Gamma-ray Bursts from Synchrotron Self-Compton Emission

Juri Poutanen

University of Oulu, Finland

Boris Stern

AstroSpace Center, Lebedev Phys. Inst., Moscow, Russia

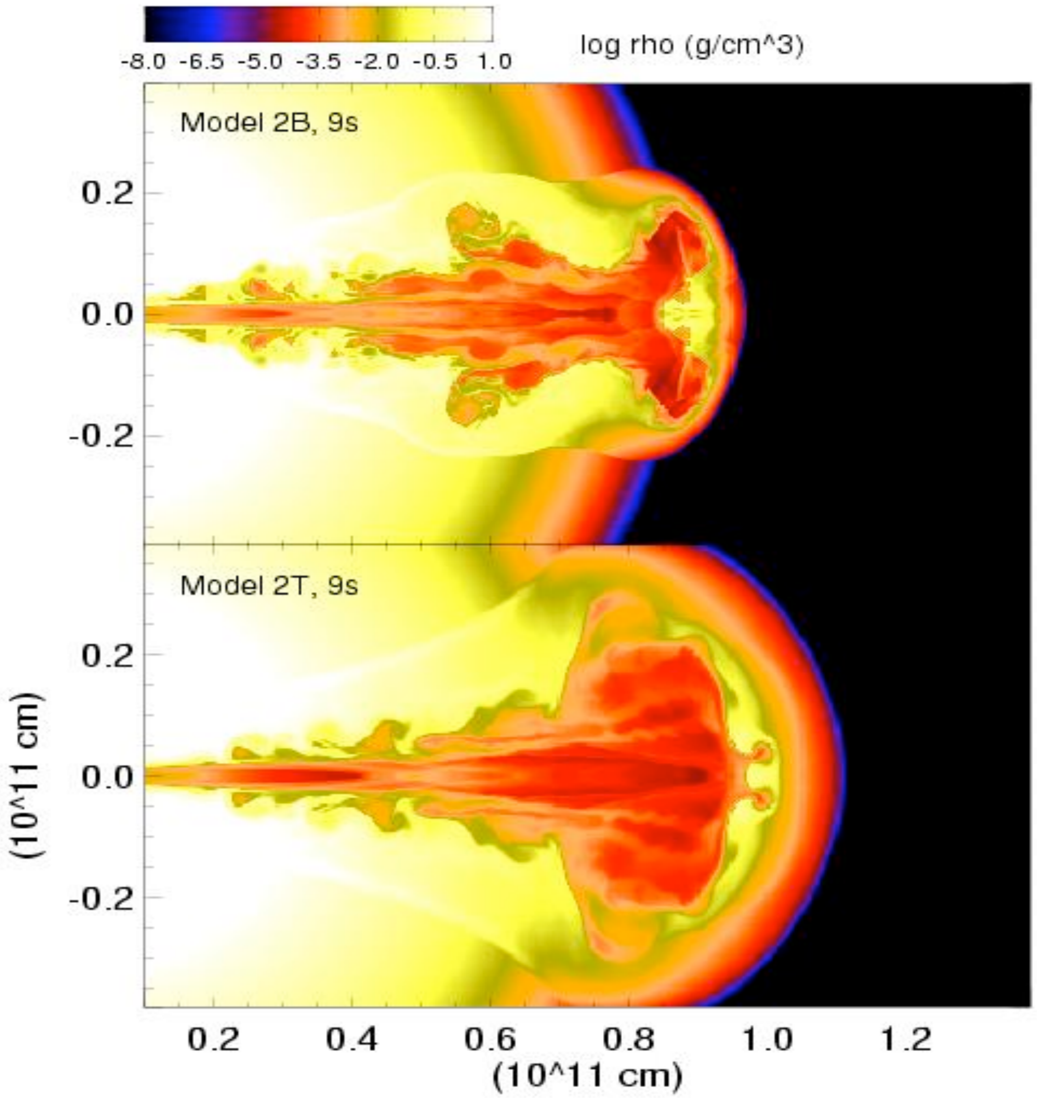
PLAN

1. Gamma-ray burst spectral properties
2. Problems with “standard” shock models
3. Particle heating
   - Synchrotron
   - Synchrotron self-Compton
   - Quasi-thermal Comptonization
4. Summary

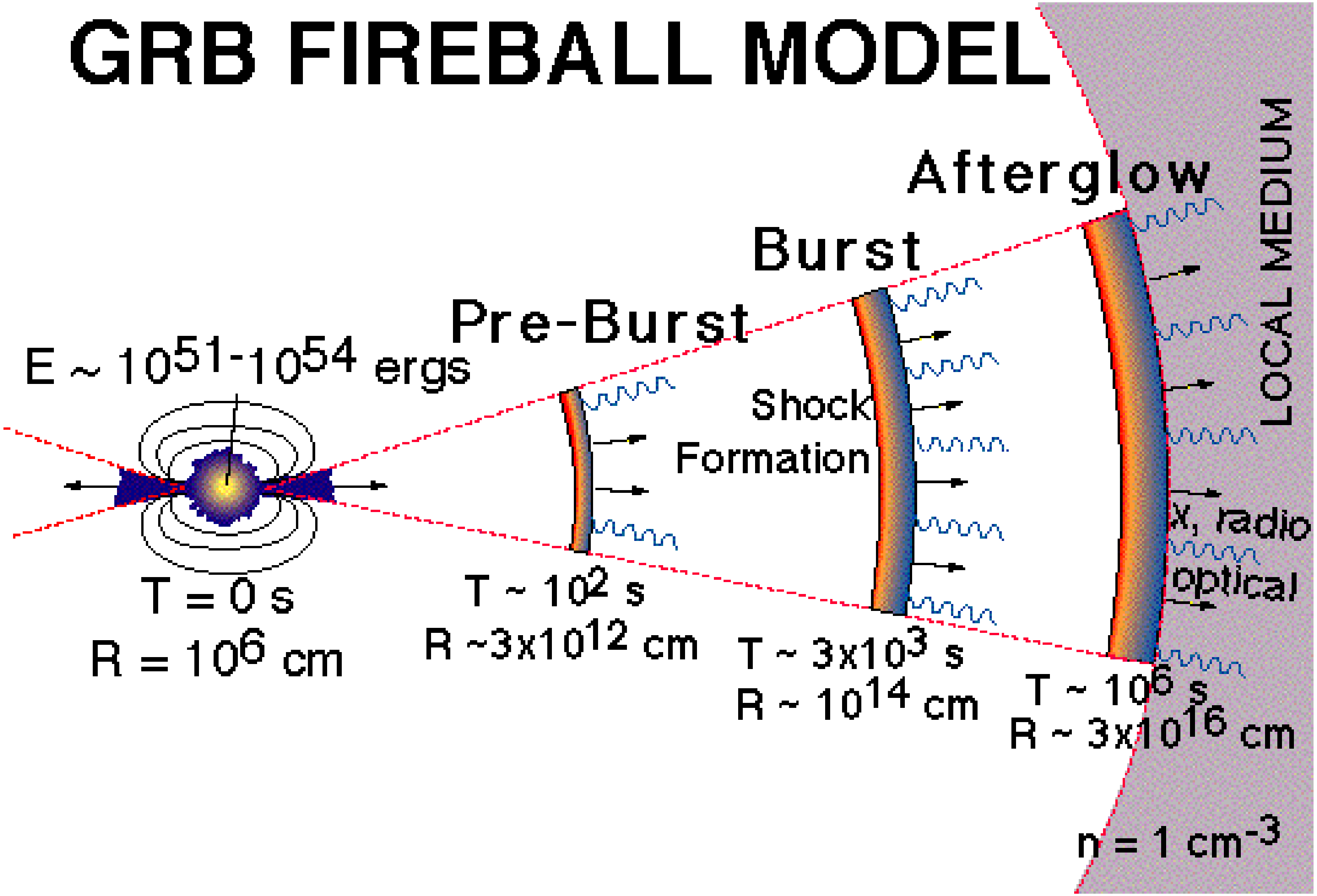
Details in :
Stern & Poutanen 2004, MNRAS, 352, L35
Poutanen & Stern 2005, Il Nuovo Cimento C, 28, 443 (astro-ph/0502424)

GRB from a jet formed during a collapse of a massive star into a black hole.

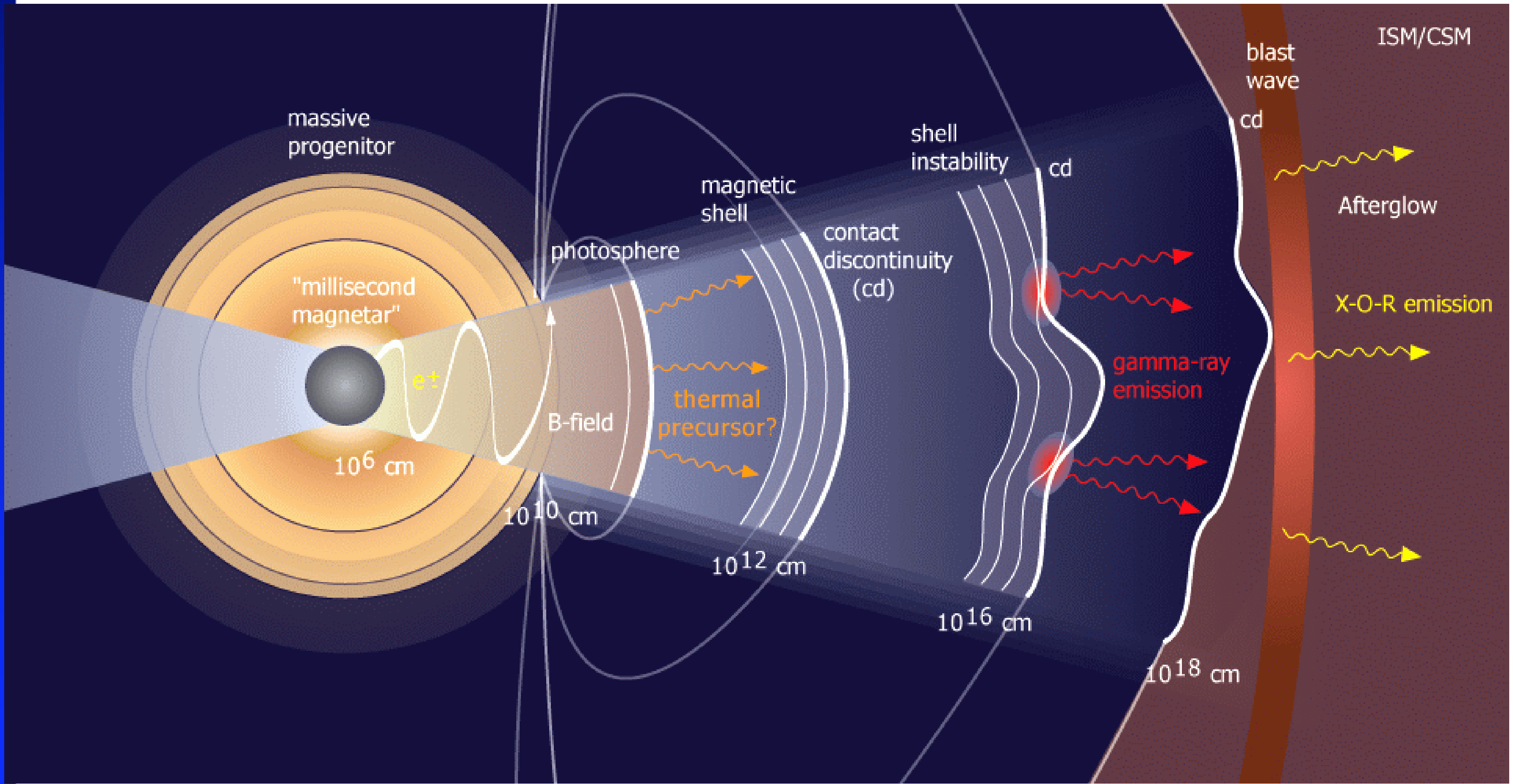
Weiqun Zhang,
S.E. Woosley,
A. MacFyden



Internal/external shock model



Poynting flux dominated outflow

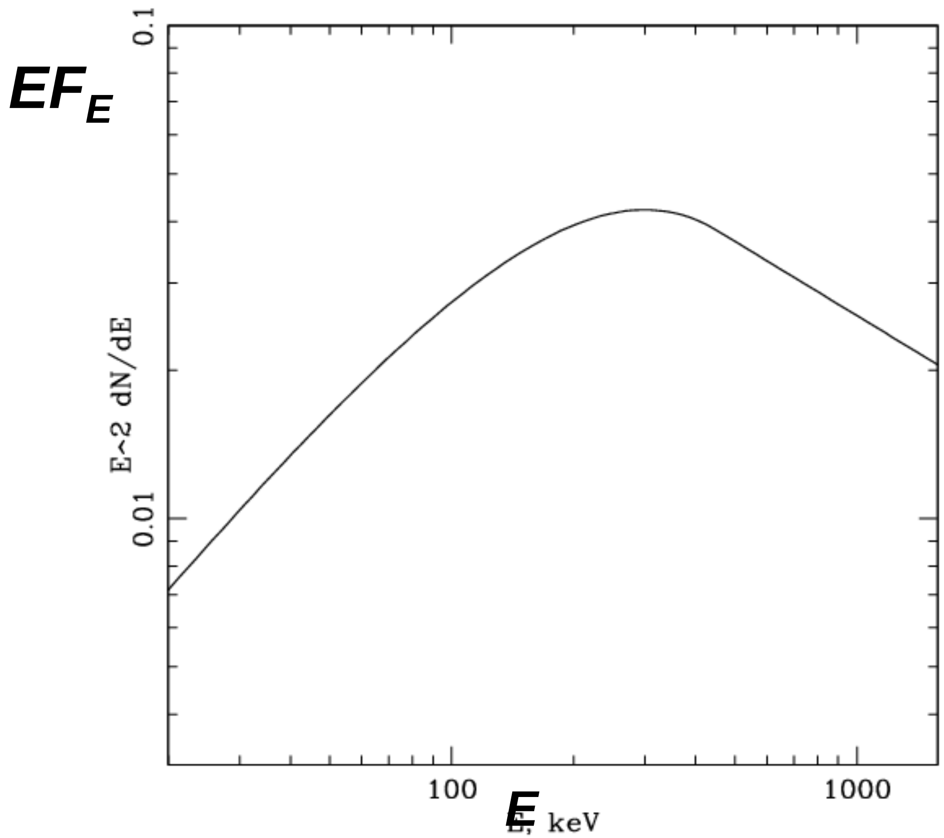


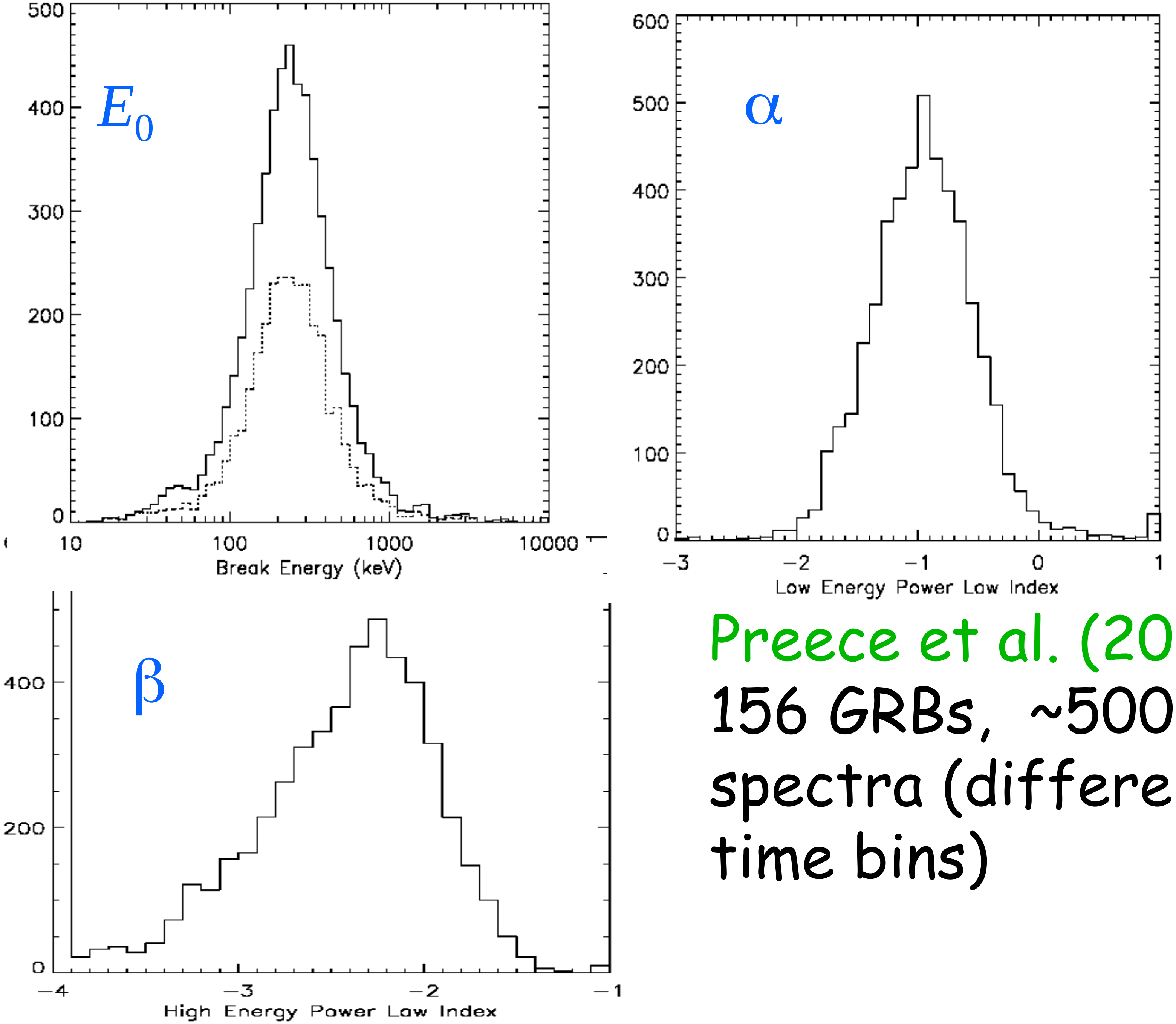
Energy spectra

`Band´ (or `GRB´) function:

$dN/dE \sim E^{\alpha} \exp(-E/E_0)$ $\quad E < (\alpha - \beta) E_0$

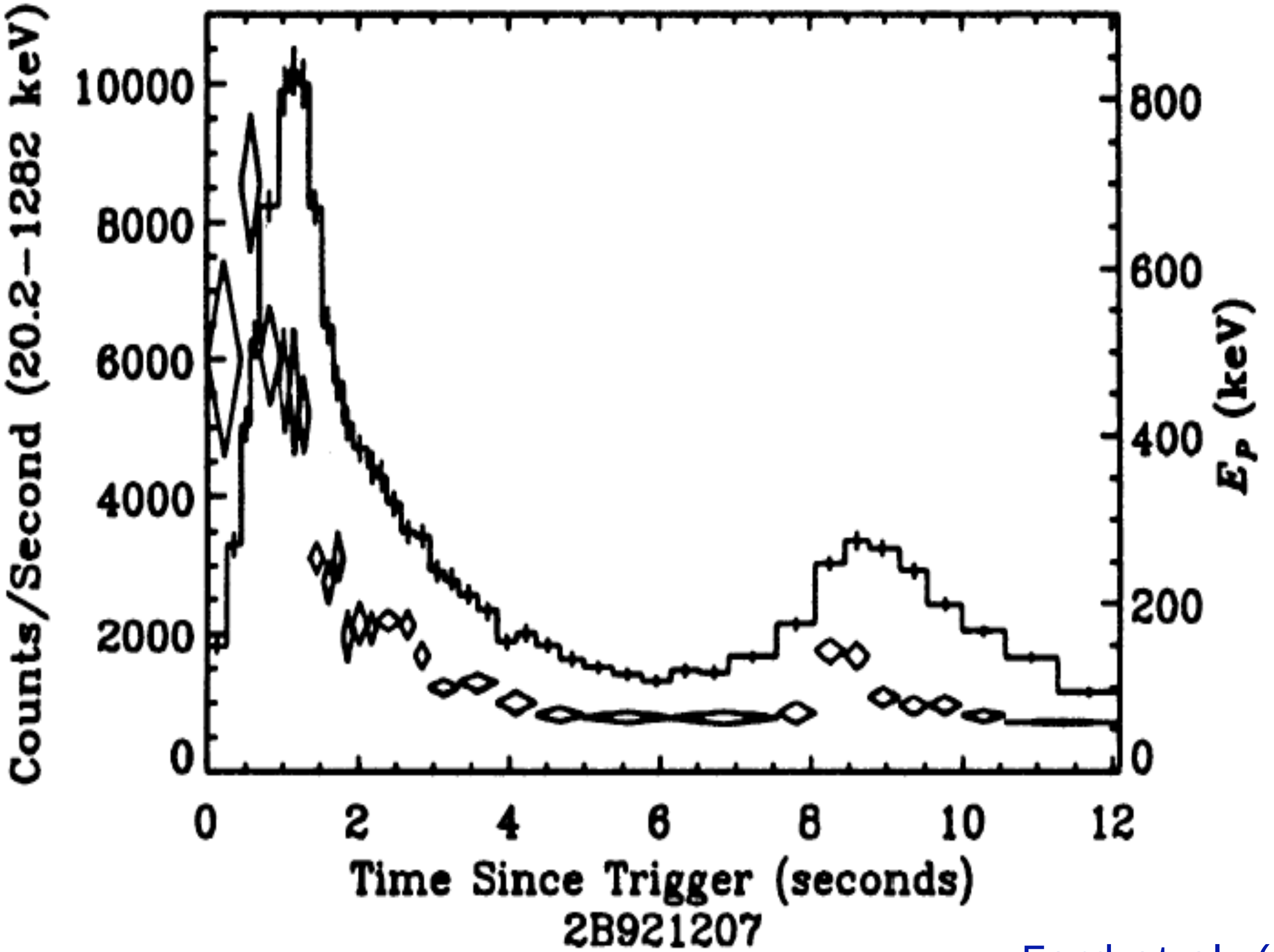
$dN/dE \sim E^{\beta}$ $\quad E > (\alpha - \beta) E_0$





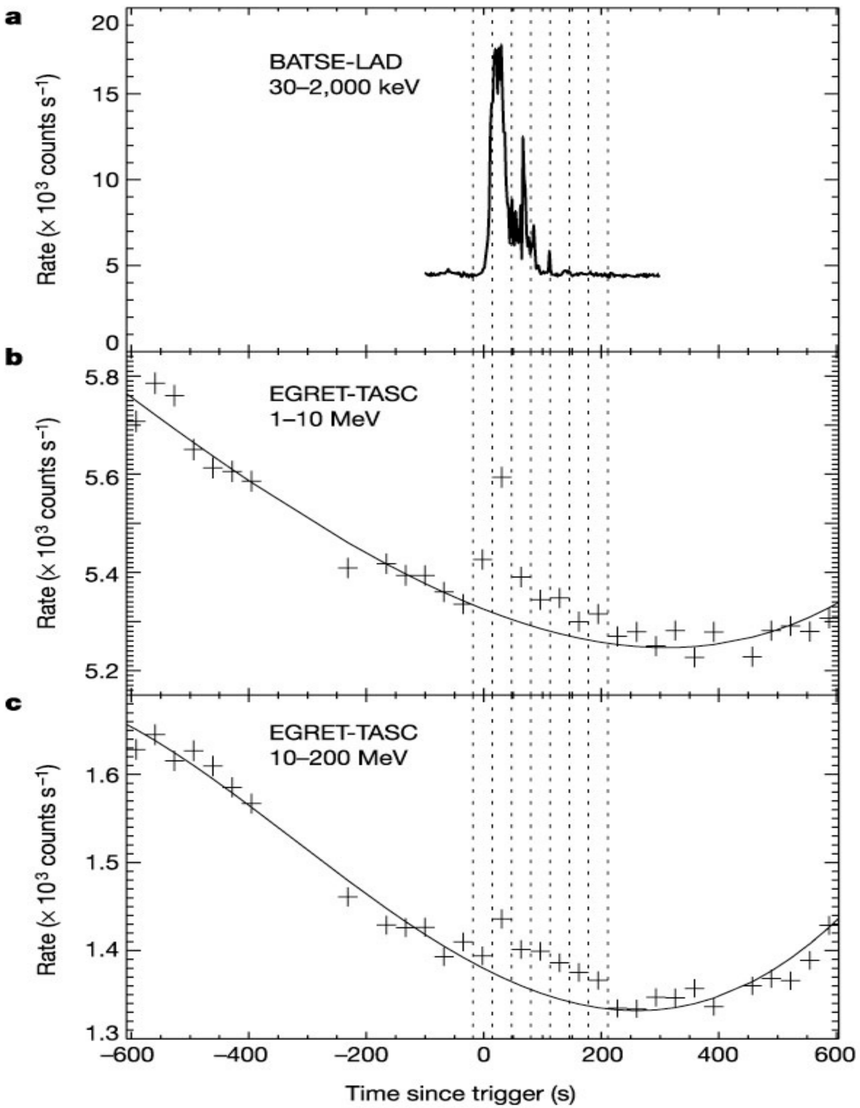
Preece et al. (2000), 156 GRBs, ~5000 spectra (different time bins)

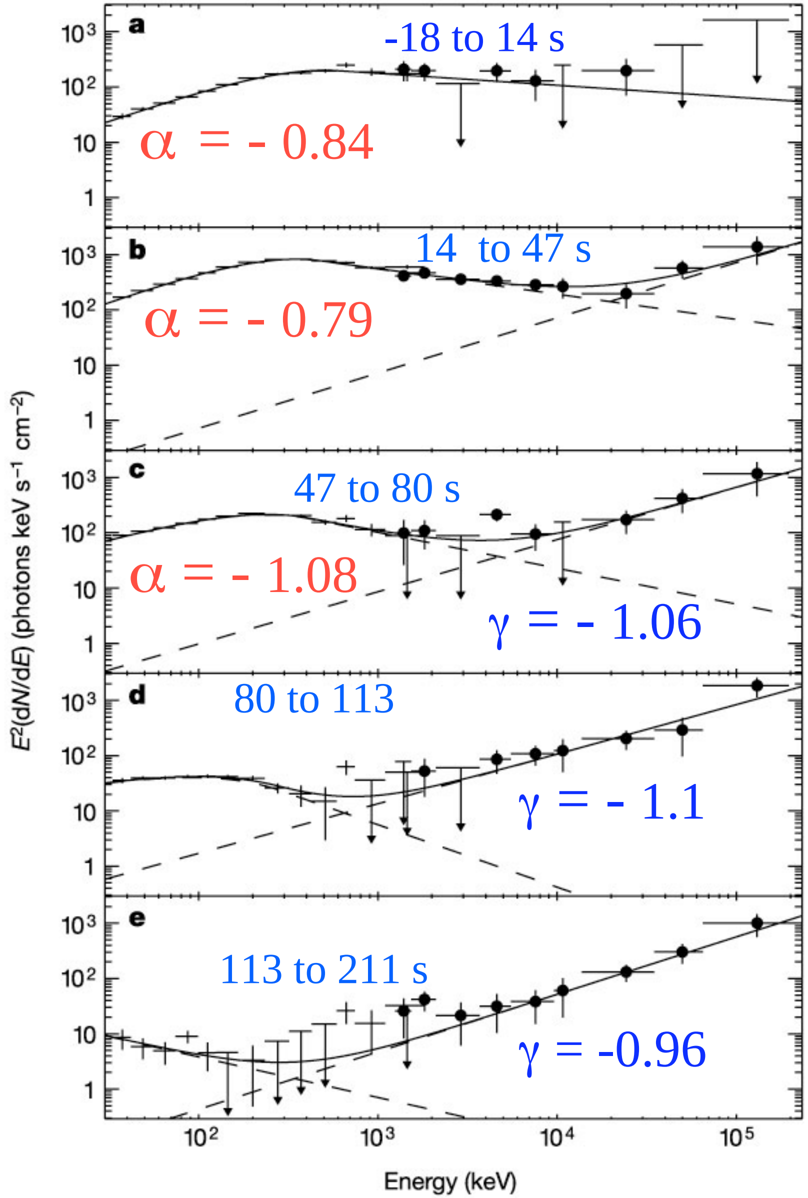
Spectral evolution



Ford et al. (1995)

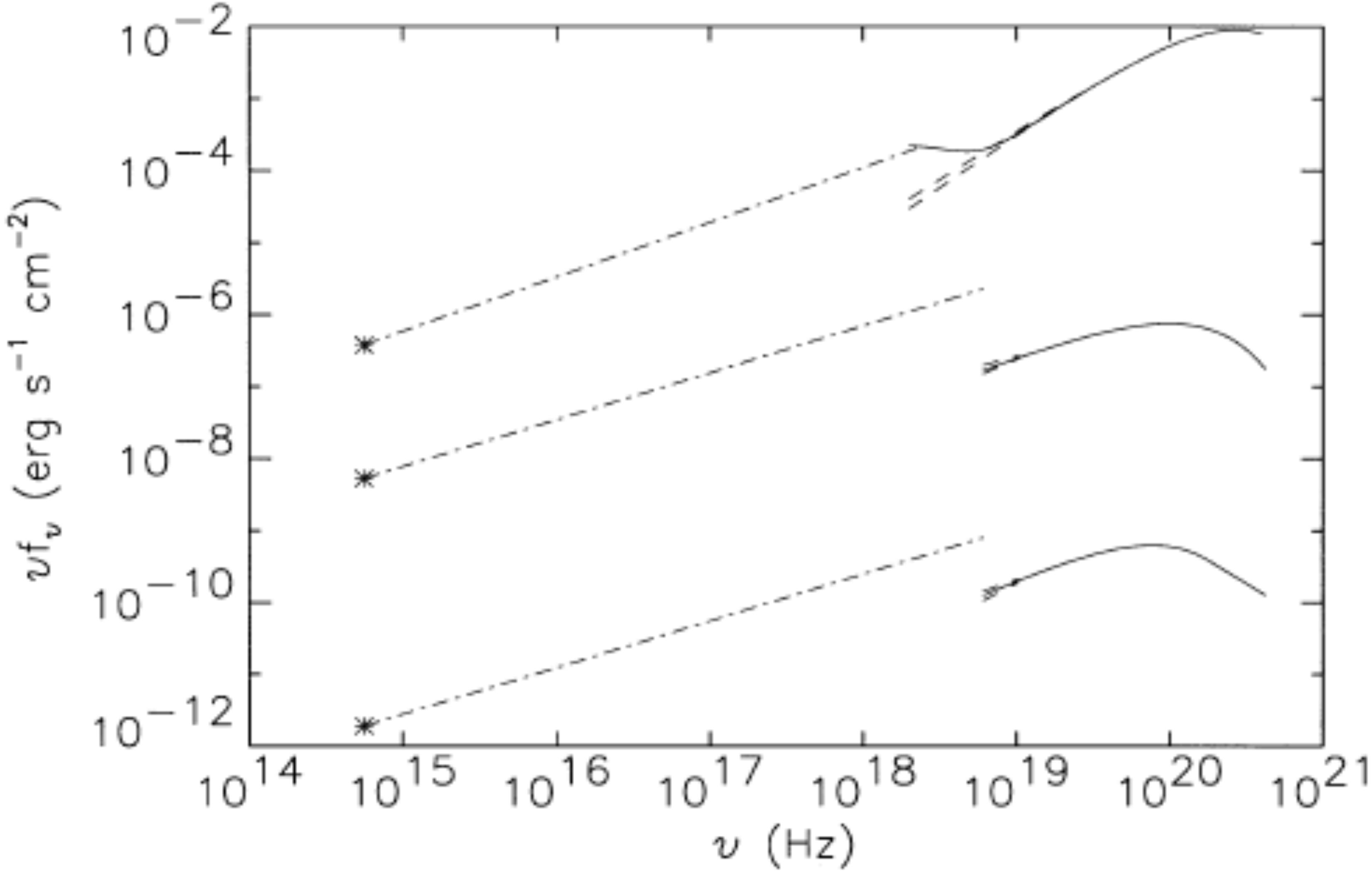
High energy emission





Gonzales et al. (2003)

GRB 990123: prompt optical emission



Briggs et al. 1999; Galama et al. 1999

Spectral properties

- Broad distribution of low energy spectral indices with peak at photon index $\alpha \approx -1$, and the hardest spectra are with $\alpha \approx 0$.
- Hard-to-soft spectral evolution during pulses
- High energy emission at 100 MeV with $\alpha \approx -1$ (GRB 941017)
- Prompt optical emission (GRB 990123)

Standard synchrotron shock model

1. $\varepsilon_B < 1$ fraction of available energy goes to magnetic fields
2. $\varepsilon_e < 1$ fraction of available energy goes to electrons
3. Electrons are assumed to obtain all this energy instantaneously

   (acceleration time $<<$ cooling time)

Synchrotron shock model

Electrons are assumed to obtain all this energy instantaneously

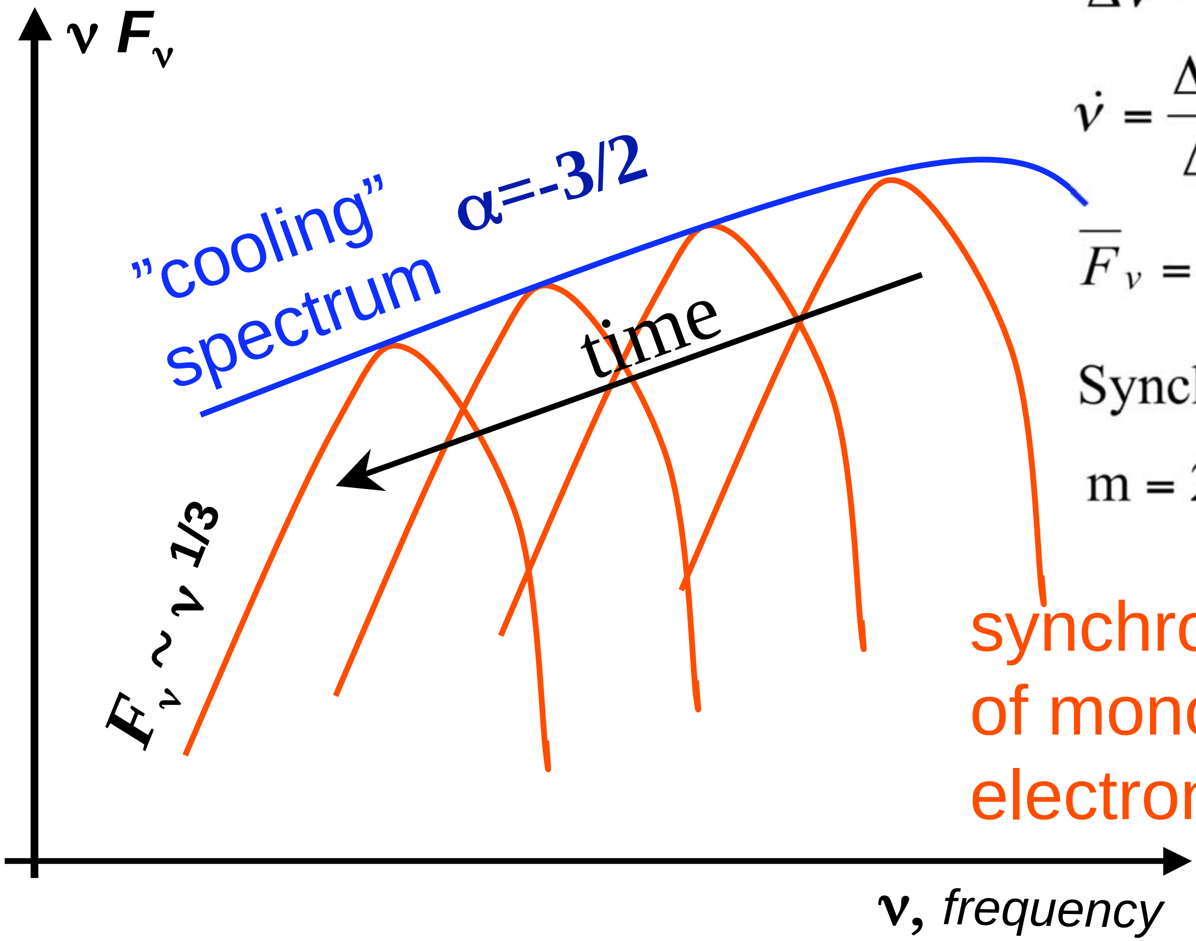
(acceleration time << cooling time),

BUT

Electron cooling time << light-crossing time

Spectra from cooling electrons

$N_\nu \sim F_\nu / \nu \sim \nu^{\alpha}$



$$\nu = \nu_b \gamma^m$$

$$\Delta\nu = \nu_b m \gamma^{m-1} \Delta\gamma$$

$$\dot{\nu} = \frac{\Delta\nu}{\Delta t} \propto \gamma^{m-1} P \propto \nu^{(m-1)/m}$$

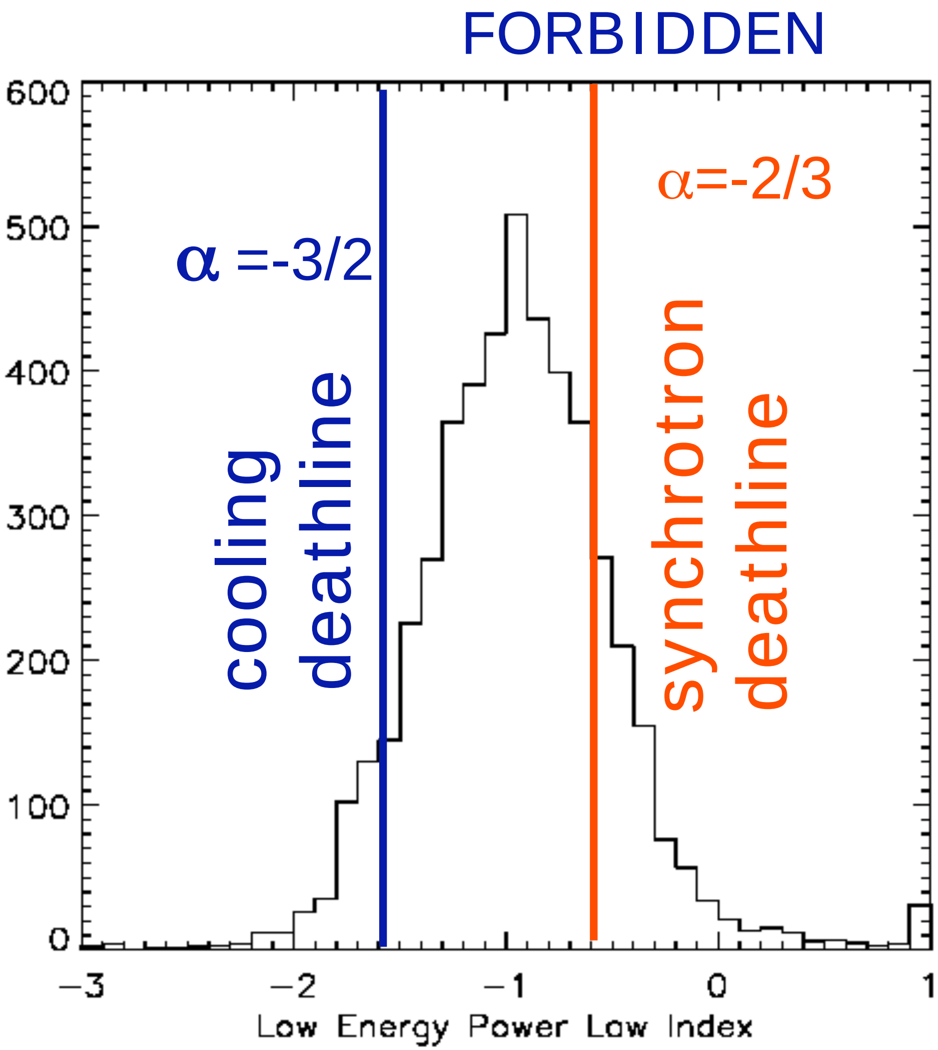
$$\overline{F}_\nu = \frac{dE}{d\nu} = \frac{dE}{dt}\frac{dt}{d\nu} = \frac{P}{\dot{\nu}} \propto \nu^{-(m-1)/m}$$

Synchrotron or Compton

$m = 2 \qquad \overline{F}_\nu \propto \nu^{-1/2}$

(e.g. Bussard 1984; Imamura & Epstein 1987; Ghisellini, Celotti, Lazzati 2000; review by Ghisellini in 2003 Rome symp.)

Cooling vs. Synchrotron "deathline"

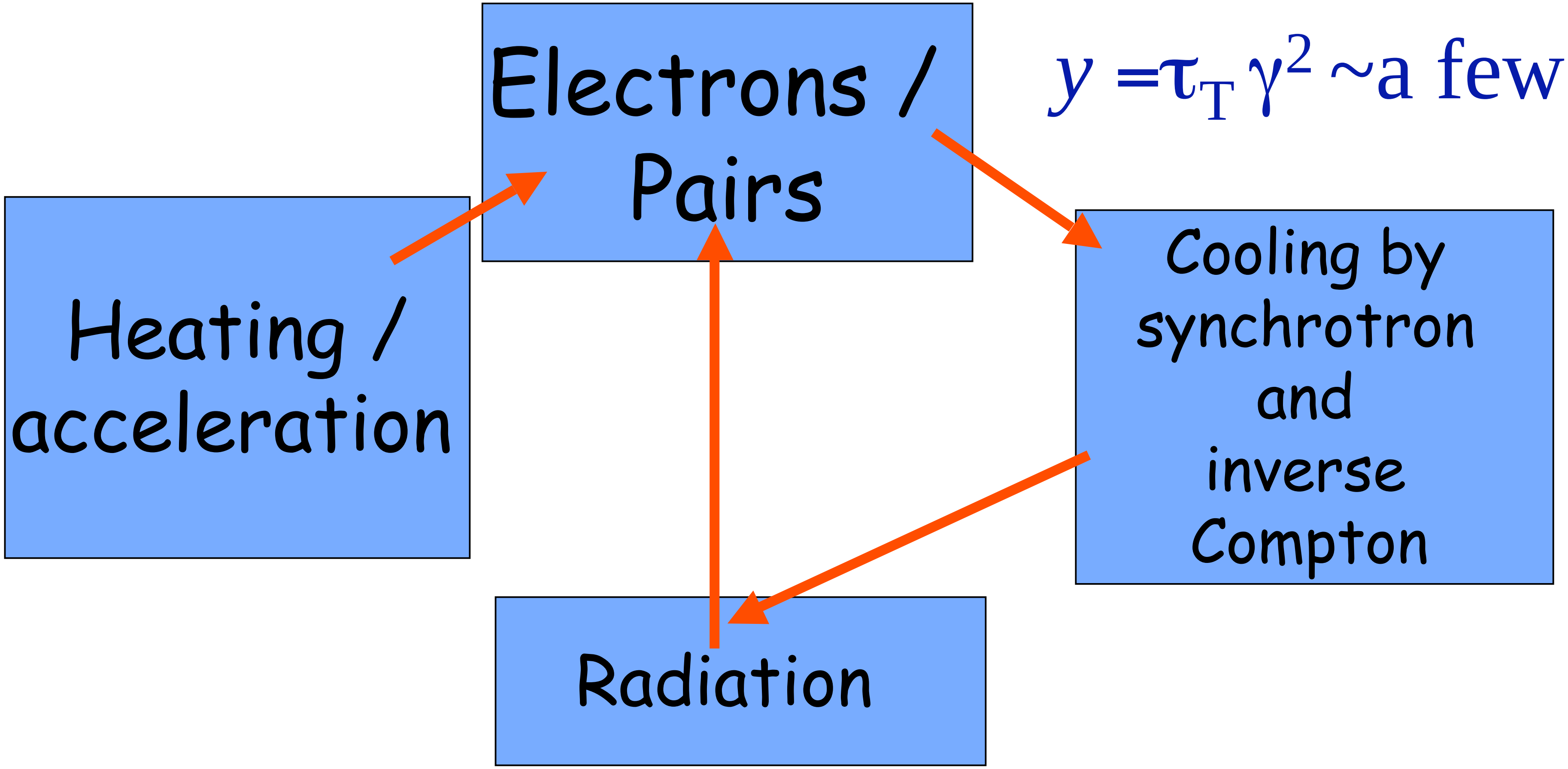


>90 % of GRBs are inconsistent with instantaneous particle injection model (synchrotron or Compton scattering)

Heating / reacceleration of particles

Energy balance $L / \tau_T = (U_B + U_{rad})\, \gamma^2$

$y = \tau_T\, \gamma^2 \sim \text{a few}$

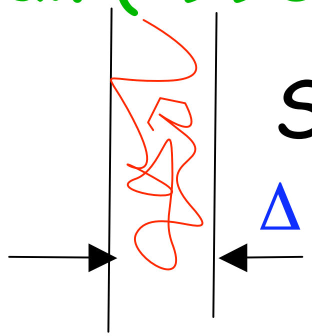


Simulations

Large Particle Monte-Carlo code

Stern et al. (1995)

PROCESSES:
Synchrotron emission
Compton scattering
pair production
pair annihilation
synchrotron self-absorption
and particle thermalization



Slab geometry

$\Delta = 0.1\,R'$

HEATING:
Electrons/pairs obtain equal amount of energy per unit time

Radiative processes

- If Thomson optical depth $\tau_T \sim 10^{-8}$ then $\gamma \sim \sqrt{(y/\tau_T)} \sim 10^4$ and synchrotron is the main cooling mechanism
- If $\tau_T \sim 10^{-2}$-10^{-4} then $\gamma \sim$ 10-100 and synchrotron self-Compton (Stern & Poutanen 2004)
- If $\tau_T \sim 1$ then $\gamma \sim 1$-2 and quasi-thermal Comptonization (e.g.Ghisellini & Celotti 1999; Stern 1999, 2003)

Optical depth

- Thomson optical depth of the (matter dominated) ejecta

$_{T,ejecta} = 0.3\, E_{kin,iso,\,54}\, R_{15}^{-2}\, \Gamma_2^{-1}$

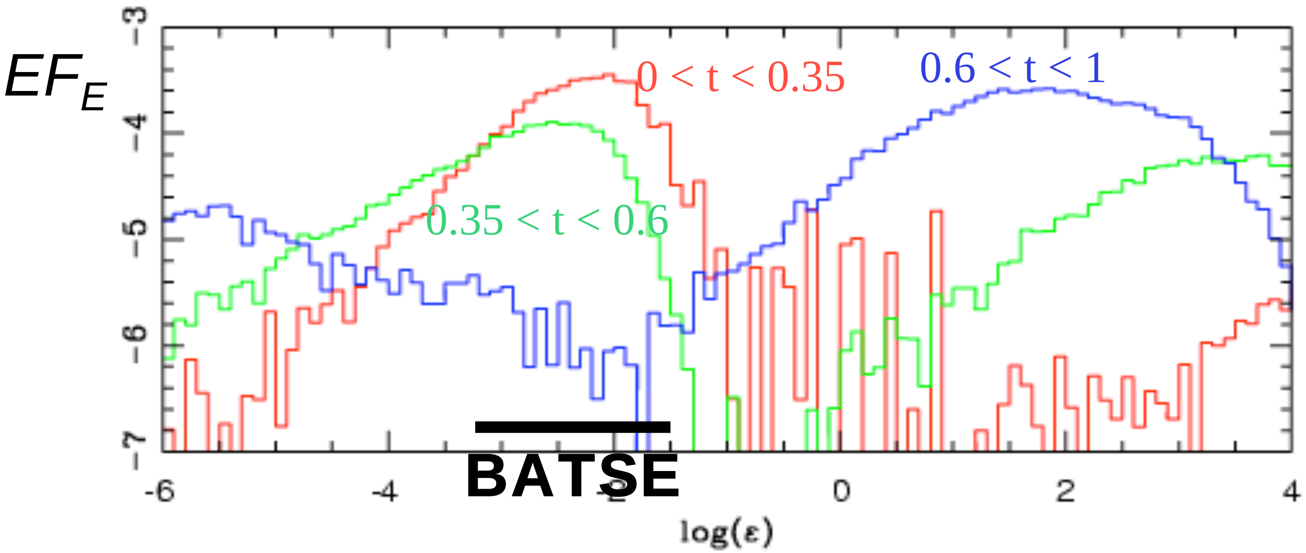
- Thomson optical depth in the

  external shock

$\tau_{T,ext} = 2 \times 10^{-4}\, R_{15}^{-1}\, M_{-5}\, w_3^{-1}$ for wind

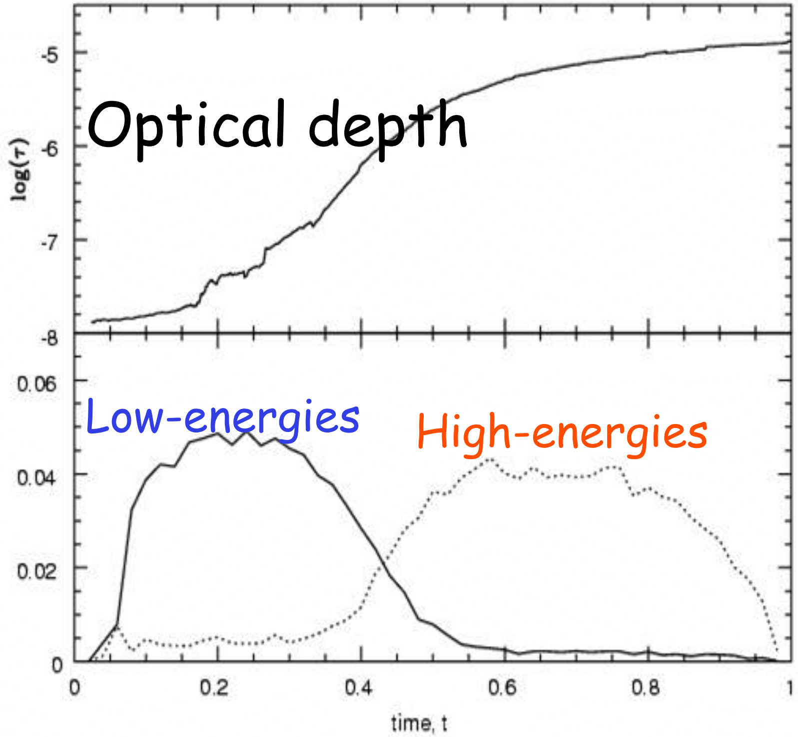
(M_{-5} - mass loss rate in 10^{-5} solar masses per year; w_3 - wind velocity in 10^3 km/s)

$\tau_{T,ext} = 2 \times 10^{-8}\, R_{17}\, n_{ISM}$ for ISM

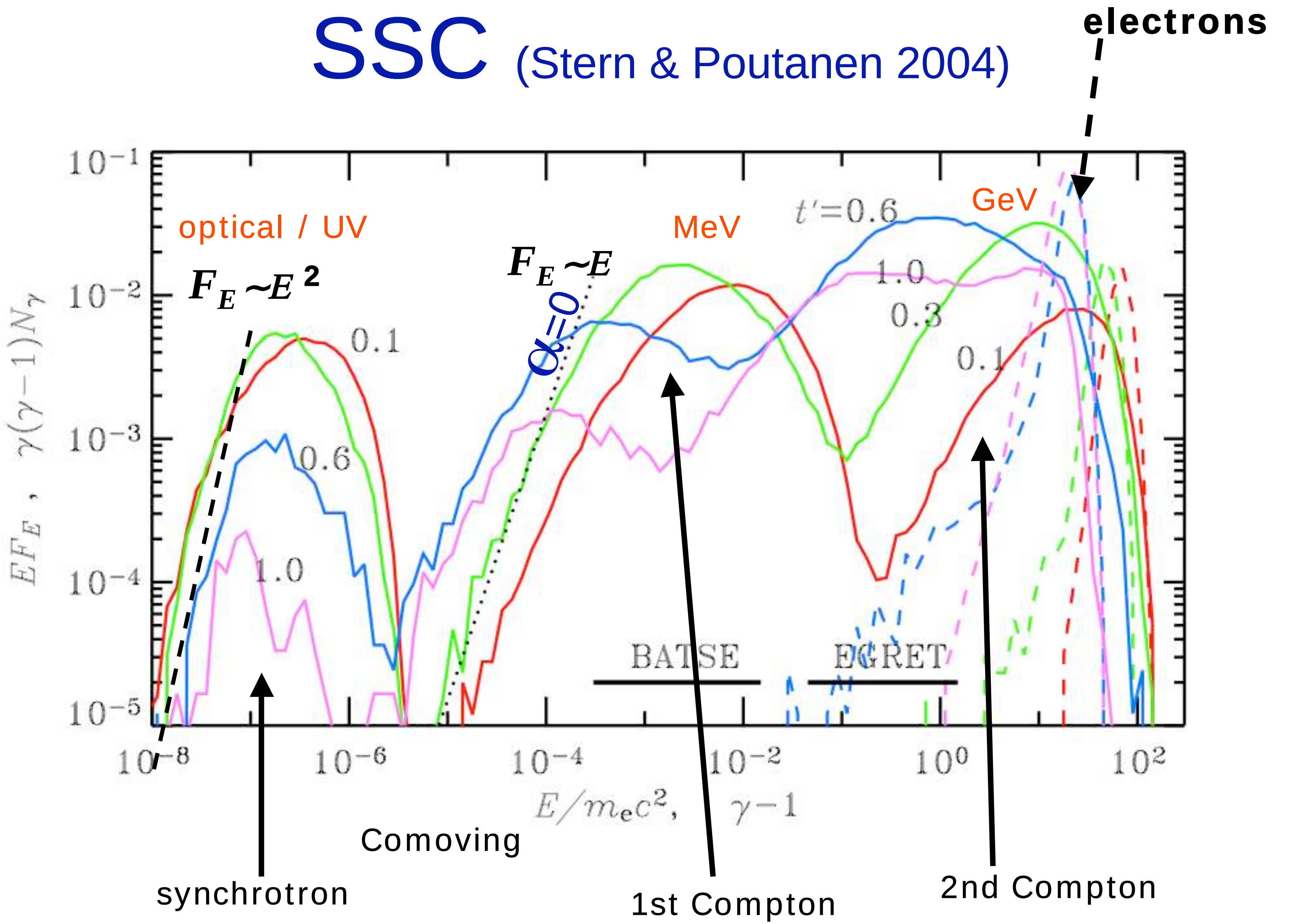


Synchrotron emission

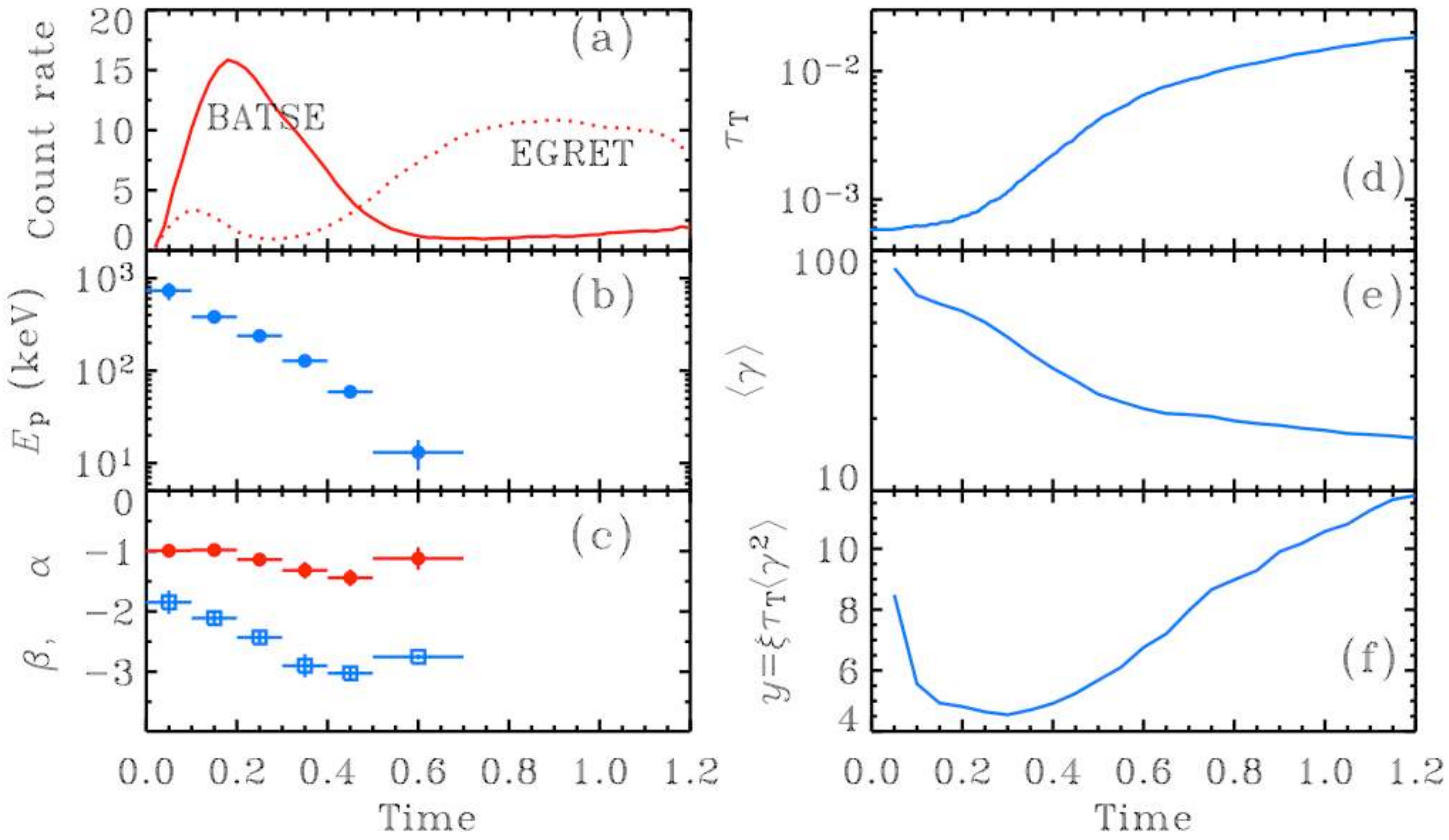
$\tau_T = 2 \times 10^{-8}$ $\boldsymbol{l} = 0.3$, $B = 10$ G



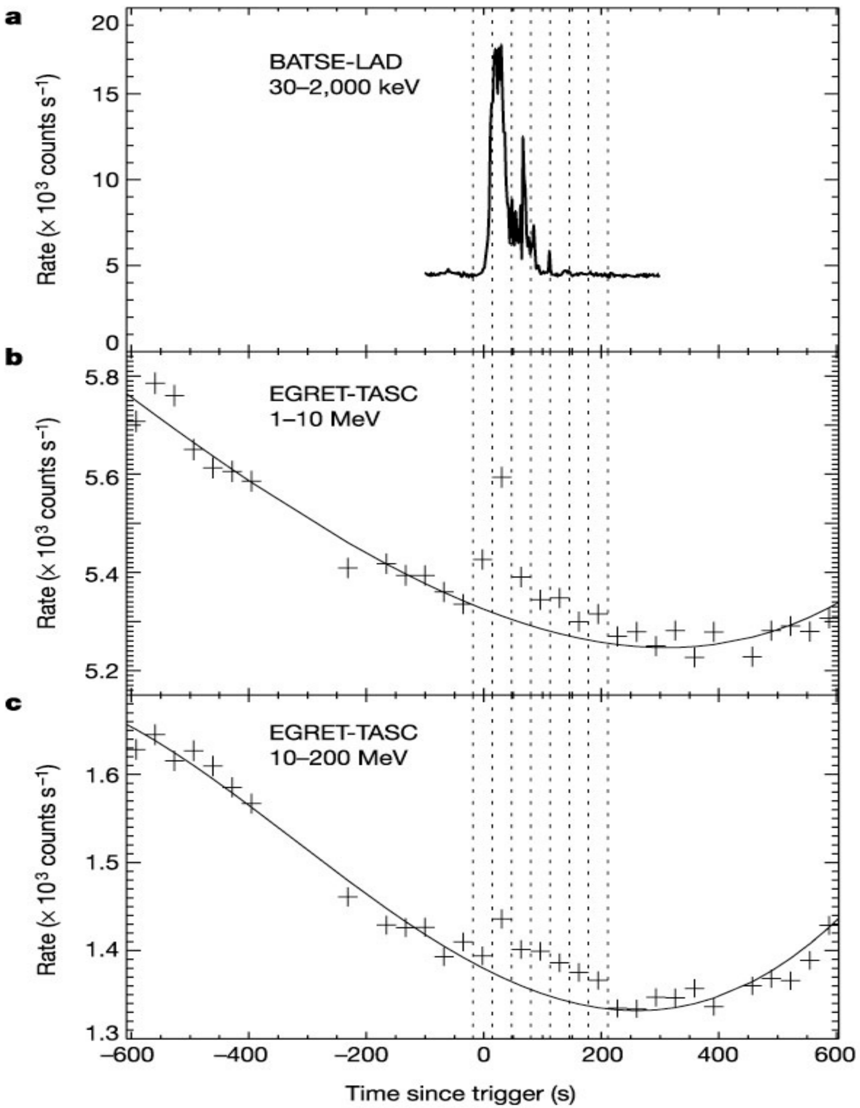
SSC (Stern & Poutanen 2004)

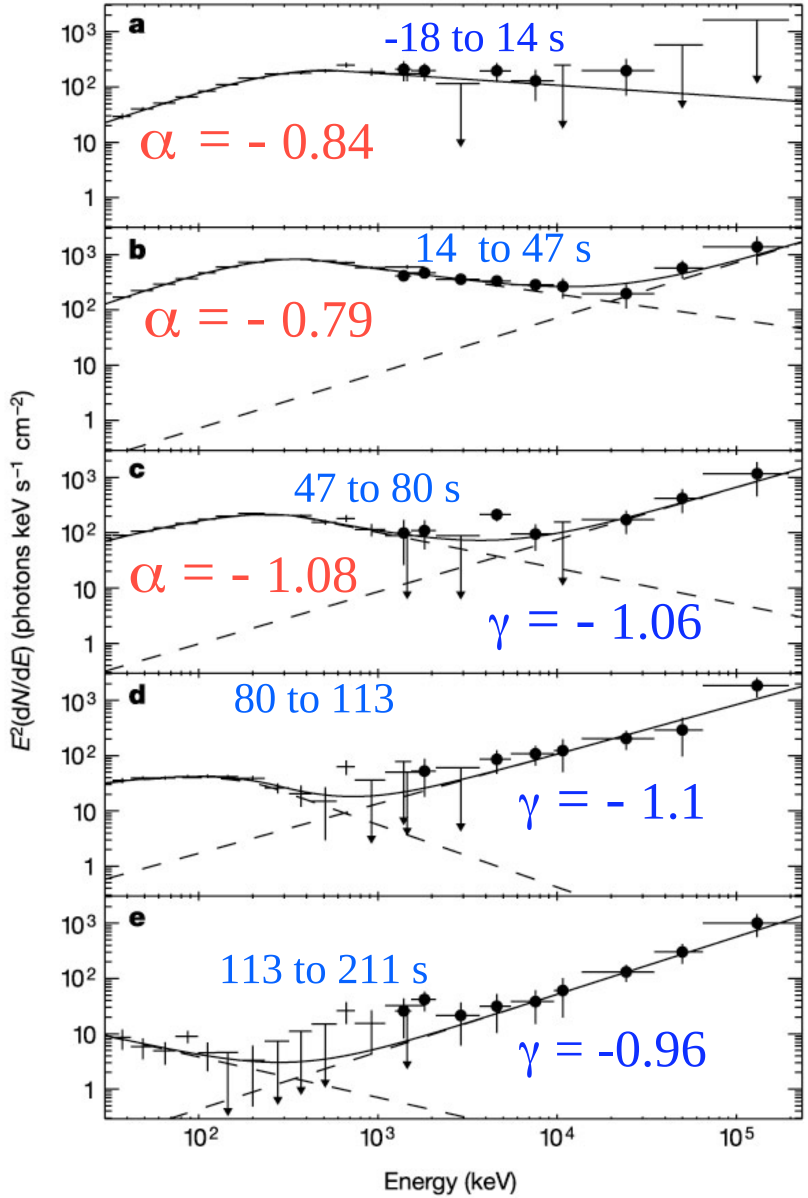


Evolution of parameters



High energy emission

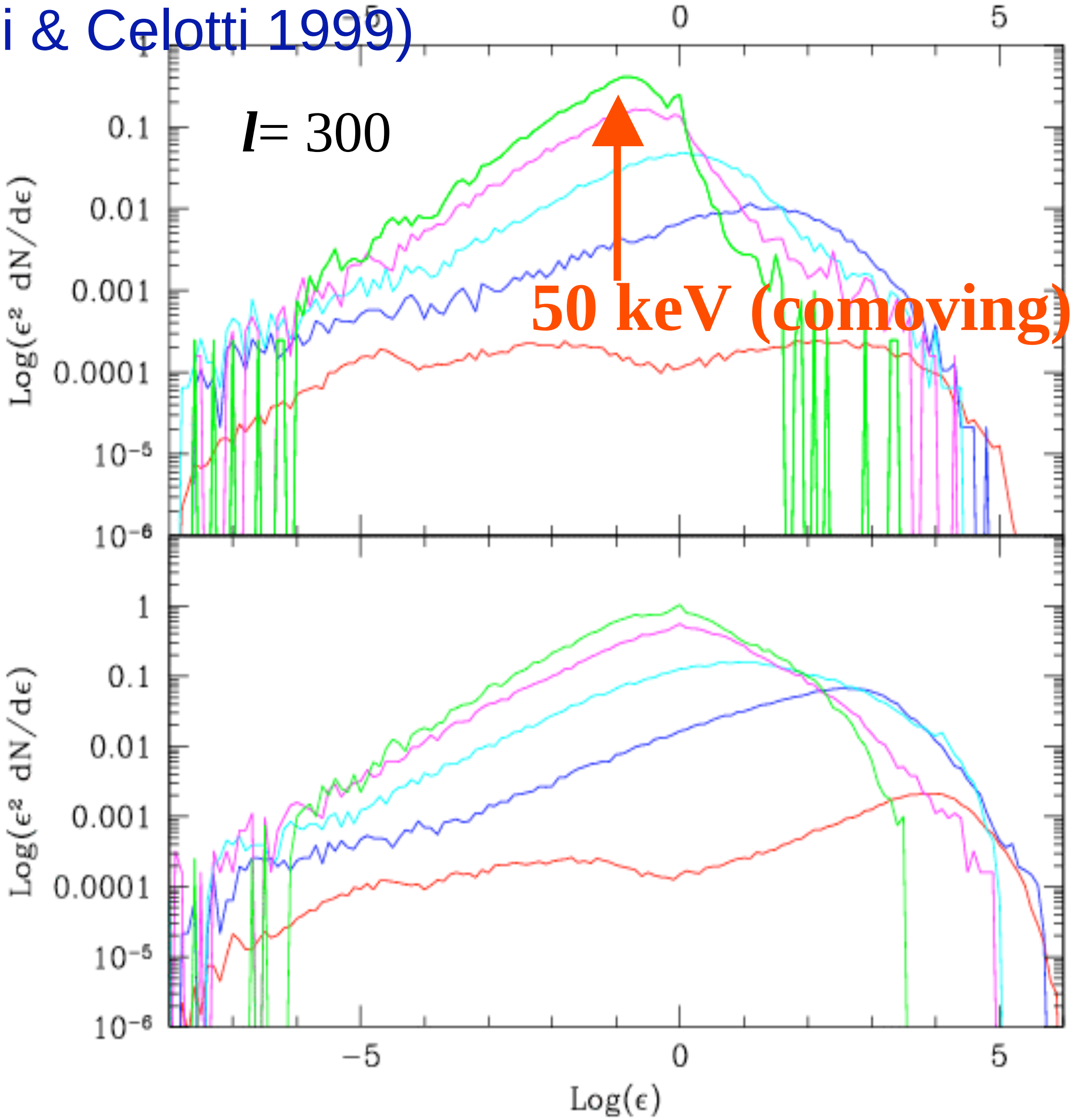




Gonzales et al. (2003)

$\tau_T \sim 1$ Quasi-thermal Comptonization

(Stern 2003, MNRAS, "Electromagnetic catastrophe"; Stern 1999; Ghisellini & Celotti 1999)



SUMMARY

- Standard shock models with particle injection produce "cooling" spectra ($F_E \sim E^{-1/2}$).

  Heating / reacceleration

  during the life-time of a source is needed.
- Radiative processes depend on τ_T and compactness
- For synchrotron emission, only $\tau_T \sim 10^{-8}$ can be reaccelerated
- Quasi-thermal Comptonization does not give very hard spectra and peaks at too high energy
- Synchrotron self-Compton emission of nearly monoenergetic electrons / pairs produces:

  (1) hard BATSE spectra $F_E \sim E^{1}$ and spectral evolution

  (2) prompt optical flash with $F_E \sim E^{2}$

  (3) 100 MeV-10 GeV emission (potentially observable by GLAST)