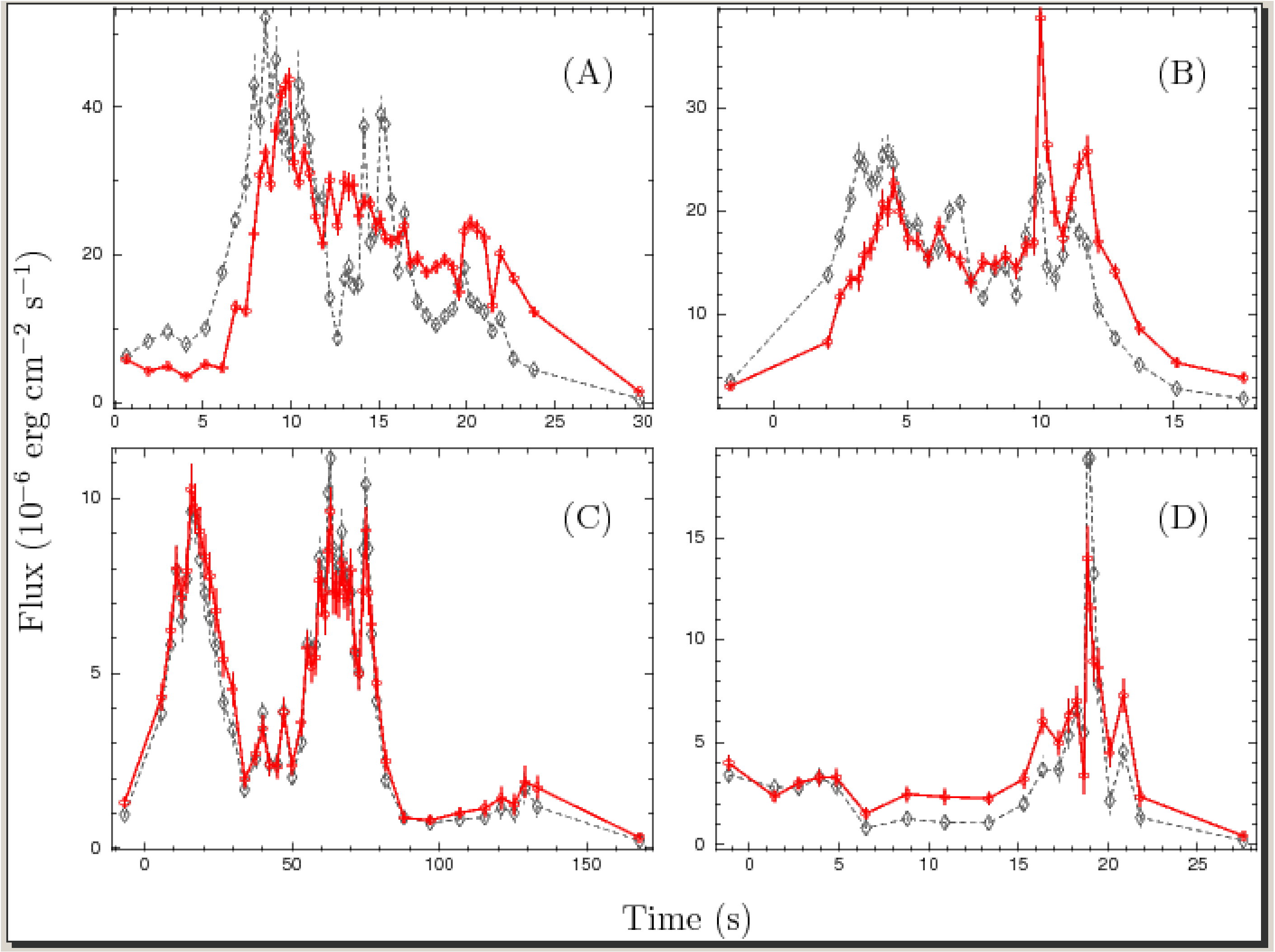
- **Solution?** Try multi-component spectral model. We select two pair of GRBs with comparable GBM fluence, but widely different LAT fluence.

Morphological Difference

Basak and Rao 2013b, ApJ 775, 31

High LAT count:
(A) 090902B,
(B) 090926A

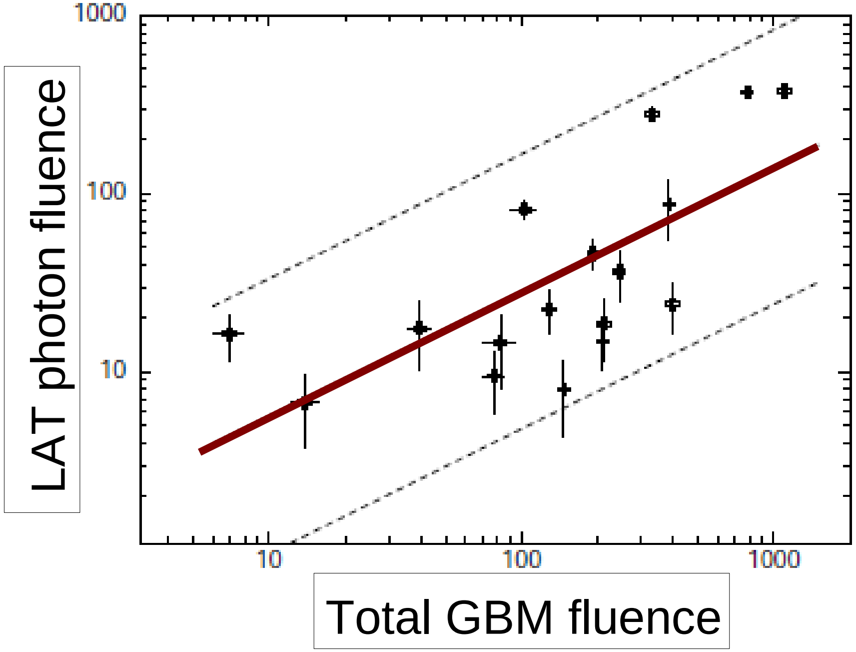
Low LAT count:
(A) 100724B,
(B) 091003

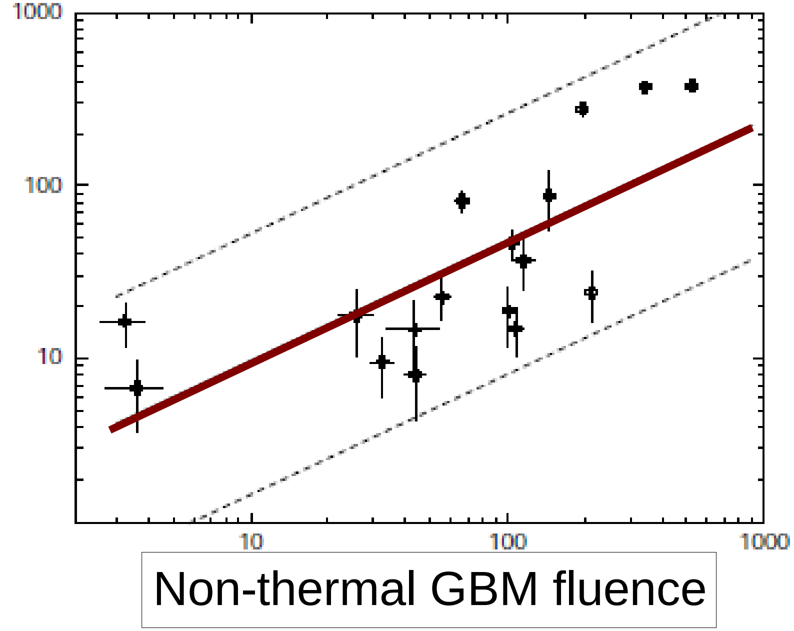


MeV-GeV Correlation

Basak and Rao 2013b, ApJ 775, 31

Correlations between the LAT fluence with the GBM fluence and GBM PL fluence





Correlation	Pearson r	Pearson P	Spearman r	Spearman P	D-parameter
Total GBM-LAT fluence	0.87	5.66E-6	0.75	5.61E-4	-1.4
Non-thermal GBM-LAT	0.88	3.21E-6	0.81	9.23E-5	2..3

Conclusions and Future Works

Conclusions:

(1) The peak of the prompt emission spectrum of GRB has a photosphric origin. However, in most general case it has another weaker peak due to the structure of the jet itself (Rao, Basak, Bhattacharya et al. 2013 arxiv: 1308.2506; Basak & Rao et al. 2013 ApJ 768, 187)

(2) The 2BBPL model is always statistically better than other models. The PL component might be a combination of Fermi acceleration within the jet and synchrotron radiation in the IS regions

(3) GeV emission is the non thermal part of the MeV emission. (Basak & Rao et al. 2013 ApJ 775, 31)

Future work:

(1) Production of PL component along with very high GeV emission has to be investigated with greater detail

(2) A full simulation of the prompt emission with varying jet profile as well as optically thin synchrotron emission to be performed

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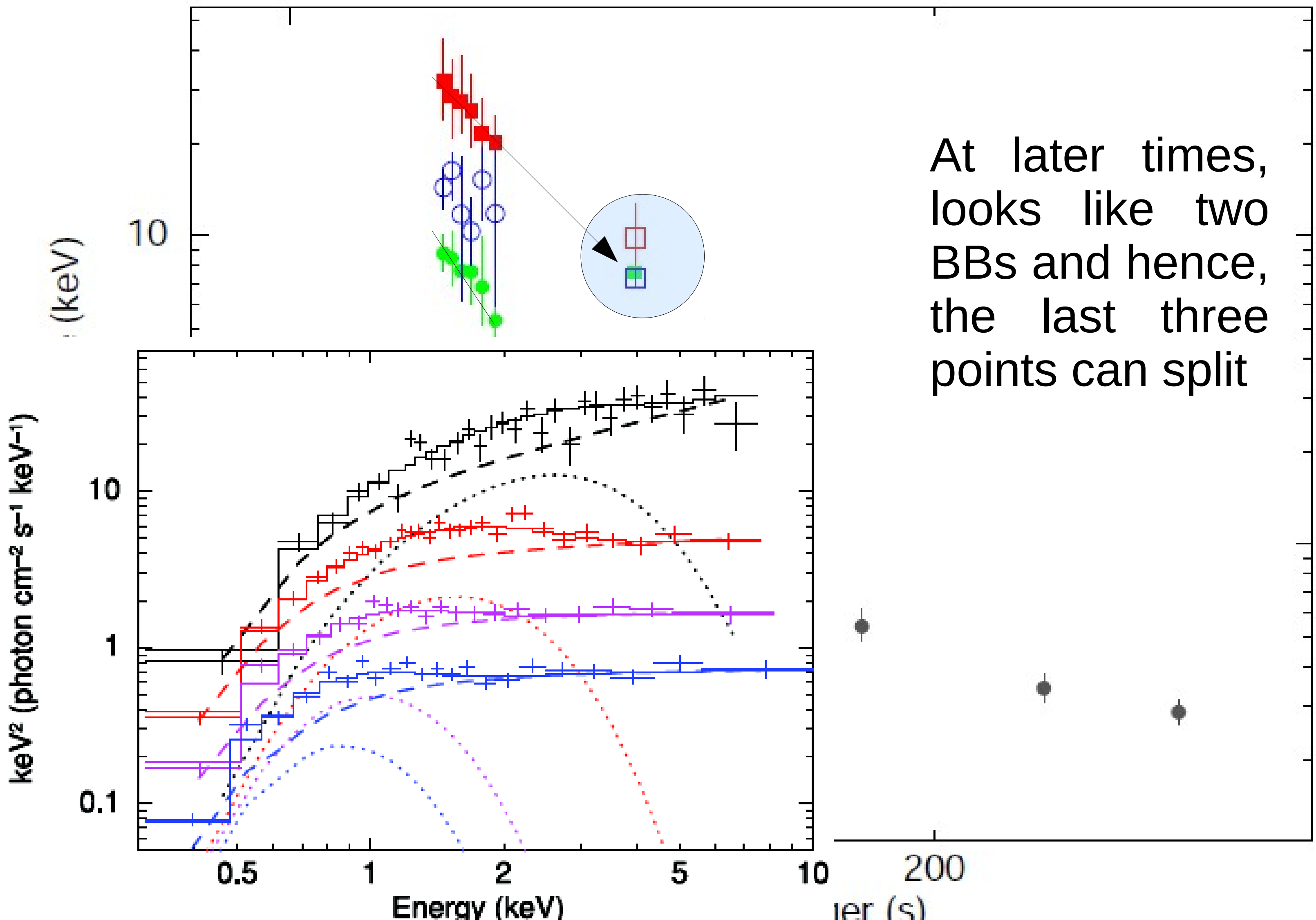

At later times, looks like two BBs and hence, the last three points can split