Thermal Gamma-Ray Bursts

Emission Components During the Earliest Epoch

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Outline

- Introduction
  - Basic observations
  - Spectral evolution
- Quasi-thermal bursts
  - Pure thermal
  - Thermal + non-thermal
- Fireball physics
  - Wind model
  - Shell model
  - Poynting flux model
- Broad-band spectra
  - Alternative Models
  - GLAST prospects
- Conclusions

GRB Spectrum - CGRO Results

The peak of the spectrum lies between ~ keV - MeV.

Empirical 'Band et al. model':

$$F_{ph} \propto E^{-\alpha}$$

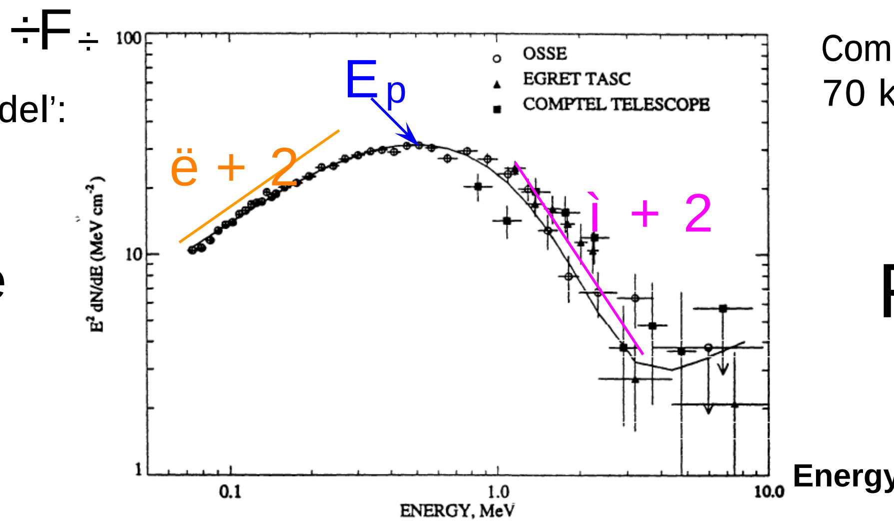


Figure 9 The spectrum of GB 910601 observed over a wide energy range, as measured by three
...nare et al 1994). A typical bro...
...d spectral up-turn above 4 Me...

Composite *CGRO* spectrum:
70 keV - 10 MeV

$$F_{ph} \propto E^{-\beta}$$

>2500 bursts (*CGRO*):

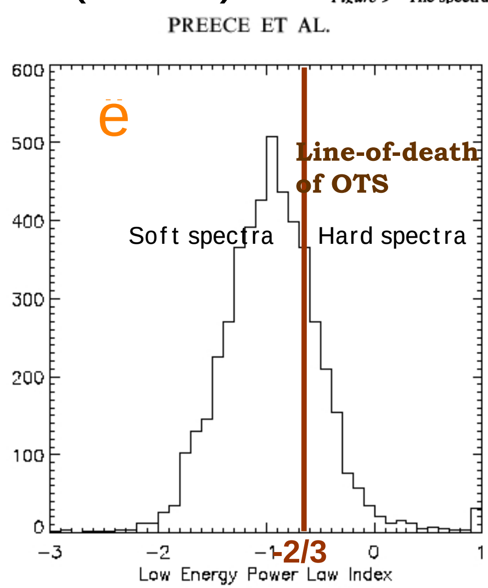
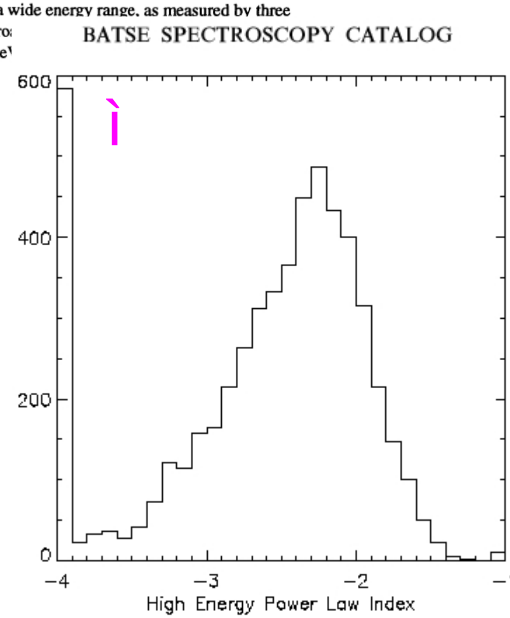


FIG. 7.—Low-energy power-law index distribution for the entire sample



Time resolved spectral parameters, Preece et al. 2000, ApJS, 126, 19

Cooling time for synchrotron emission and inverse Compton

$$t_{cool} = \frac{E}{\dot{E}}\frac{(1+z)}{2\Gamma} = \frac{\gamma m c^2}{4/3\,\sigma_T c \gamma^2 U_B (1+\frac{U_r}{U_B})} \approx 10^{-6}\,\mathrm{s}$$ (Ghisellini et al. 2000)

which is much shorter than the typical dynamical time scale

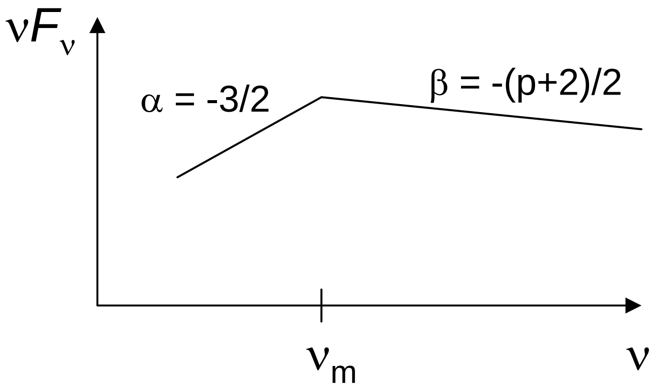
$$t_{dyn} = R/2\Gamma^2 c \approx 1\,\mathrm{s}\ (\frac{R}{10^{15}\mathrm{cm}})$$

and/or the integration time (~1 s).

The electrons are therefore in the fast cooling regime $\alpha = -3/2$.

(e.g. Piran 1999)

Resulting spectrum:



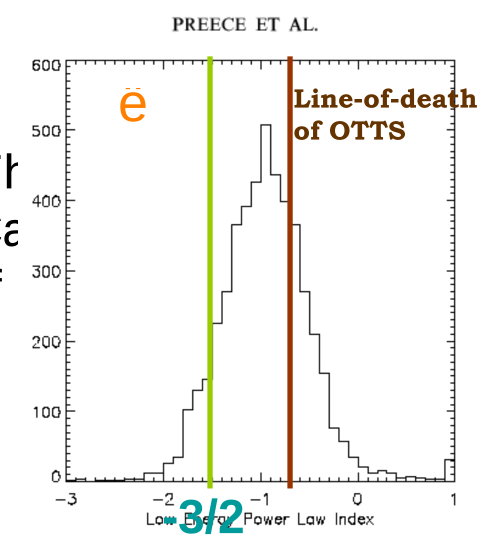
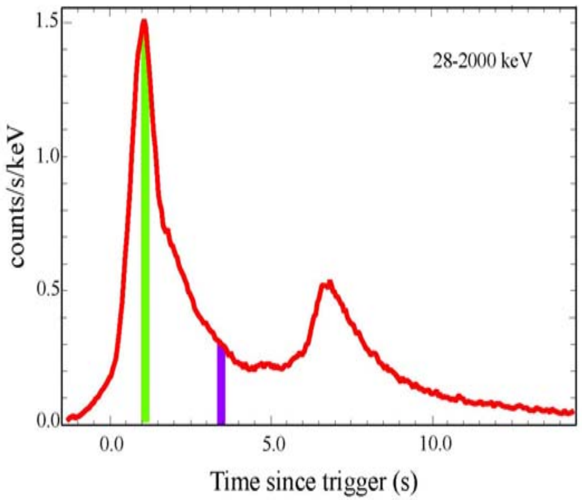


FIG. 7.—Low-energy power-law index distribution for the entire sample

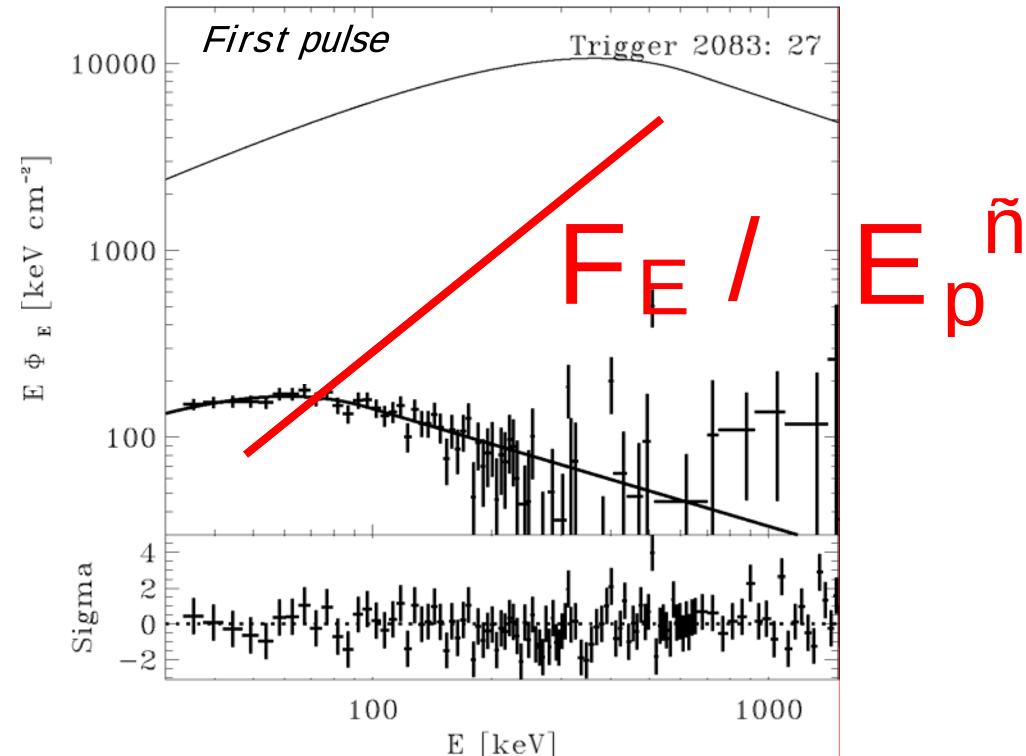
- Th… itted efficiently.
- Ca… t curve variability if … o long.

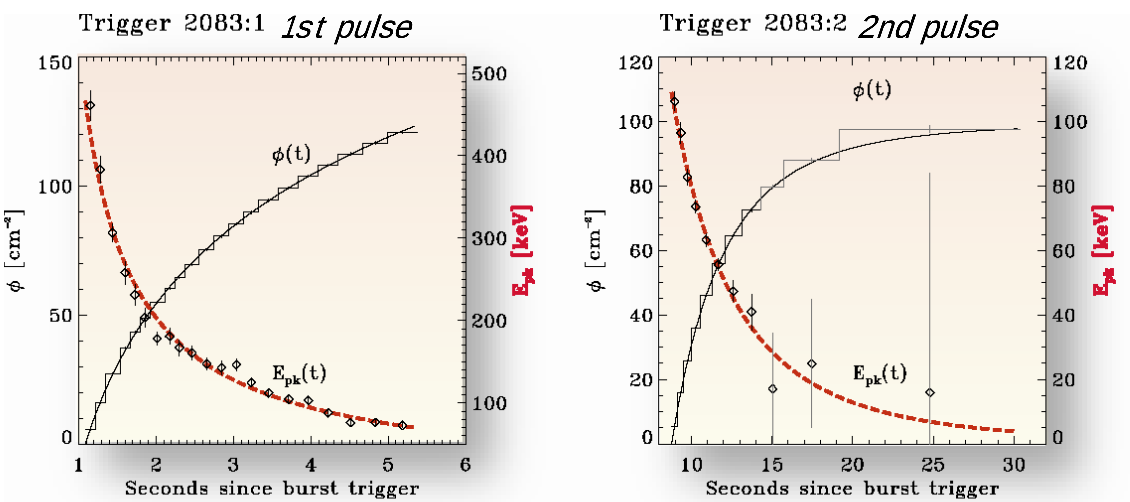
Spectral Evolution, example 1

GRB 921208



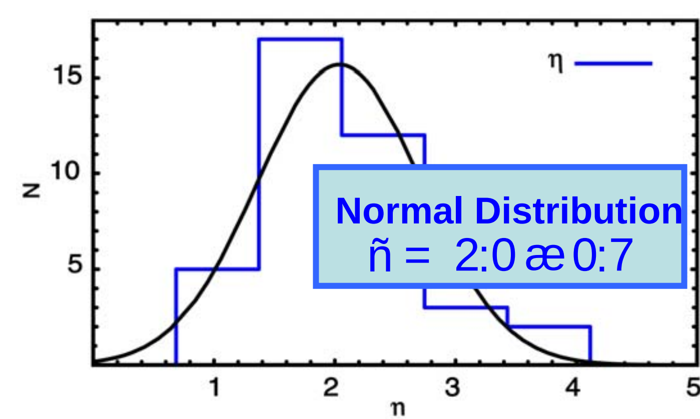
Band et al. model fit





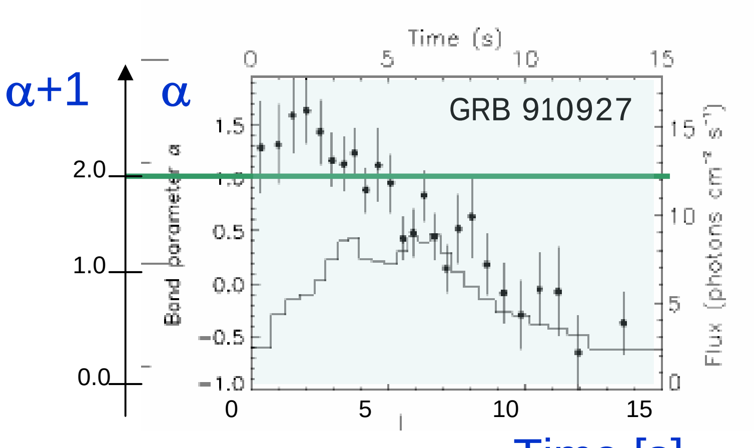
Ryde & Svensson (2002)

Power-law hardness-intensity correlation (Borgonovo & Ryde 2001 ApJ 548, 770)



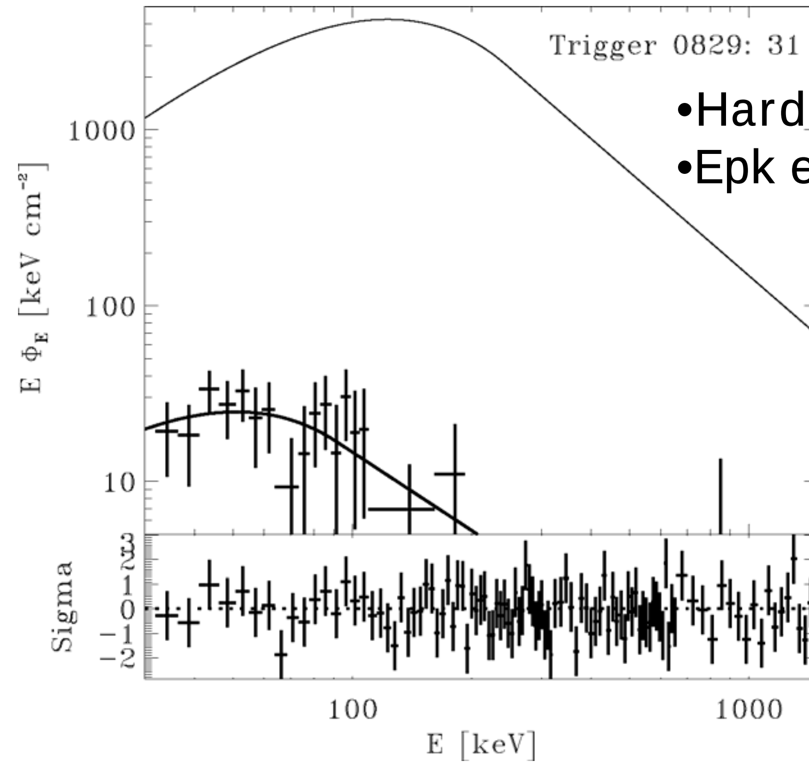
Spectral Evolution, example 2

GRB 910927: Strong α-evolution



Crider et al. (1997)

Band et al. model fit



- Hard initial α
- Epk evolution

- **Spectral Evolution:** The time resolved spectra evolves from hard to soft; E_p decreases and α gets softer.

- A few bursts are thermal during an initial phase. Noted by Ghirlanda in 2003 and Preece 2002

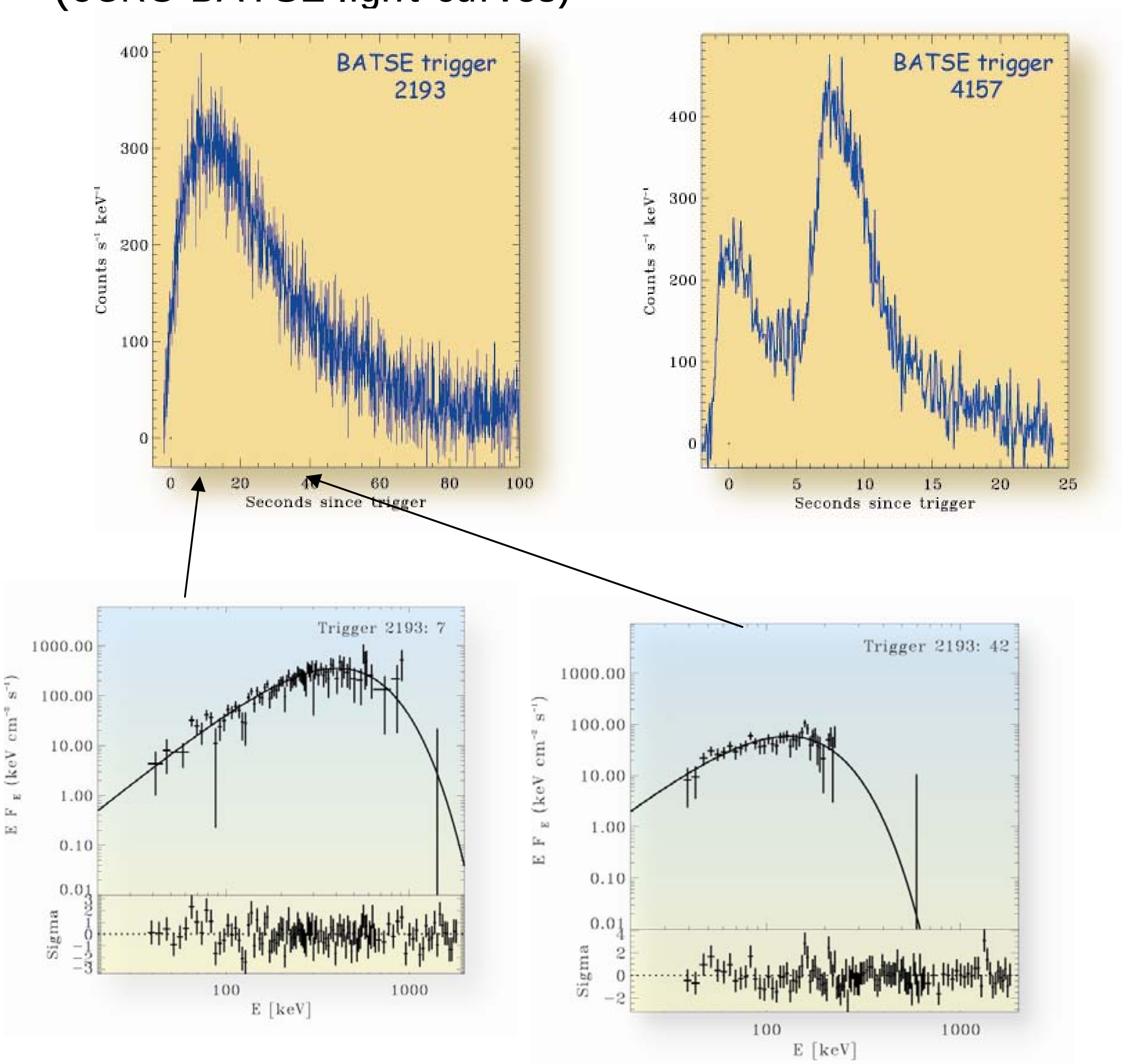
- Some bursts are indeed thermal throughout their duration (~1 % of all bursts)

Quasi-thermal Bursts

Pure Thermal Pulses:

Ryde 2004, ApJ, 614, 827

(CGRO BATSE light curves)



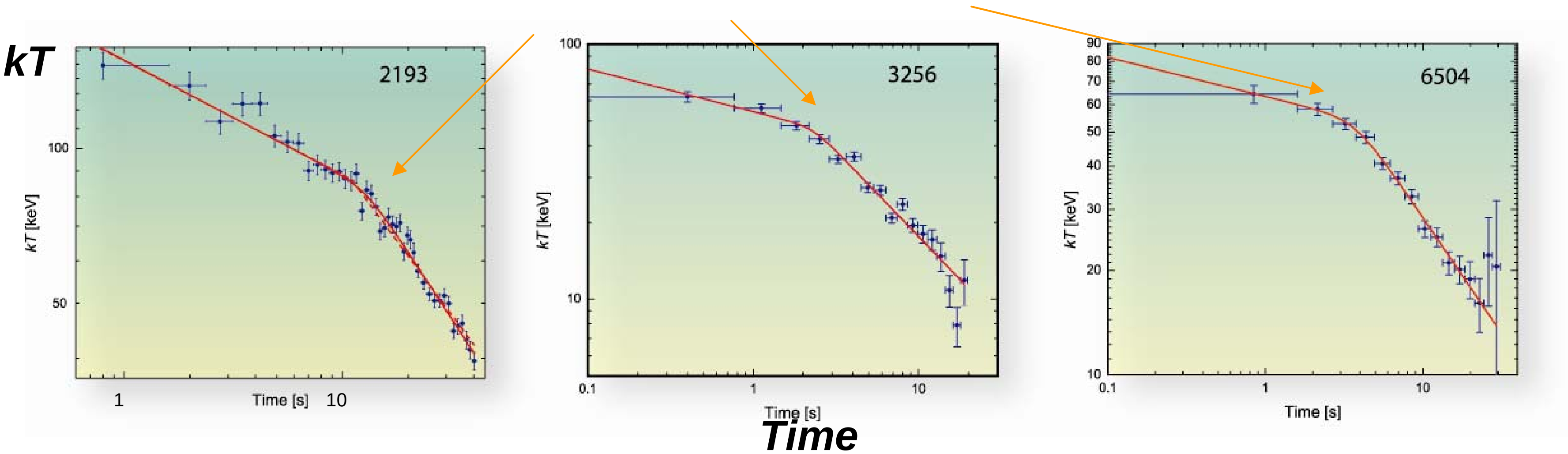
Planck spectrum:

$$N_E(E;t) = A(kT)^2 \frac{x^2}{(e^x - 1)}$$

$$x \equiv E/kT$$

Cooling of the emitting plasma

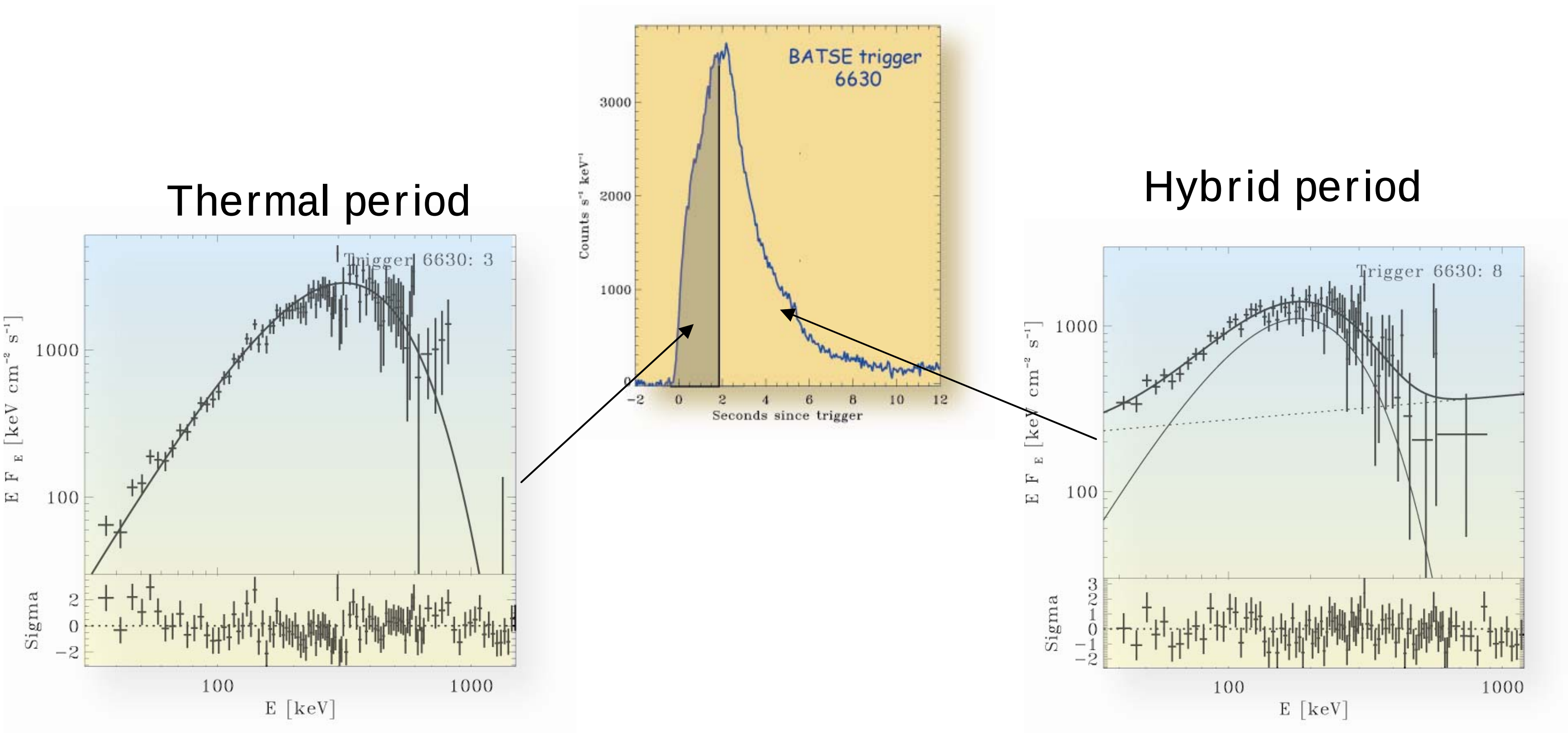
Breaks at approximately the pulse peak



Late Time Decay:

$kT / \; t^{V}$ à 0:7

Thermal/non-thermal (initially thermal)



Interpretation:

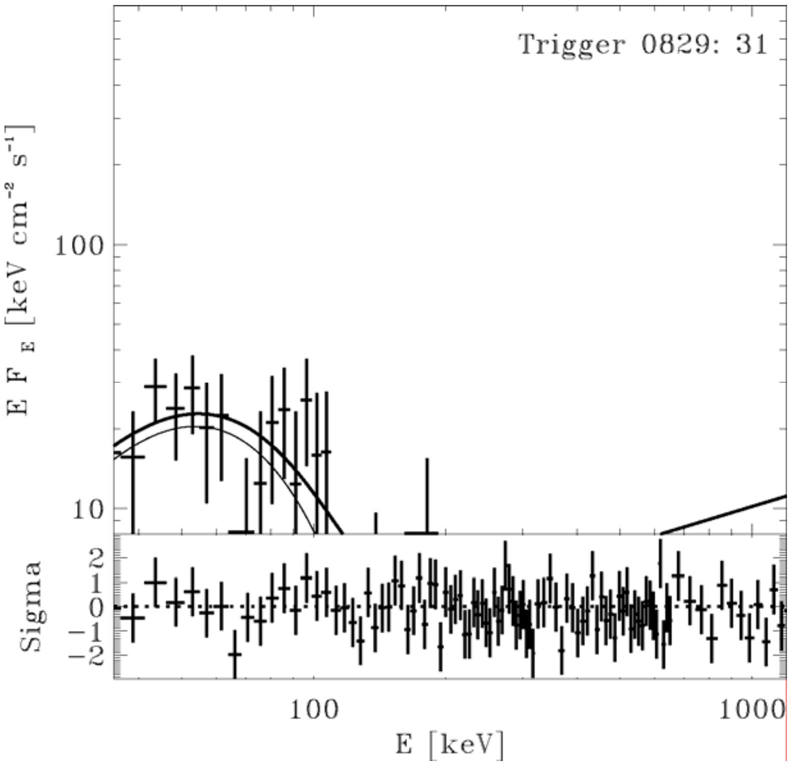
Photospheric and non-thermal synchrotron emission overlayed.

α-evolution is due to varying amplitudes of the components

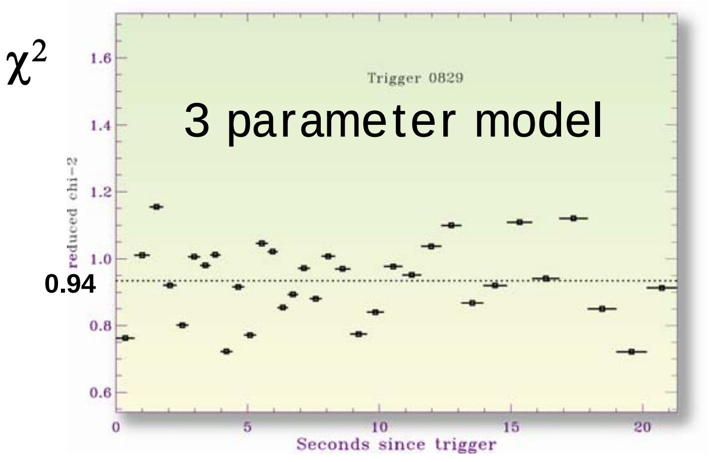
Revisit GRB 910927:

Black body + power law with

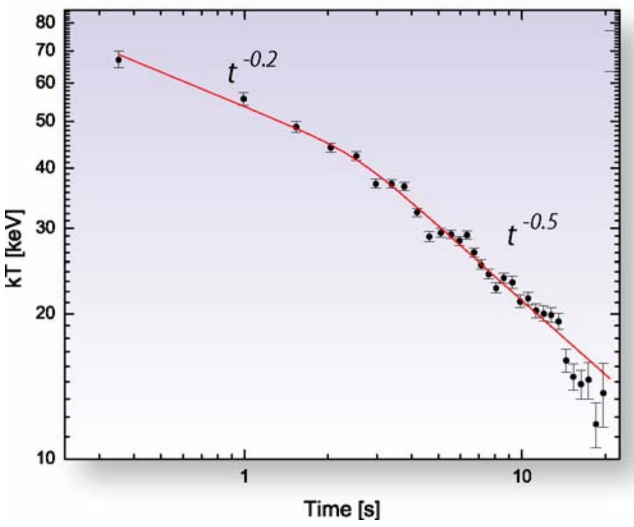
α = -1.5 (cooling spectrum)



Chi-square

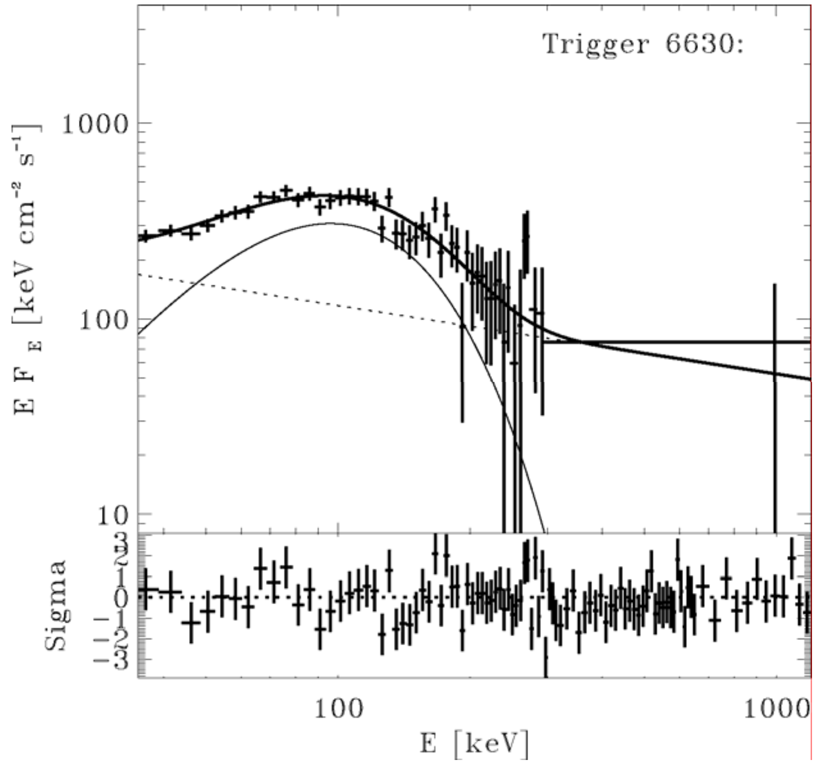


kT of the thermal component

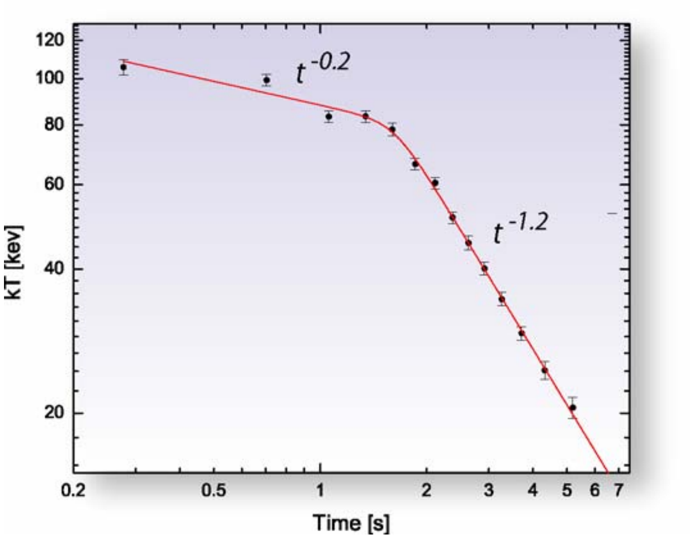


Yet another example: GRB 980306

Varying power law index; α = -1.5 to -2.1



Cooling spectrum with ν_m passing the window



Where are these thermal spectra emitted?

- ? -

Most outflow models predict a strong photospherical emission.

And are these spectra really black bodies?

In general, you would expect a modified black body radiation due to

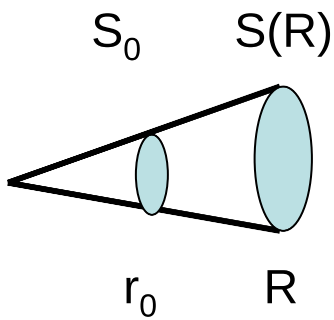
- Curvature effects: multi-color black body
- Compton scattering atmosphere :
  Depending on the degree of Comptonization
  the spectrum will be modified BB.

<u>Alternative models which give hard α-values:</u>

- Small-pitch angle synchtroton, jitter radiation: $\alpha=0$
- Inverse Compton of single e-: $\alpha=0$
- Self-absorbed synchrotron: $\alpha=3/2$
- Wien spectrum: $\alpha=2$

Fireball Physics

Piran 1999
Beloborodov 2003



Axisymmetric flow driven by thermal pressure.

$$S(R) = S_0\left(\frac{R}{r_0}\right)^{\psi}$$

$\Psi = 2$ radial funnel
$\Psi = 1$ parabolic funnel

Relativistic ideal fluid $w' = 3P' >> \rho' c^2$ (adiabatic)

Mass conservation: $$S\rho'\Gamma c = \dot{M}_b$$

Energy conservation: $$S(w' + P')\Gamma^2 c = L_{th}$$

Combination gives $w = \frac{3}{4}\frac{L_{th}}{S\Gamma^2 c} \Rightarrow \frac{w}{\rho} = \frac{3}{4}\frac{L_{th}}{\dot{M}_b \Gamma}$ i.e. independent of collimation!

Equation of state:

$$w \propto \rho^{4/3} \Rightarrow w^{1/4} \propto \Gamma^{-1} \Rightarrow T\Gamma = \text{const}$$

The Lorentz boost balances the adiabatic losses.
This is the temperature that would be observed at infinity if the radiation could escape.

More specifically

$$È = \left(\frac{R}{r_0}\right)^{Ñ=2}$$

$$T = \left(\frac{R}{r_0}\right)^{à Ñ=2}$$

$\Gamma T = T_{obs} \sim$ const

$\Gamma \sim R$ or $R^{1/2}$

What is T_0?

$$w = \frac{L_{th}}{Ò 0 r_0^2 c} = aT_0^4$$

with $L = 10^{51}$ erg/s

$r_0 = 3\ 10^6$ cm

$z = 1$

$$kT_0 = 600 \text{ keV}$$

Coasting phase:

$$w = úc^2 + 3P$$

=> Γ = const

Conservation laws: $\sim\rho/\Gamma$

Adiabatic expansion coasting phase:

$kT^0 / ú^{0\ 1=3}$ Adiabatic relation for electromagnetic radiation

$ú^0 / R^{à 2} È^{à 1}$ Comoving density of a thin shell expanding relativistically

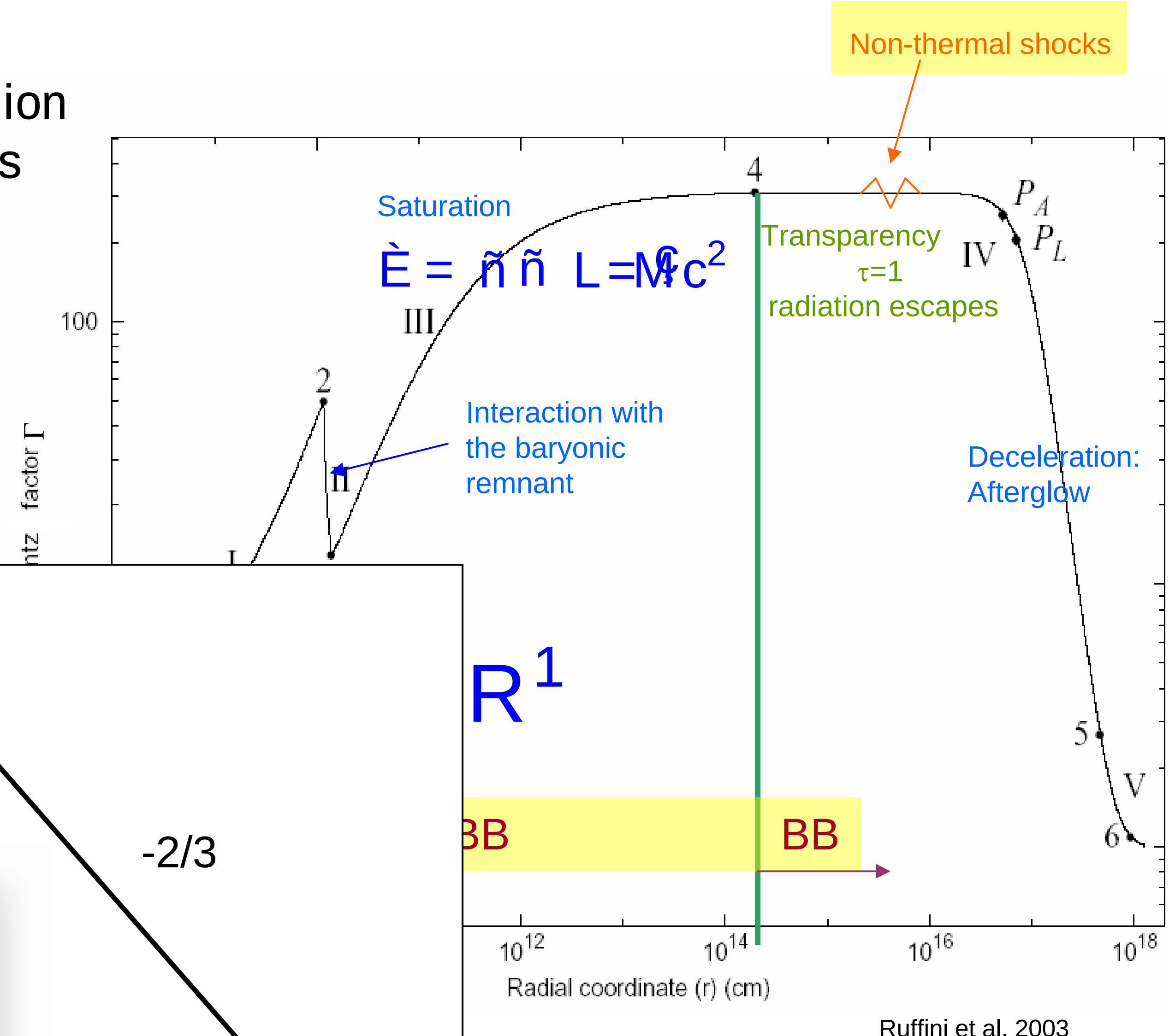
Mass conservation => $\rho \sim S^{-1} \sim R^{-\Psi}$

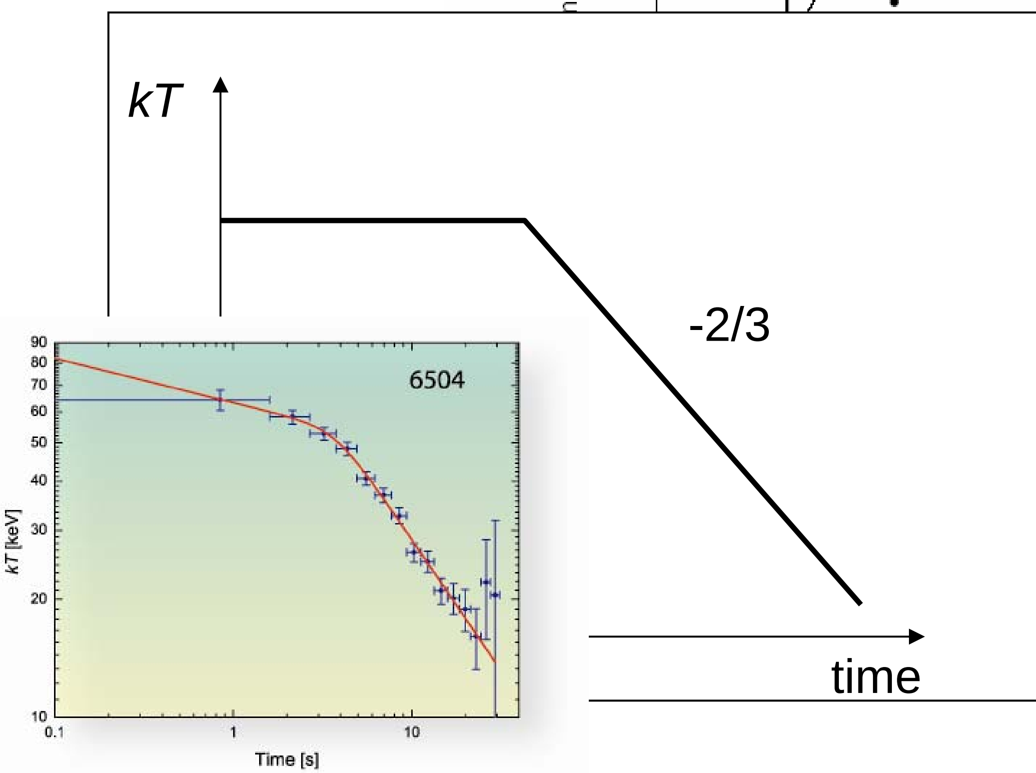
Temperature in the observer frame $kT / kT^0 È / t^{à 2=3}$; $È =$ const

Lorentz factor evolution as a function of radius (lab frame):

È= p 1 / 1à ì 2

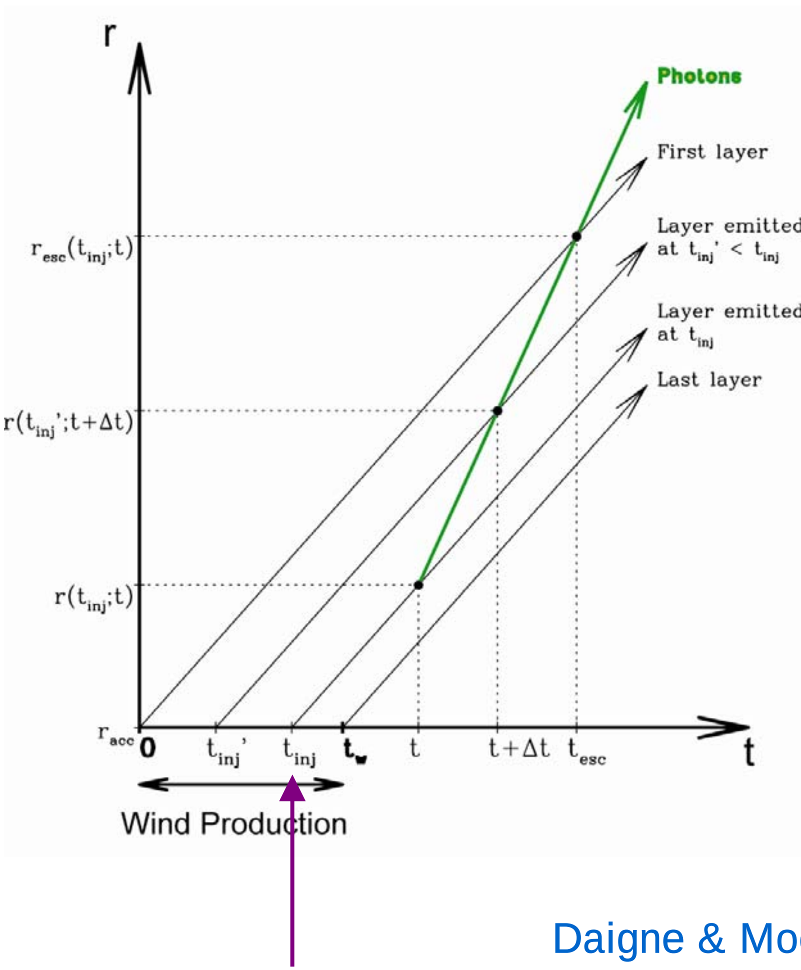
ì = v=c





I. Short duration Wind

(dynamical time ~light crossing time)



ü(t inj ; t) = ð w , [upper: r esc(t inj ;t), lower: r (t inj ;t)] dü(r)

dü(r) = ôú 0 dl 0

dl 0(r) ' dr / 2È

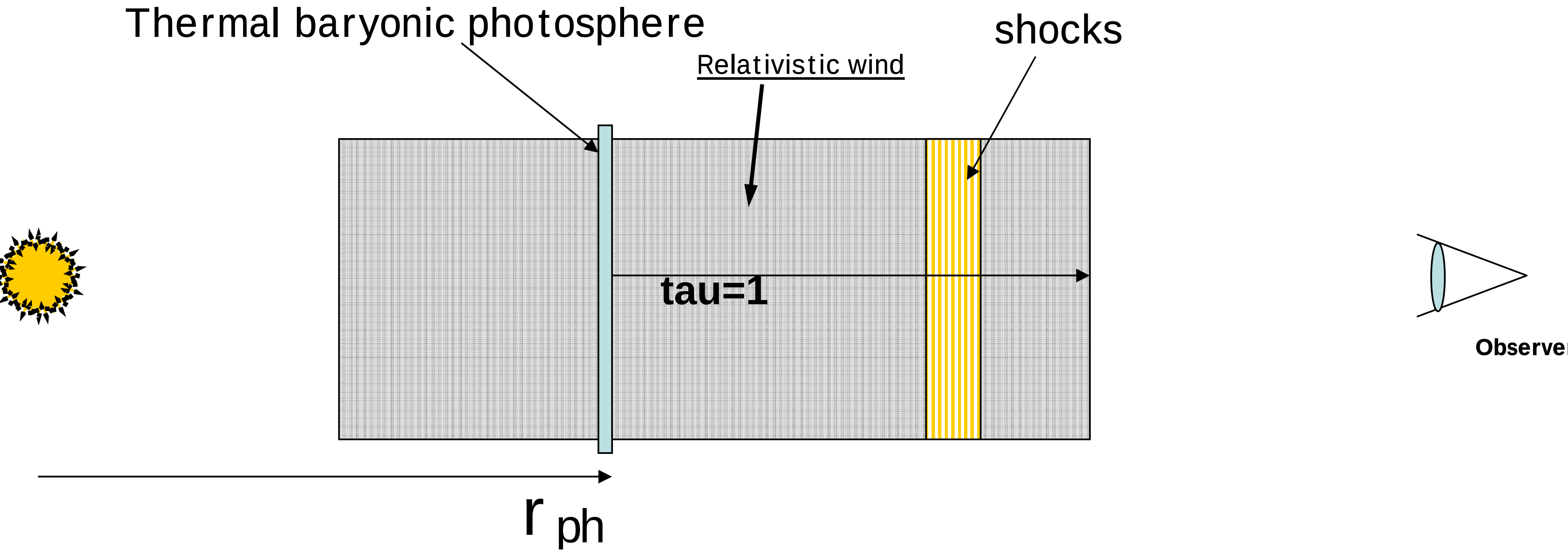
ú 0 ' M¢ / È4ùr 2c

Lorentz contraction *and* Light travel effects

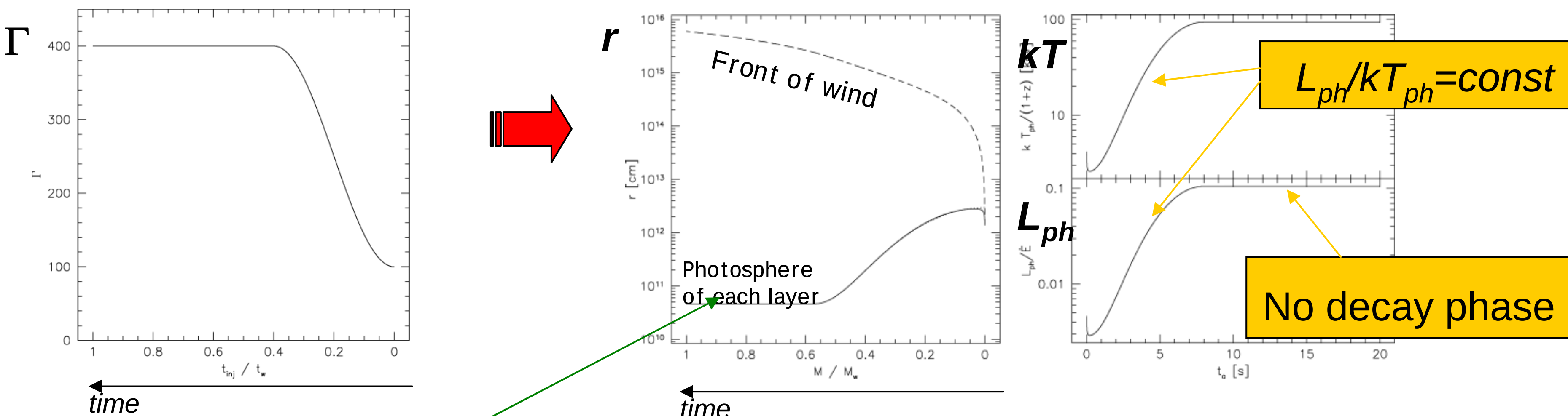
τ=1 =>

r ph = 3:0 â 10 12 ô 0:2 E¢ 52 È à 3 2 cm

Daigne & Mochkovitch (2002) predict that the thermal emission could be rather bright in the γ-rays.

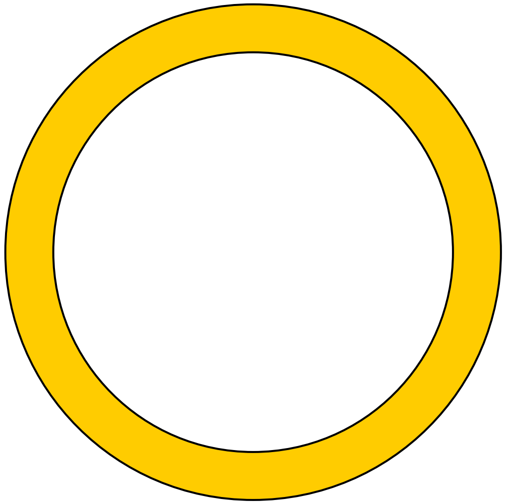


R_{ph} is approximately the same for all shells unless Γ and/or $\dot{E}$ varies.
Daigne & Mochkovitch (2002) *assume a constant $\dot{E}$ and a Γ that varies with injection time:*



Needs $\dot{E}$ *to increase linearly in time*

Does not provide a satisfactory explanation



II. Thin shell

Typically the thin shell becomes optically thin at a certain radius and a flash of thermal emission is emitted at a single temperature $kT /\ R^{à 2=3}$.

Radiation emitted below R_{ph} is thermal and would probe the temperature dependency with radius. Thermal emission and $\gamma = 4/3$

But very weak => efficiency problem.

- Another problem with the kinetic, thin-shell model are the time-scales:

$$R_{sat}=2cÈ^2 = 10^{à 5}s \left(\frac{R}{10^7 cm}\right)\left(\frac{E}{10^{52} erg}\right)\left(\frac{M}{5á10^{à 6} M_{ì}}\right)$$

$R_{sat} \sim 10^9$ cm

Need underloaded fireballs ø $10^{à 9} M_{ì}$ and large R:

$R_{sat} \sim 10^{15}$ cm

II: Thin shell, cnt'd

- Radiation dominated outflow: $R_{ph} = R_{sat}$. But γ –> 5/3, thermal?

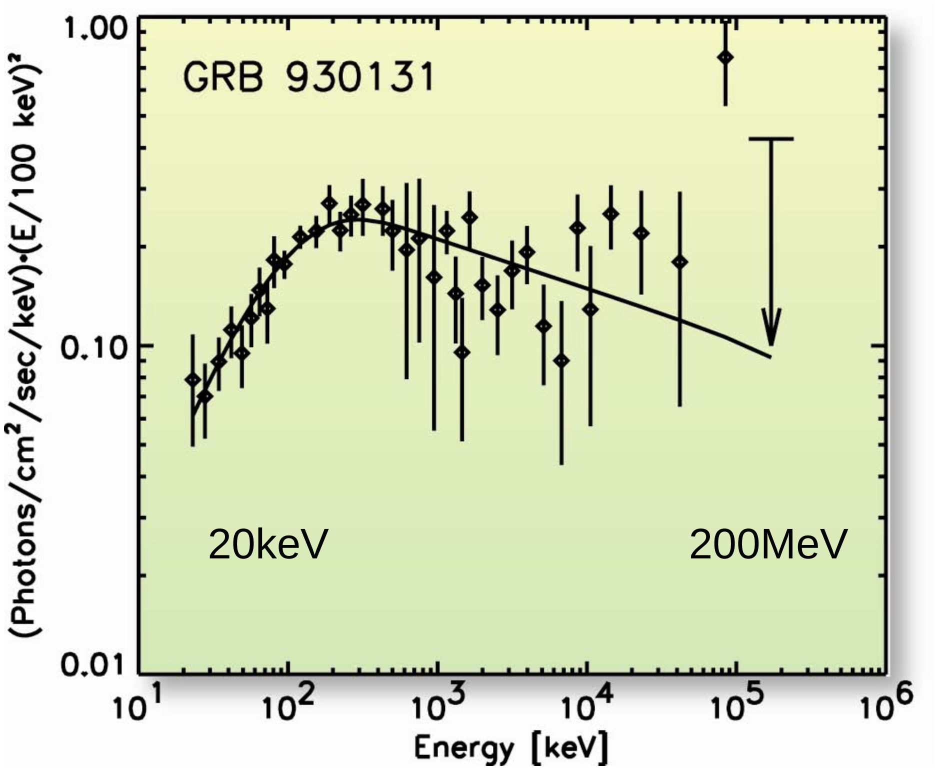
- Pair fireballs ($e^+ e^- \gamma$ winds): È / R and ÈT = const beyond R_{ph} until ü ø $10^{à\,5}$. Quasi black body emission (Grimsrud & Wasserman 1998)

 Saturation not at R_{ph} but when scattering time ~ expansion time.

Broad band spectral coverage

To find out more, we need a broader spectral coverage.

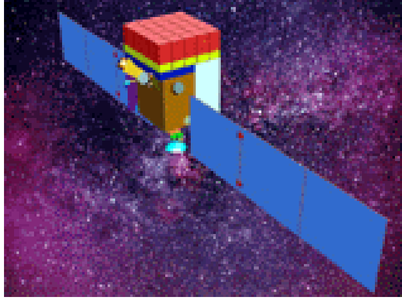
Composite spectrum of GRB 930131;
BATSE, COMPTEL, and EGRET instruments



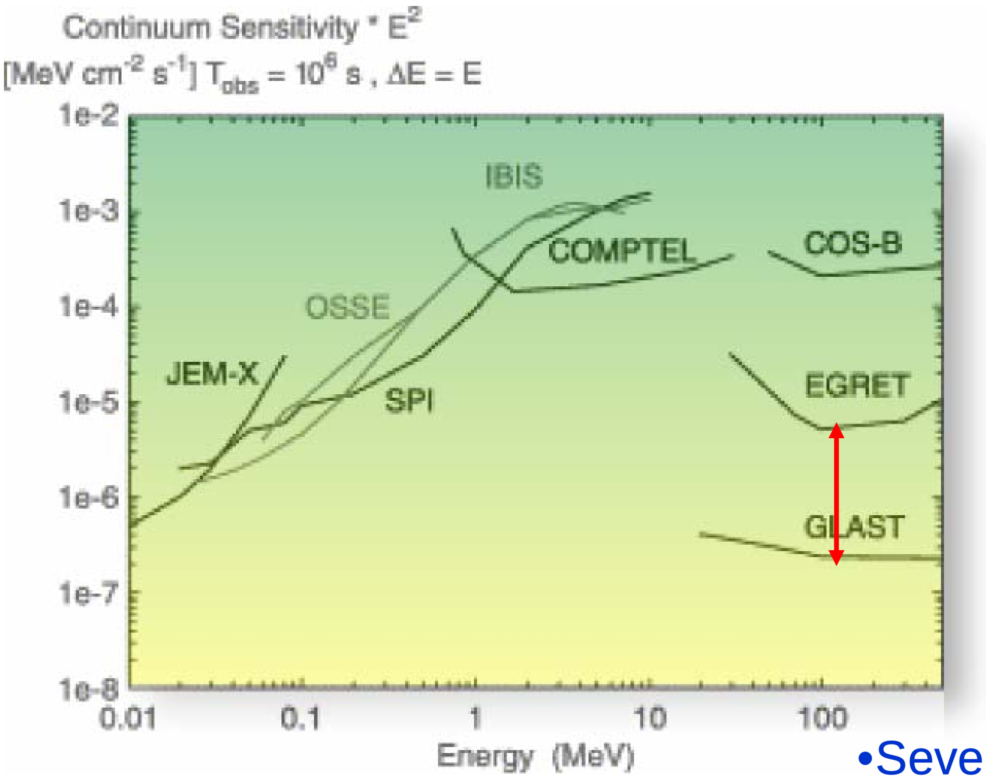
COMPTEL:
0.75 – 30 MeV

EGRET:
30MeV-30GeV

GLAST Sensitivity



Gamma Ray Burst Monitor (GBM): 10 keV – 25 MeV
Large Area Telescope (LAT): 20 MeV – 300 GeV



- For GRBs -> ~5 times better sensitivity
- Good localization 30"- 5' (FOV 2-3 sr)
- Good energy resolution ~10%
- 50 – 150 bursts/year

- Several spectral components?
- Self-compton component? (E > í$_e^2$ Ep)
- IC ambient rad. field?
- IC photospheric radiation?
- Ultra relativistic hadrons induce EM cascades through photomeson and photo-pair production

Conclusions

- Settling the issue of emission mechanisms during the prompt phase is an urgent task. Models depend on this result.
- *Several spectral components* are present in the high-energy band:

  Thermal photospheric emission and non-thermal synchrotron emission from either internal shocks or magnetic reconnections . The relative strengths vary from burst to burst and depend on the initial conditions of the outflow.
- *A radiation dominated fireball or a Poynting flux* dominated fireball is needed to explain the behavior of the thermal pulses, with a near constant initial temperature and a later decay $t^{-0.7}$.
- *GLAST* will with its increased sensitivity and extended energy range open up an important energy window for GRBs and be able to disentangle the high energy emission components

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