The impact of Fermi on the study of Gamma-ray Bursts

Asaf Pe'er

CfA/ITC

Fermi symposium, May 2011

Bottom line

- The broad band spectra seen by Fermi does not fit into any of the frameworks of existing models.

- Fermi results forces us to re-think of questions that were thought to be solved.

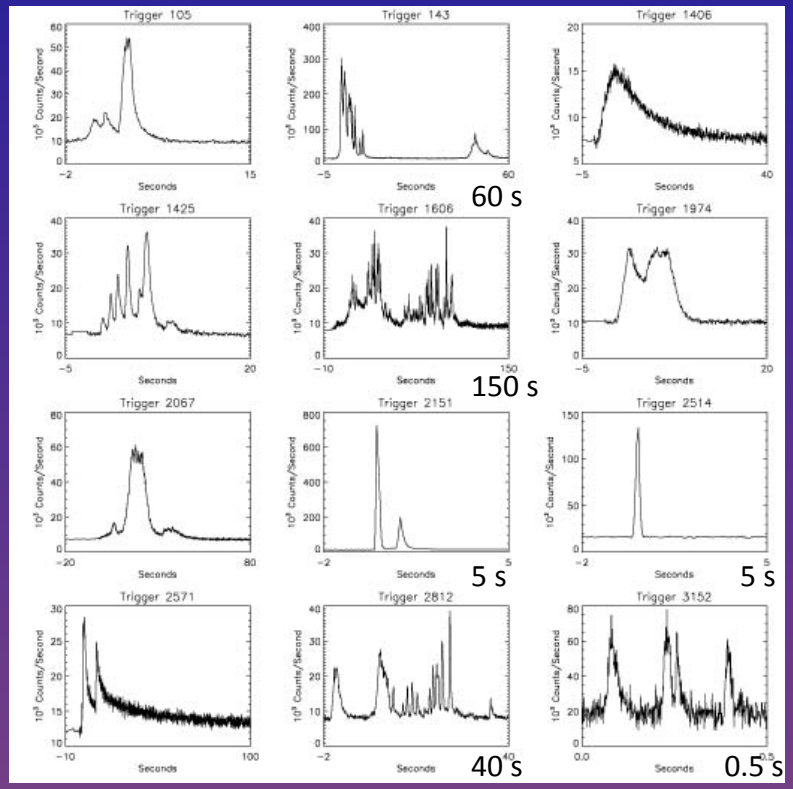
Outline

- What we (thought we) know before Fermi ?
- What are the basic questions ?
- What we (don't) know now ?

Background: a few facts on GRBs

Duration: few s

Variability: >~10 ms

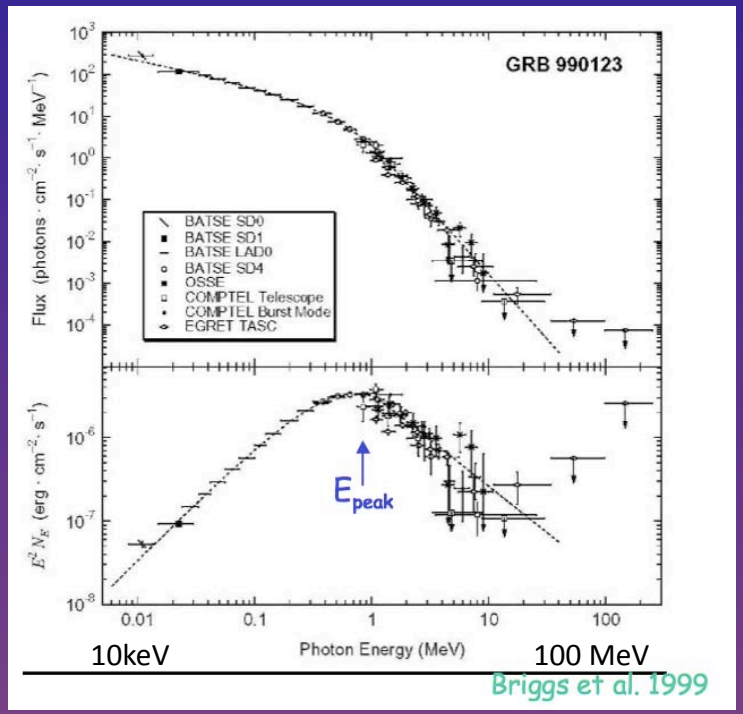


Redshift measurements ->
at cosmological distances
→E_{iso}~10^{52}-10^{54} erg !

Observed Flux: ~10^{-7} - 10^{-4} erg cm^{-2} s^{-1}

Typical observed energy: <~ MeV

Spectrum: non-thermal

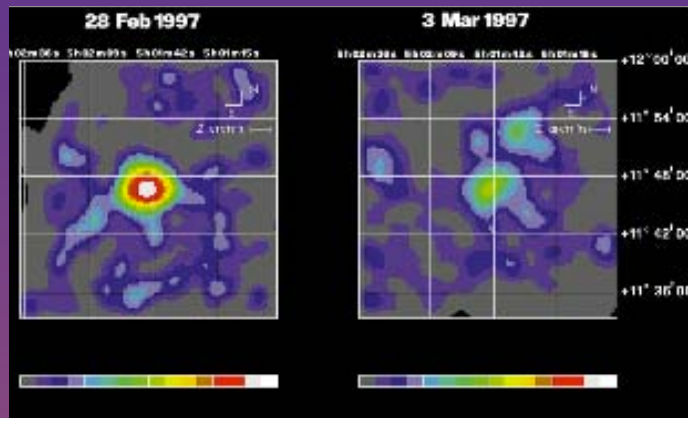


"Band" function:
Broken power law (4 free parameters)
-- good fit to (narrow band) spectra

What do we know for certainty about GRBs ?

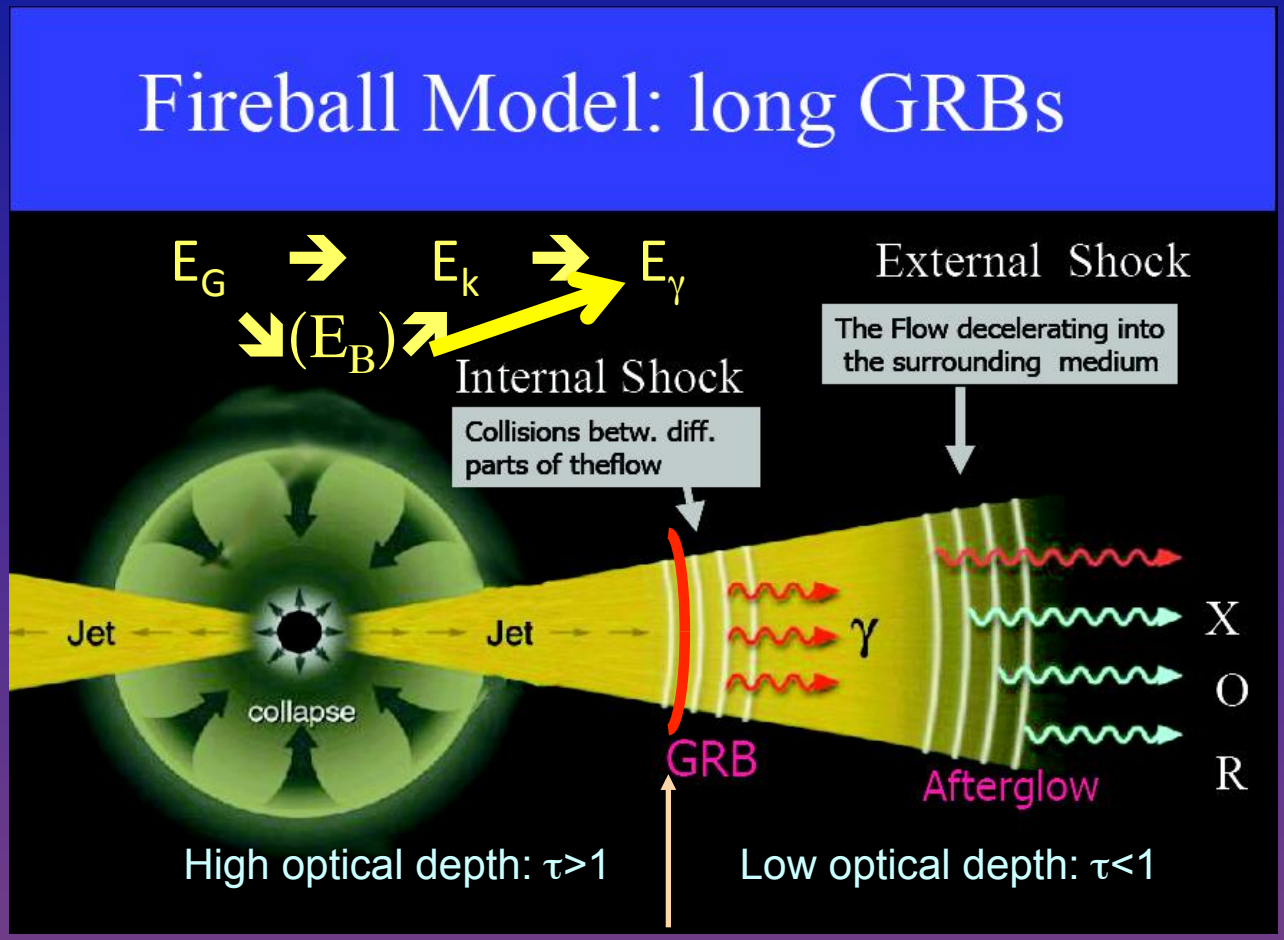
1. Transients; duration few seconds; no repetition
2. Cosmological
3. Energetic: ~10^{52} – 10^{54} erg
4. Lightcurve: zoo; variable
5. Spectrum: non-thermal;
   -- extends up to >GeV; peaks at sub-MeV

   4+5: → large L.F., Γ>~100
6. Afterglow
7. SNe connection (to some)



General picture: the "fireball" model

•Paczynski (1986); Goodman (1986); Rees & Meszaros (1992, 1994);



Pros:

In qualitative agreement with all obs;

Obtain AG as a prediction

Cons:

No quantitative explanation of obs. (Emission ?)

Some parts are not explained at all (e.g., particle acc.)

Some parts are 'problematic' (e.g., Internal shocks)

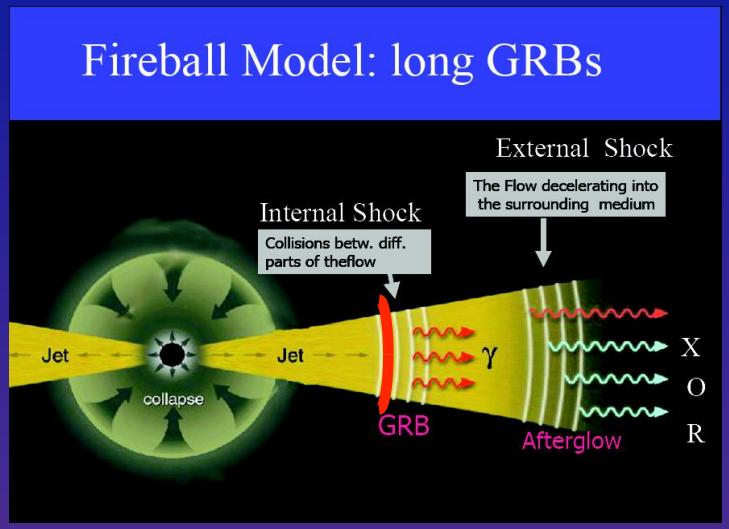
"fireball" model: general framework

Source of energy

Kinetic energy (jet)

Dissipation

Radiation



What do we want to know ??

Basic (GRB) physics

1. Progenitor /Central engine

2. Jet launching mechanism;
   - jet composition

3. Jet dynamics, dissipation & radiative processes

4. How are GRBs connected to other objects ?
Stellar evolution, star formation, host galaxies, pop-III stars, SNe, Binaries, GW, cosmic rays, ν's…

5. GRBs and basic physics:
Cosmology, Lorentz violation,…

The basic questions

Apart from the general framework:
E_G -> E_k -> E_γ + AG,
the details of the fireball model are highly uncertain !!

1. Nature of the progenitor:
   Collapsar ? Magnetar ? BH-BH / BH-NS / NS-NS Merger ?

2. Jet launching mechanism:
   photons ? magnetic (Blandford-Znajek) ? Neutrino heating ?

3. Why relativistic speeds ? Γ_{GRB} >~100, Γ_{AGN} <~30

4. Jet composition: Leptonic ? Hadronic ? Poynting – flux dominated ?

5. Dissipation mechanism: efficiency problem in internal shocks

6. Radiative processes: understanding the broad band spectrum
   -> particle acceleration

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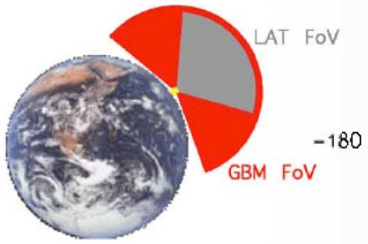
6. Radiative processes: understanding the broad band spectrum
   -> particle acceleration

We see photons ! Have to deduce all the rest !!

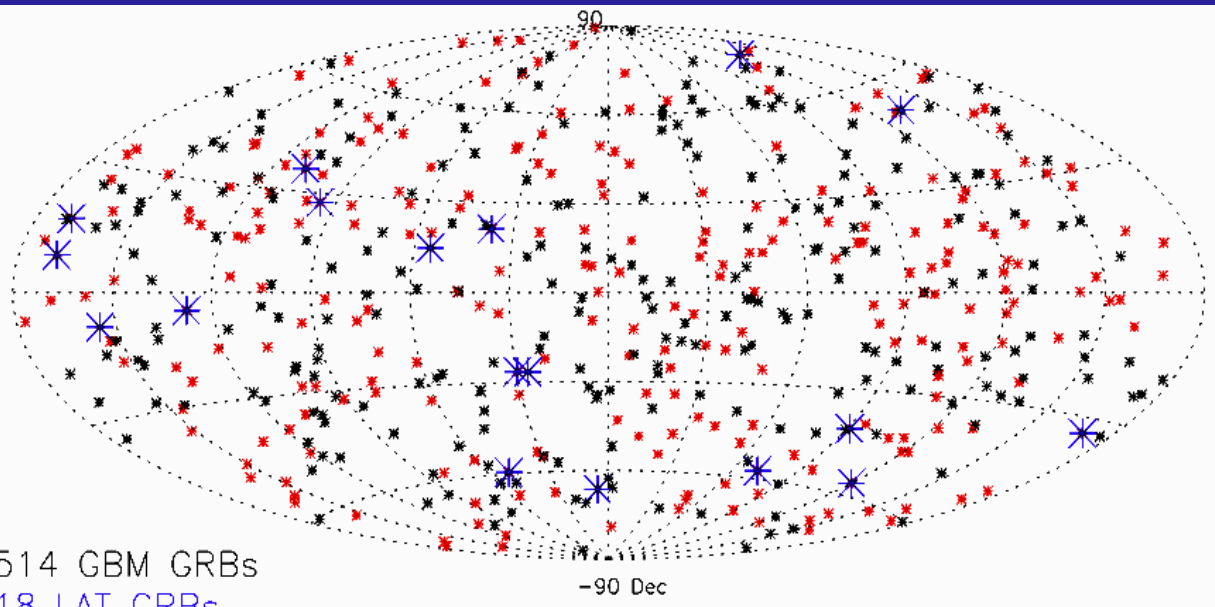
What did Fermi tell us ? (I)

Fermi GRBs as of Aug 2010



GBM 8 keV - 40 MeV

LAT ~50 MeV - 300 GeV



514 GBM GRBs
18 LAT GRBs
In Field-of-view of LAT (264)
Out of Field-of-view of LAT (250)

The GBM detects ~250 GRBs/year (~540 total)

~18% short

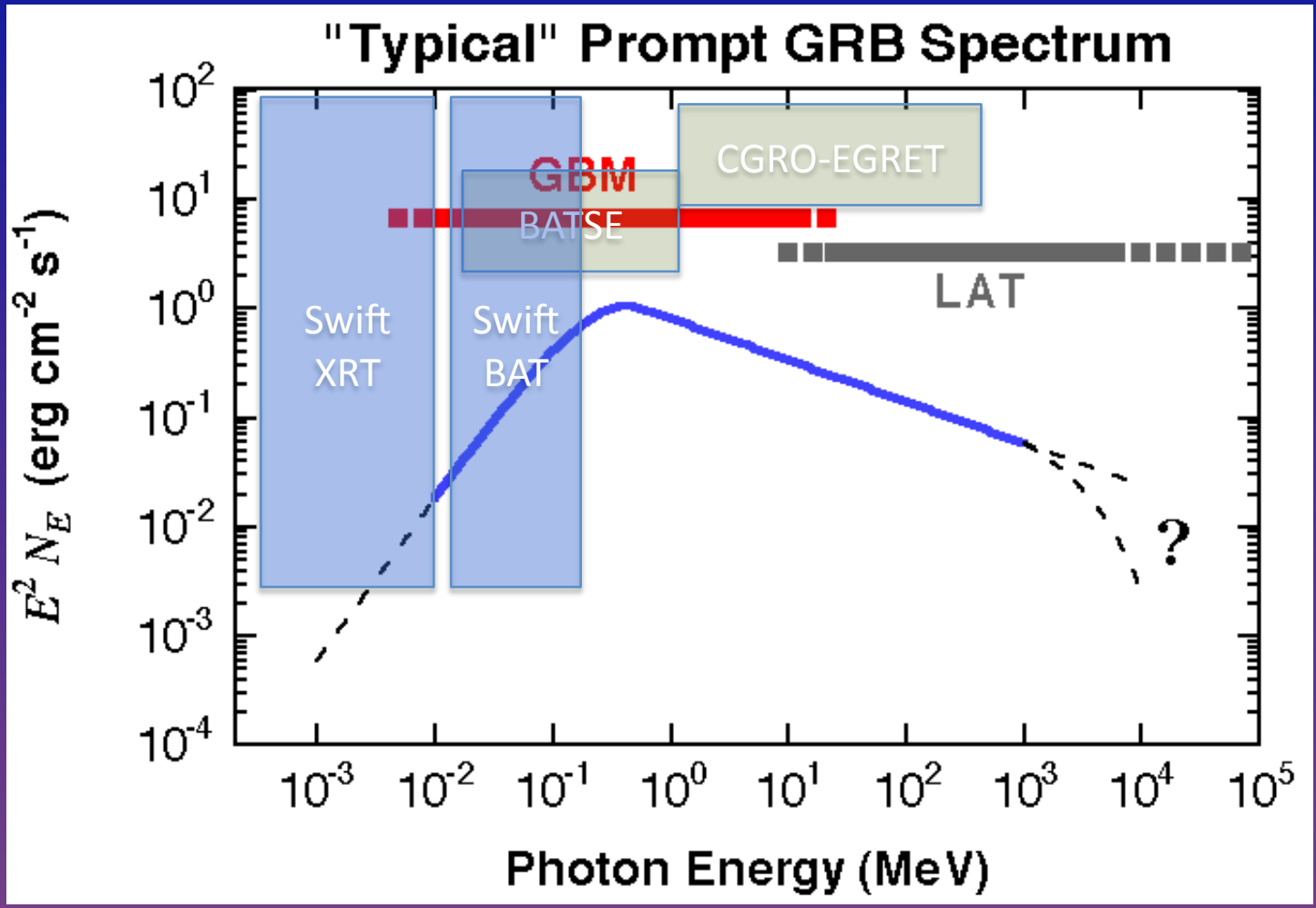
~50% in the LAT FoV

The LAT detects ~10 GRBs/year: 20 total as of today

<~10% of GRBs are detected by LAT

See Preece & Omodei talks

Fermi bridges a gap



I. Since 2000, no coverage of the spectral peak;

II. >MeV data became available

Main results from Fermi observations

1 High energy photons ~30 GeV → High $\Gamma \sim 1000$

See Hascoet's talk

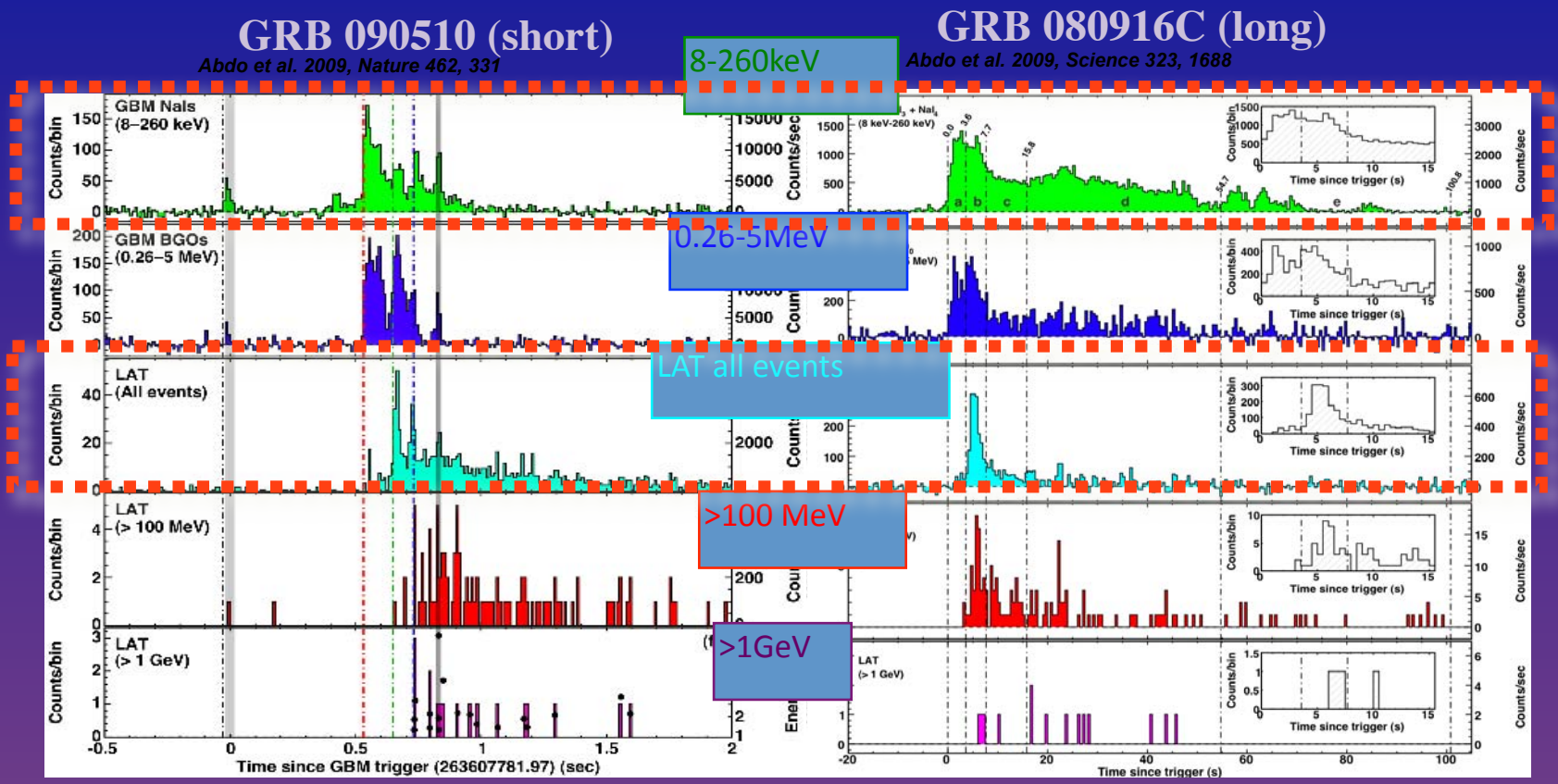
2 Delayed onset of high energy emission

- ✪ Long-lived high-energy emission

3 Spectrum:
Multiple distinct emission components + cut-offs
Photospheric emission revealed in prompt spectra

See Preece & Omodei talks

Delayed onset of the high energy emission



Delay: ~0.5s

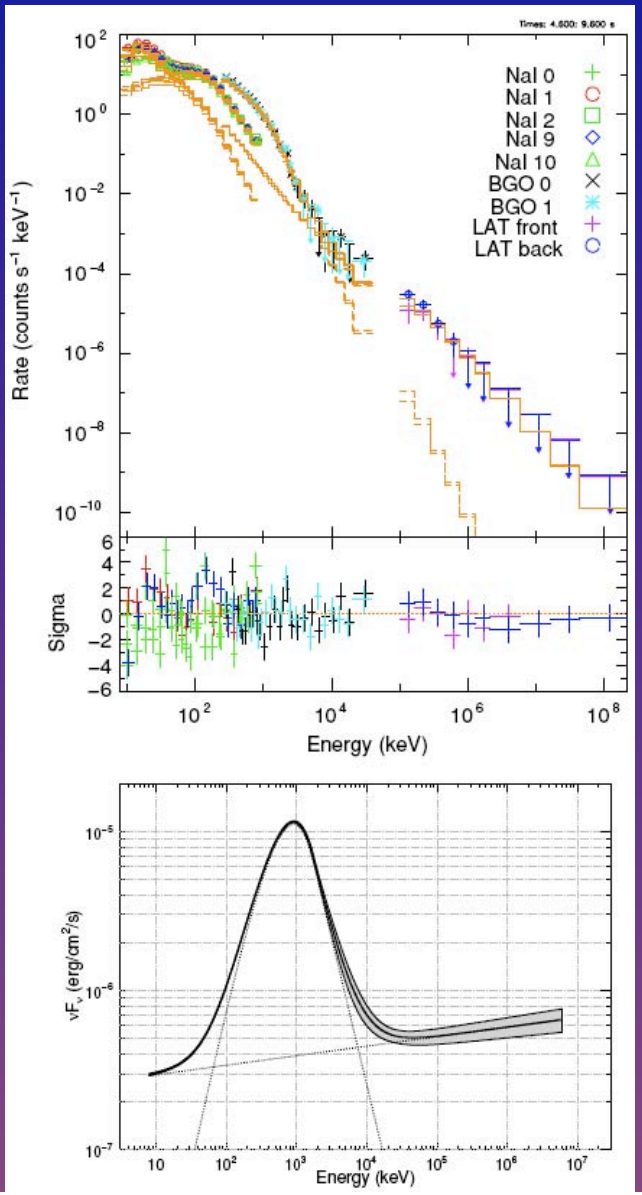
Delay: ~5s

(Credit : Fermi collaboration)

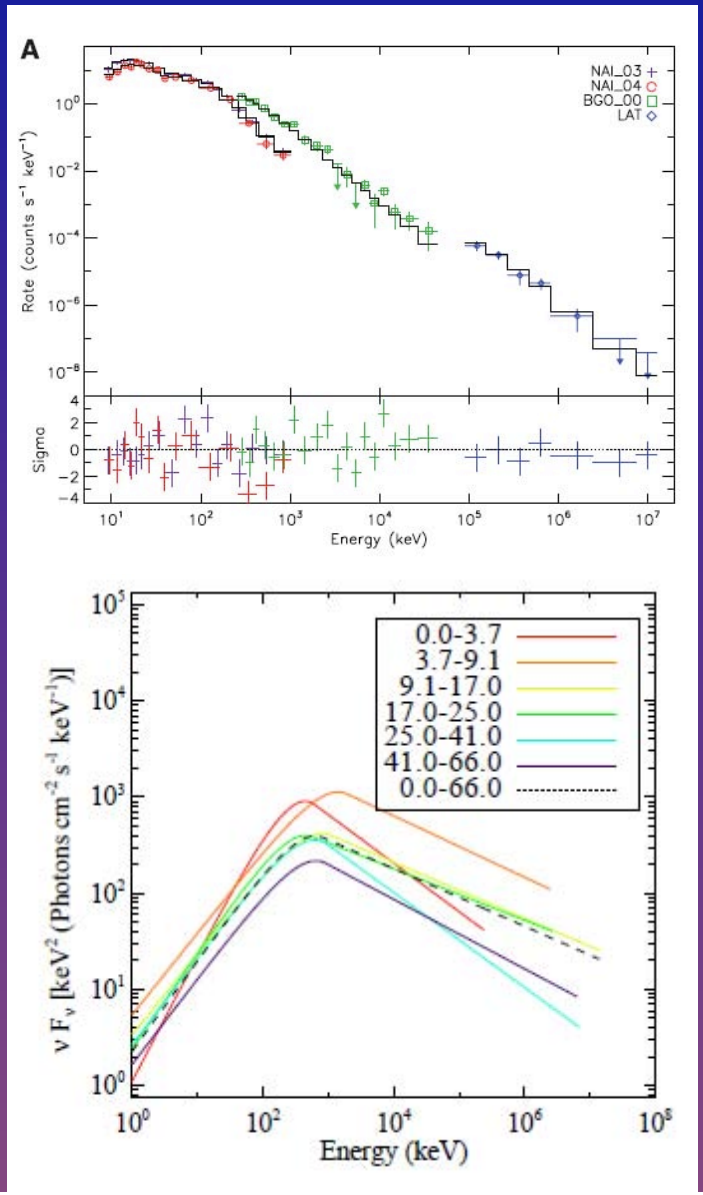
Many GRBs show a delayed onset!

GRB Observations: spectrum

090902B (Abdo+09)



080916C(Abdo+09)



GRB Observations: spectrum

090902B (Abdo+09)

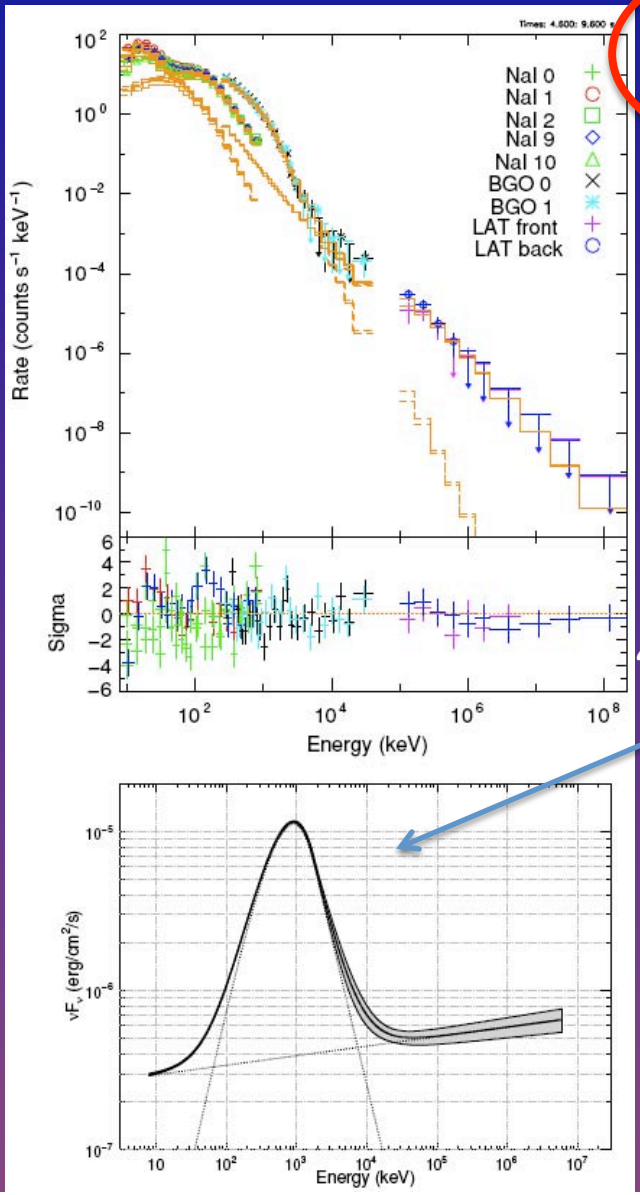
080916C(Abdo+09)

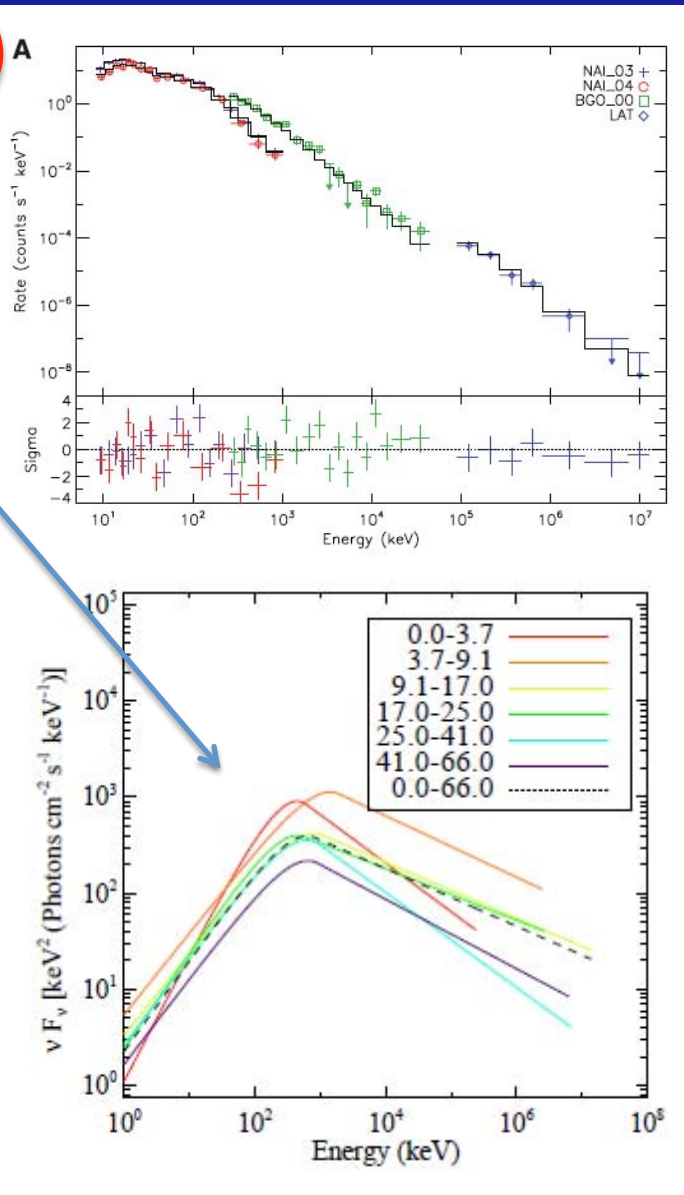
Qualitative difference

Extended Broken power law ("Band")

vs.

"Steep" broken P.L. (Thermal) + extra component





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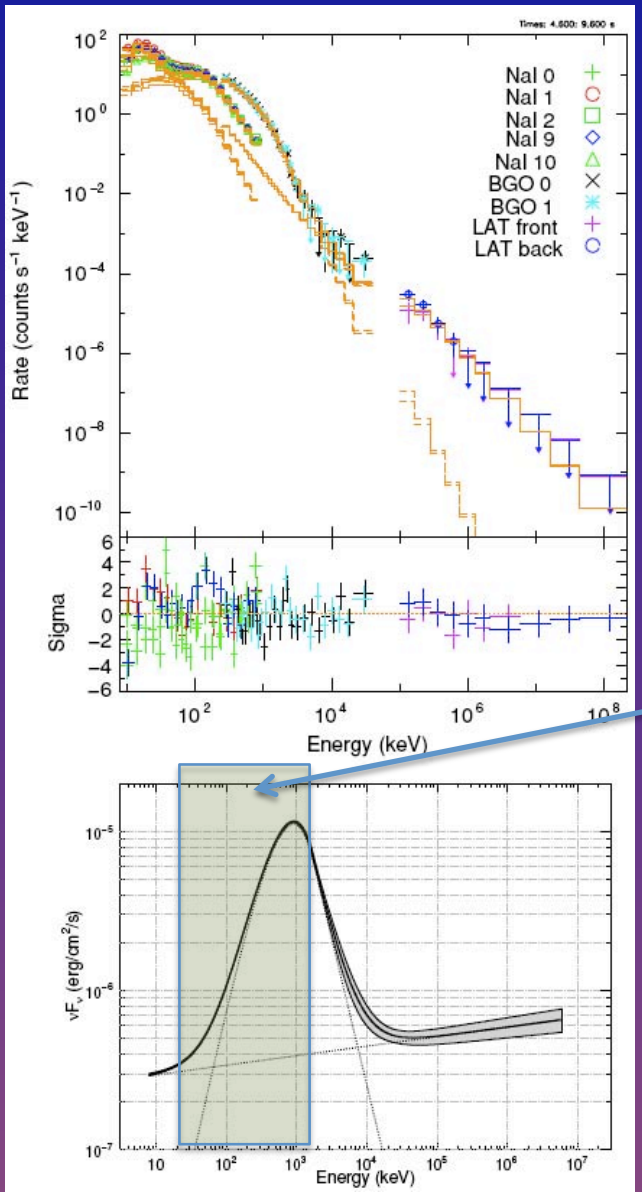
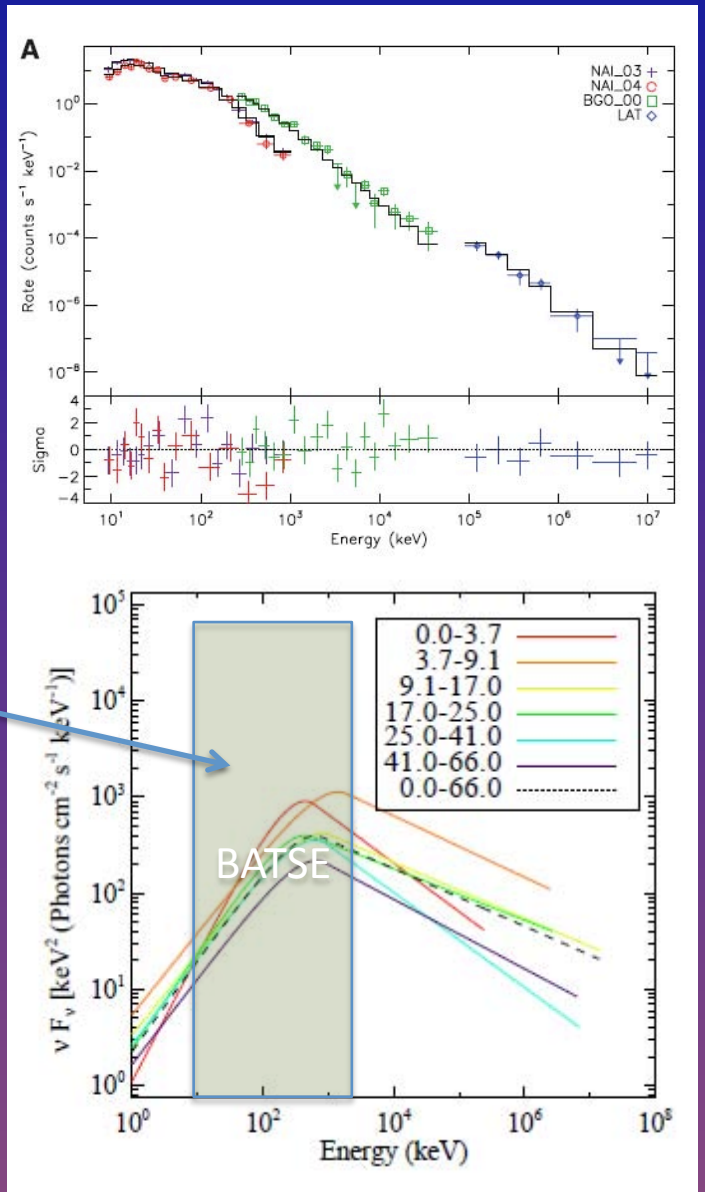


BATSE spectral range

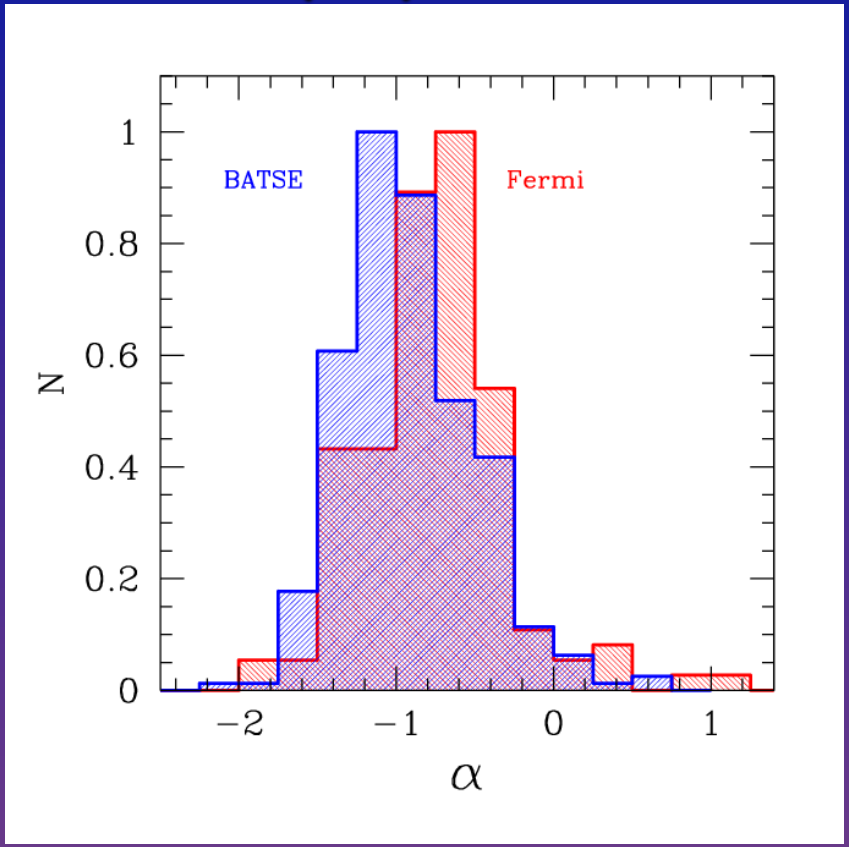
080916C(Abdo+09)



Global overview: GBM bursts

Most GRBs have similar properties to BATSE bursts

BATSE data: Kaneko+06



Nava+11

(picture taken from Ghisellini)

→Violate 'synchrotron line of death' (Preece98);
→Emission mechanism cannot be (only) synchrotron

see Preece & Nava's talks

Global overview: GBM bursts

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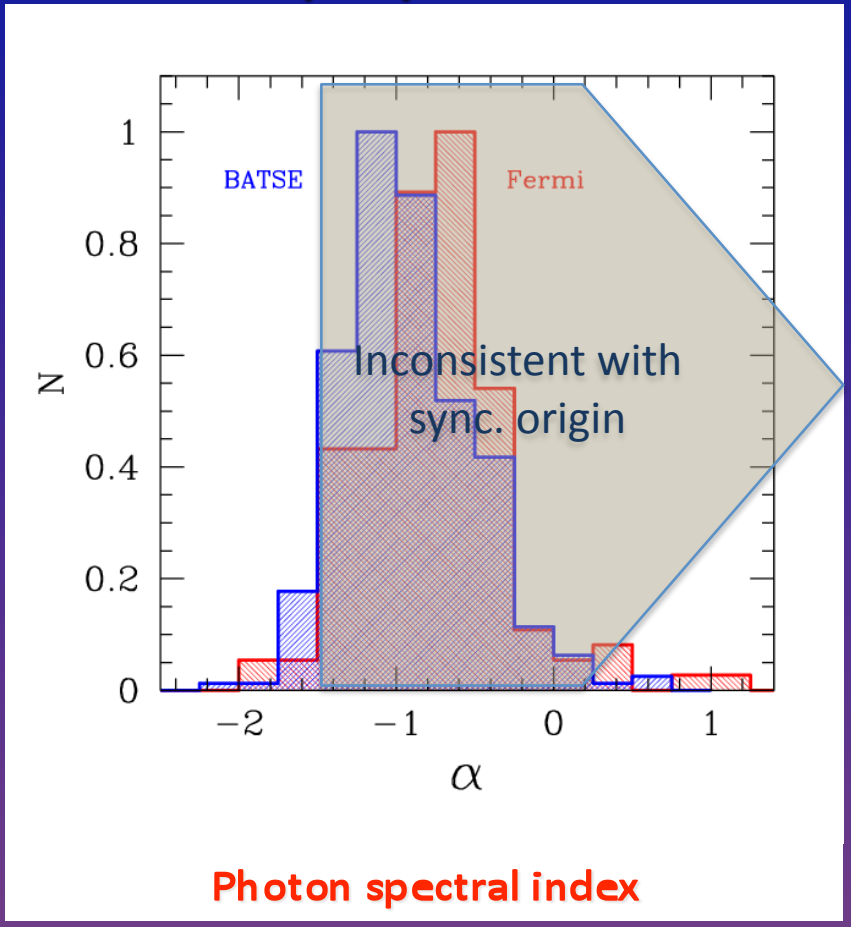

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→Violate 'synchrotron line of death' (Preece98);

→Emission mechanism cannot be (only) synchrotron

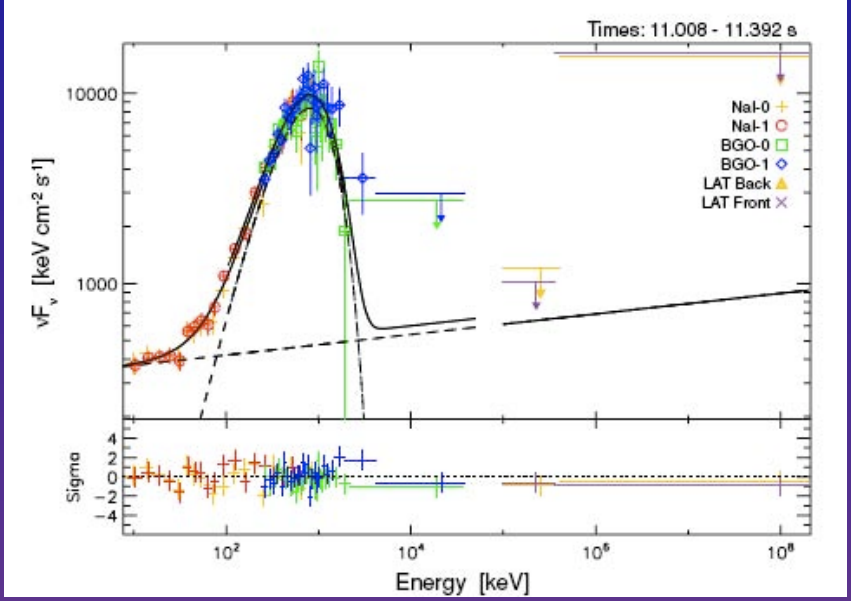
(but see Daigne+10)

see Preece & Nava's talks

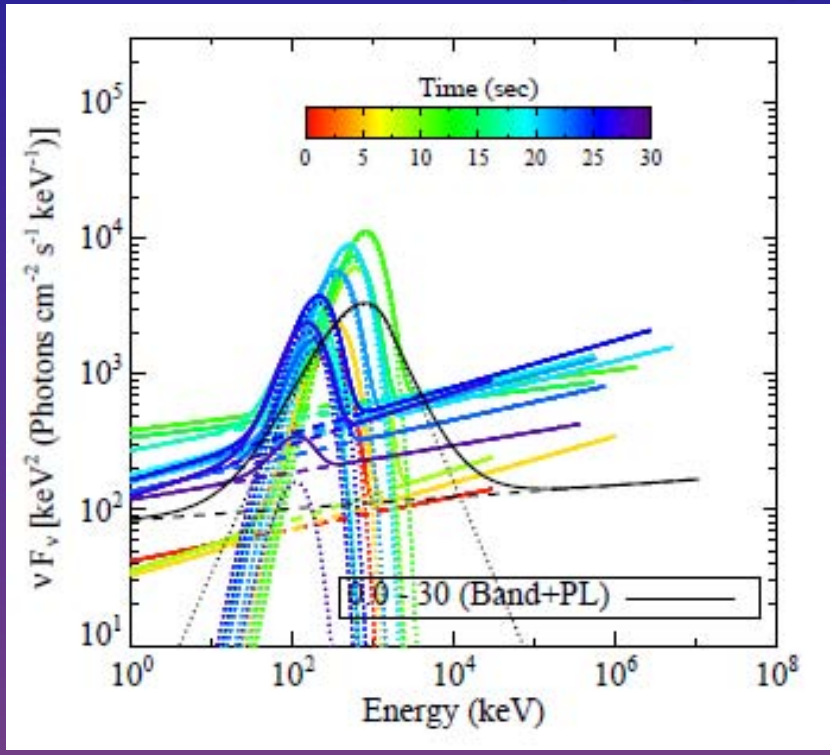
Photospheric component: natural extension

090902B:

(multi-color) black body (Ryde+10)



time resolved (Zhang+11)



1. Theoretically expected.
2. Clearly identified

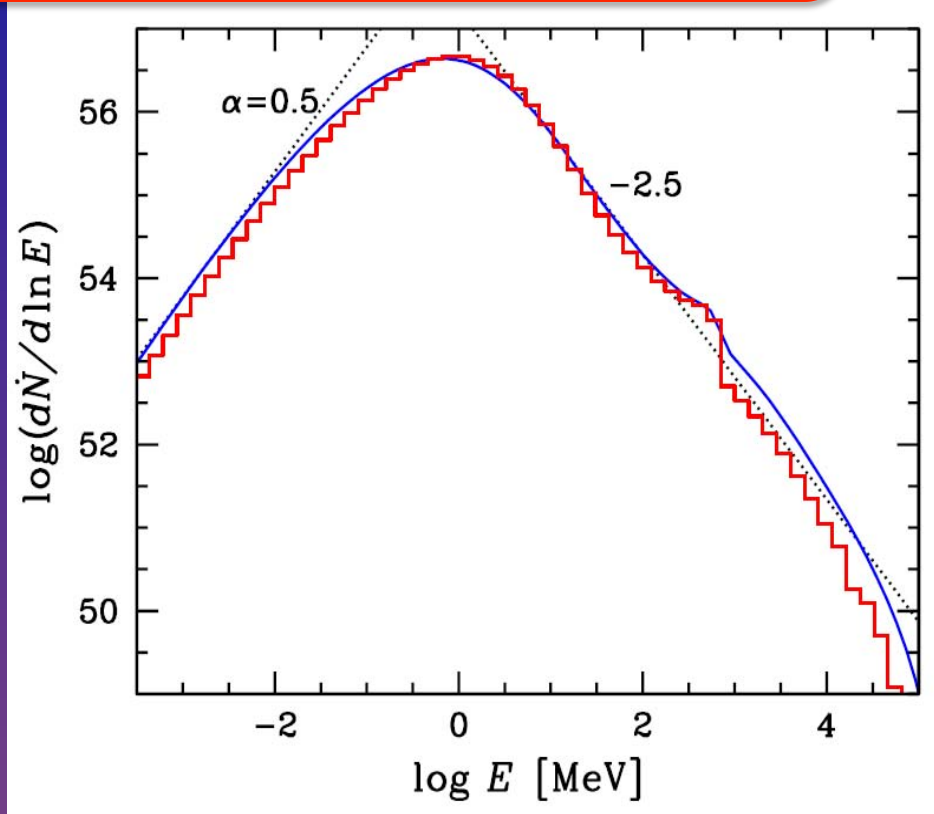
BUT

1. Can explain only part of the spectrum
2. Fairly rare

Modification of Planck spectrum

Idea: a heating mechanism below the photosphere modifies the Planck spectrum

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



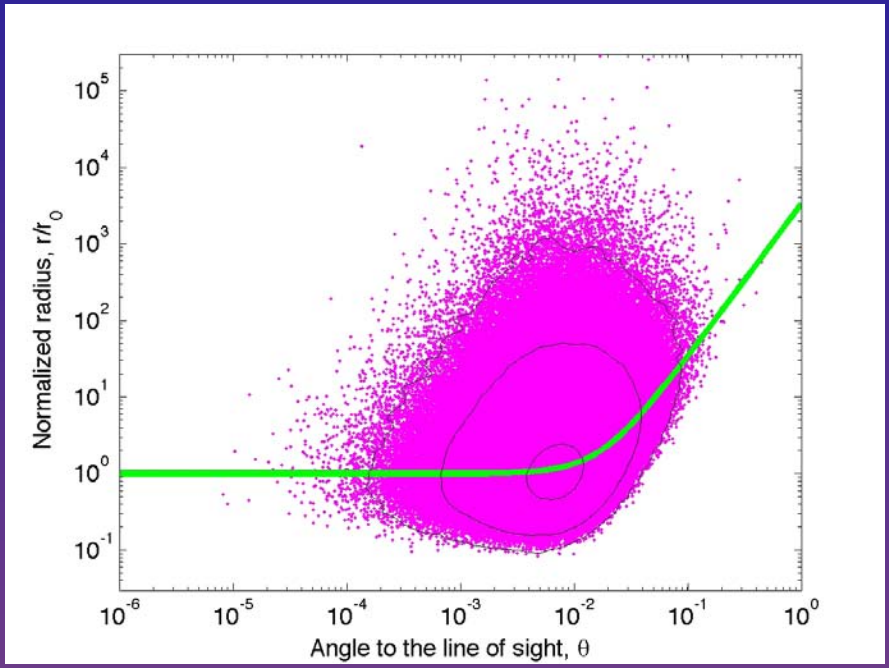
(picture taken from Vurm)

Emission from the photosphere is NOT seen as Planck !

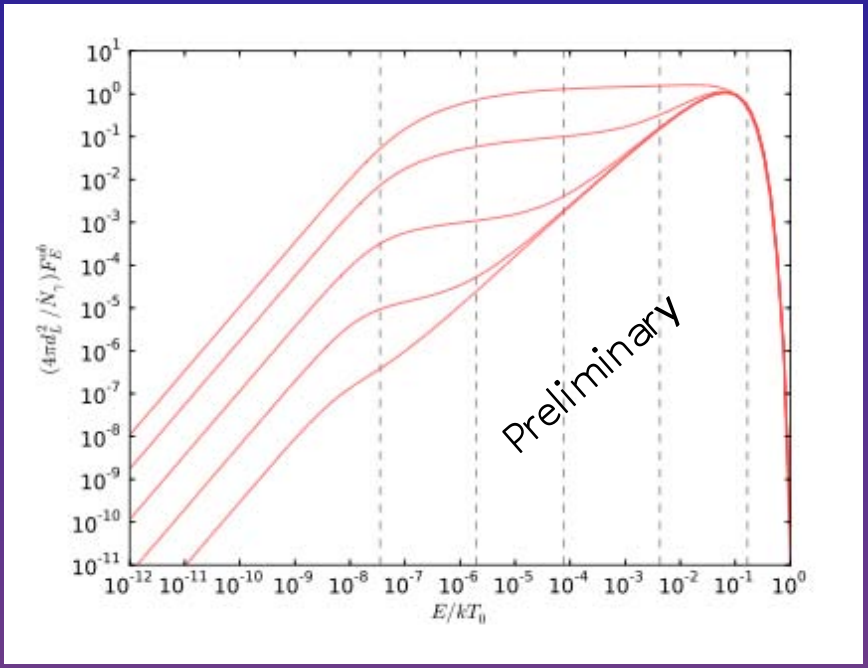
A lot of on-going research..

Modification of Planck spectrum

Geometrical broadening: 'photosphere' is NOT a single radius, but is 3-d



AP 08; AP & Ryde 11



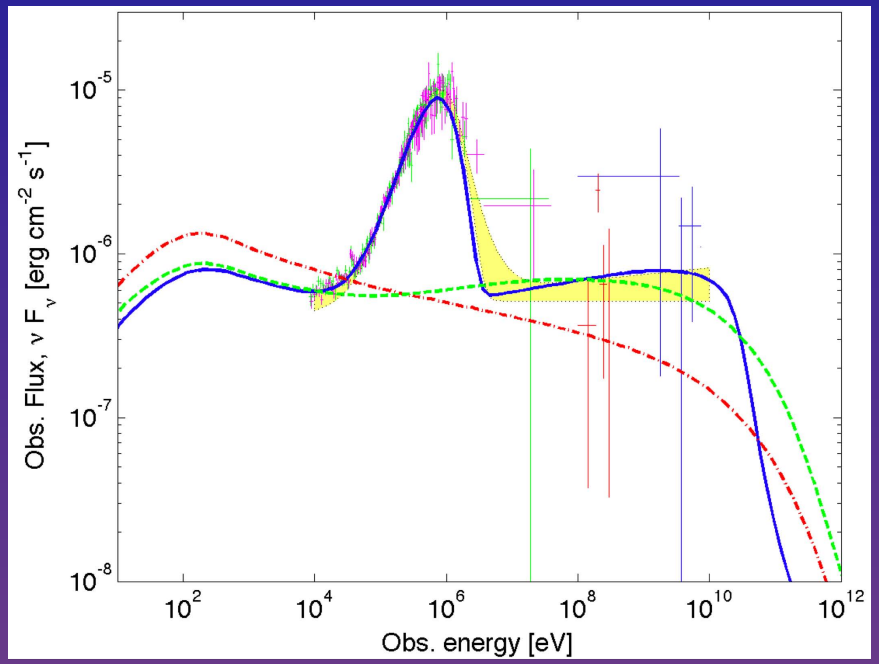
Lundman + (in prep.)

'Limb darkening' in relativistically expanding plasma;
Emission from the photosphere is NOT seen as Planck !

A lot of on-going research..

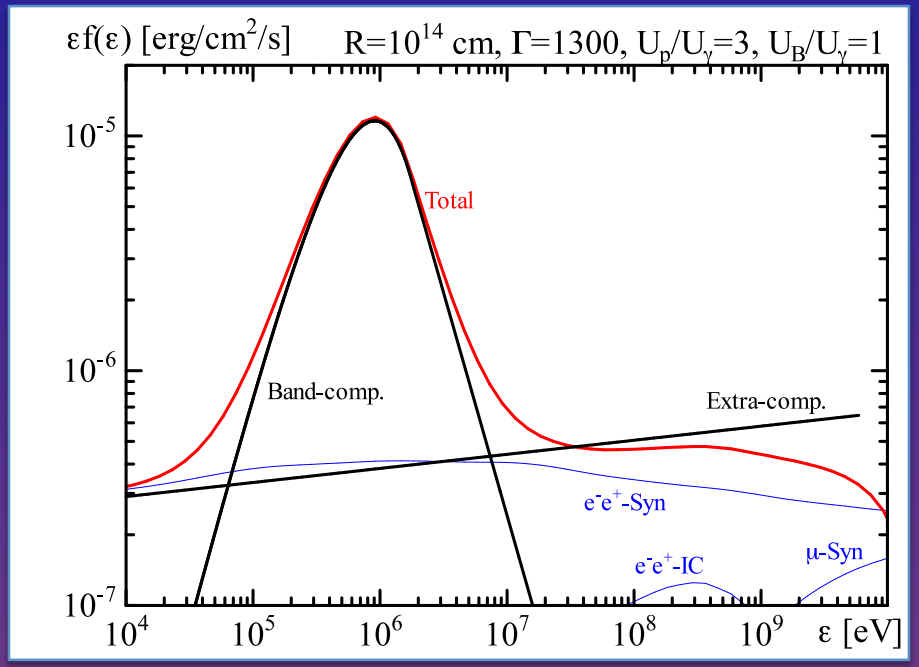
Origin of extra spectral component

090902B



Leptonic **(AP + 11)**

Sync+SSC
+Thermal Comptonization



Hadronic cascade **(Razzaque+09, Asano+ 10, Dermer & Razzaque 10 Meszaros & Rees 11)**

see Asano's talks

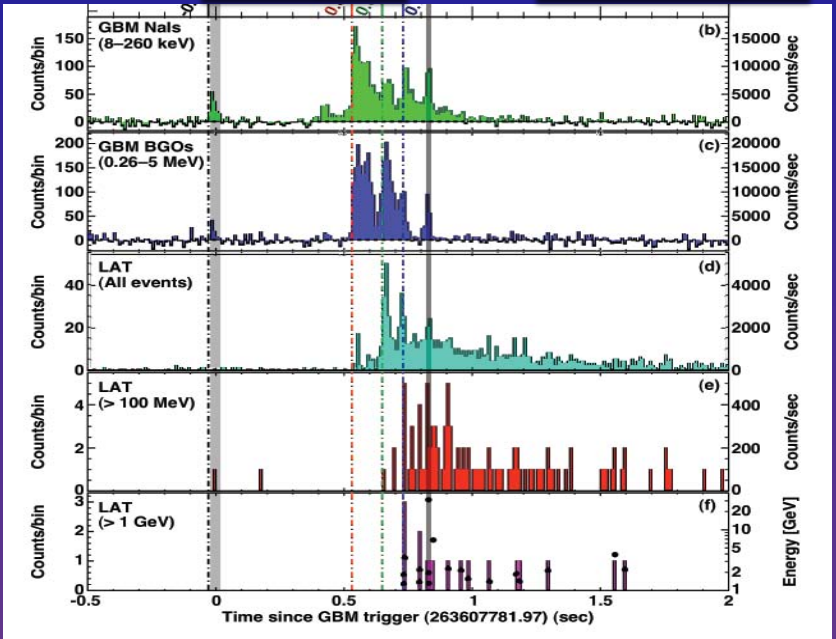
Delayed onset of LAT photons: clue for different origin ?

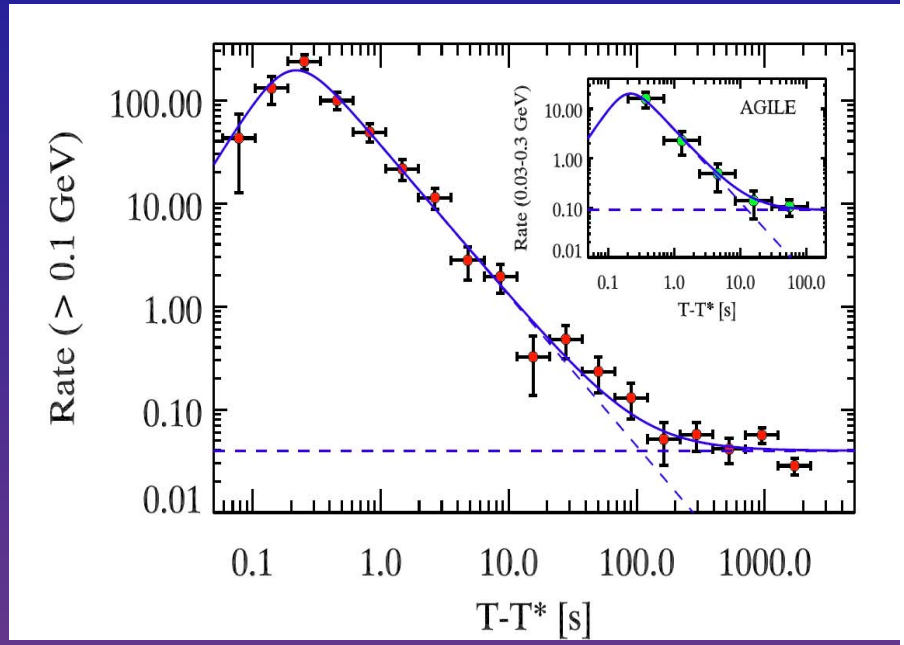
090510(Abdo+09); Short !

Lightcurve of LAT photons

Ghirlanda+10

LAT is delayed and last longer

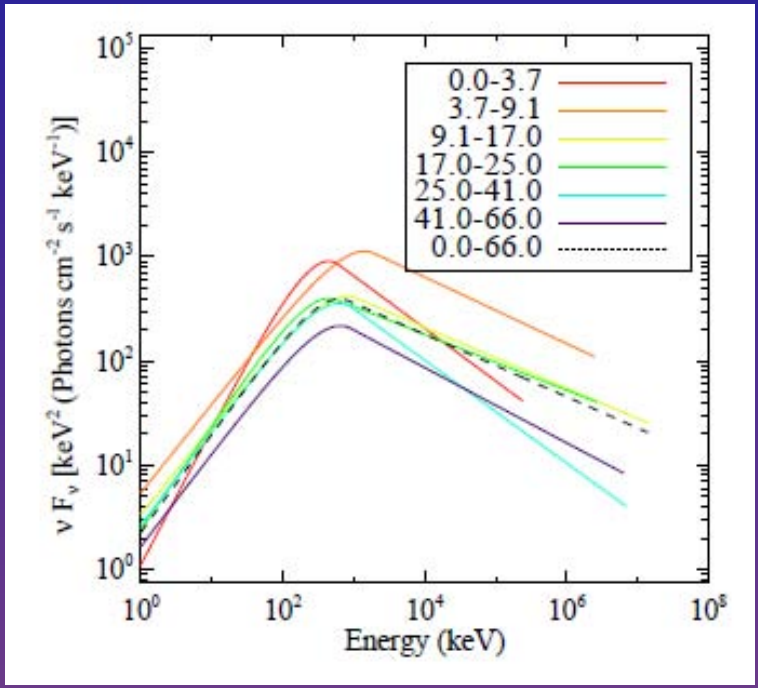




- External shock origin — Kumar & Barniol-duran 09, 10, Ghirlanda+10, Ghisellini+10
- Upscattered 'cocoon' photons — Toma+09
- Opacity / acceleration mechanism change — Zhang+11

But in many cases no evidence for spectral break ?

080916C(Abdo+09)



1. Need a refine data analysis: 'hidden' component - ?

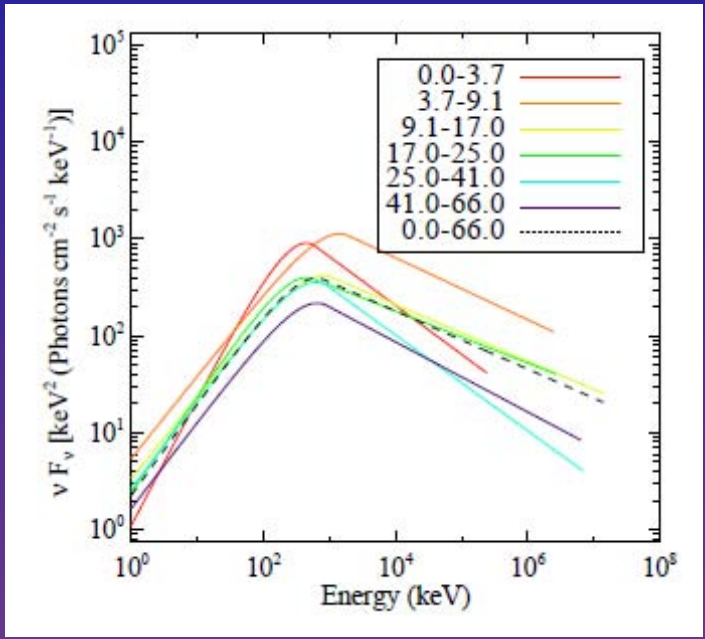
2. Need a refine theory; Origin of emission mechanism – Still unclear !

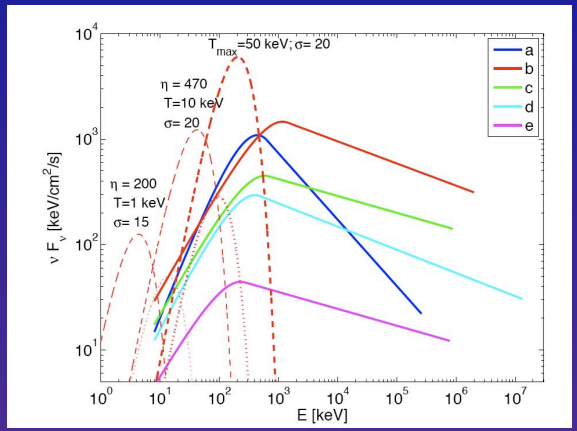
   Evidence for magnetized outflow ?

Zhang & AP 09

Lack of photospheric emission: Evidence for magnetized outflow ?

080916C(Abdo+09)





Zhang & AP 09

Zhang & Yan 11:
'Internal-collision-induced Magnetic Reconnection and Turbulence' (ICMART) model

Renewed interest in magnetized outflows

Connects to a wealth of jet acceleration models

e.g., Tchekhovskoy+09, Metzger+10, Komissarov+10, …

The basic questions

Apart from the general framework:
E_G -> E_k -> E_γ + AG,
the details of the fireball model are highly uncertain !!

1. Nature of the progenitor:
   Collapsar ? Magnetar ? BH-BH / BH-NS / NS-NS Merger ?

2. Jet launching mechanism:
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3. Why relativistic speeds ? Γ_{GRB} >~100, Γ_{AGN} <~30

4. Jet composition: Leptonic ? Hadronic ? Poynting – flux dominated ?

5. Dissipation mechanism: efficiency problem in internal shocks

6. Radiative processes: understanding the broad band spectrum
   -> particle acceleration

The basic questions

	FERMI's driven works
1. Nature of the progenitor:	Continuous works; further constraints by higher Γ
2. Jet launching mechanism:	Continuous works; **interest in magnetic models**
3. Why relativistic speeds ?	Still unclear
4. Jet composition:	Still unclear; many possibilities
5. Dissipation mechanism:	**More than a single region;** **Connection between prompt and early AG**
7. Radiative processes: -> particle acceleration	**Interest in photospheric models;** constraints by lack of LAT detection

Bottom line

- The broad band spectra seen by Fermi does not fit into any of the frameworks of existing models.

- Fermi results forces us to re-think of questions that were thought to be solved.

Asaf Pe'er, May 2011

Special thanks to Felix Ryde and Bing Zhang

Synchrotron line of death (I)

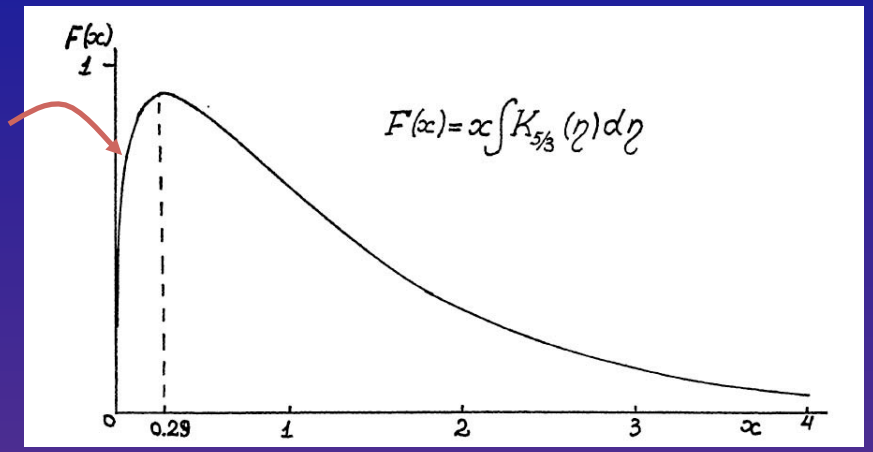
Sync. emission from a single electron (Ginzburg & Syrovatskii, 1965):

$P(\nu) \sim \nu^{1/3}$ ($\nu << \nu_c$)

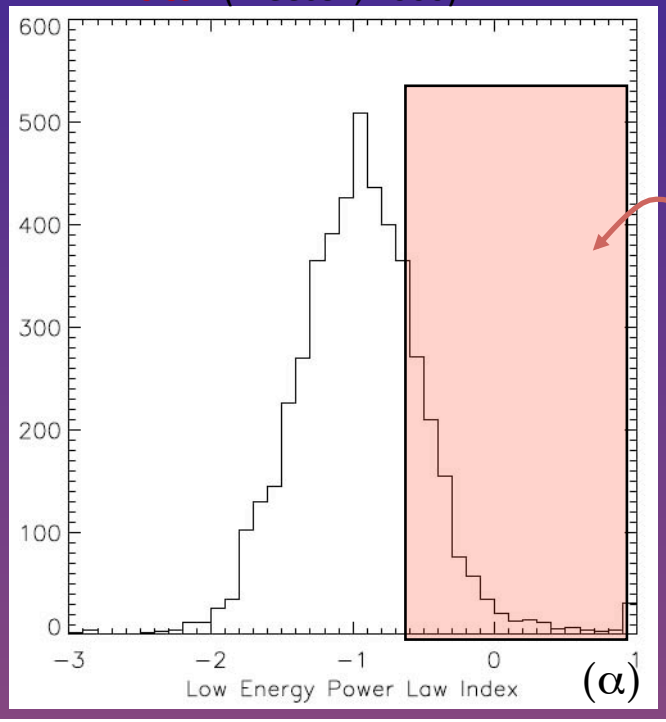
↓

$\nu F_\nu \sim \nu^\alpha$, $\alpha <= 4/3$

$\partial F_\nu / \partial \nu \sim \nu^\alpha$, $\alpha <= -2/3$



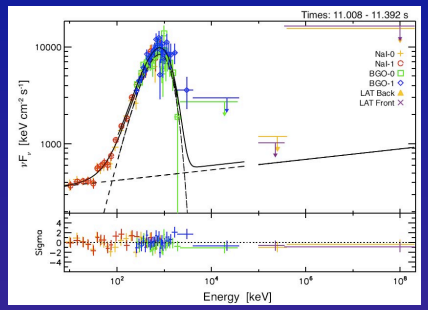
Data: (Preece+, 2000)



Inconsistent with synchrotron interpretation

($\partial F_\nu / \partial \nu$)

Synchrotron line of death (II): Rapid cooling



If the sub-MeV peak is due to synchrotron:

Electrons are injected above energy E_m;

They **radiate** -> cool down

Cooling rate:

$$\frac{dn_{el}(E,t)}{dt} = \frac{\partial}{\partial E}\left(n_{el}\frac{\partial E}{\partial t}\right); \qquad \frac{\partial E}{\partial t} = P(sync,Comp) \propto E^2$$

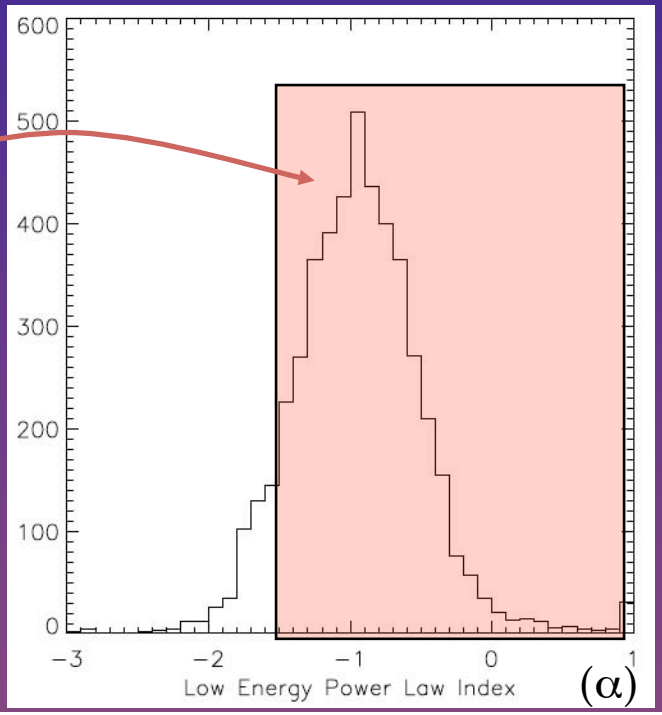
Steady state:

$$\rightarrow n_{el}(E) \propto E^{-2}$$

$$\rightarrow P(\nu) \propto \nu^{-(p-1)/2} \propto \nu^{-1/2}$$

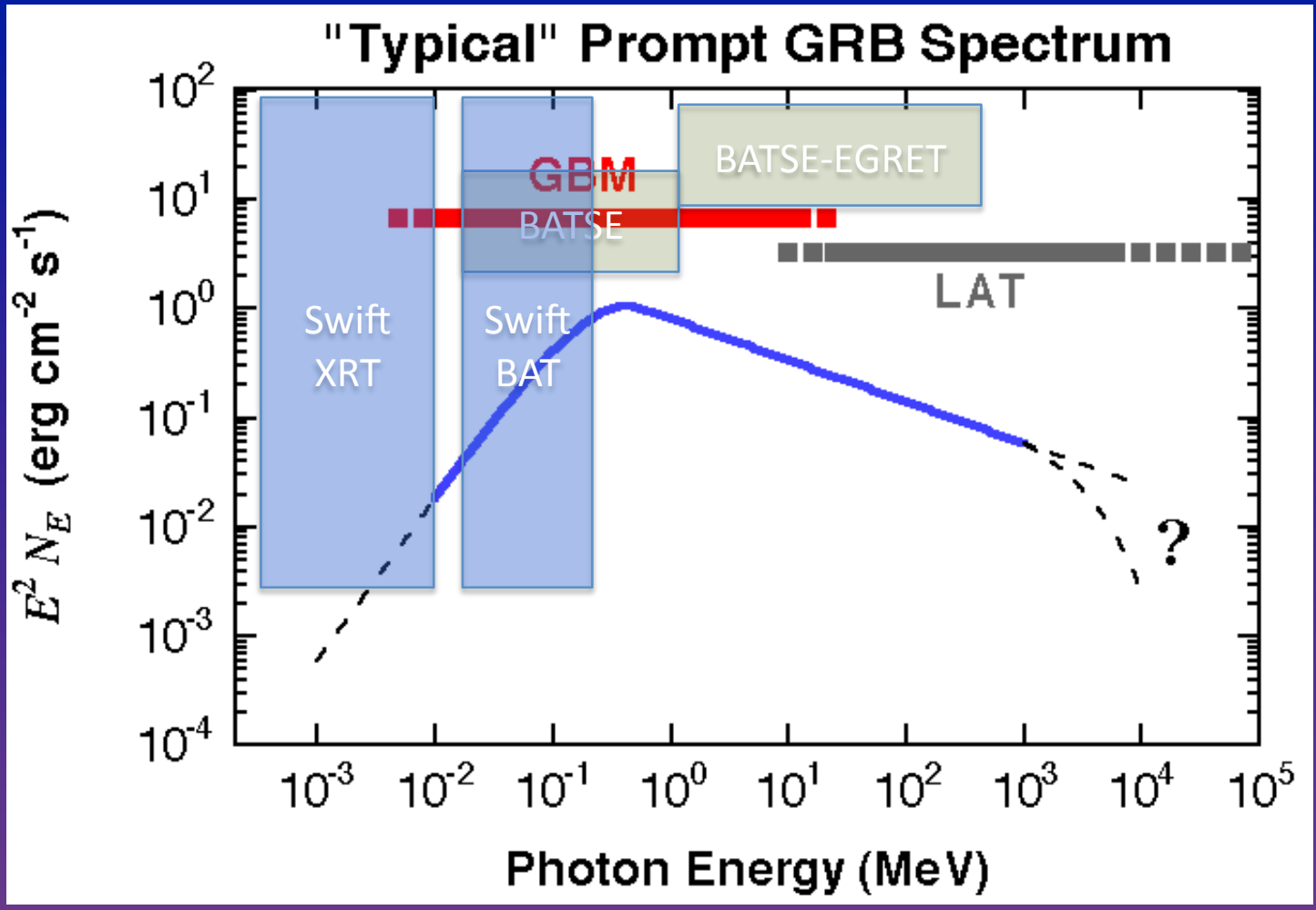
$\partial F_\nu/\partial\nu \sim \nu^\alpha$, $\alpha <= -3/2$

Data: (Preece+, 2000)



Low energy spectral slope - Inconsistent with synchrotron interpretation

Back >>



Swift – XRT: 0.2-10 keV, BAT: 15-150 keV

CGRO - BATSE: 20 keV – 2 MeV EGRET - TASC: 1- 200 MeV

I. Since 2000, no coverage of the spectral peak;
II. >MeV data became available