Fermi observations of the jet photosphere in GRBs: interpretations and consequences

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Stockholm University and OKC

On behalf of the *Fermi* GBM and LAT teams

Rencontres du Vietnam, Quy Nhon, August 14, 2013

Bottom line:

- The emission mechanisms for GRBs are still unclear, but *Fermi* observations show that the photosphere plays an important role.

- The inclusion of the thermal component is the first step towards an **understanding the physical origin** of the prompt emission.

- *Fermi* provides evidence of subphotospheric heating (*Photosphere* $\not\rightleftarrows$ *Planck function*)

We need time resolved spectroscopy!

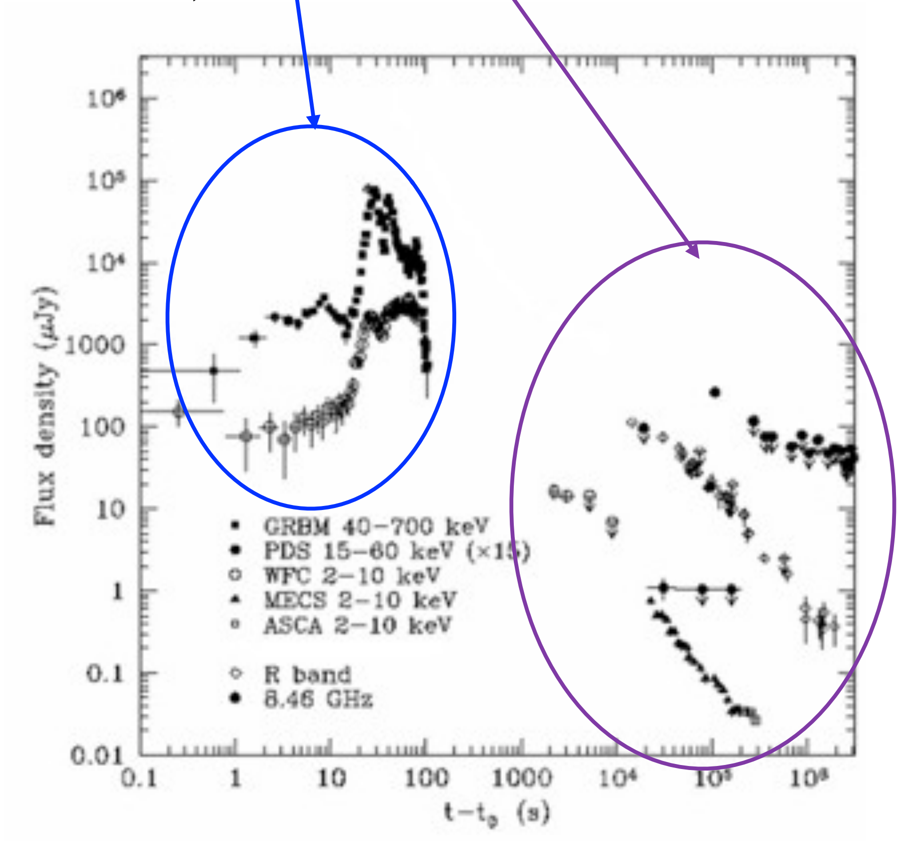
GRBs: general properties

- Transient
- Very bright sources
- Observe ~1 per day
- Isotropically distributed on sky
- Cosmological distance (highest z~9)

Two phases:

• The PROMPT phase: lasting ~ 100s mainly in the kev-MeV band;

• The AFTERGLOW phase lasting >3000s;



Very different light curves...

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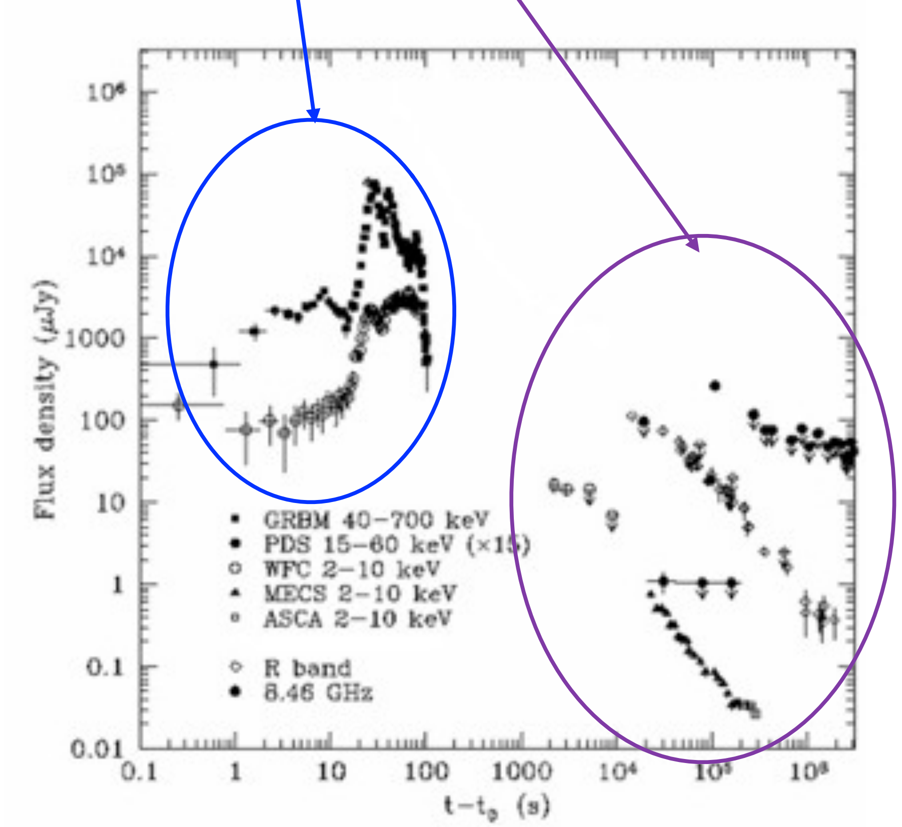

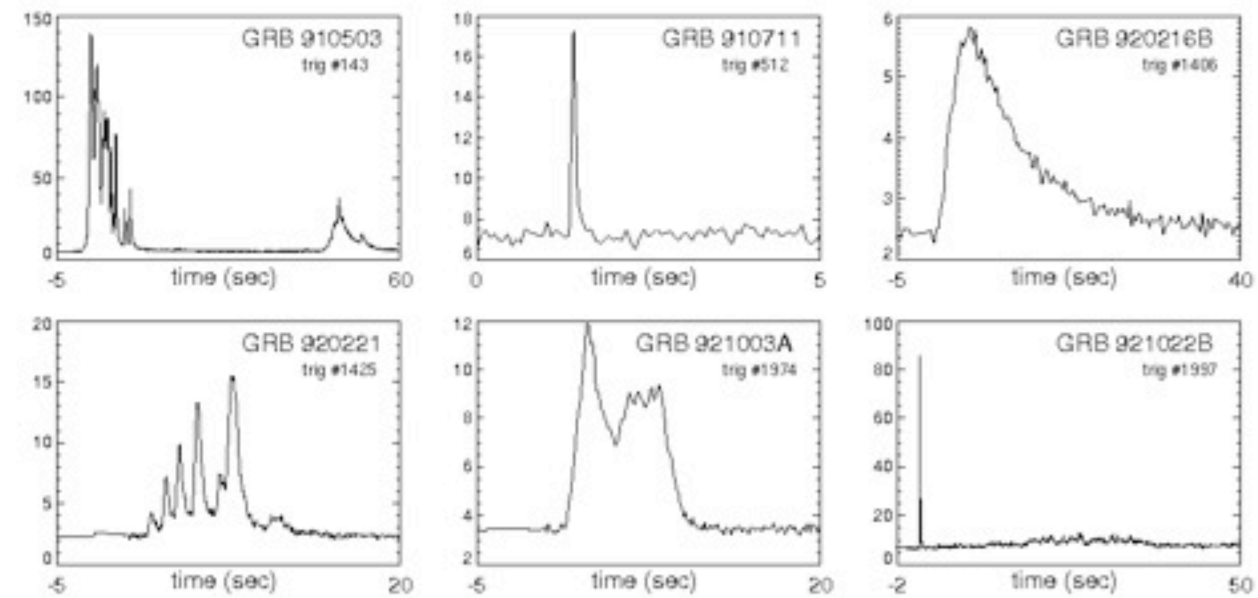

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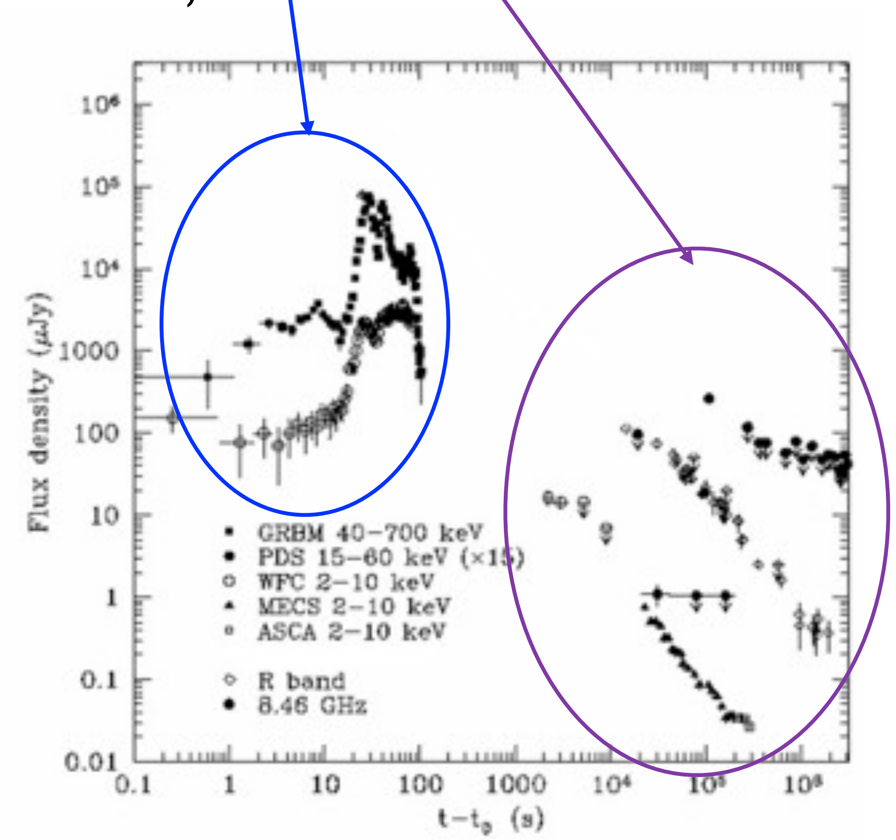
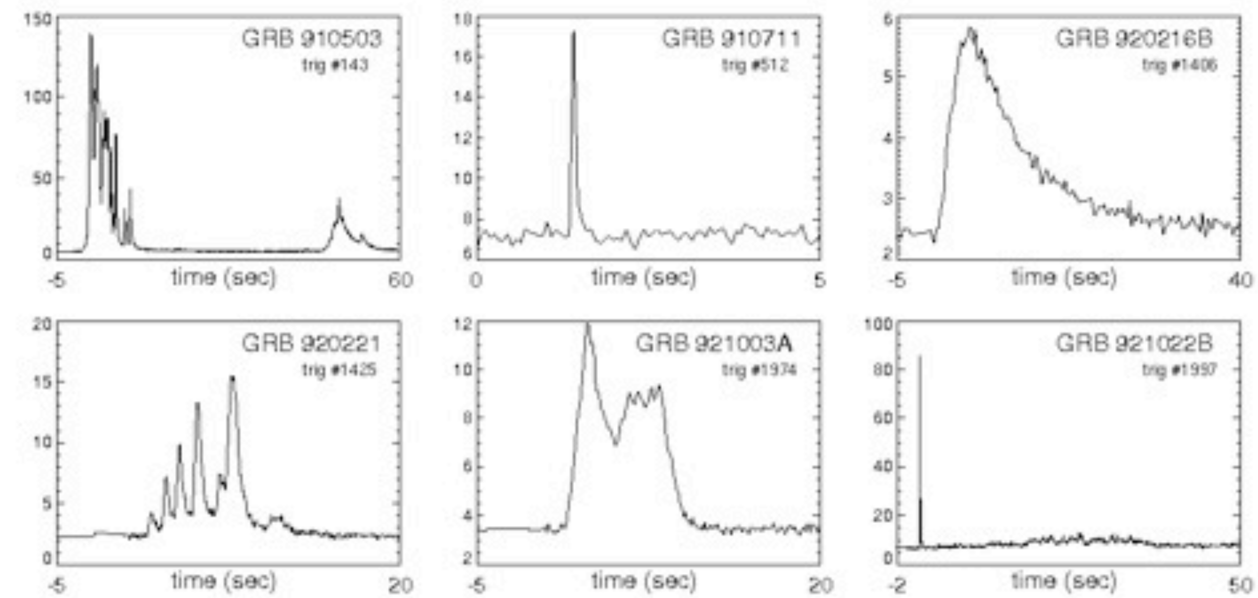
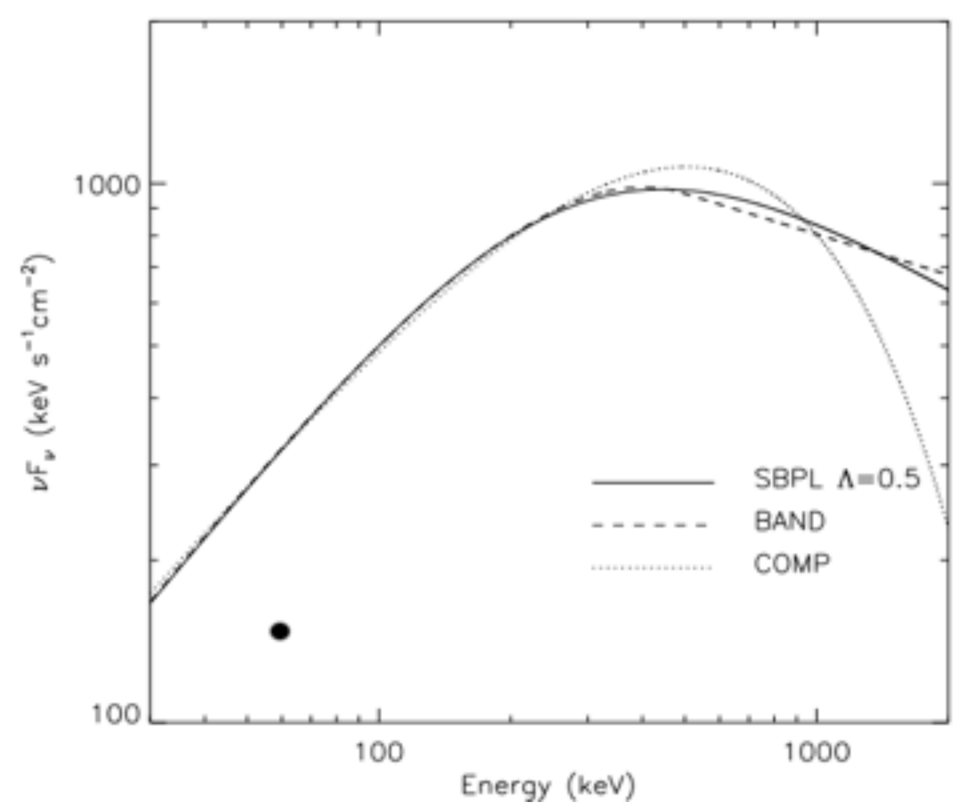


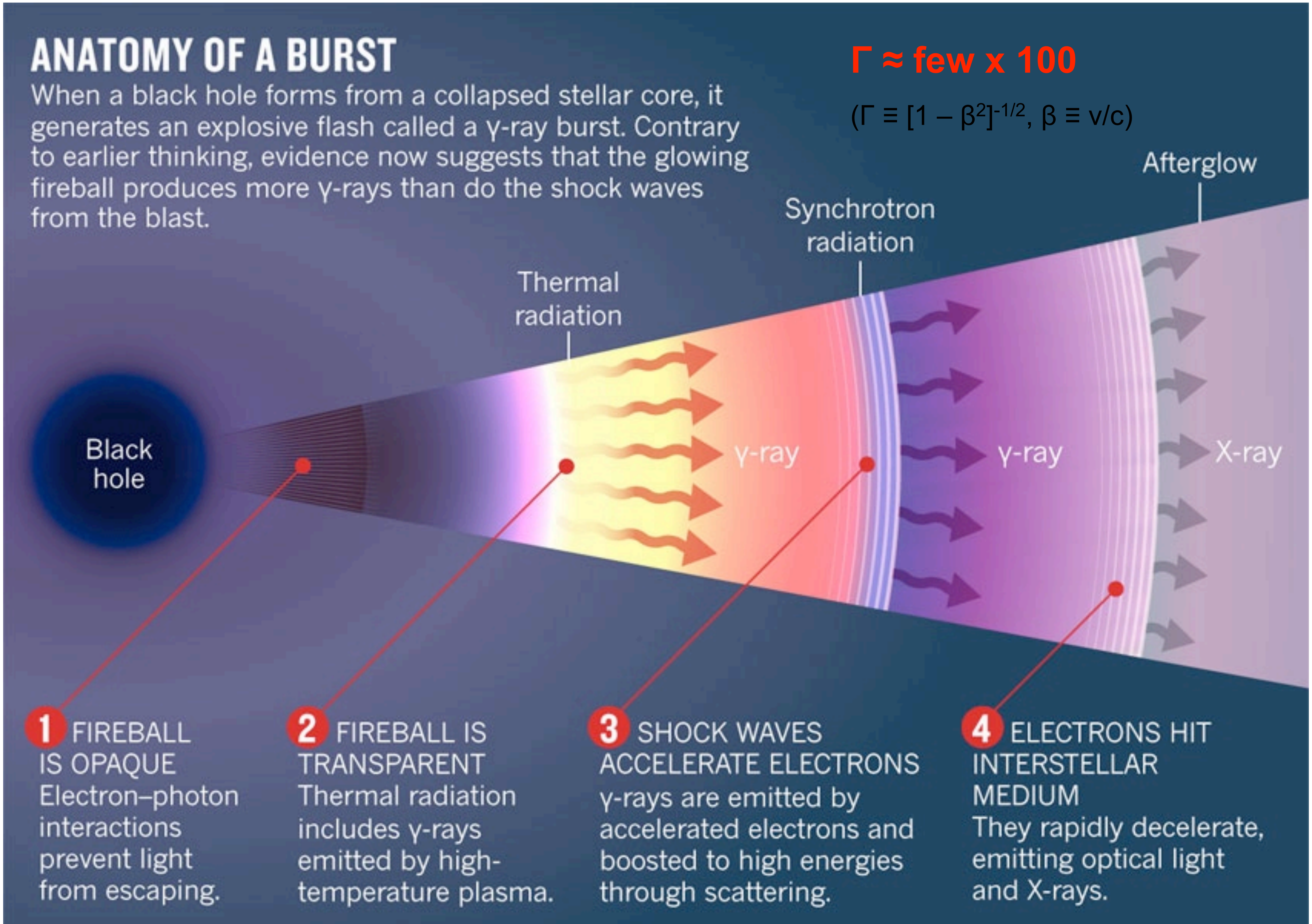


...but spectra quite similar.



Gravitational potential energy → “Fireball”

(Mészáros 2006)



Should there be thermal emission in GRBs?

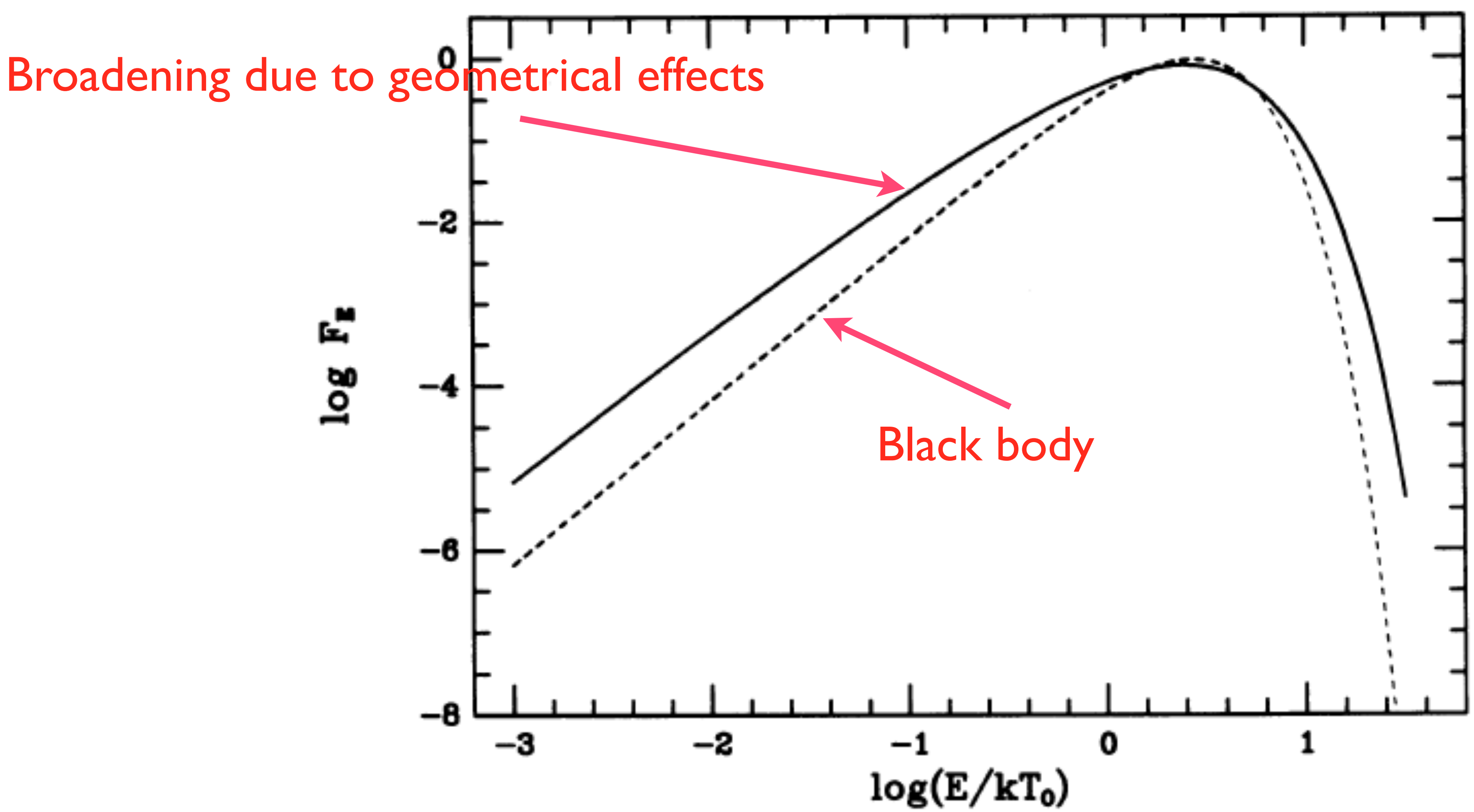
1986: Thermal emission from the fireball

Variability >~10 ms
Cosmological distances
Observed Flux: ~10^{-7} - 10^{-4} erg cm^{-2} s^{-1}
Typical observed energy: <~ MeV

→ Fireball model, high optical depths

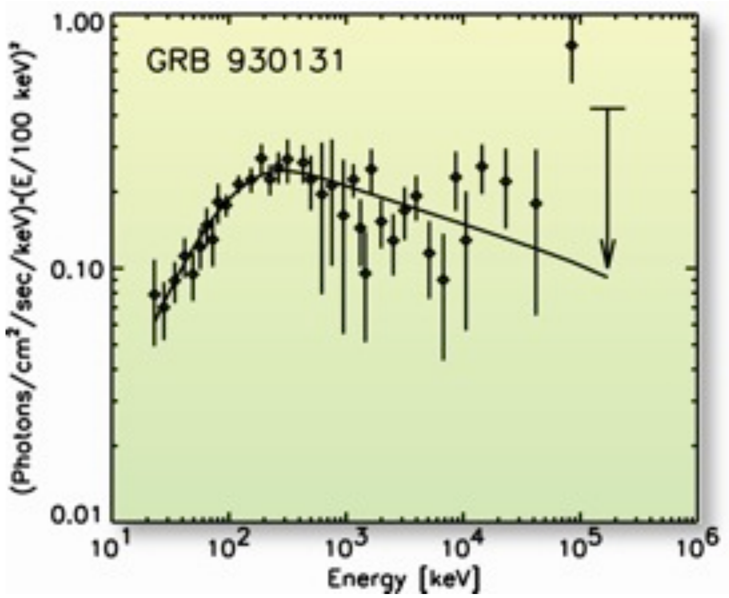
→ Strong thermal component expected ~1 MeV and at 10^{12} cm

Goodman (1986), Paczyński (1986), Thomson (1994) etc.

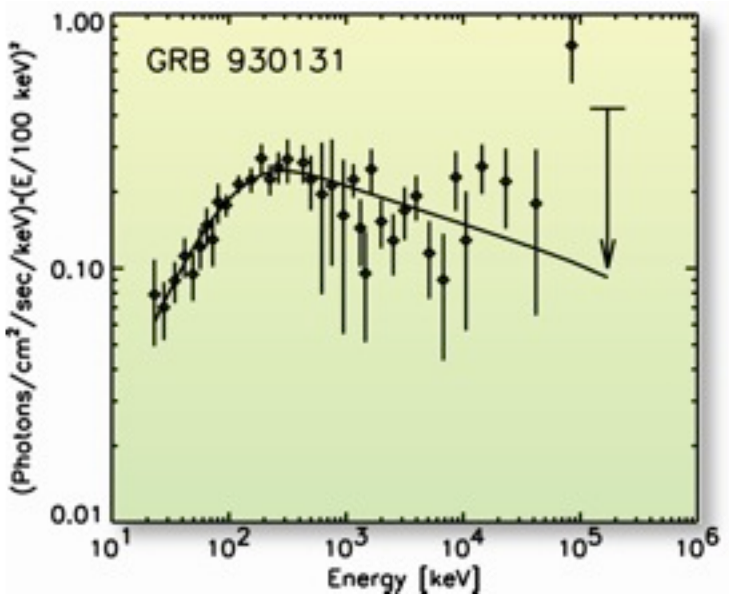


Paczyński 1986, ApJL, 308, 47

FIG. 1.—*Solid line*: energy distribution of the flux received by a distant observer at rest with respect to the center of mass of the fluid. The vertical scale in arbitrary units. (*Dashed line*): corresponding distribution for a blackbody at the initial temperature of the fluid.



Observed spectra are *not* Planck spectra



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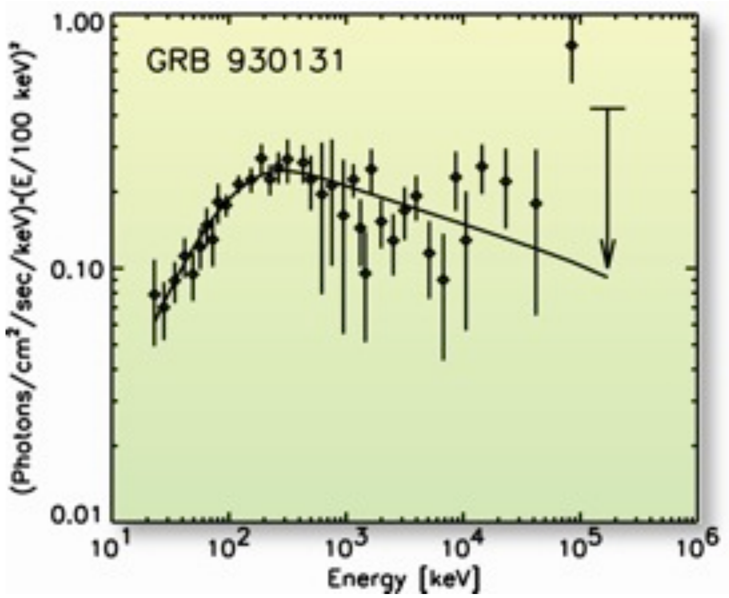
Solution?



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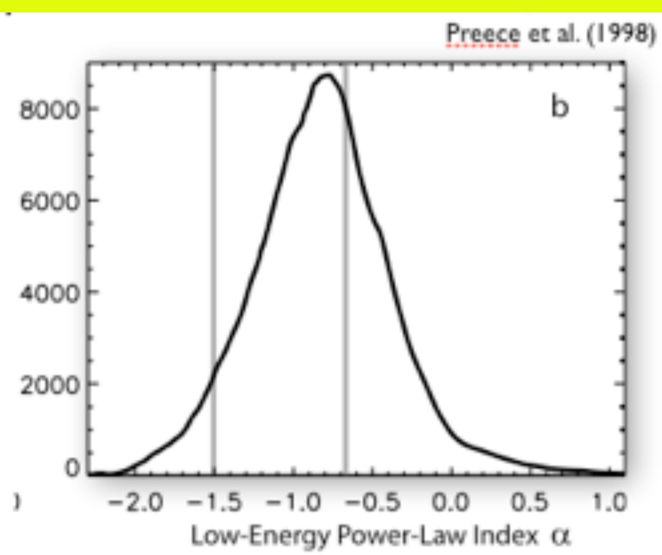
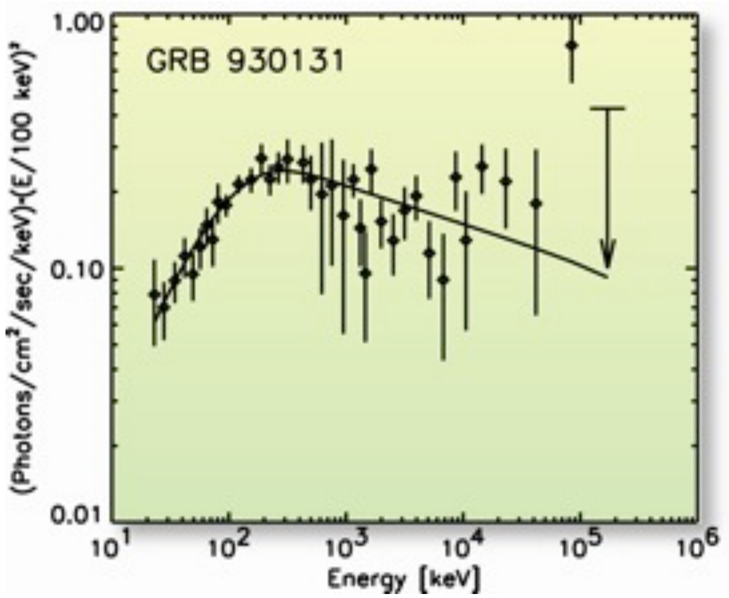
Solution?

Optically thin
synchrotron emission
in internal shocks; jitter radiation, IC

- Line of death
- shock acceleration
- efficiency of internal shocks



Slope of cooling spectrum $\alpha = -1.5$



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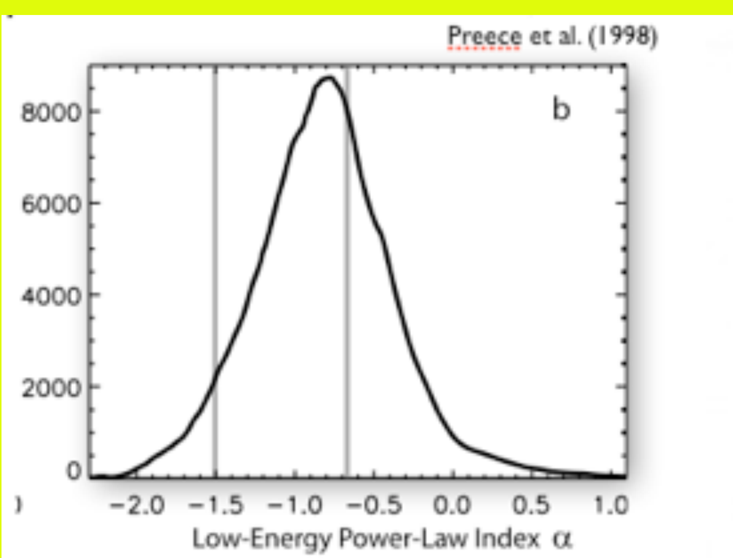
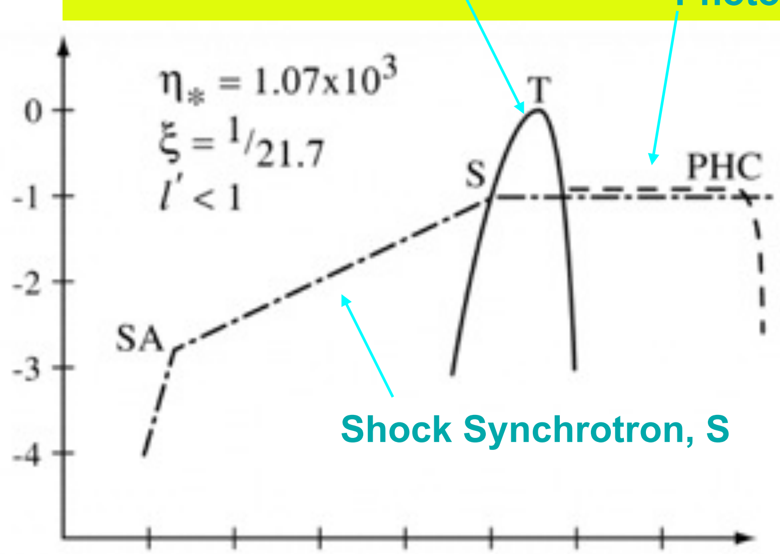
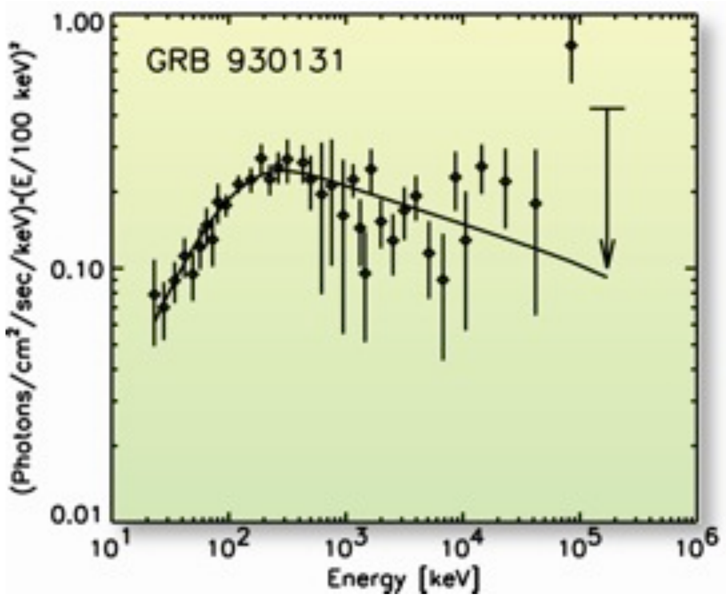


Slope of cooling spectrum α = -1.5

Multiple spectral components (e.g. Mészáros et al. 2002)





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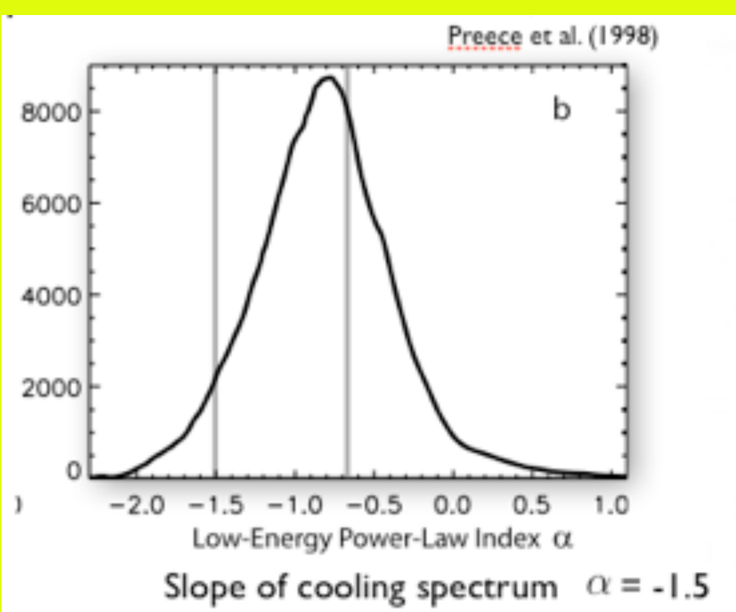

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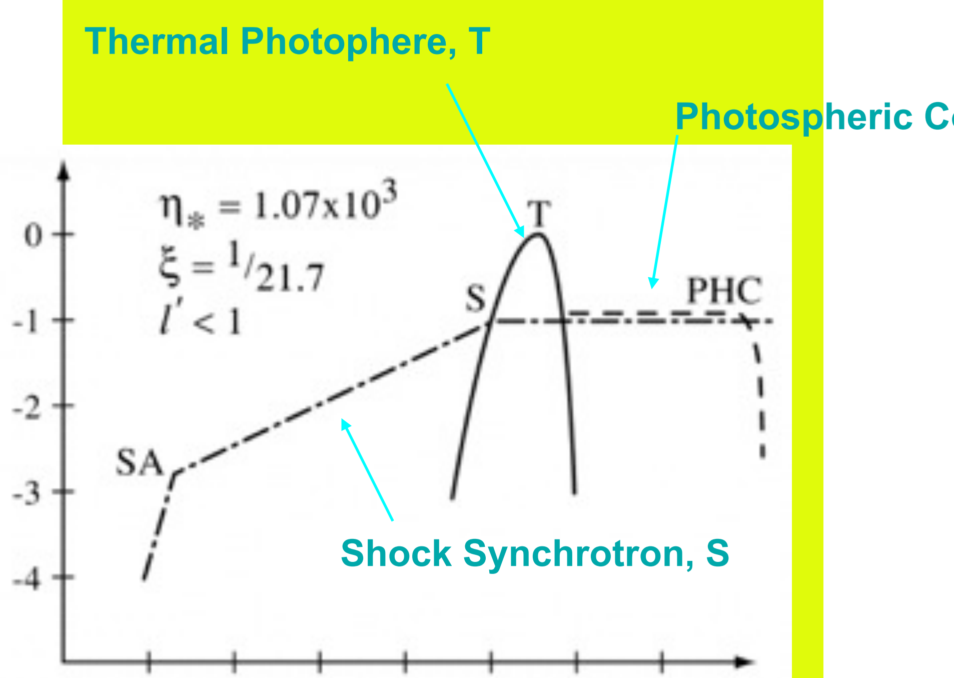
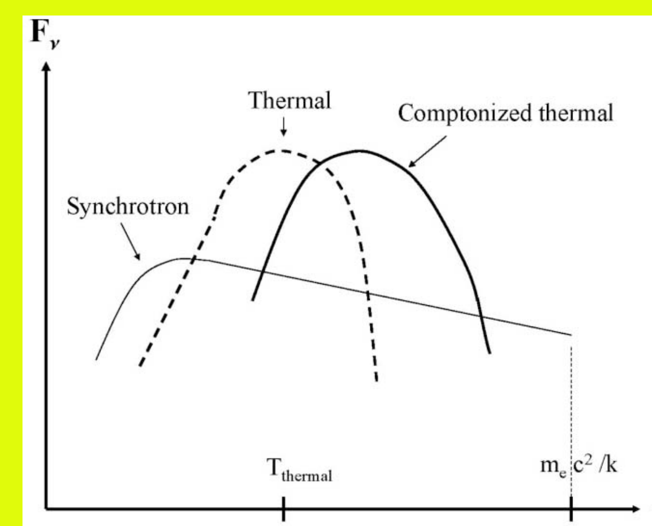


The emission from the photosphere is **not Planckian**

- Subphotospheric dissipation (Rees & Mészáros 2005, Pe'er et al 2006 Daigne & Mochkovitch (2002), Giannios (2007) and Lazzati (2009), Beloborodov 2011)

- Geometrical effects (Pe'er 2008, Lundman et al. 2012)



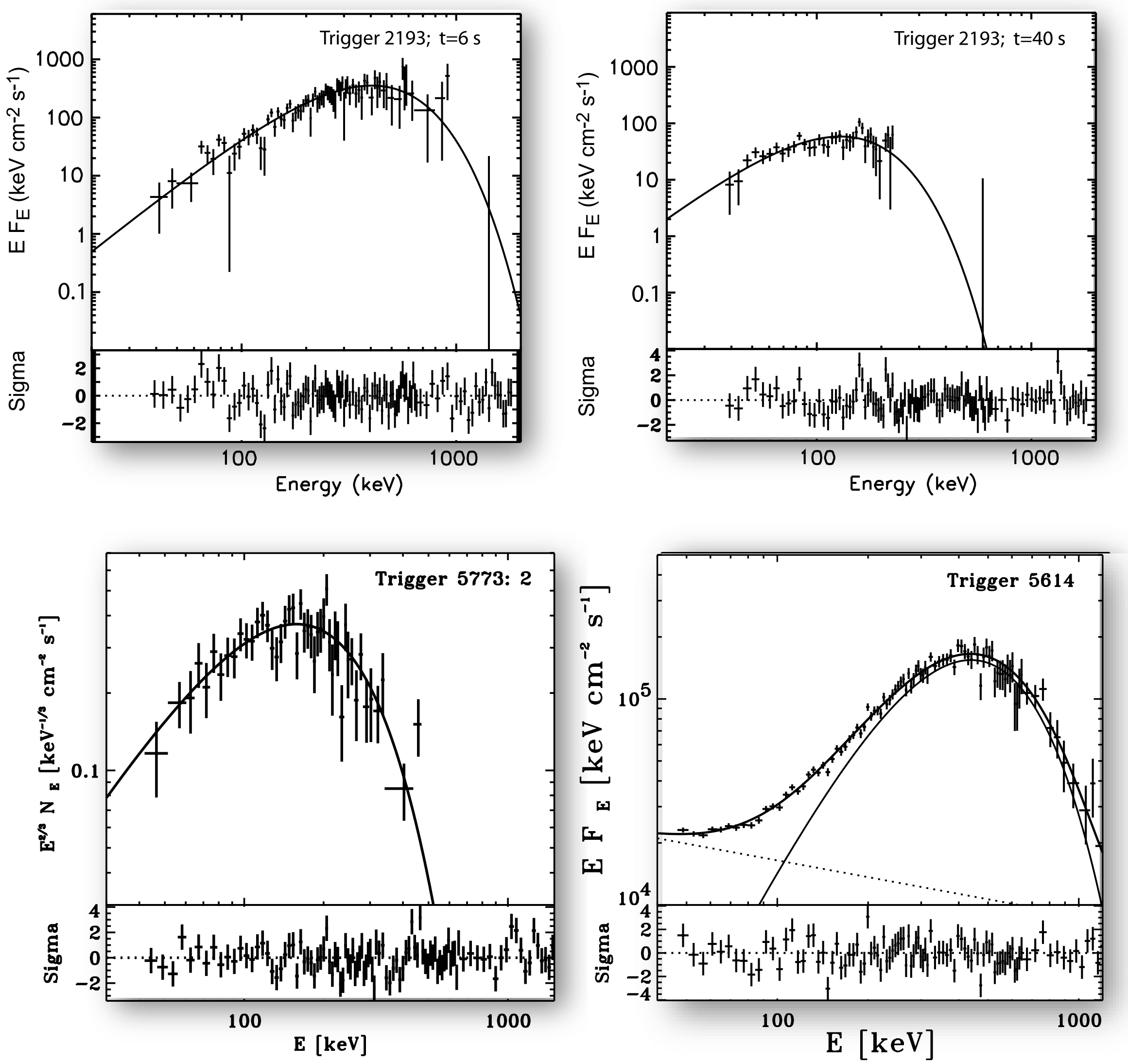
CGRO BATSE ERA (1994-2000)

Photospheric emission in BATSE bursts

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

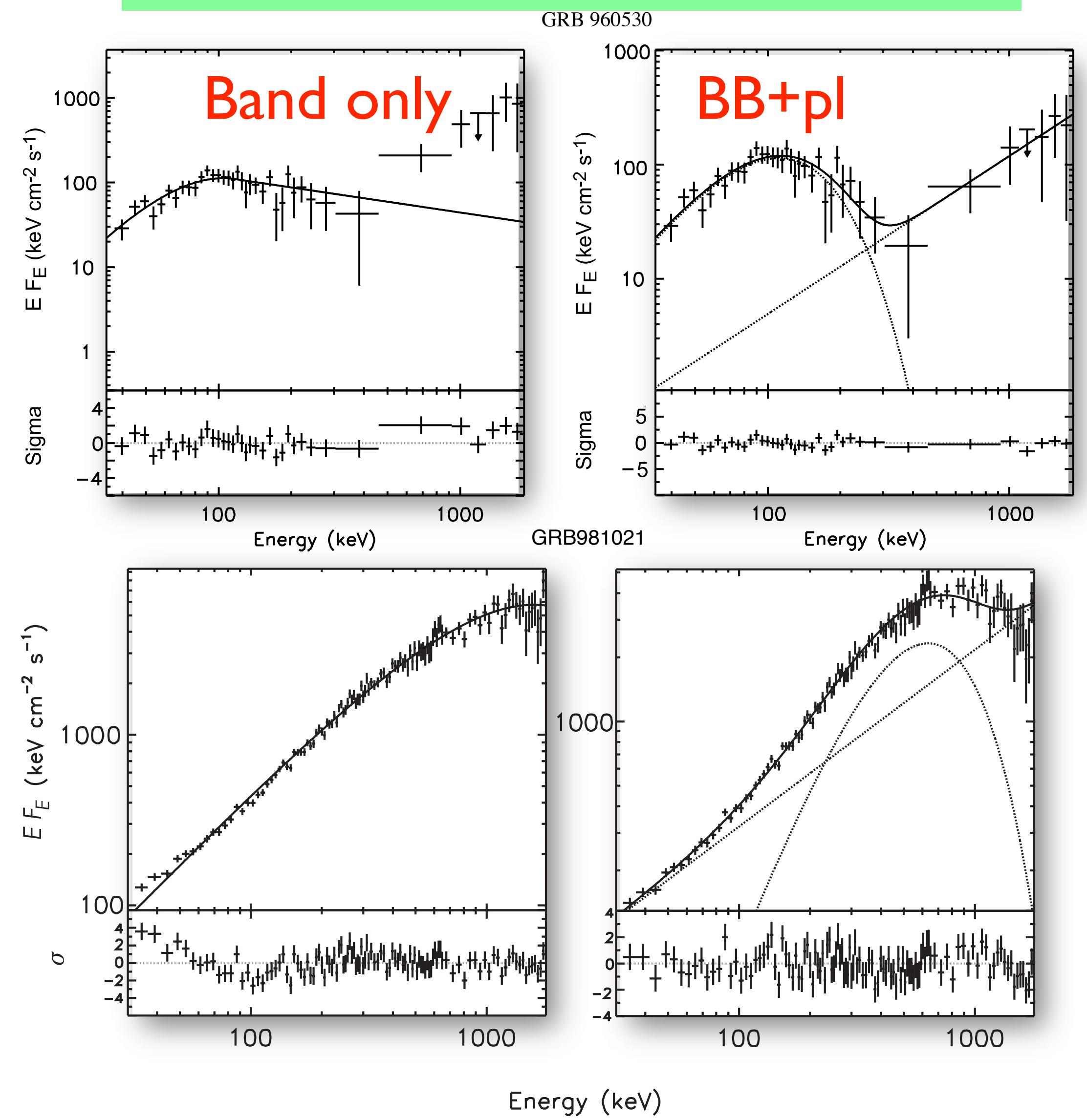
Spectral fit: Black body combined with a power law: $$N_{\rm E}(E,t) = A(t)\ \frac{E^2}{exp[E/kT(t)]-1} + B(t)\ E^s$$

Photosphere (Planck function)



Ryde 2004
(see also Ghirlanda et al. 2003)

Additional non-thermal emission



EGRET TASC peak at E_p = 1600 keV

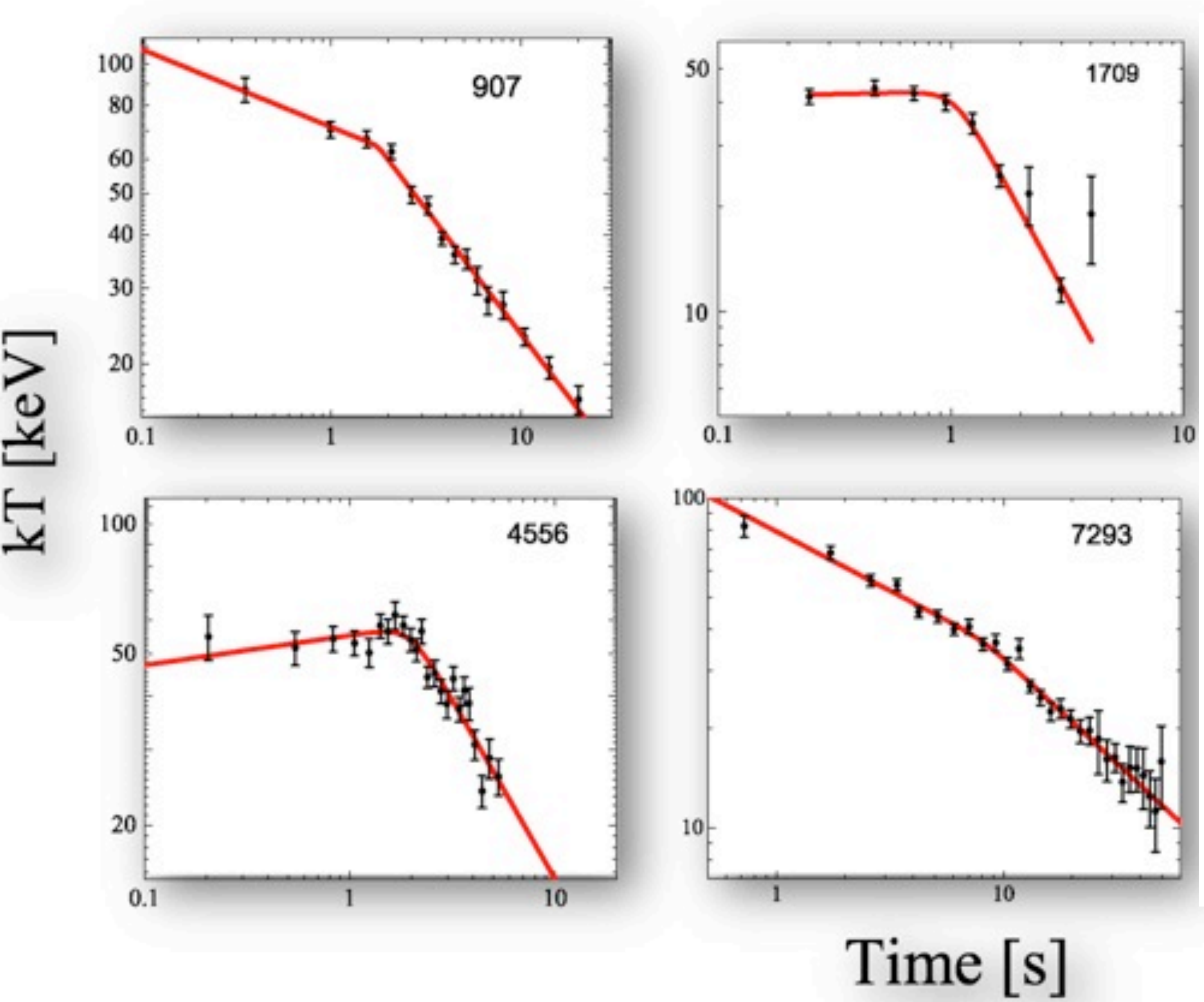
Ryde 2005

CGRO BATSE ERA (1994-2000)

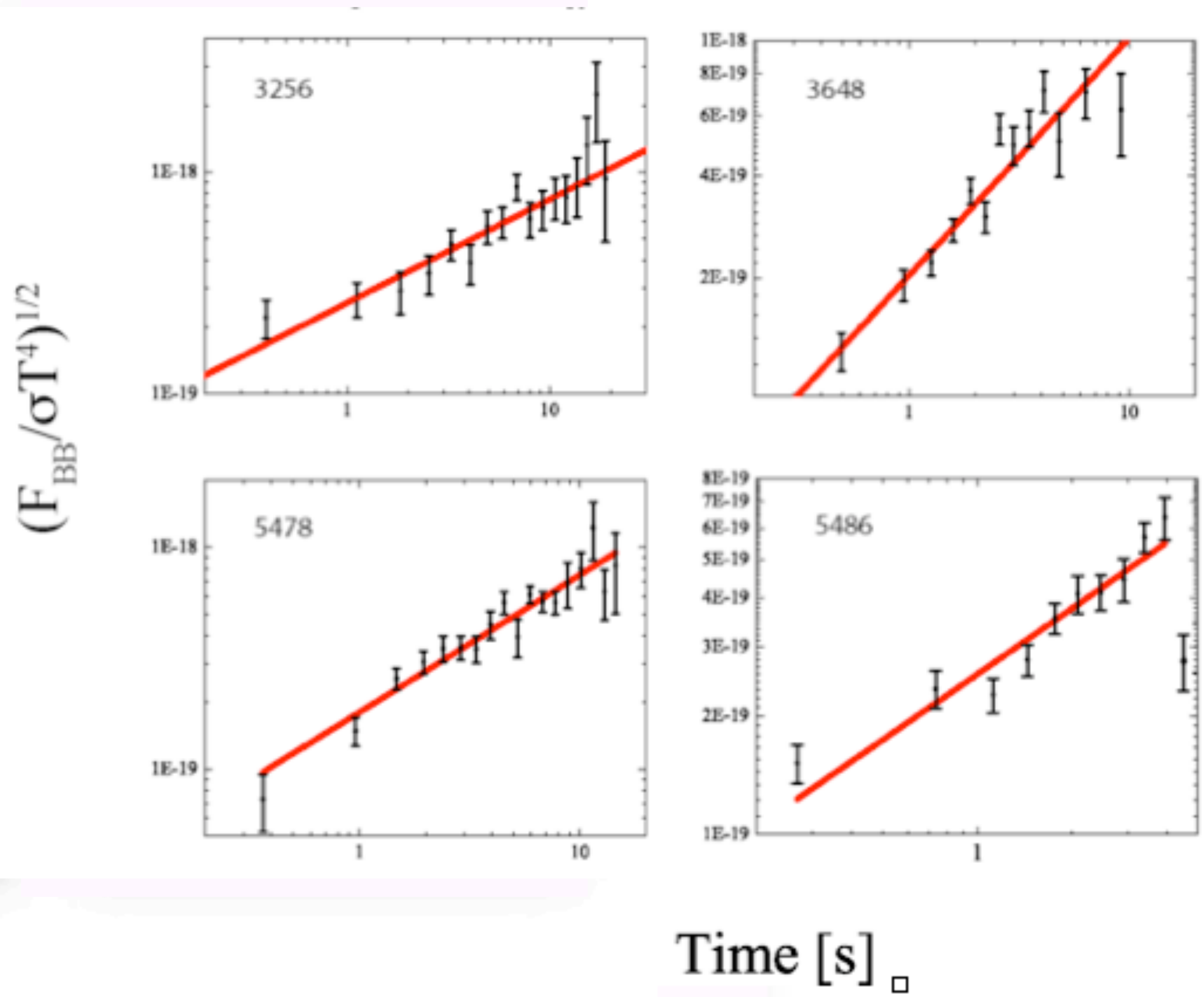
The spectral peak is due to a peaked thermal component. *Behavior of the thermal component:*

$$F(t) = A(t)\,[kT]^4\,\pi^4/15$$

Temperature Evolution *kT*



Evolution of the normalization, *A(t)*



Ryde & Pe'er 2009

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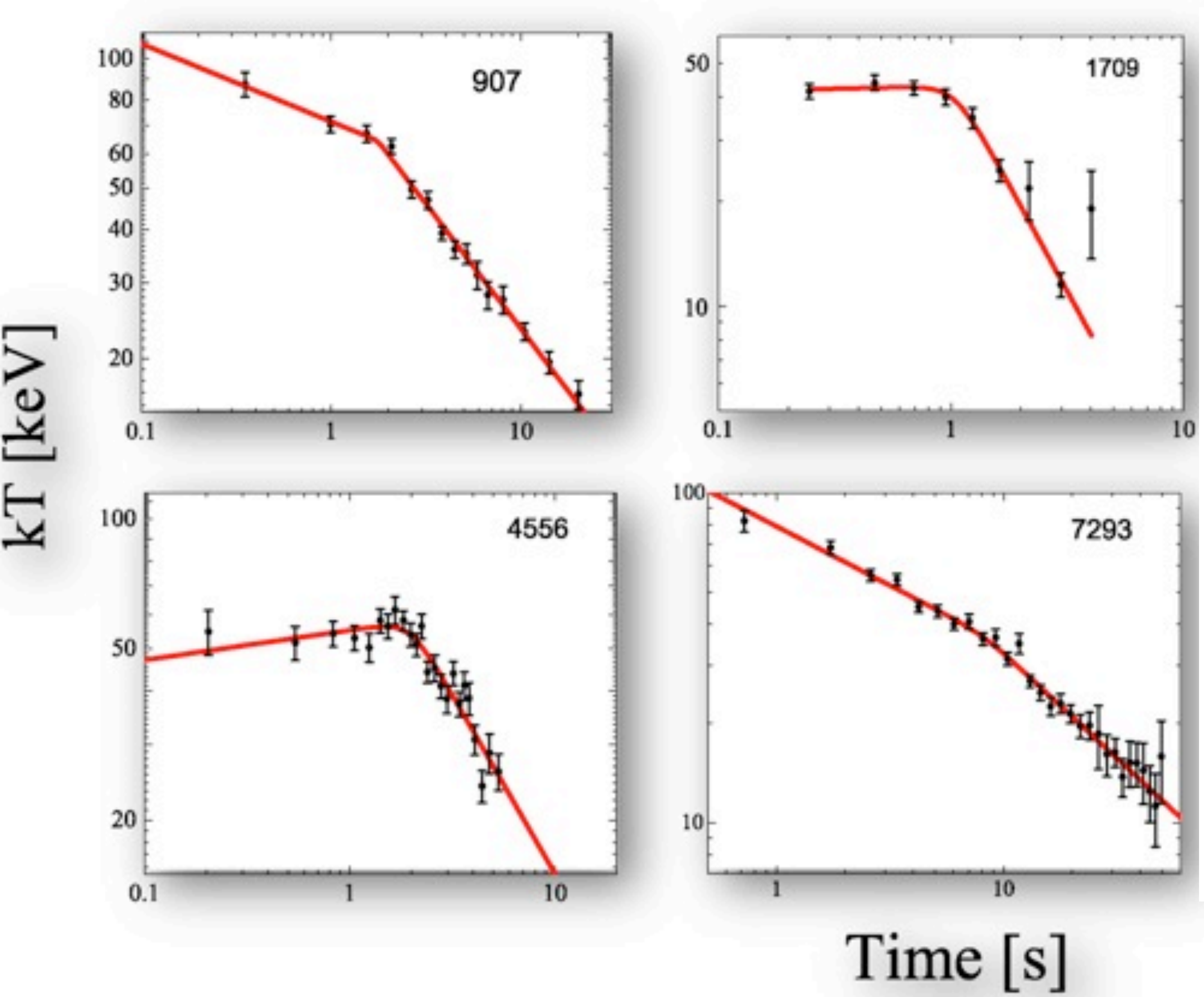

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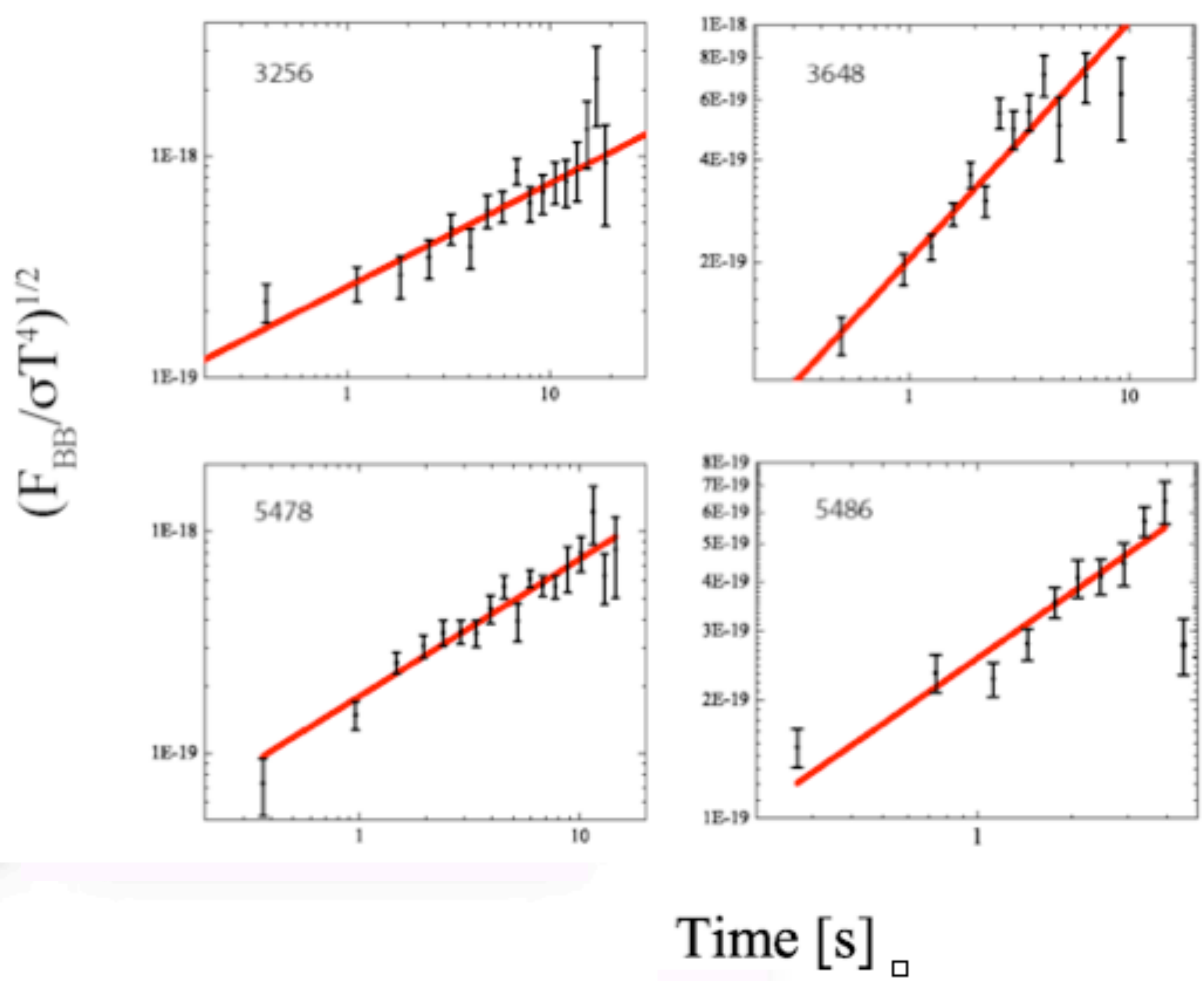
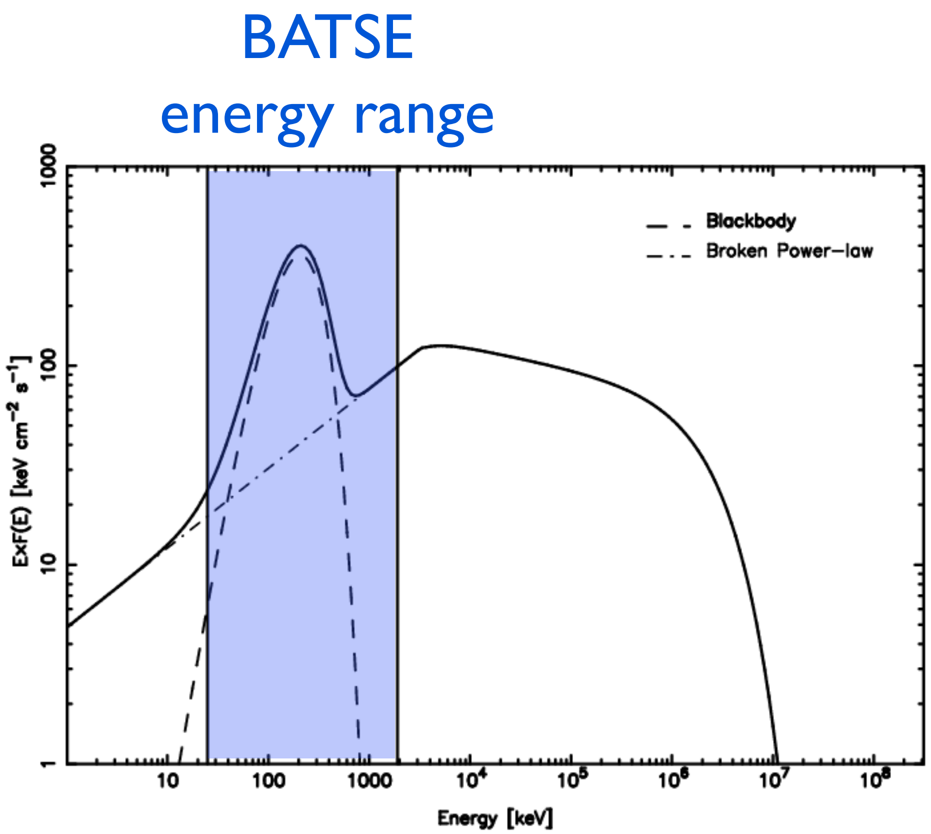


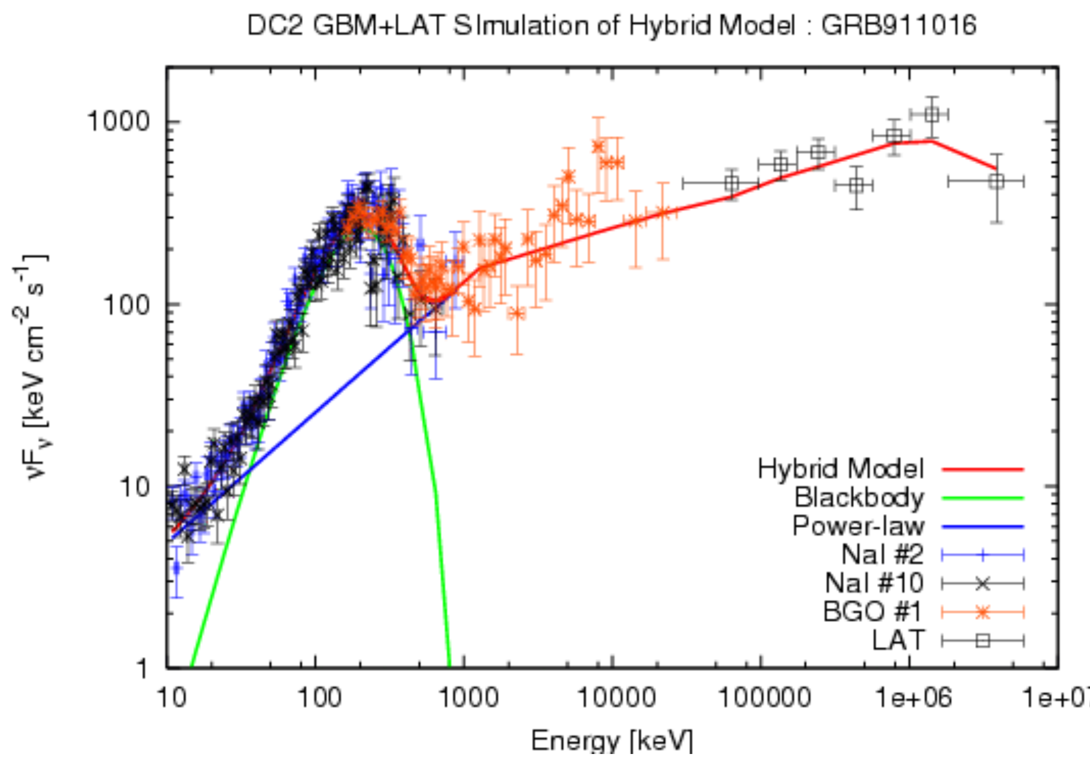
Distinct recurring behavior

Ryde & Pe'er 2009

Predictions for *Fermi* based on BATSE results

Simulations using prelaunch models of the response: gtobsim





Battelino, Ryde, Omodei, & Longo (2007)

Predictions for *Fermi* based on BATSE results

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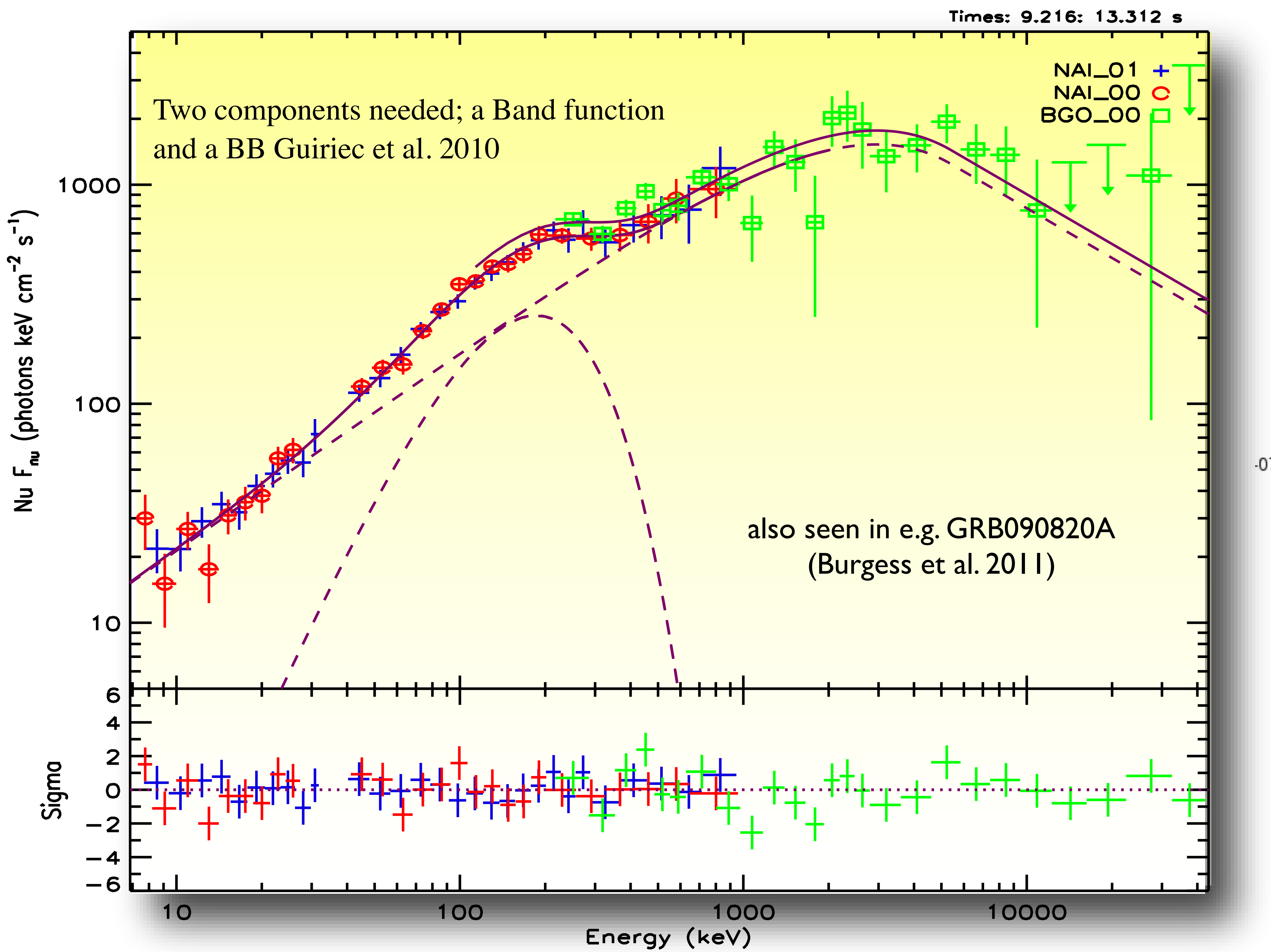
GRB100724B



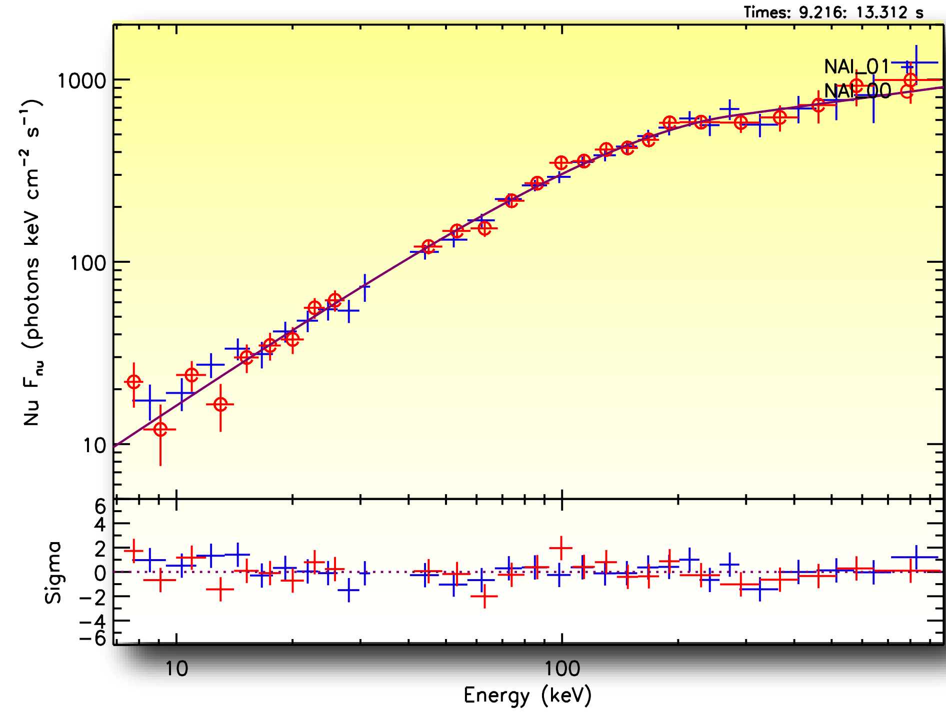
Photosphere in GRB100724B

Guiriec+10

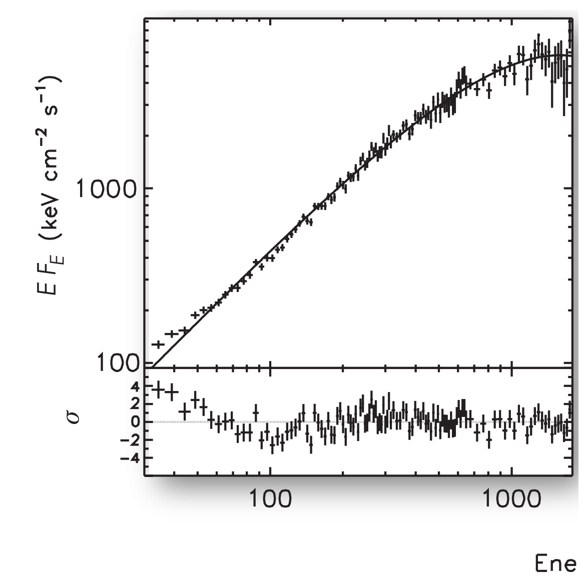
Limiting the band width to 8 keV - 1500 keV (Comparing the BATSE fits)

Band model

NaI
Band

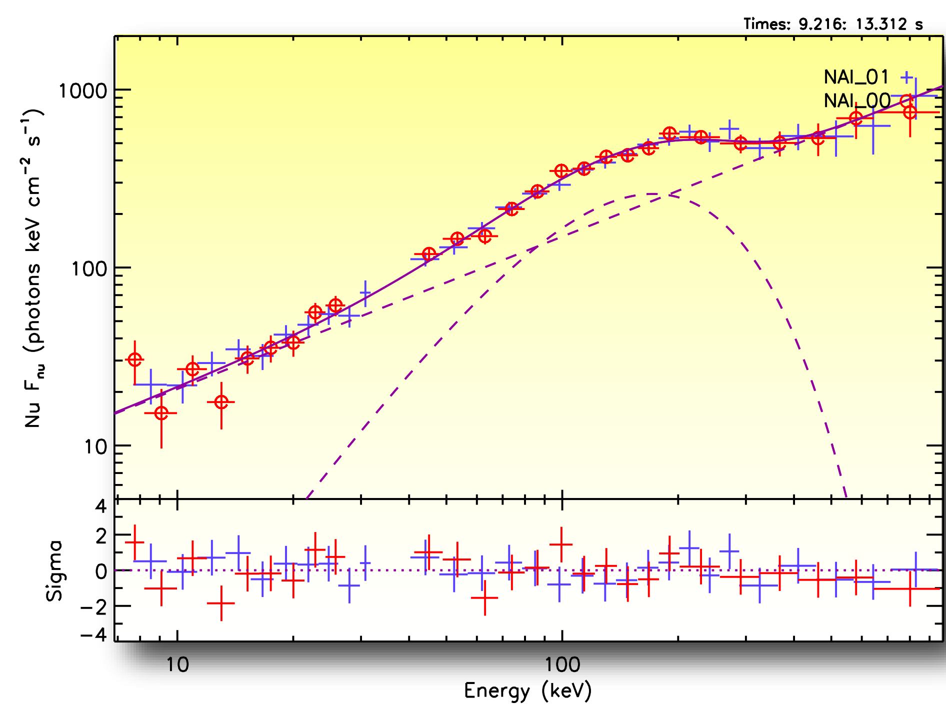


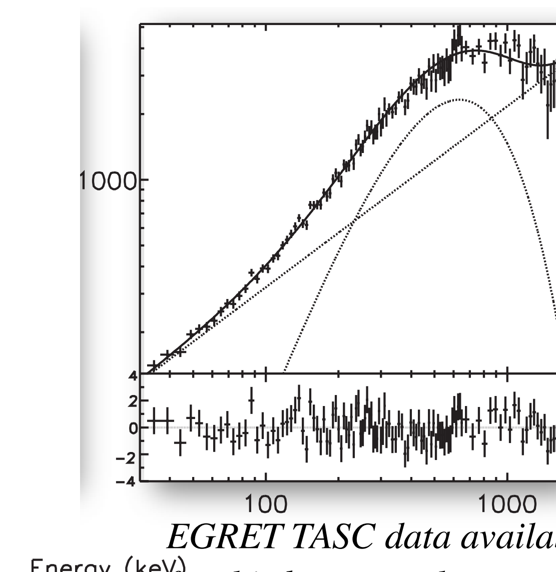
CGRO BATSE fits of GRB981021 (Ryde & Pe'er 2009)



BB+pl model

NaI
BB+pl





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

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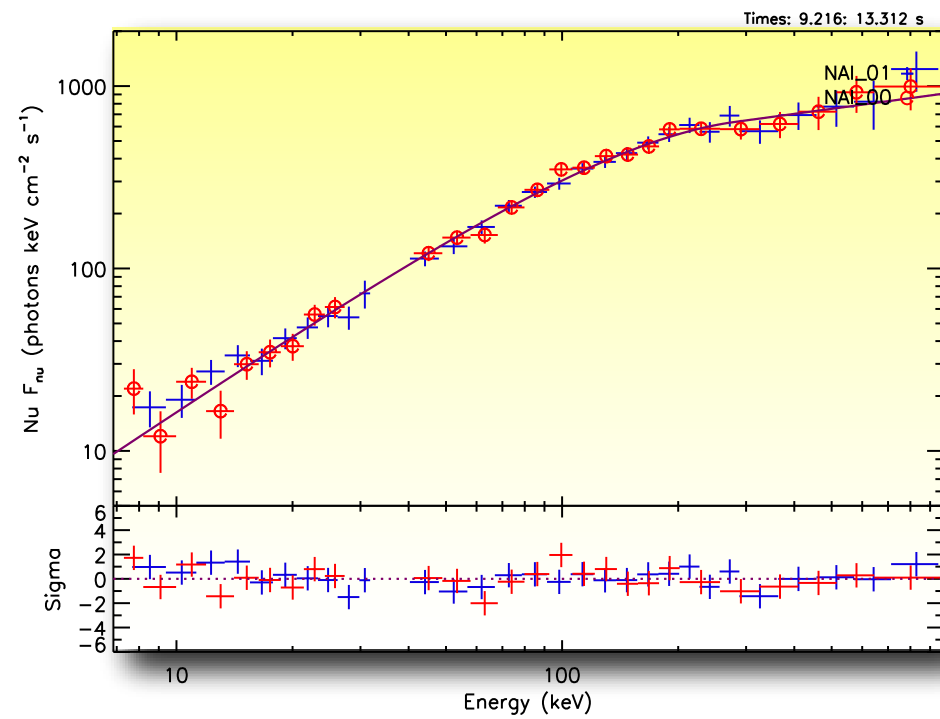

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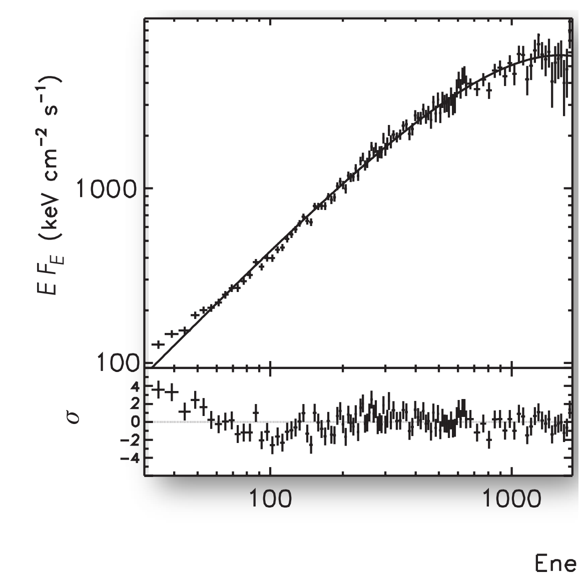

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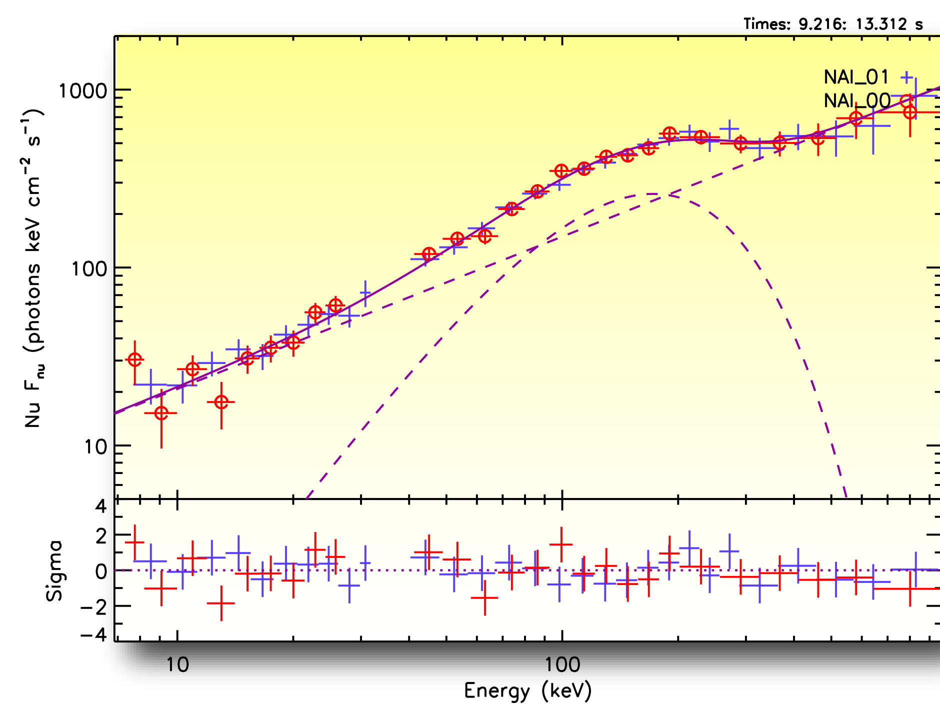

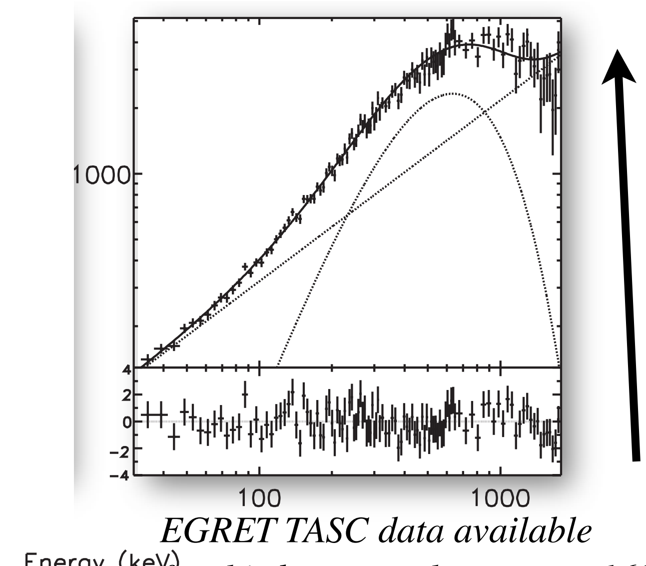

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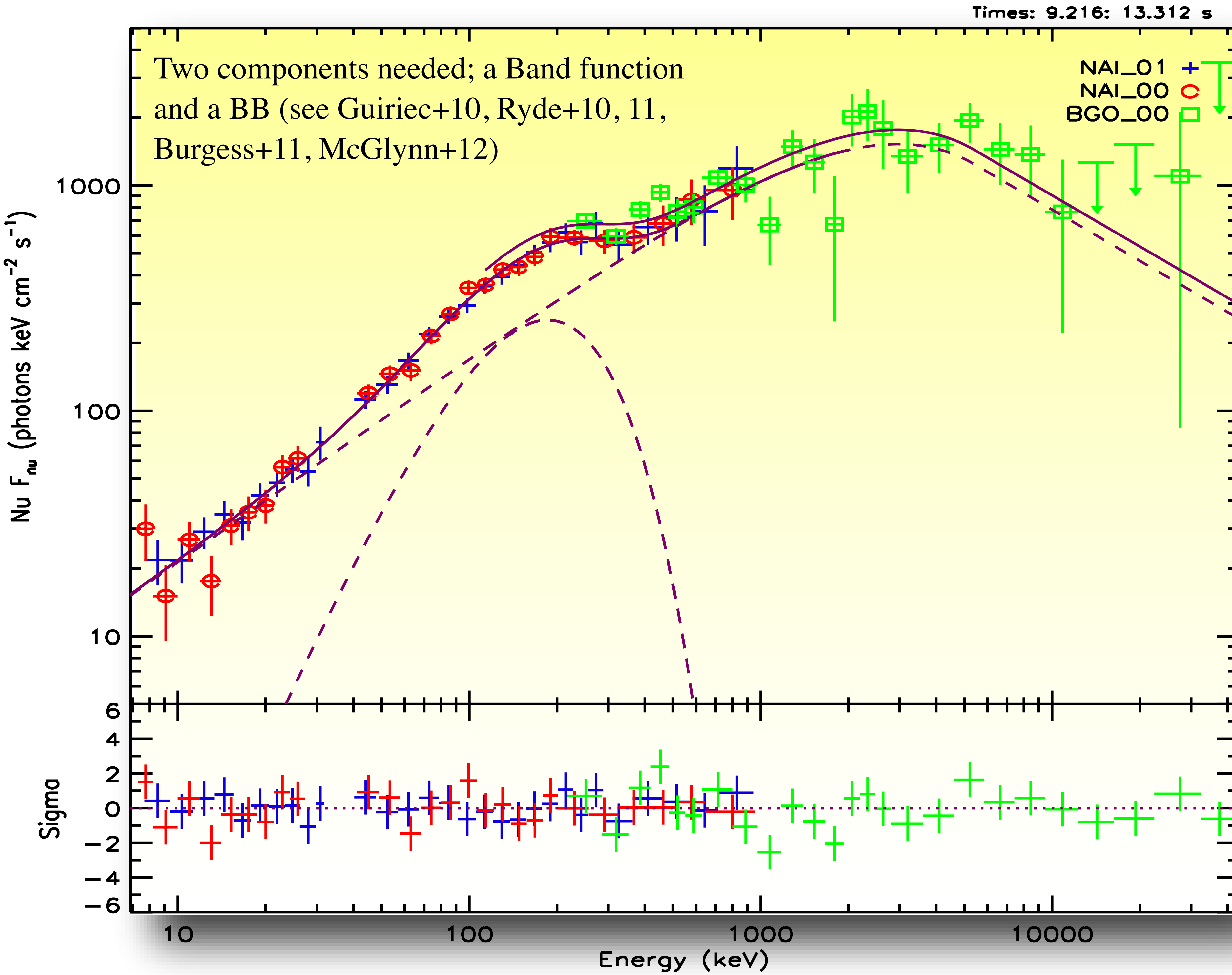
Fermi Gamma-ray Space Telescope

Photosphere in GRB100724B

Guiriec+10



ts)

of GRB981021

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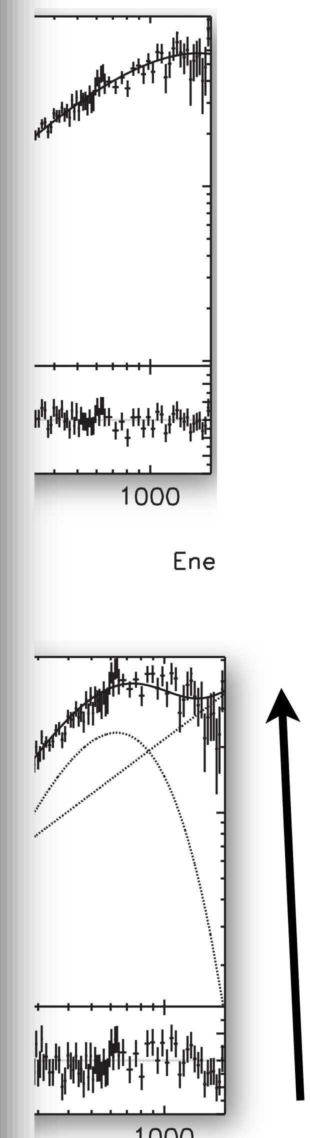


data available

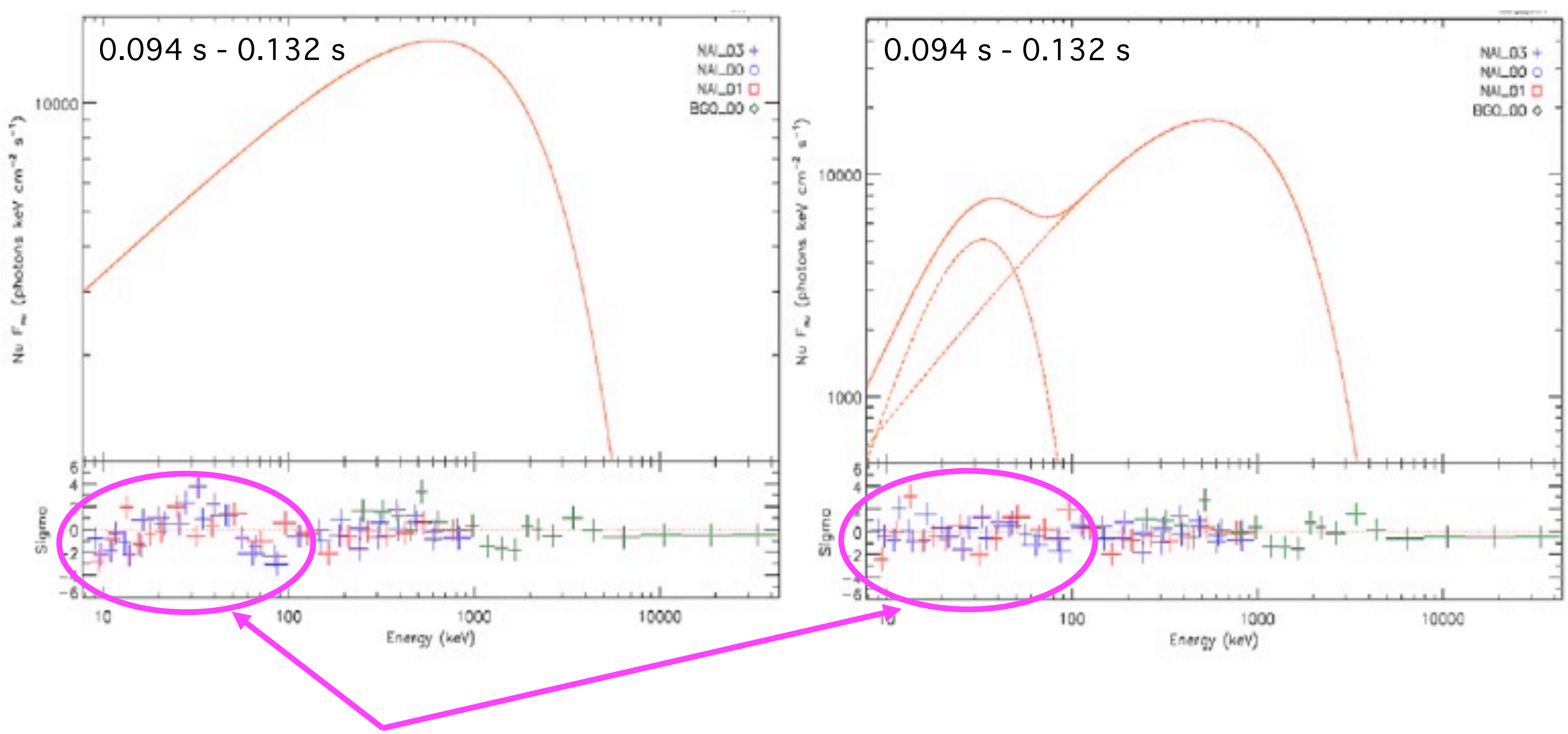
peak energy = 1600 keV

GRB 120323A

Time resolved spectra consist of two peaks, one at 30 keV and one at ~ MeV

Time resolved spectrum:

(Guiriec et al. 2012)



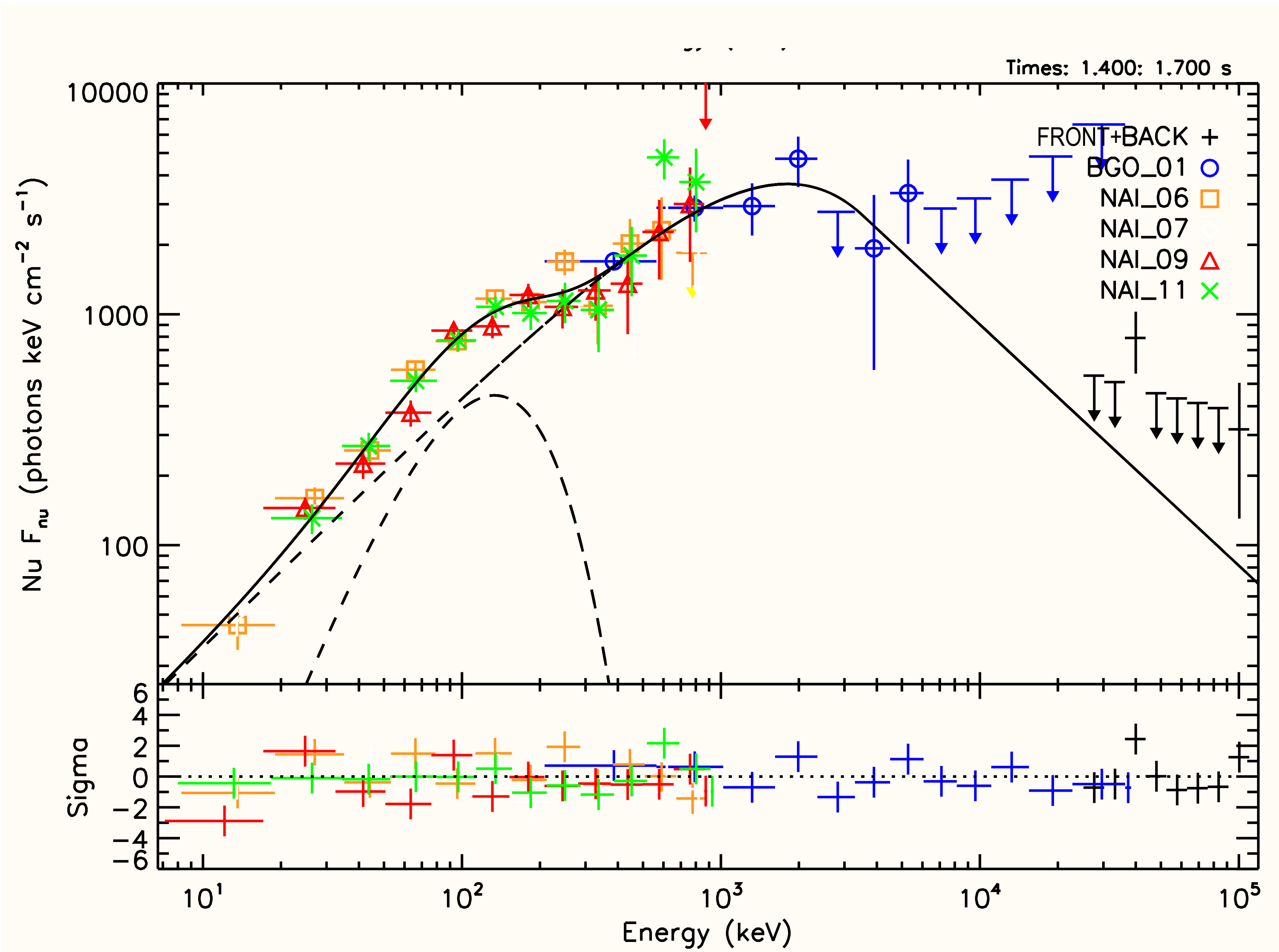
Best fit model: Band function + Planck function

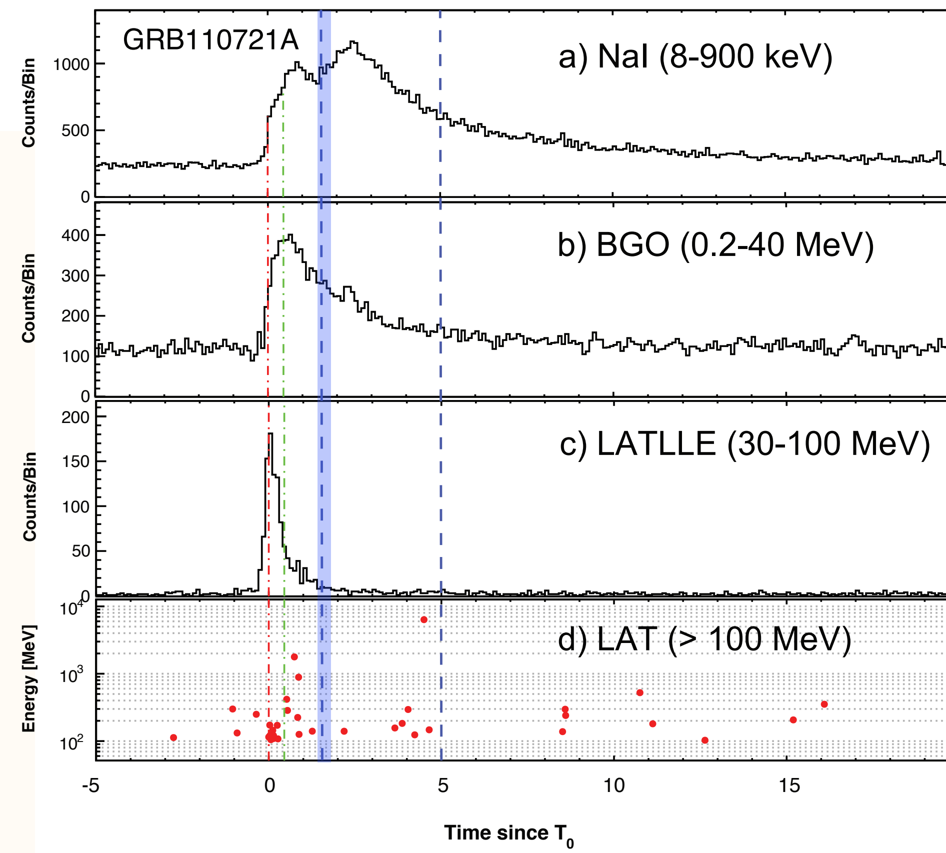
GRB 110721A

(Axelsson et al. 2012)

Time resolved spectra consist of two peaks, one at 100 keV and one at ~ MeV

Time resolved spectrum:





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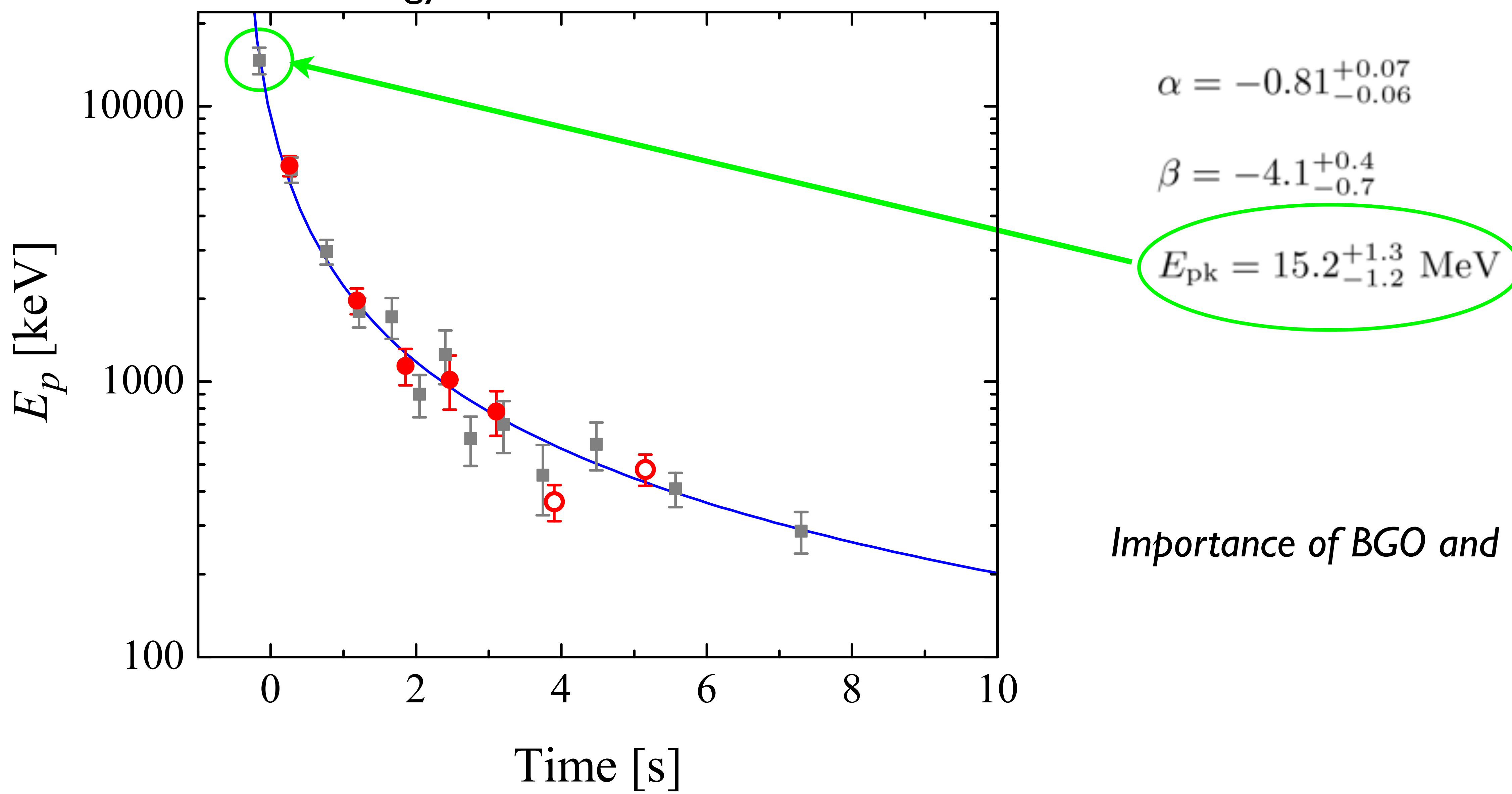
GRB 110721A

Exceptionally high peak energy 15 MeV during initial time bin [-0.32: 0 s]

Peak energy evolution as a function of time



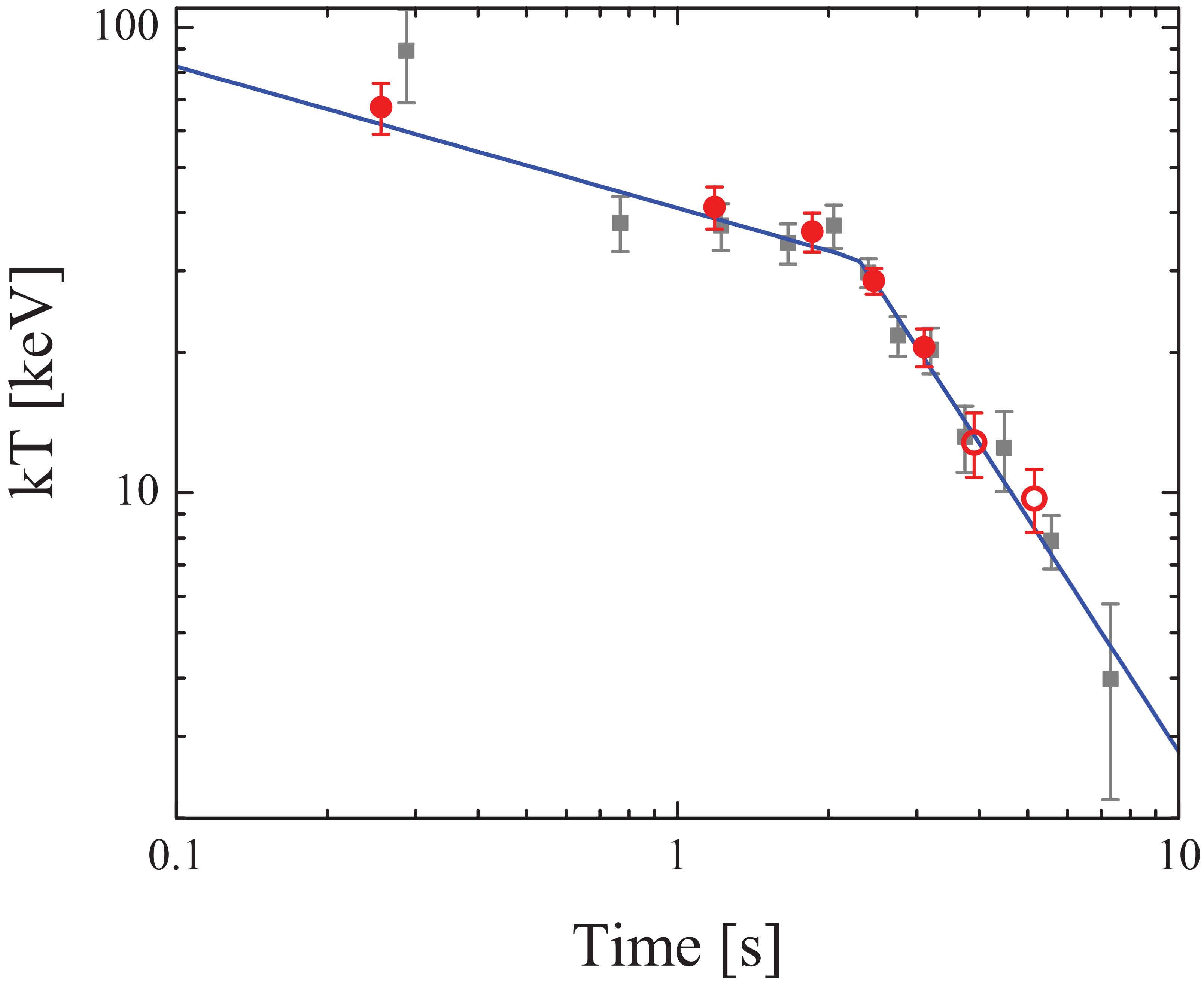
Importance of BGO and LLE data!

$$E_p = A_{pl}(t - t_0)^p \qquad p = 1.89 \pm 0.35 \quad t_0 = -0.8 \pm 0.3 \text{ s}$$

cf. Lloyd & Petrosian (1998)

GRB 110721A

Significant temperature evolution



Filled points: >5σ detection of an extra (blackbody) component

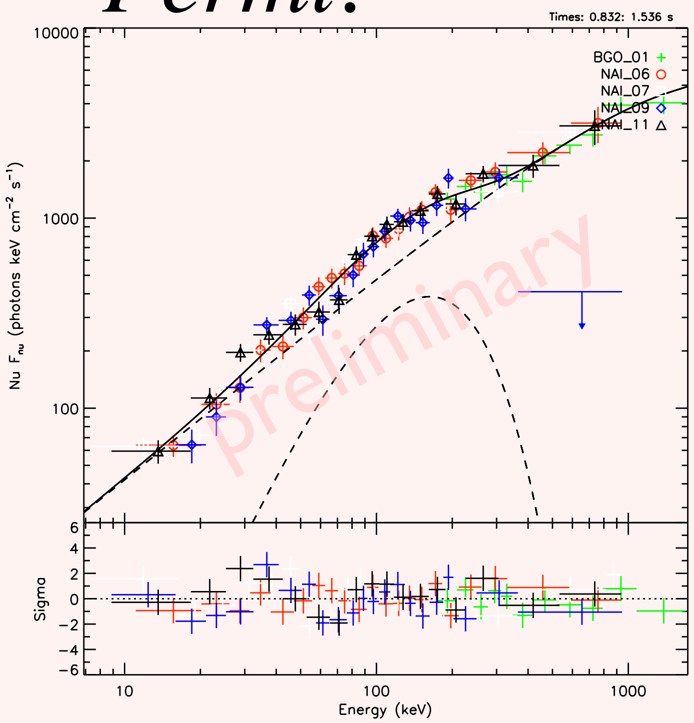
Open points: ~3σ detection of an extra (blackbody) component

Grey points: higher time resolution gives lower significance in each bin. However the characteristic trend is confirmed.

Evolution different from E_p and normalization!

Comparison to BATSE analysis:

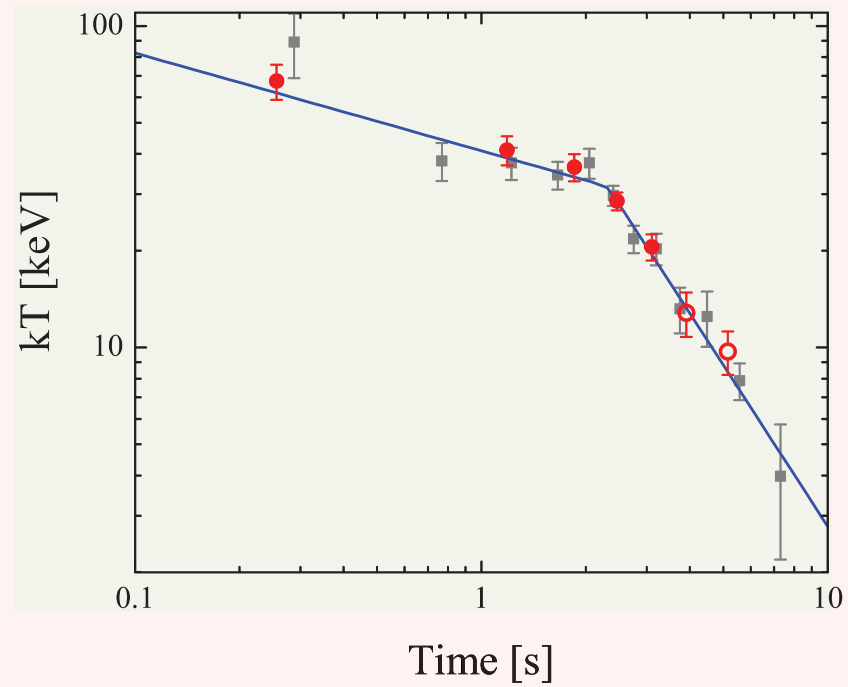
Fermi:

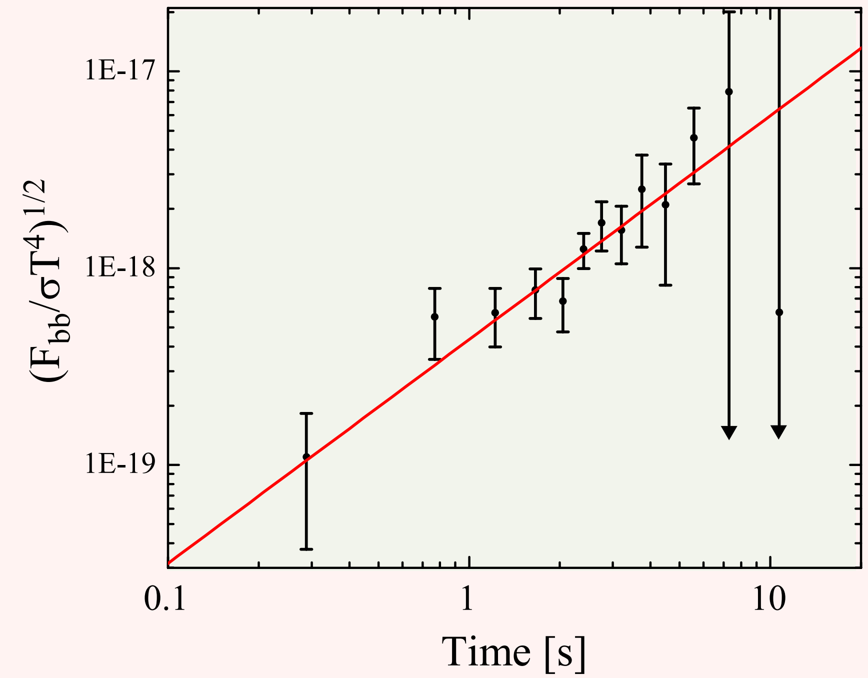


Temperature

GRB110721

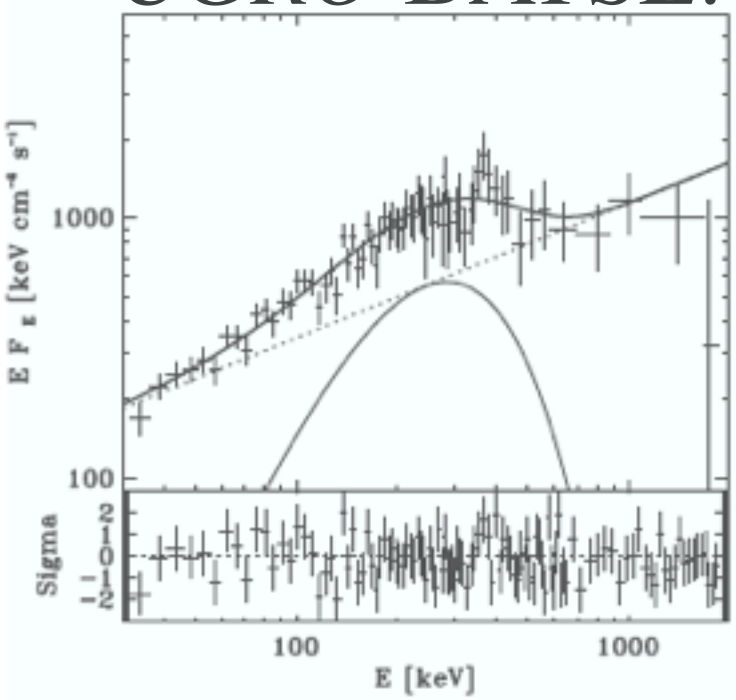
Normalization

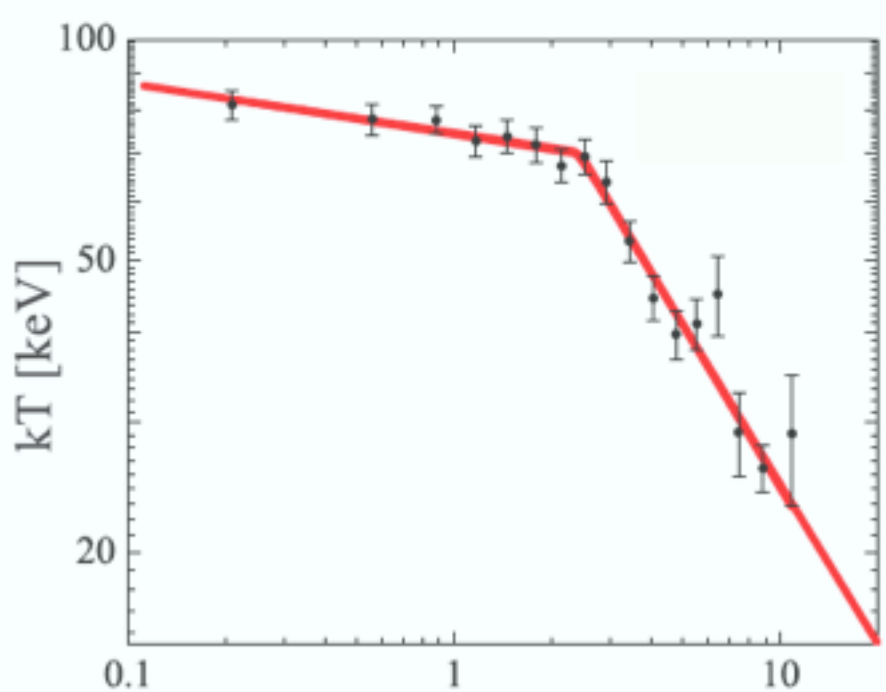


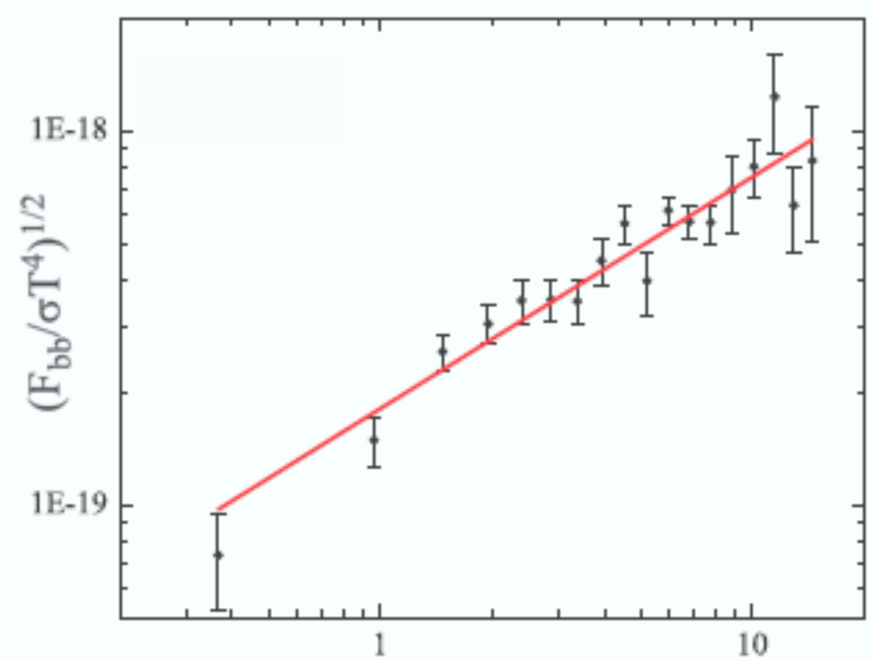


Axelsson et al. (2012)

CGRO BATSE:





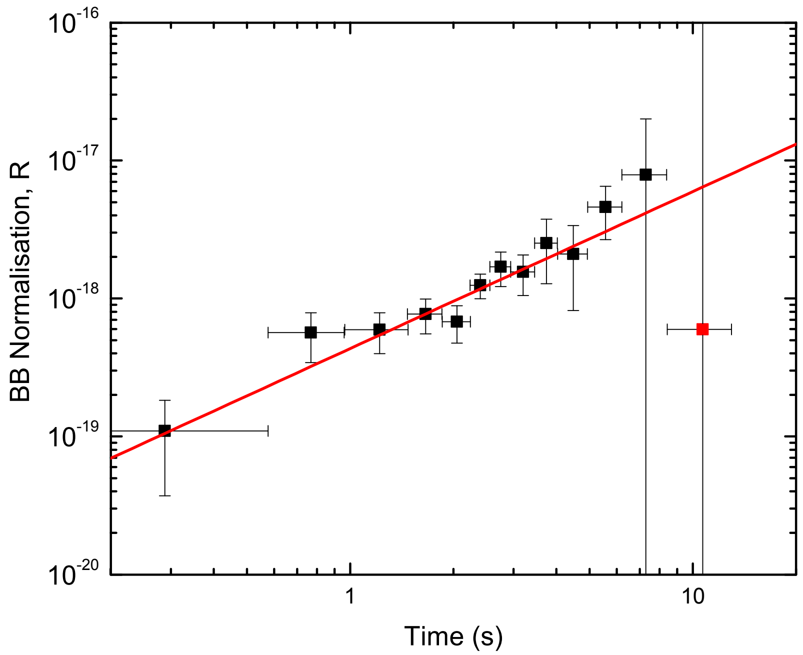


Ryde & Pe'er (2009)

Observables give physical parameters of outflow

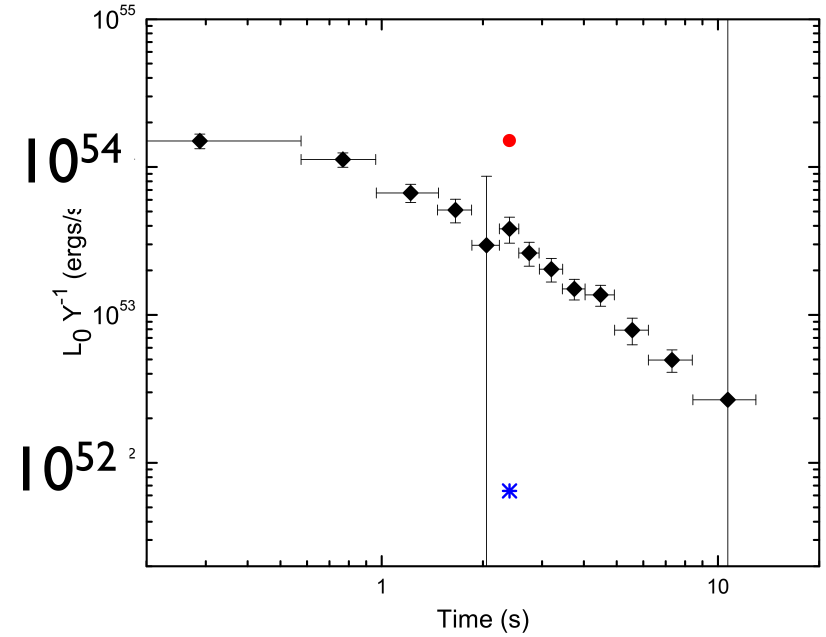
Blackbody normalisation $\mathcal{R}$

$$\mathcal{R} \equiv \left(\frac{F_{\rm BB}}{\sigma_{\rm SB} T_{\rm ob}^4}\right)^{1/2} = \xi \, \frac{(1+z)^2}{d_L} \frac{r_{\rm ph}}{\Gamma}$$



Luminosity, L_0

$$L_0 = 4\pi d_{\rm L}^2 Y F$$



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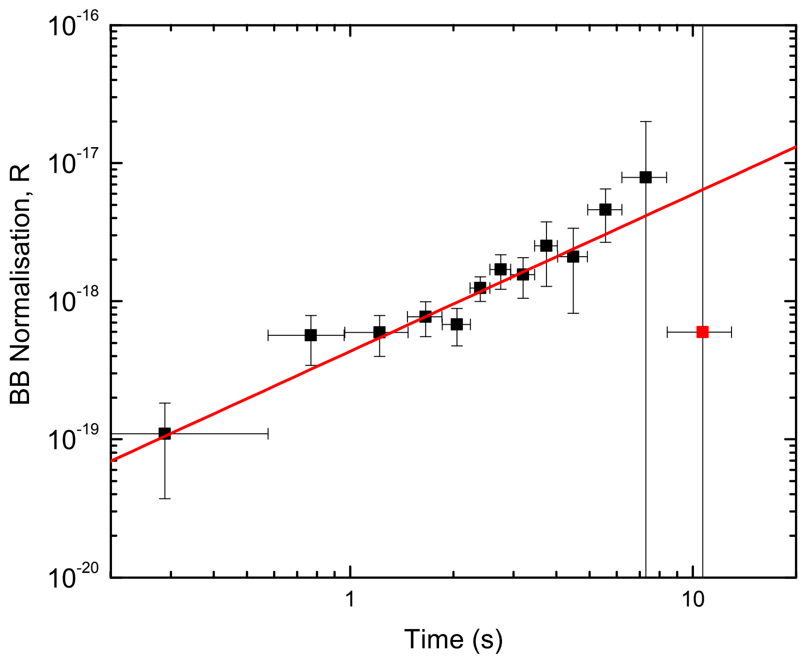

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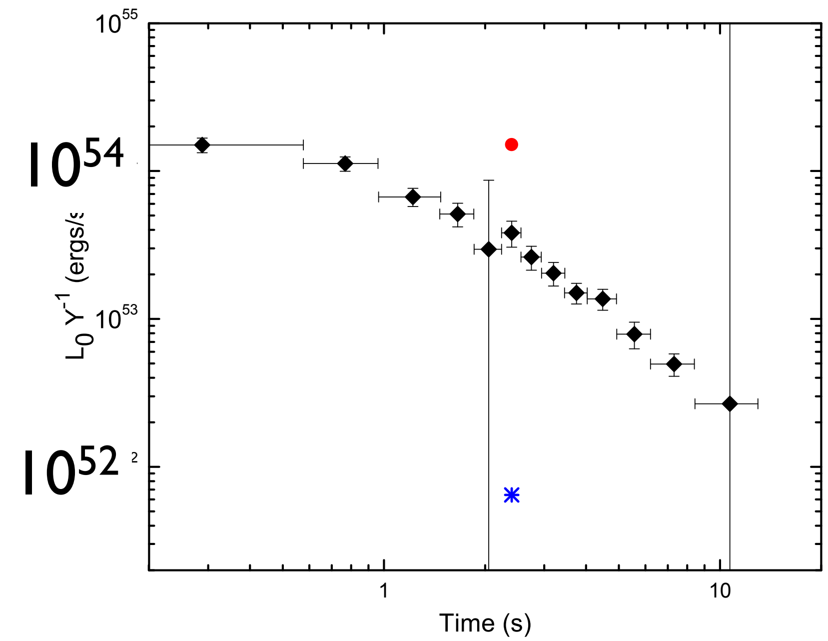
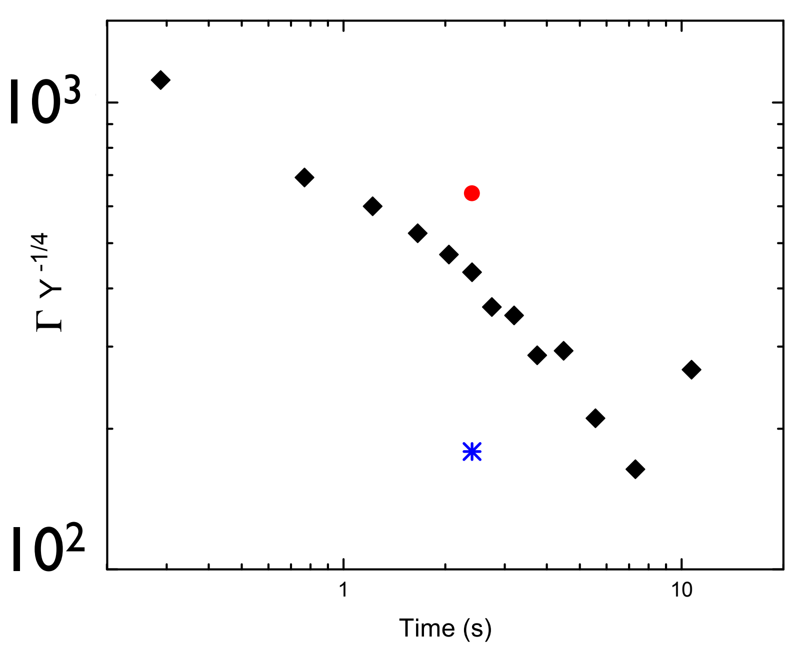
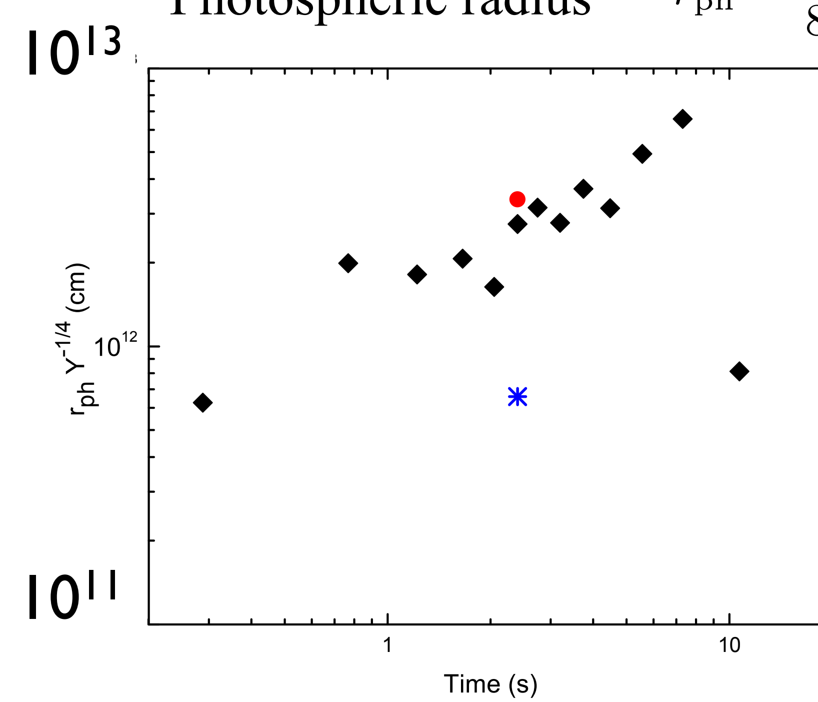


Lorentz Factor

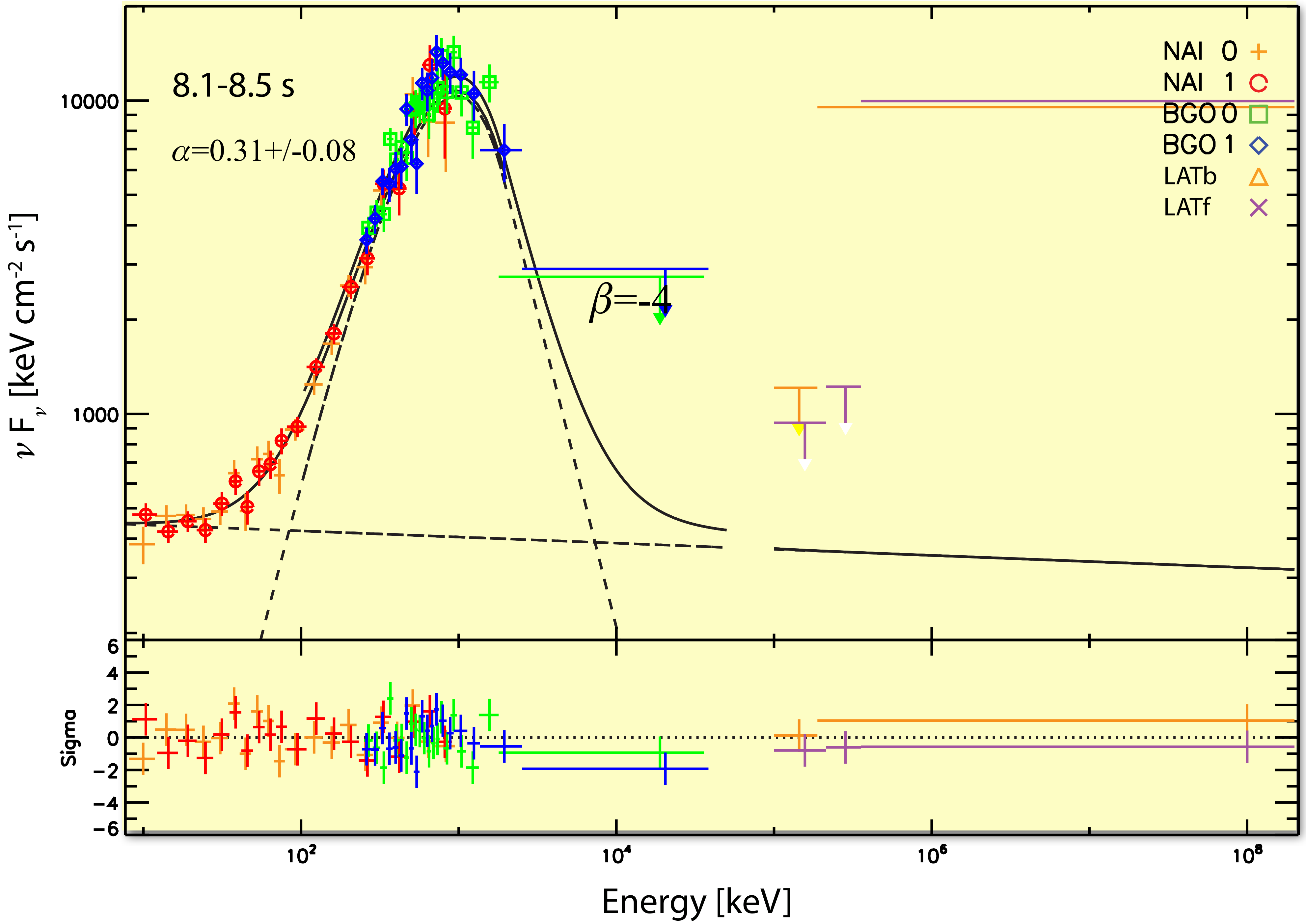


Photospheric radius $r_{\rm ph} = \frac{L_0 \sigma_T}{8\pi\Gamma^3 m_p c^3}$



Changing the shape of the thermal component

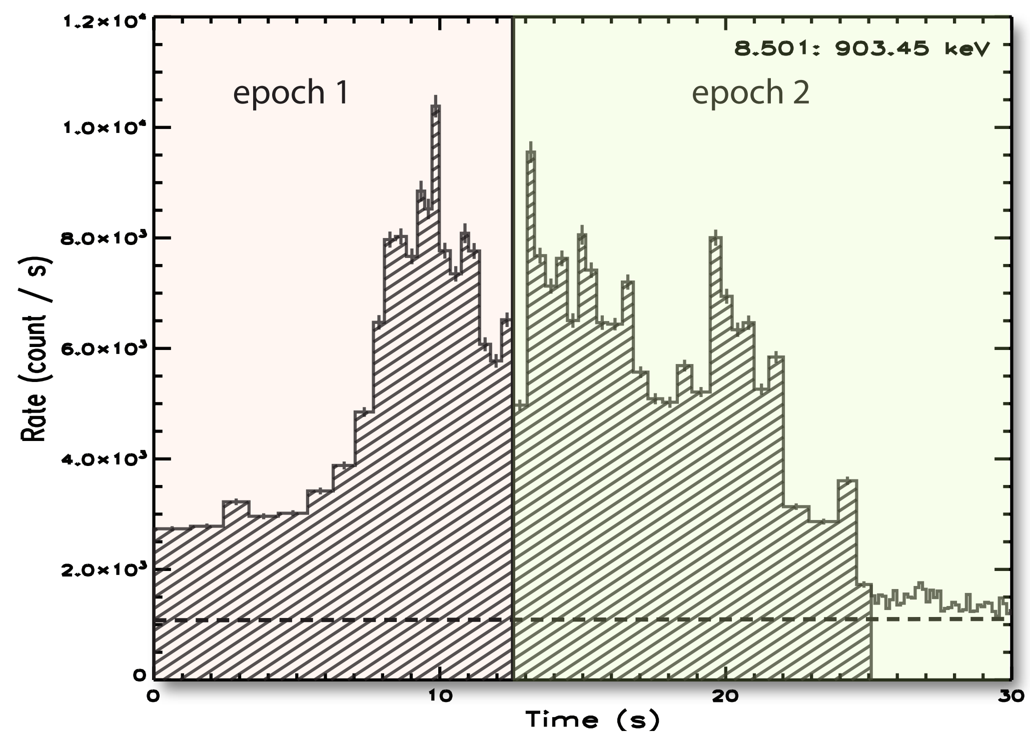
Photosphere in GRB090902B

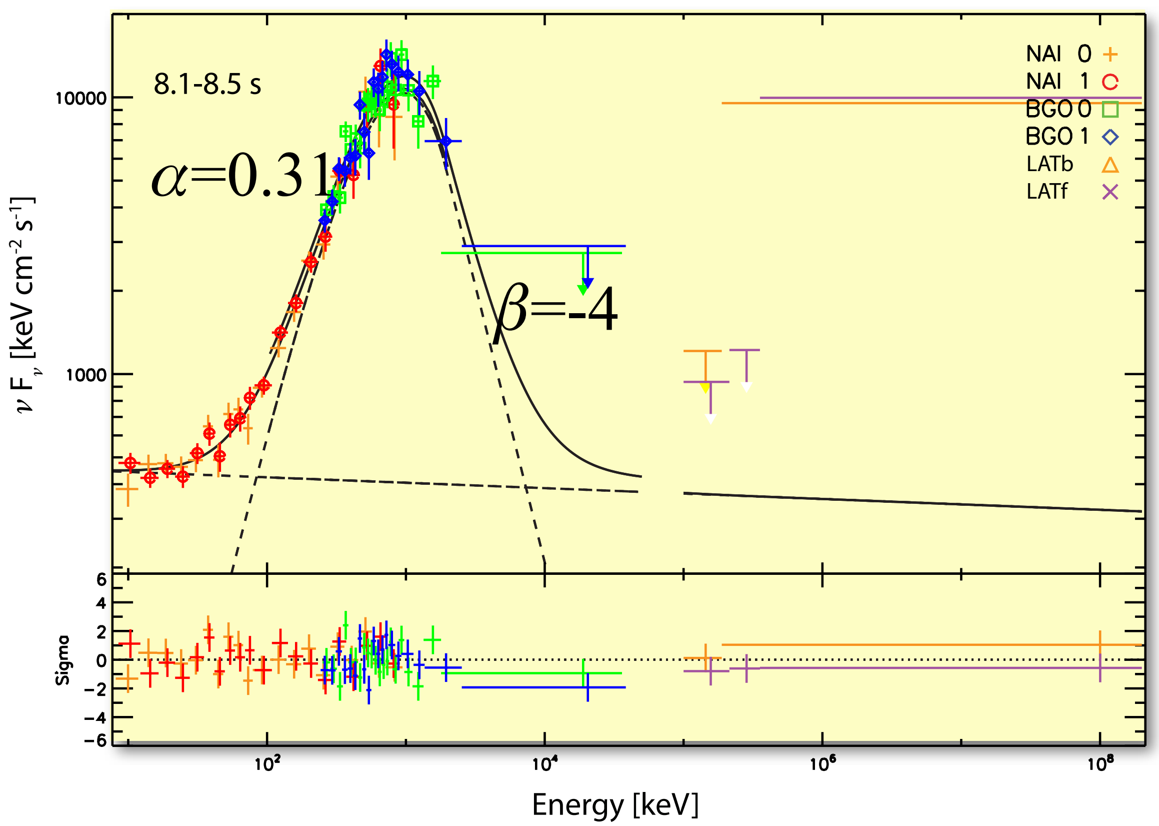


$$\Gamma = 750 \qquad R_{\rm ph} = (1.1 \pm 0.3) \times 10^{12}\, Y^{1/4}\ {\rm cm}$$

Ryde et al. 2010

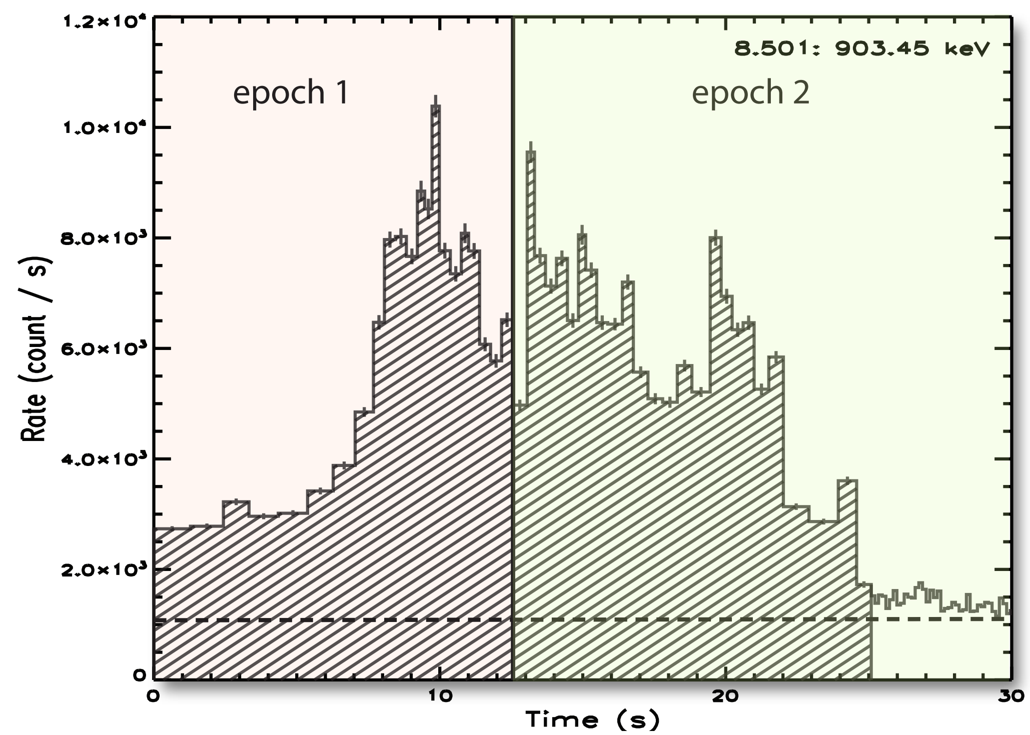
Photosphere in GRB090902B

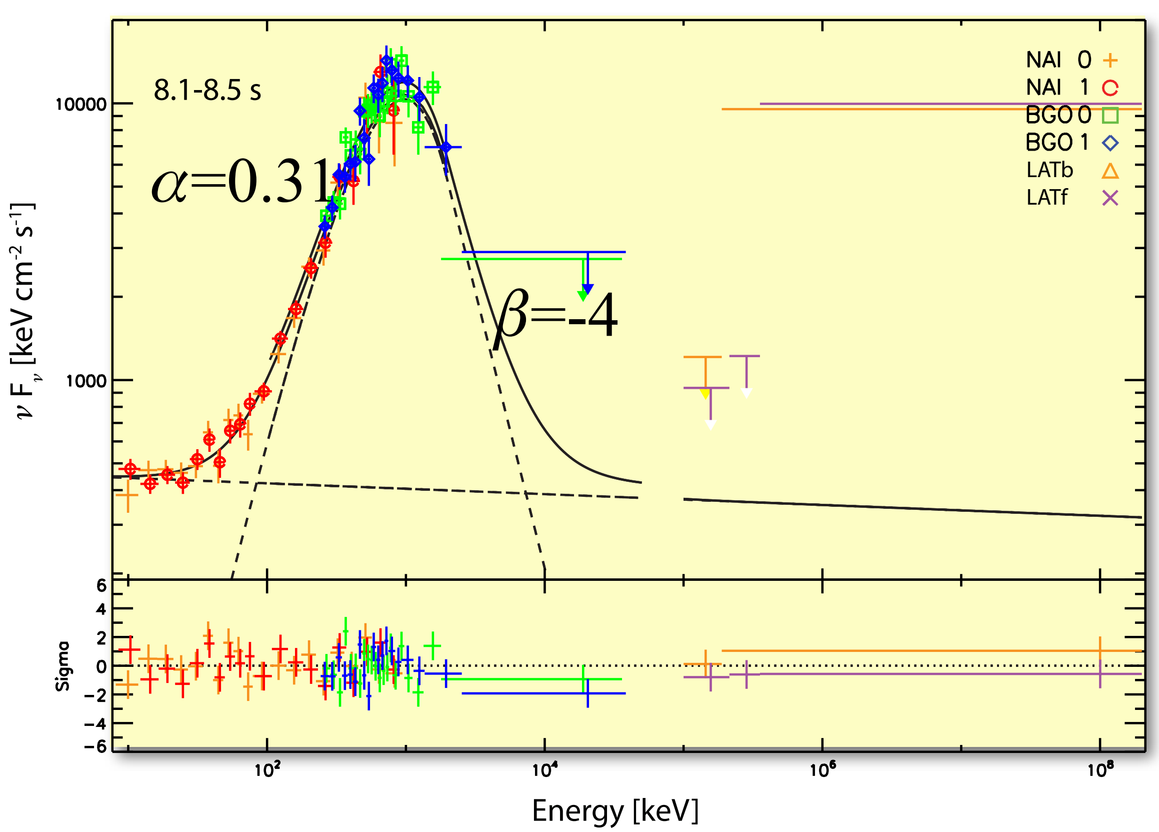


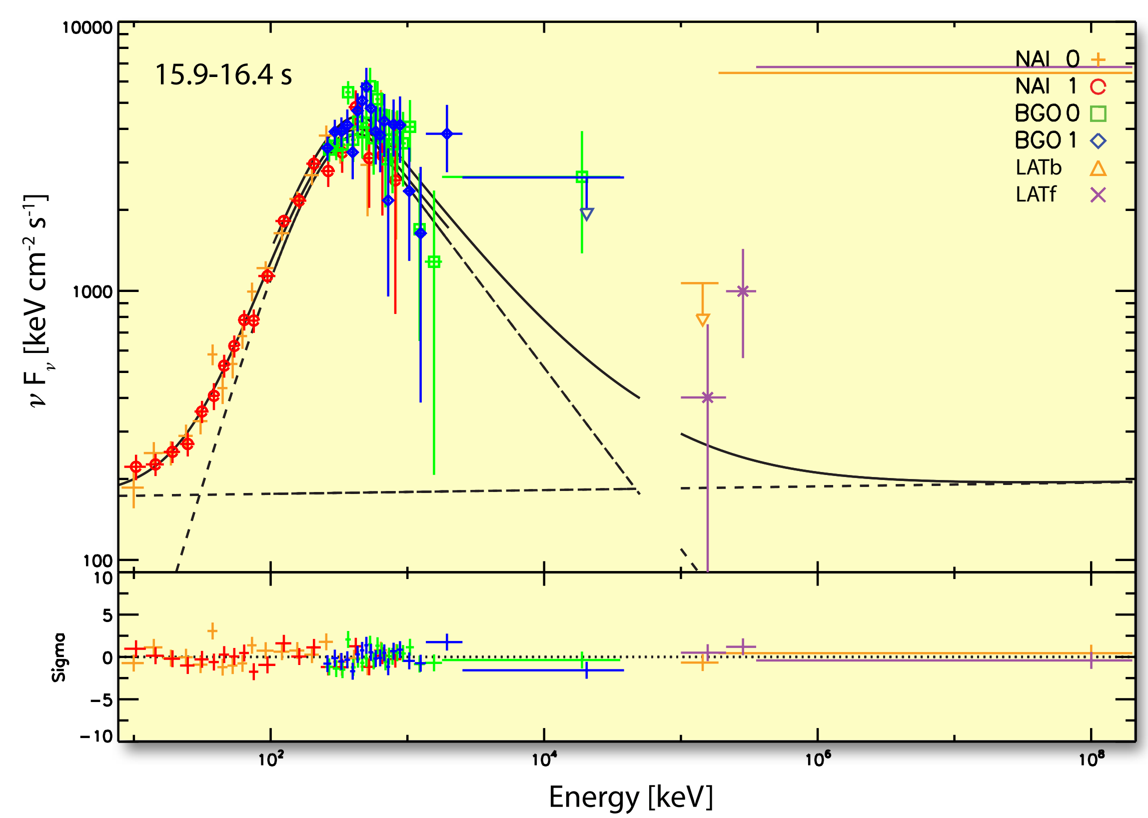


Ryde et al. 2011

Photosphere in GRB090902B





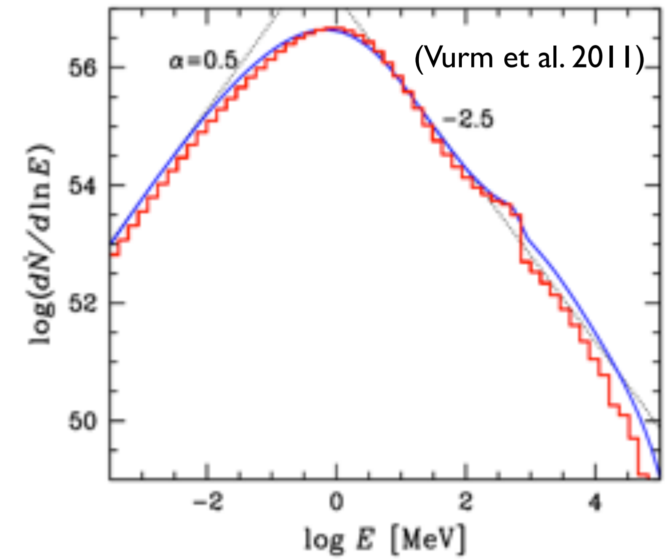


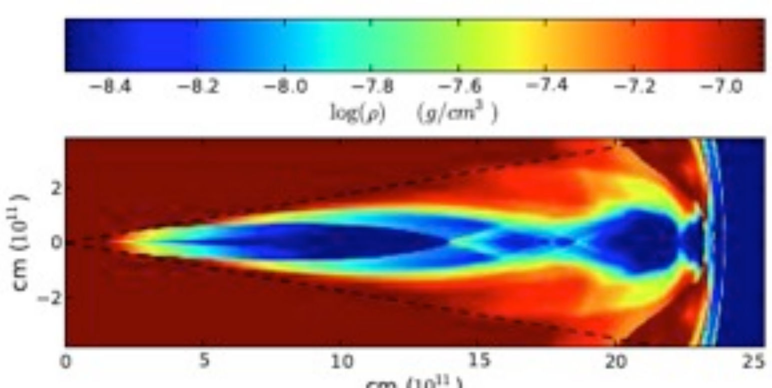
Ryde et al. 2011

Possible explanation I

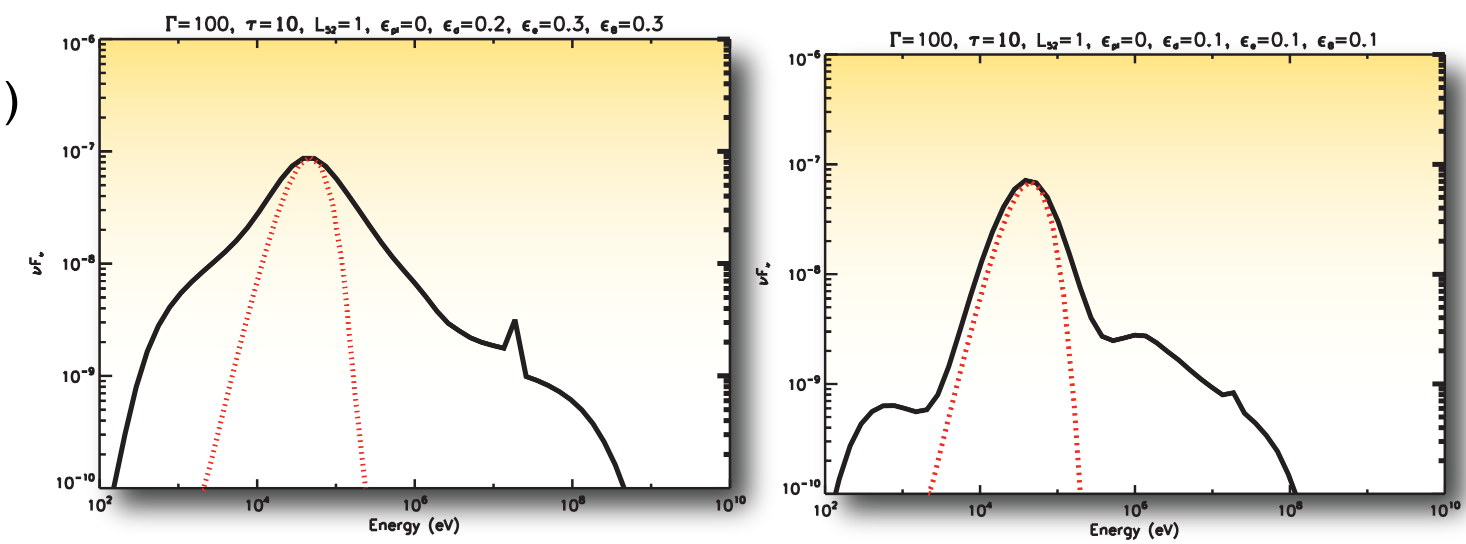
Idea: a heating mechanism below
the photosphere modifies the Planck spectrum
Rees & Meszaros 2005

- Internal shocks
  (Peer, Meszaros, Rees 06, Toma+10, Ioka10)
- Magnetic reconnection
  (Giannions 06, 08)
- Weak / oblique shocks
  (Lazzati, Morsonoi & Begelman 11, Ryde & Peer 11)
- Collisional dissipation
  (Beloborodov 10, Vurm, Beloborodov & Poutanen 11)





Lazzati et al. 09 numerical simulation of jet propagation.
See also Mizuta 11, Toma11

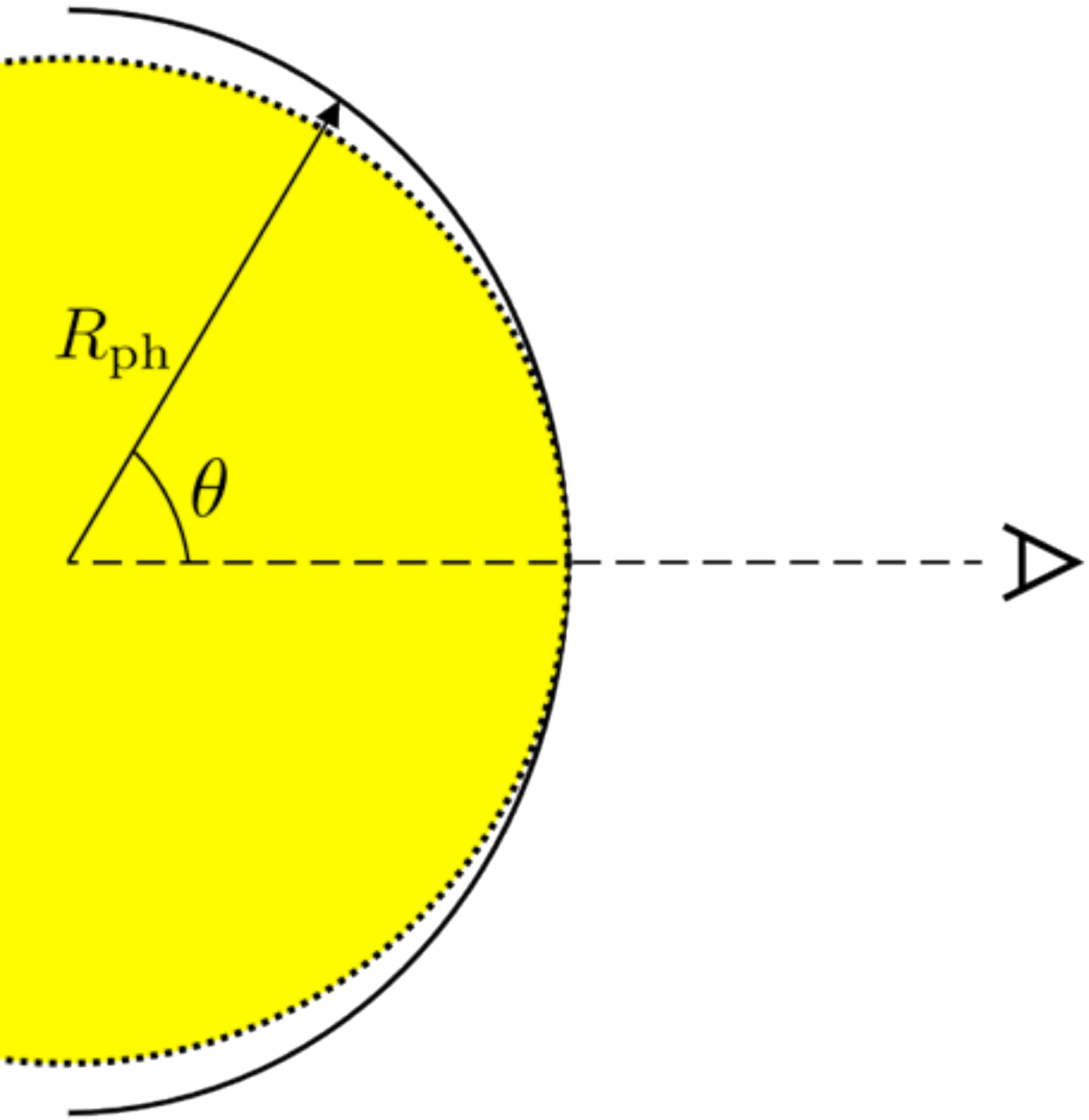


Nymark et al. 2011, Pe'er et al. 2006

Emission from the photosphere is NOT seen as Planck !

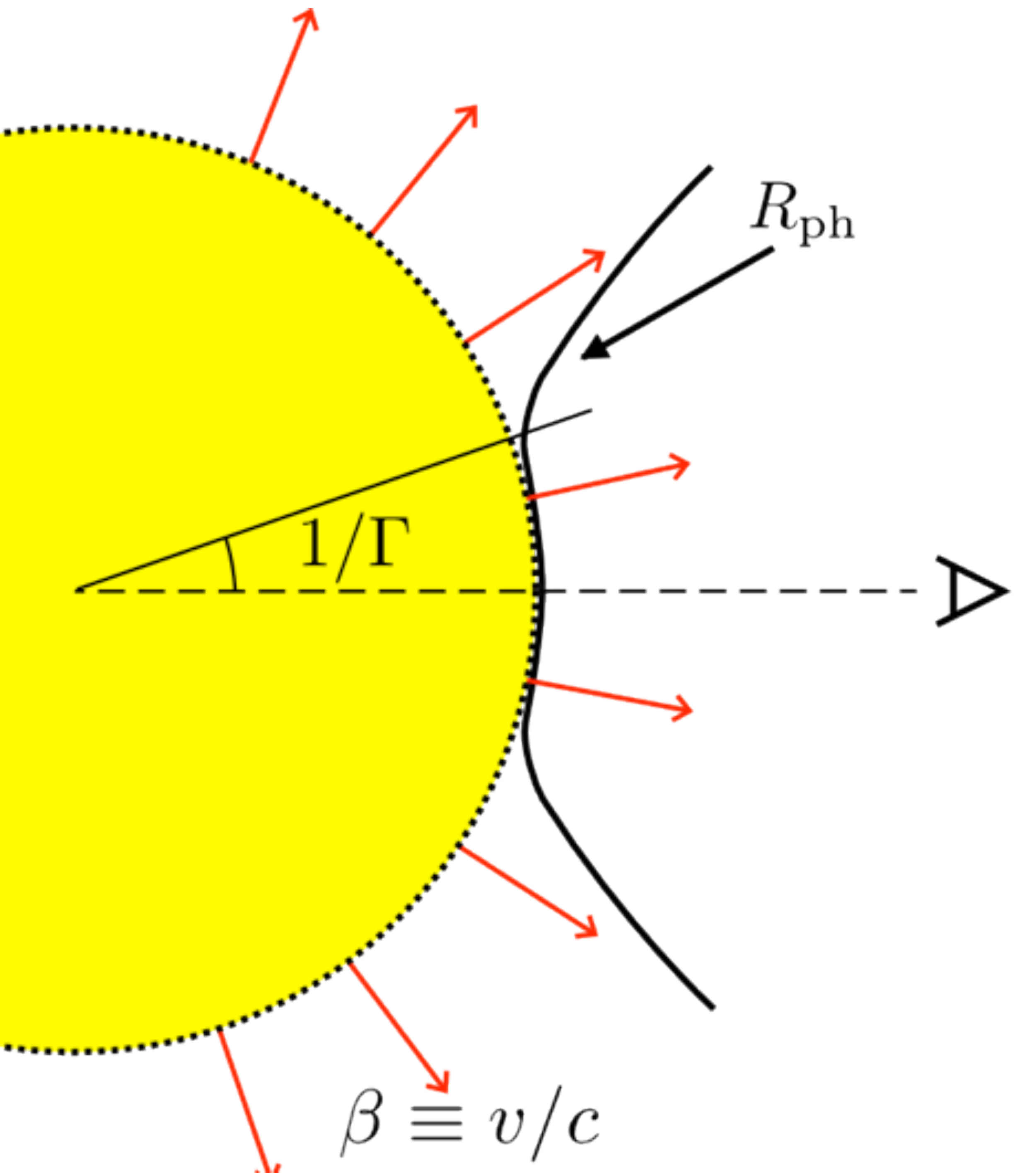
Possible explanation 2

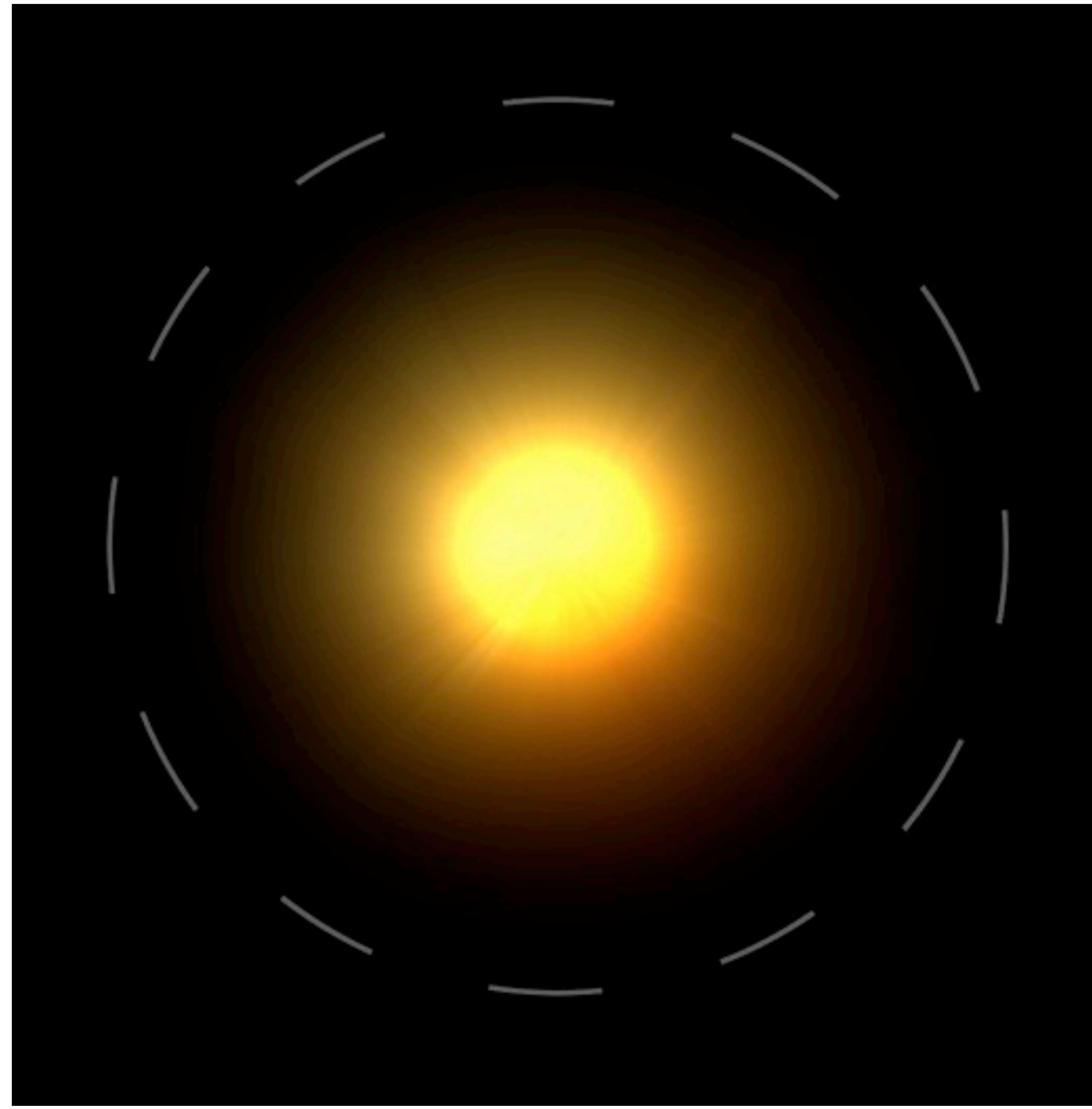
Geometrical broadening



Angle dependent photosphere

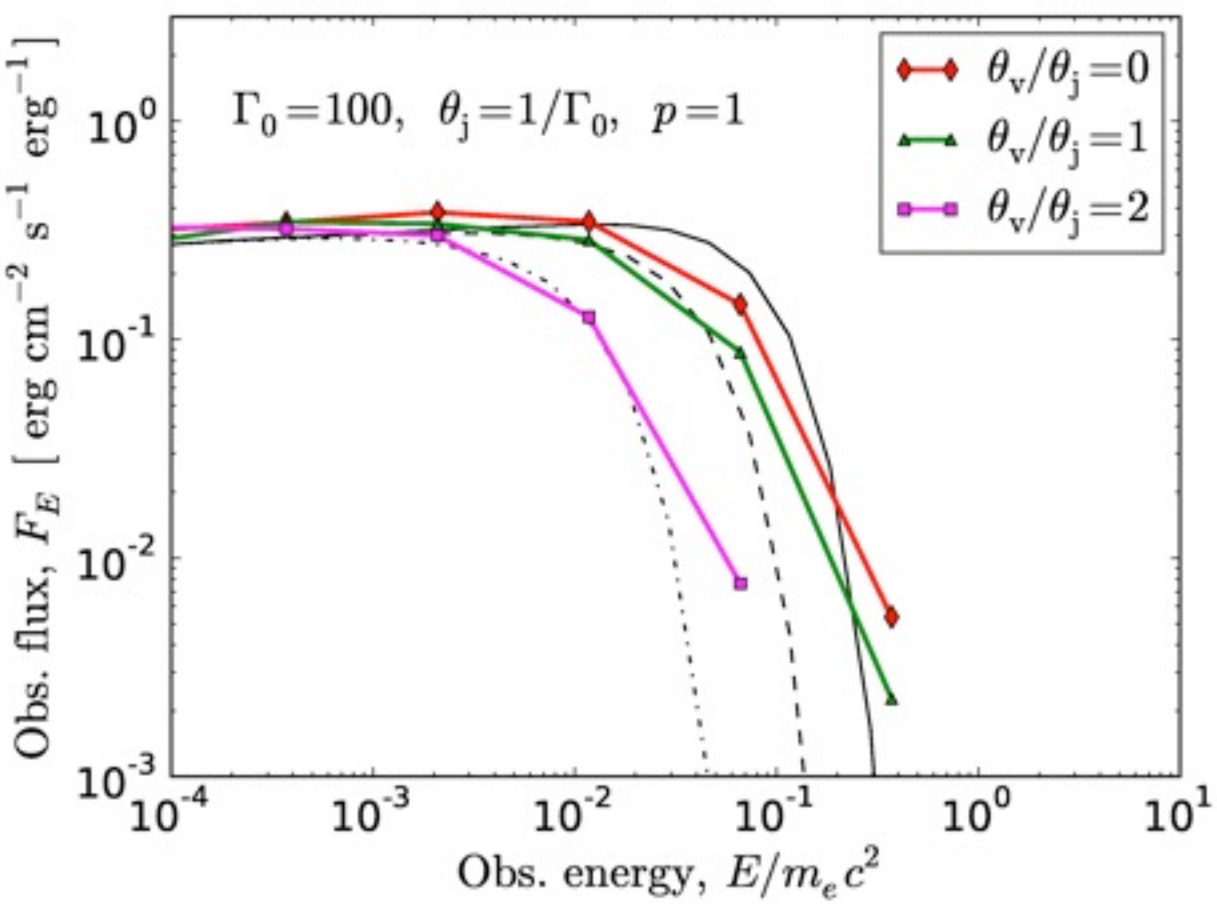
Photosphere in a relativistic explosion

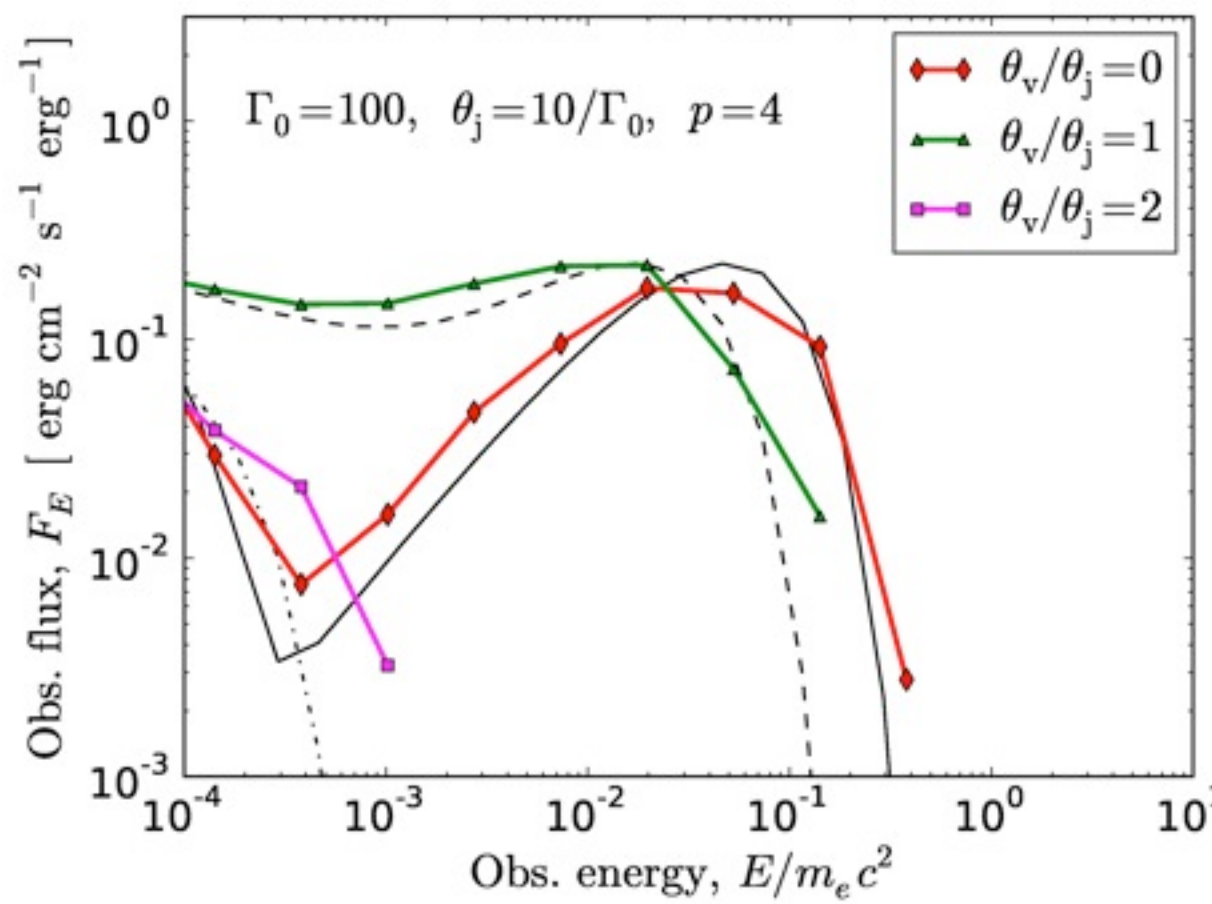




Simulations show:

- Geometrical effects **can produce broadening** of the spectrum without introducing synchrotron photons
- For **narrow jets** ($\Theta_j \leq$ few/Γ_0) broadening observed at any viewing angle
- For **wider** jets, broadening when observed at $\boldsymbol{\Theta_v \approx \Theta_j}$





Lundman et al. 2012

Conclusions

- The emission mechanisms for GRBs are still unclear, but Fermi observations show that the photosphere plays an important role

- The inclusion of the blackbody is the first step towards an **understanding the physical origin** of the prompt emission: The Band function does not provide it.

- The **addition of a photospheric component** improves the fit in many cases, and follows well-defined characteristics.

- The spectrum emerging from the photosphere does **not need to be a Planckian**. Several broadening mechanisms, e.g. subphotospheric dissipation or geometrical.

Thank you!

Analytical and Monte Carlo study of geometrical effects (Lundman et al. 2012)

Analytic model

- Considers last scattering positions of photons
- Local emissivity is given by the 'scattering density' attenuated by the optical depth

Monte Carlo simulation

- Tracks photon propagation within regions of varying electron density and Lorentz factor
- Full photon propagation below the photosphere, including Comptonization of photons