The connection between thermal and non-thermal emission in GRBs (GRB090902B as a case study)

Based on work by

Asaf Pe'er (CfA / ITC)

in collaboration with

Felix Ryde, Sinéad McGlynn (Stockholm)
Bin-Bin Zhang, Bing Zhang (UNLV)
Robert D. Preece, Chryssa Kouveliotou (NASA/MSFC, UAH)

November 2010

Pe'er et. al., 2010 (arXiv:1007.2228);

See also: Pe'er & Ryde, 2010 (arXiv:1008.4590); Zhang et. Al., 2010 (arXiv:1009.3338)

Outline of this talk

1. Basic idea: thermal component contributes to the prompt GRB emission;
   The thermal-non thermal connection

2. Complexities

3. GRB090902B as a demonstration tool for analysis method

Thermal emission ? - Motivation

We see: Photons.

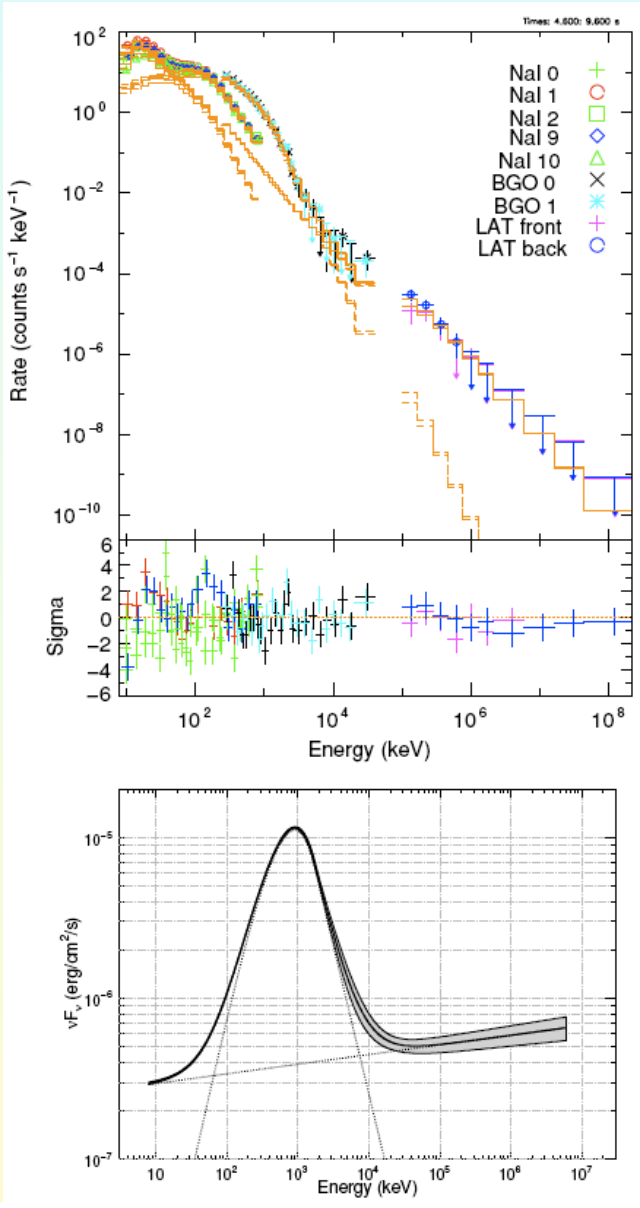
Required: ***physical interpretation***
"Band" fit is a **mathematical function**, and hence *does not provide it !*

(Possible interpretation:
synchrotron -> fail [too steep]).

1) What is/are the radiative process(es) ?
- physical conditions ?

2) "Band" function sometimes fails at high (Fermi/LAT) energies !

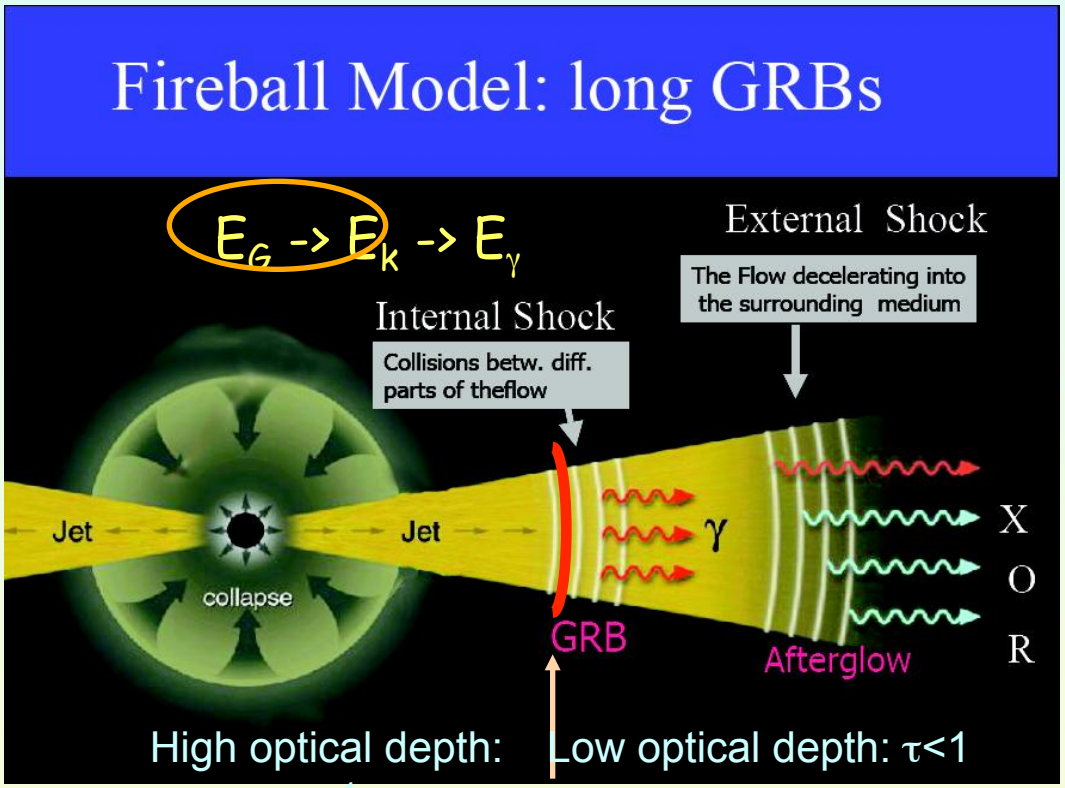
GRB090902B (Abdo+09)



Why thermal emission ? - theory

In fireball model, energy is converted **TWICE:**

1) Gravitational (collapse, merger) -> kinetic (jet)
2) Kinetic -> Dissipation (Efficiency problem)



Photospheric radius: $r_{ph} = 6*10^{12}\ L_{52}\ \Gamma_2^{-3}$ cm

- Goodman (1986)
- Paczynski (1986)
- Thompson (1994)
- Liang (1997)

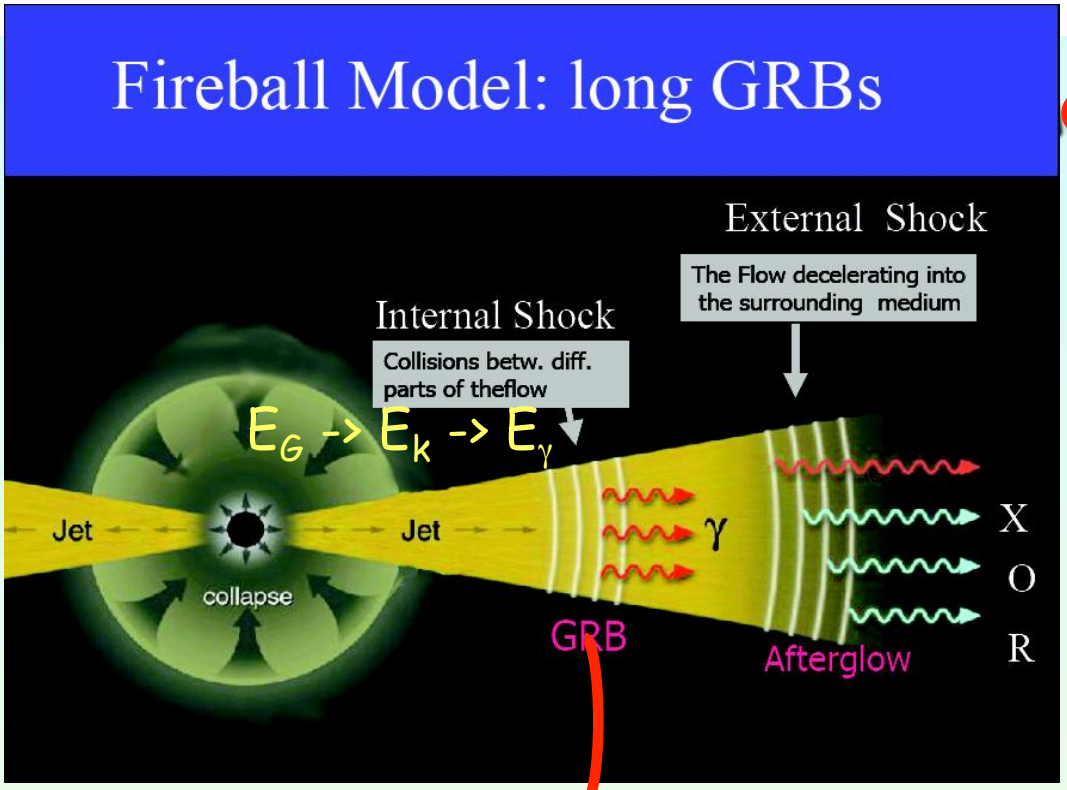
- Meszaros & Rees (2000)
- Daigne & Mochkovitch (2002)
- Meszaros, Ramirez-ruiz, Rees & Zhang (2002)
- Nakar, Piran & Sari (2004)
- Rees & Meszaros (2005)
- Giannios (2006)
- Beloborodov (2010)

Photons emitted in the inner part **inevitably thermalize !**

Natural outcome of fireball !

photosphere in 1-d >>

odel:



High optical depth: $\tau>1$ Low optical depth: $\tau<1$

Key Idea:

We see simultaneously photons emitted from different radii.

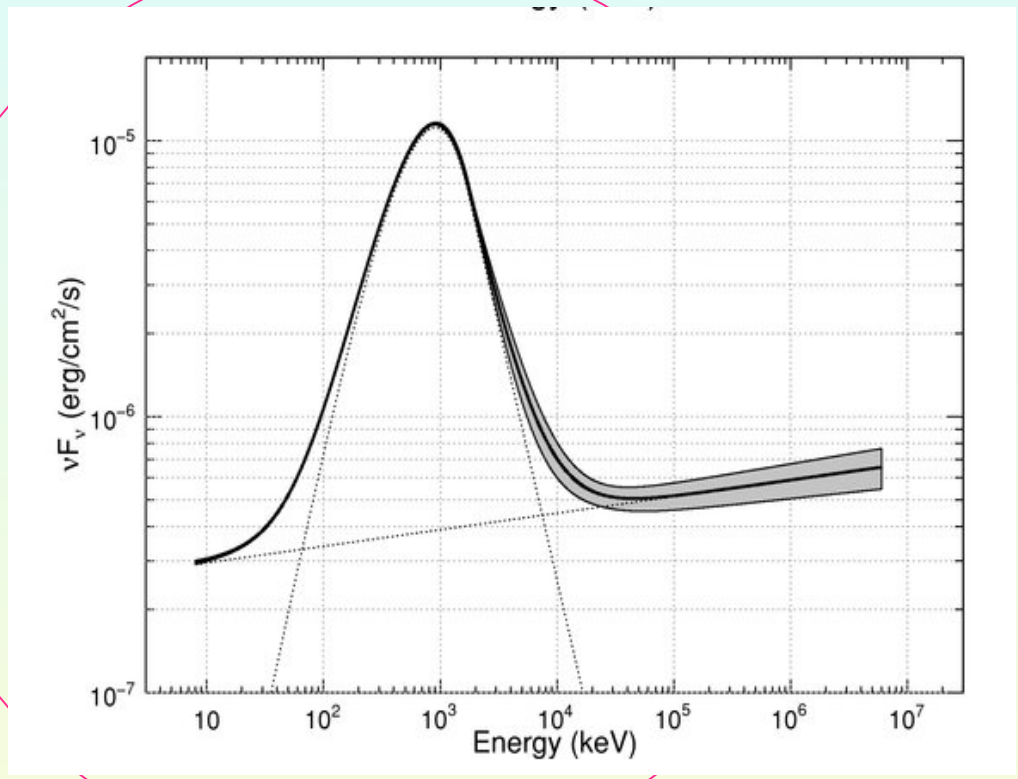
1)Photosphere – the innermost (≈thermal; comes first !)

2) $r_\gamma > r_{ph}$ – some dissipation radii (Non-thermal)

Natural outcome of fireball !

Theorist's ideal world….
(GRB090902B)

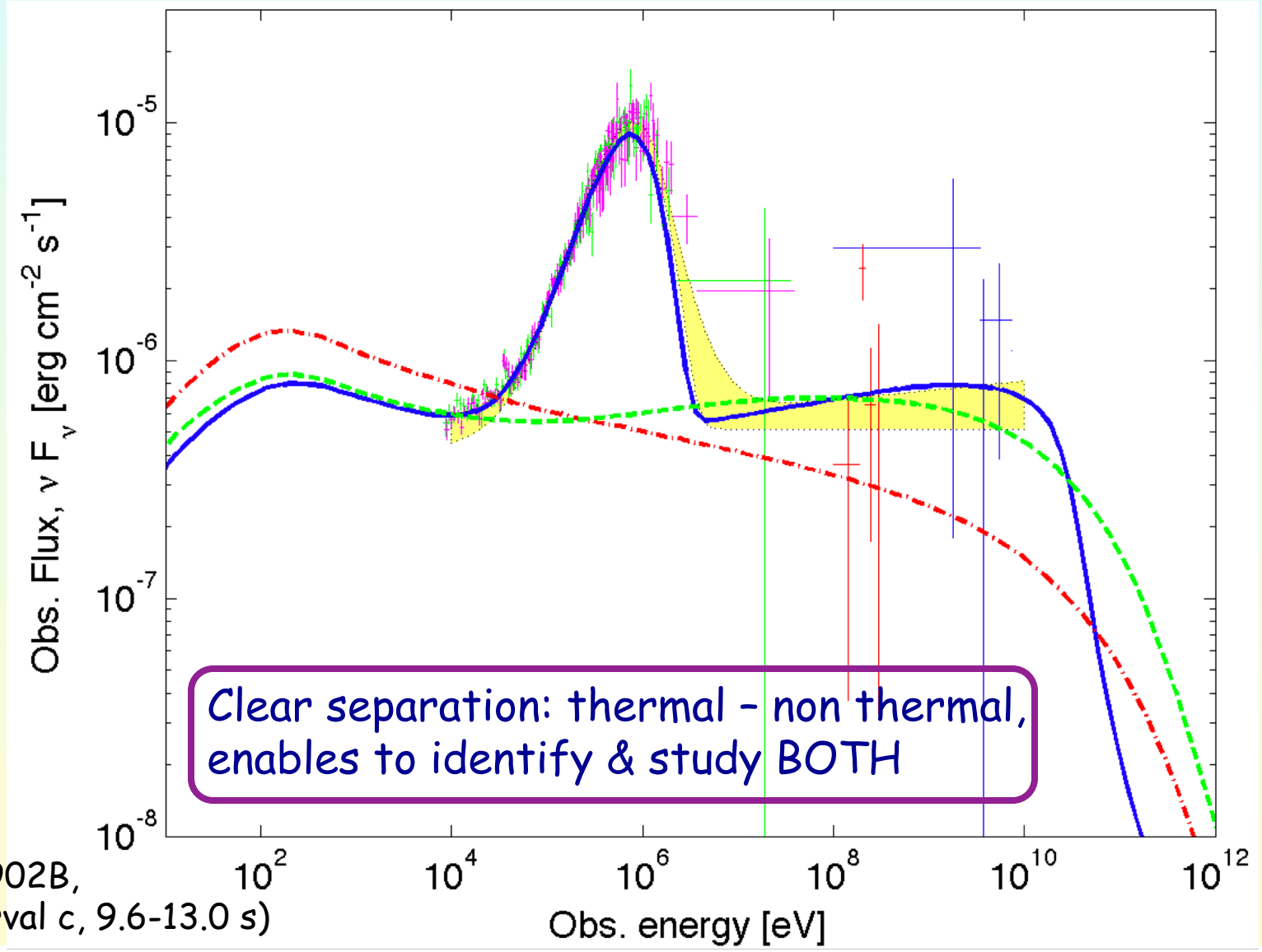
(Abdo+09)



(GRB090902B,
time interval b, 4.6-9.6 s)

Theorist's ideal world….
(GRB090902B)

(Pe'er+10)



(GRB090902B,
time interval c, 9.6-13.0 s)

But why don't we always see it ?
(life isn't so easy…)

1. It may be weak ($r_{ph} >> r_s$);
   -> but put the numbers, and get $r_{ph}/r_s = 6\, L_{54}\, \Gamma_3^{-4}\, r_{0,8}^{-1}$
   -> For Fermi bursts, Γ>~1000, -> Pronounced thermal emission

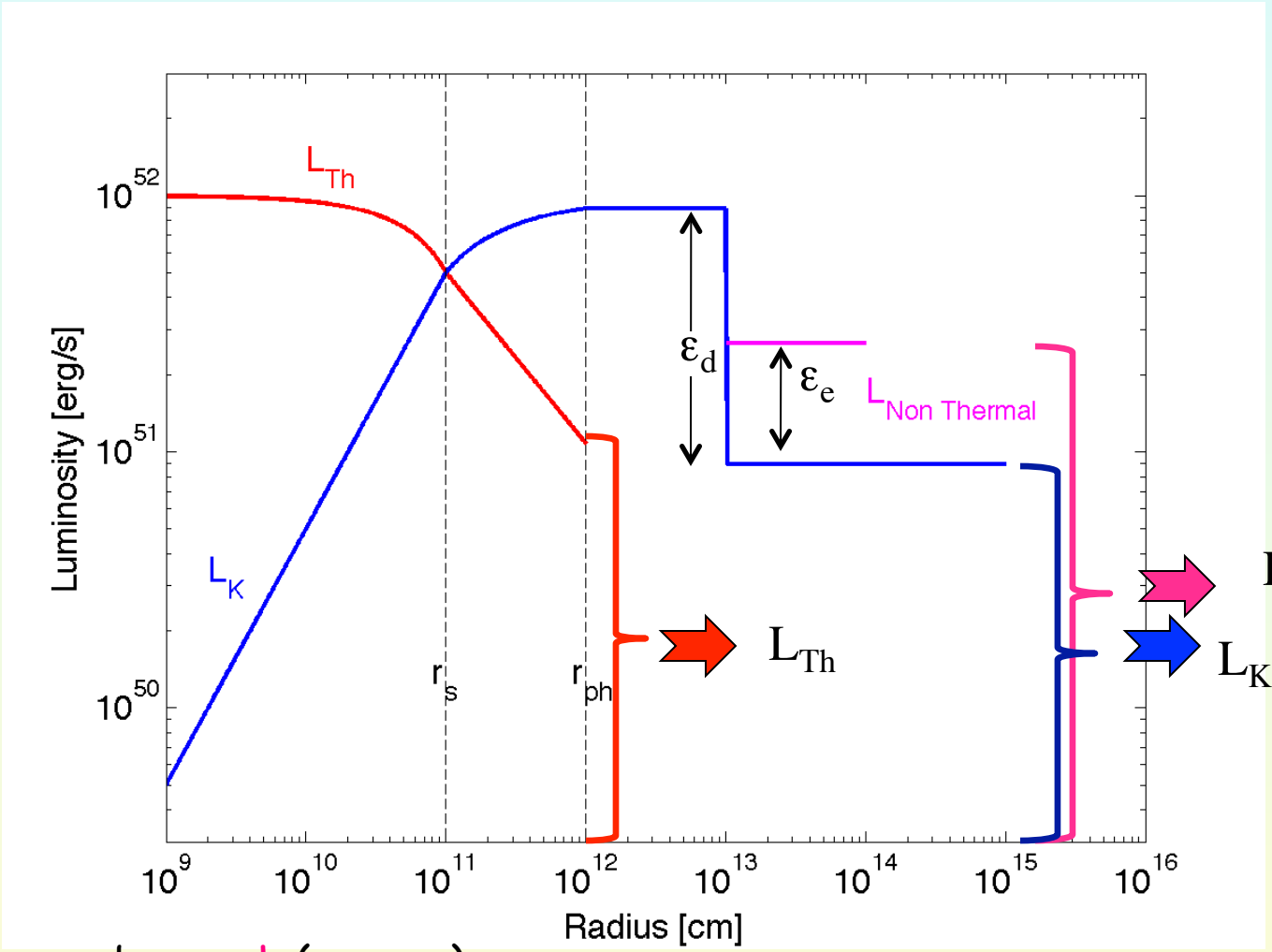
2. Hidden: e.g., magnetized outflow (Zhang & Pe'er, 2009)
   – see Zhang's, Medvedev's talk's

3. Modified:
   e.g., by energetic electrons injected close to the photosphere
   (Pe'er, Meszaros & Rees, 2005/2006);
   - see Toma's, Beloborodov's talk

4. Smeared Externally (Γ, L changes with time)
   Internally

5. Something is wrong in the "fireball" model (?)

Thermal photons in "classical" fireball model



1. It may be weak ($r_{ph} >> r_s$);
   -> but put the numbers, and get $r_{ph}/r_s = 6\, L_{54}\, \Gamma_3^{-4}\, r_{0,8}^{-1}$
   -> For Fermi bursts, Γ>~1000, -> Pronounced thermal emission

But why don't we always see it ?
(life isn't so easy…)

1. It may be weak ($r_{ph} >> r_s$);
   -> but put the numbers, and get $r_{ph}/r_s = 6\, L_{54}\, \Gamma_3^{-4}\, r_{0,8}^{-1}$
   -> For Fermi bursts, Γ>~1000, -> Pronounced thermal emission

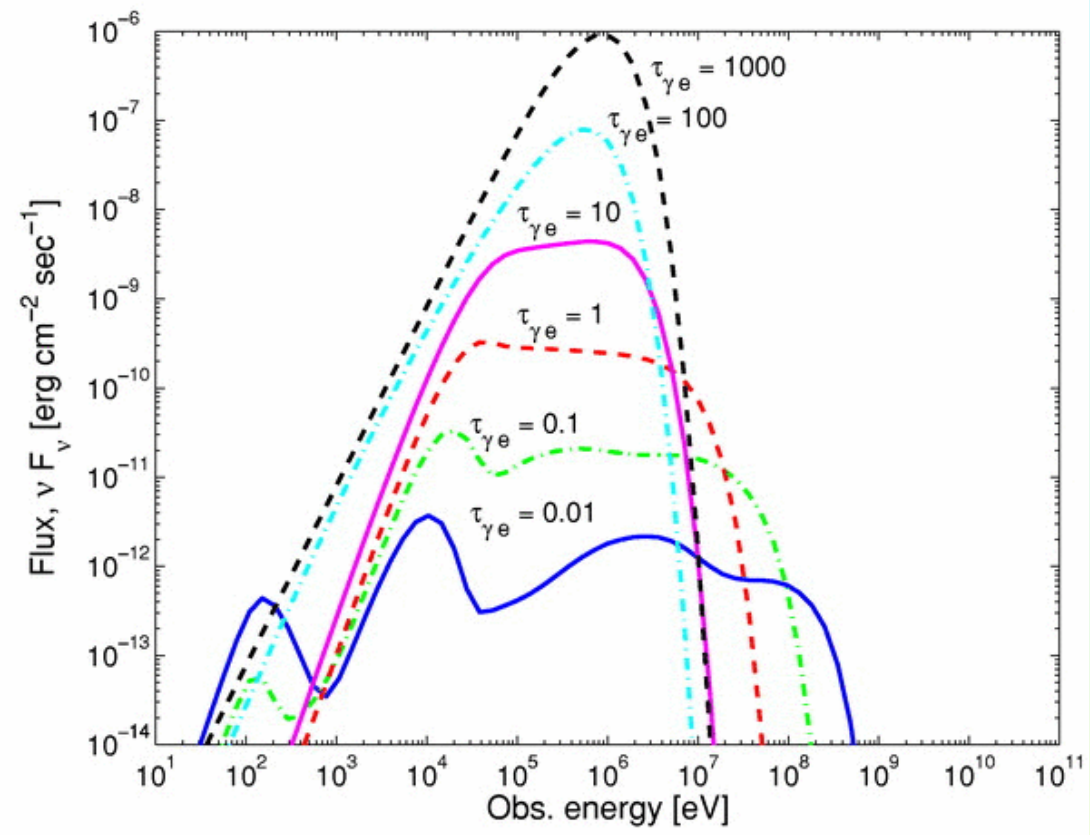
2. Hidden: e.g., magnetized outflow (Zhang & Pe'er, 2009)
   – see Zhang's, Medvedev's talk's

3. Modified:
   e.g., by energetic electrons injected close to the photosphere
   (Pe'er, Meszaros & Rees, 2005/2006);
   - see Toma's, Beloborodov's talk

4. Smeared Externally (Γ, L changes with time)
   Internally

5. Something is wrong in the "fireball" model (?)

Modification of thermal emission



Pe'er, Meszaros & Rees 2006

Injection of energetic electrons **close** to the photosphere – Modifies the spectrum;

(See Beloborodov's, Toma's talks)

Thermal photons serve as seed photons for IC - **Electrons rapidly cool**

Effect is non-linear !! (e^- reach quasi steady state- not power law)

Real life spectra is not easy to model !! (**NOT** simple broken Power law)

But why don't we always see it ?
(life isn't so easy…)

1. It may be weak ($r_{ph} >> r_s$);
   -> but put the numbers, and get $r_{ph}/r_s = 6\, L_{54}\, \Gamma_3^{-4}\, r_{0,8}^{-1}$
   -> For Fermi bursts, Γ>~1000, -> Pronounced thermal emission

2. Hidden: e.g., magnetized outflow (Zhang & Pe'er, 2009)
   – see Zhang's, Medvedev's talk's

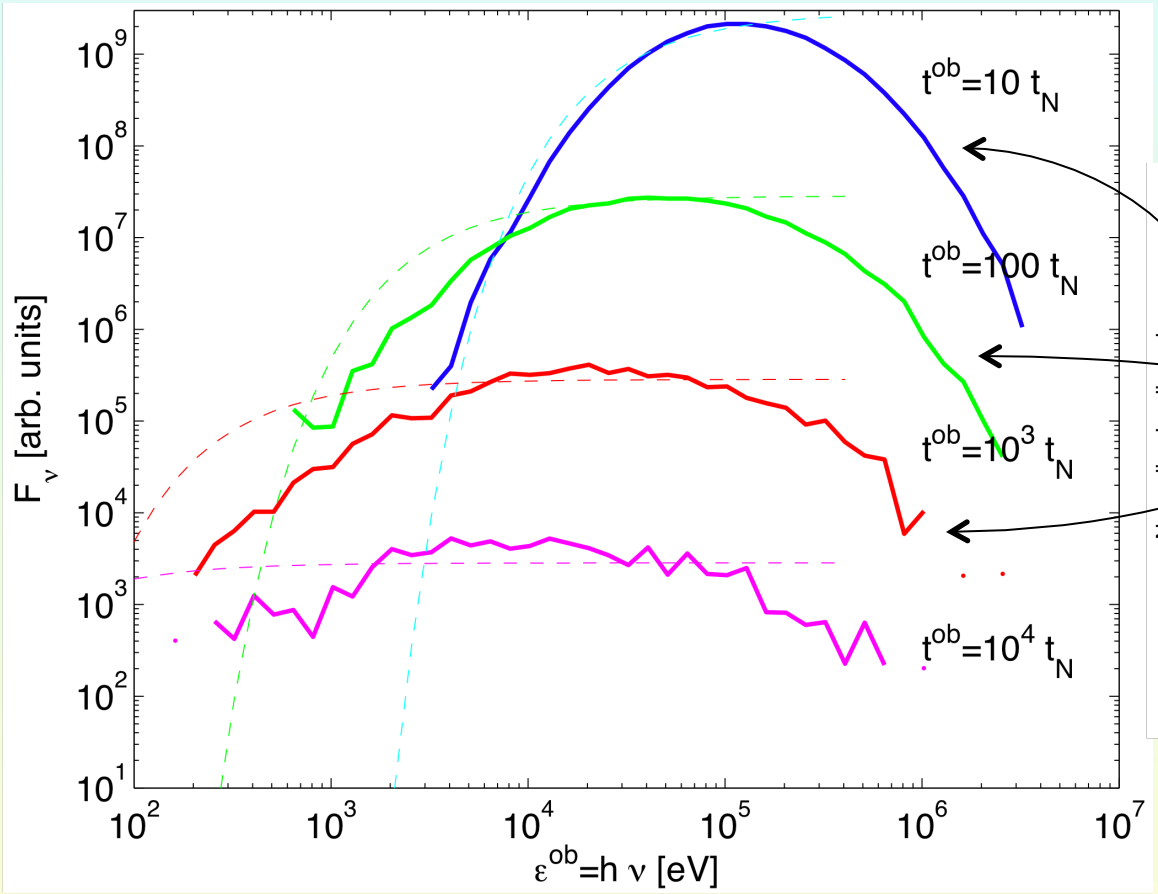
3. Modified:
   e.g., by energetic electrons injected close to the photosphere
   (Pe'er, Meszaros & Rees, 2005/2006);
   - see Toma's, Beloborodov's talk

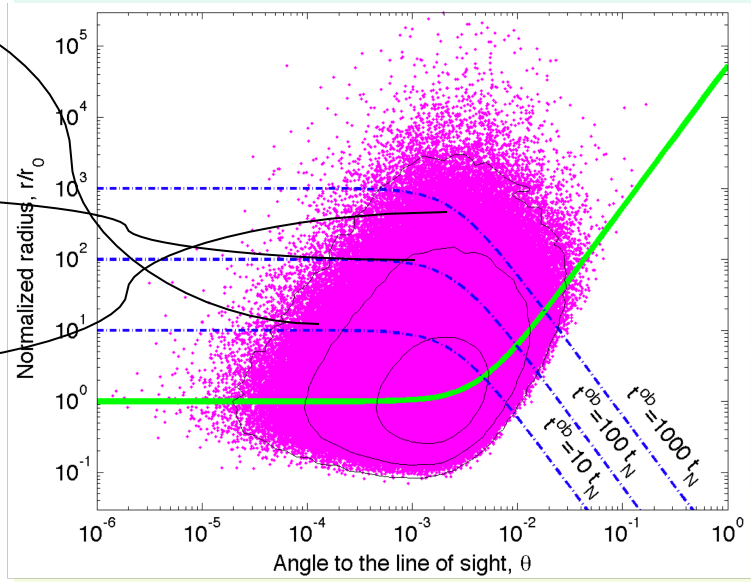
4. Smeared Externally (Γ, L changes with time)
   Internally

5. Something is wrong in the "fireball" model (?)

Intrinsic smearing: multicolor black body

We see *simultaneously* thermal photons
emitted from a range of radii, angles -> Doppler shifts





Resulting thermal spectrum is **modified Planck !!** (multicolor BB)

At late times, $F_\nu \sim \nu^0$ -> Identical to "Band" α

Pe'er & Ryde (2010)

But why don't we always see it ?
(life isn't so easy…)

1. It may be weak ($r_{ph} >> r_s$);
   -> but put the numbers, and get $r_{ph}/r_s = 6\, L_{54}\, \Gamma_3^{-4}\, r_{0,8}^{-1}$
   -> For Fermi bursts, Γ>~1000, -> Pronounced thermal emission

2. Hidden: e.g., magnetized outflow (Zhang & Pe'er, 2009)
   – see Zhang's, Medvedev's talk's

3. Modified:
   e.g., by energetic electrons injected close to the photosphere
   (Pe'er, Meszaros & Rees, 2005/2006);
   - see Toma's, Beloborodov's talk

4. Smeared Externally (Γ, L changes with time)
   Internally

5. Something is wrong in the "fireball" model (?)

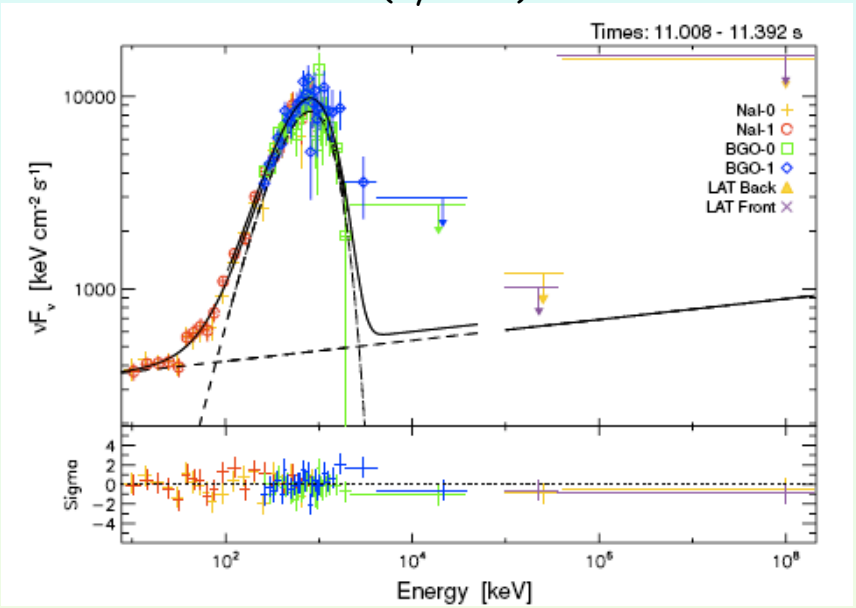
Thermal emission as probe of GRB physics

Measurement of T^{ob}, $F_{BB}{}^{ob}$ -> r_{ph}, Γ

$$\mathcal{R} \equiv \left(\frac{F^{ob.}}{\sigma T^{ob.4}} \right)^{1/2} \propto \frac{1}{d_L} \frac{r_{ph}}{\Gamma}$$

relativistic aberration

(Ryde+10)



Known:

1) $F^{ob.}$
2) $T^{ob.}$
3) redshift (d_L)

$$\mathcal{R} \equiv \left(\frac{F^{ob.}}{\sigma T^{ob.4}} \right)^{1/2} \propto \frac{1}{d_L} \frac{r_{ph}}{\Gamma} \propto \frac{1}{d_L} \frac{L_{iso}}{\Gamma^4}$$

Unknown:

1) $L_{iso} = 4\pi d_L^2 F$
2) $\Gamma \propto \left[(1+z)^2 d_L \frac{F_{Th}}{\mathcal{R}} \right]^{1/4} \left(\frac{L}{L_{Th}} \right)^{1/4}$
3) r_{ph}

Photospheric radius: $r_{ph} = 6*10^{12}\, L_{52}\, \Gamma_2^{-3}$ cm

Pe'er et. al. (2007)

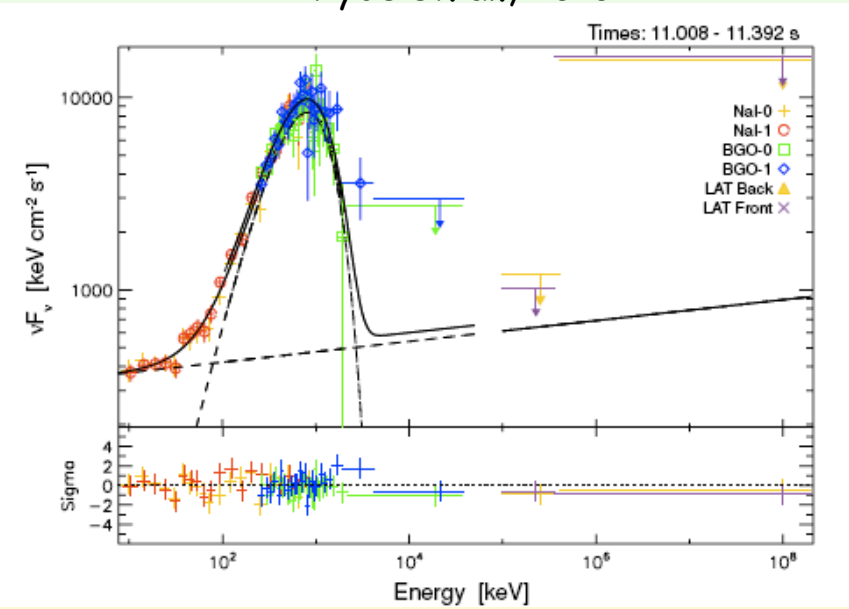
Analysis method: how to approach a good-looking GRB (I)

1) Identify thermal component:
T, F_{BB}, d_L -> L_{Th}, $\Gamma=780(L/L_{Th})^{1/4}$, r_{ph}

2) Opacity arguments:
$\tau_{\gamma\gamma}(11\ GeV) <= 1$ -> $r_\gamma >= 10^{15.5}$ cm
(Independent on the uncertainties in δt !)

$r_\gamma > r_{ph}$ -> At least two emission zones

GRB090902B, time interval C
Ryde et. al., 2010



Analysis method: how to approach a good-looking GRB (II)

3) Identify non-thermal component below thermal peak

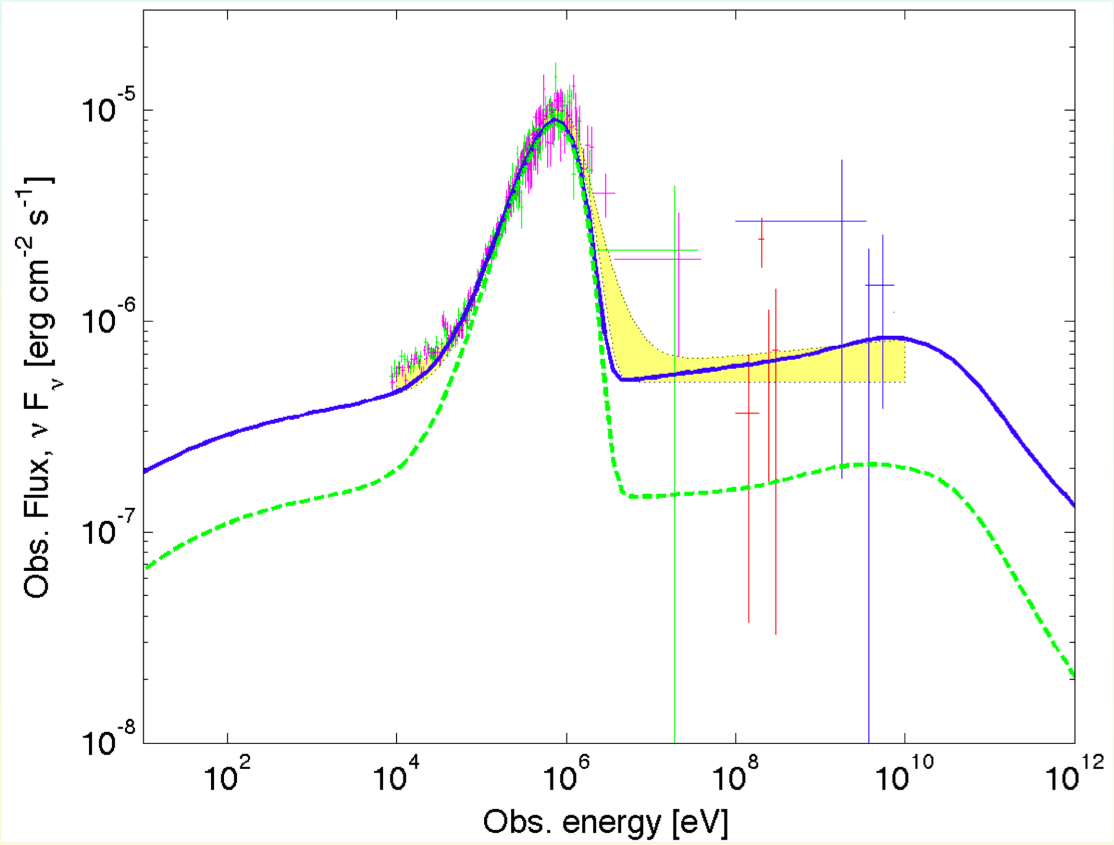
Synchrotron emission:

$\varepsilon_c < \varepsilon_m <$ keV -> fast cooling:

-> all the electron energy is lost

-> N.T. flux determines ε_e.

GRB090902B, time interval C
Pe'er et. al., 2010



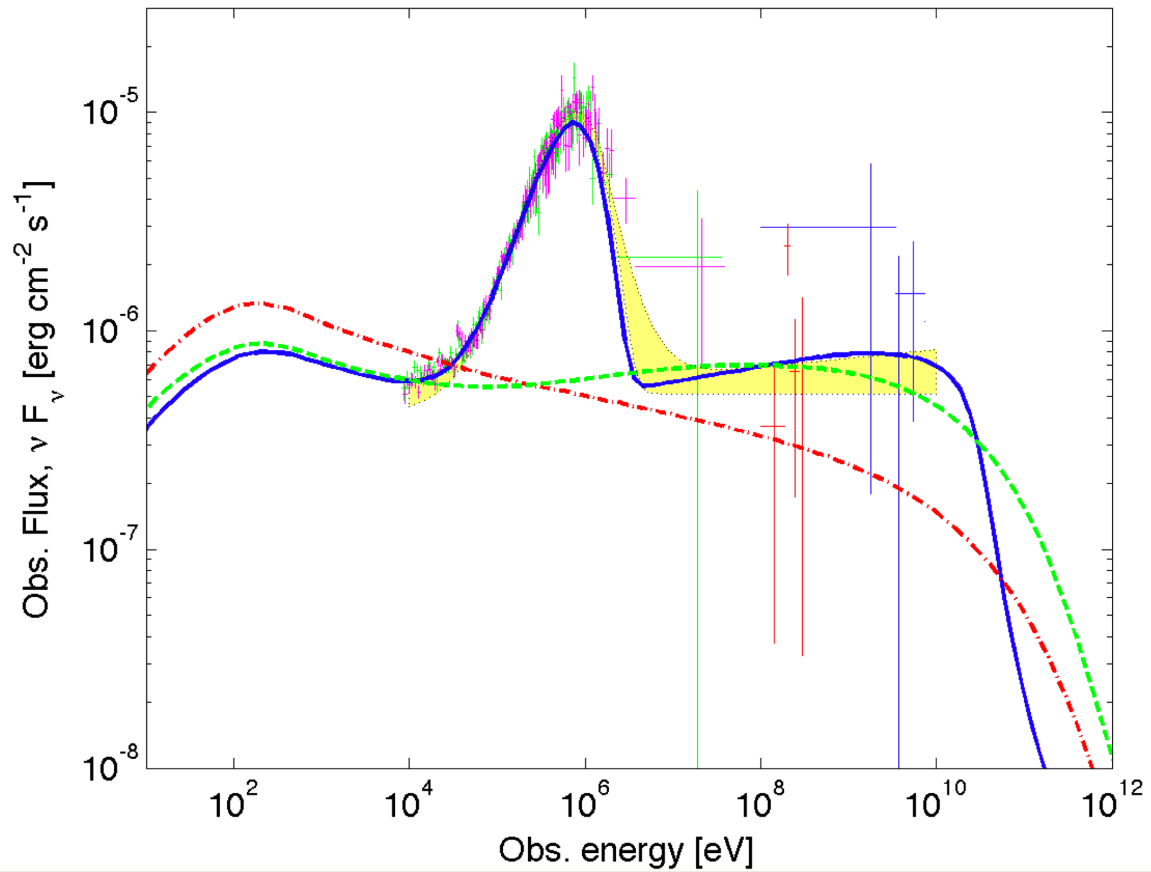
ε_e=0.5

ε_e=0.17

Analysis method: how to approach a good-looking GRB (III)

4) Spectrum at high energies can result from various processes – e.g., Sync., SSC, Comp. of thermal or Hadronic.

Define $\hat{Y}=U_{th}/U_B$, to determine thermal contribution to Comptonization.

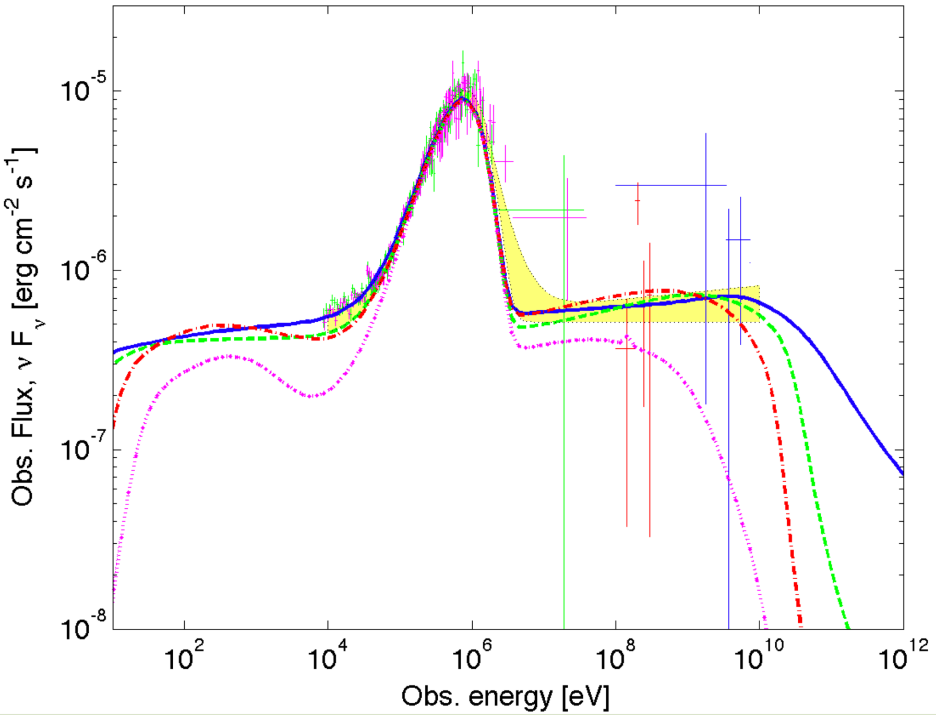


Pe'er et. al., 2010

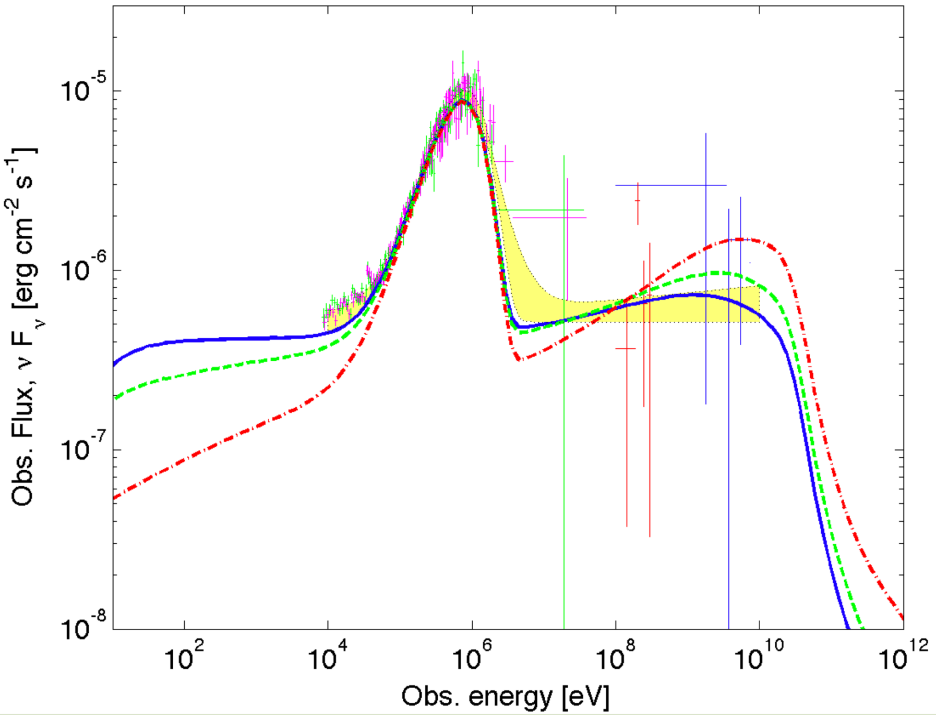
Sync.
Sync+SSC
Sync, SSC + thermal
+ Comptonized thermal

Fitting: Numerical results

Emission radius



Magnetic field strength



$R_\gamma = 10^{17}, 10^{16}, 10^{15.5}, 10^{15}$ cm

ε_B=0.33, 0.1, 0.01

5) Use AG measurements to remove degeneracy - determine ε_d -> L/L_{Th}

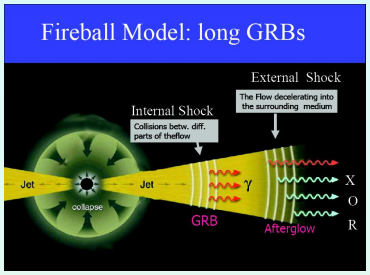
Cenko et. al., 2010

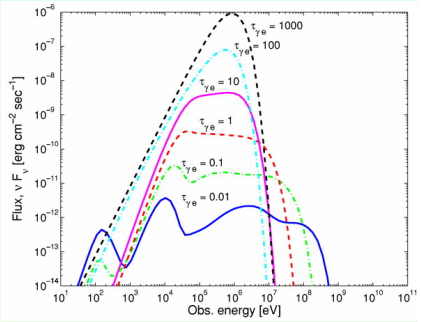
Full determination of physical values at both emission zones

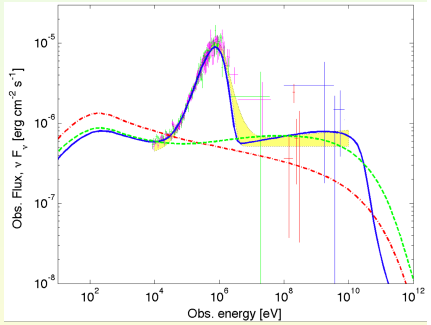
Pe'er et. al., 2010

Take home points

- Thermal emission is an inherent part of the fireball model
- Natural explanation to steep slopes seen
- Various effects modify it, often not easily identified ! (see Guiriec+ 2010 on GRB100724B)
- Once identified, carries significant physical meaning – measure Γ, r_{ph}
- High energy, non-thermal part is composed of (~equal) contributions of sync, SSC, and Comp. of thermal







Pe'er et. al., arXiv:1007.2228; Pe'er & Ryde, arXiv:1008.4590