Radiative transfer in GRB jets

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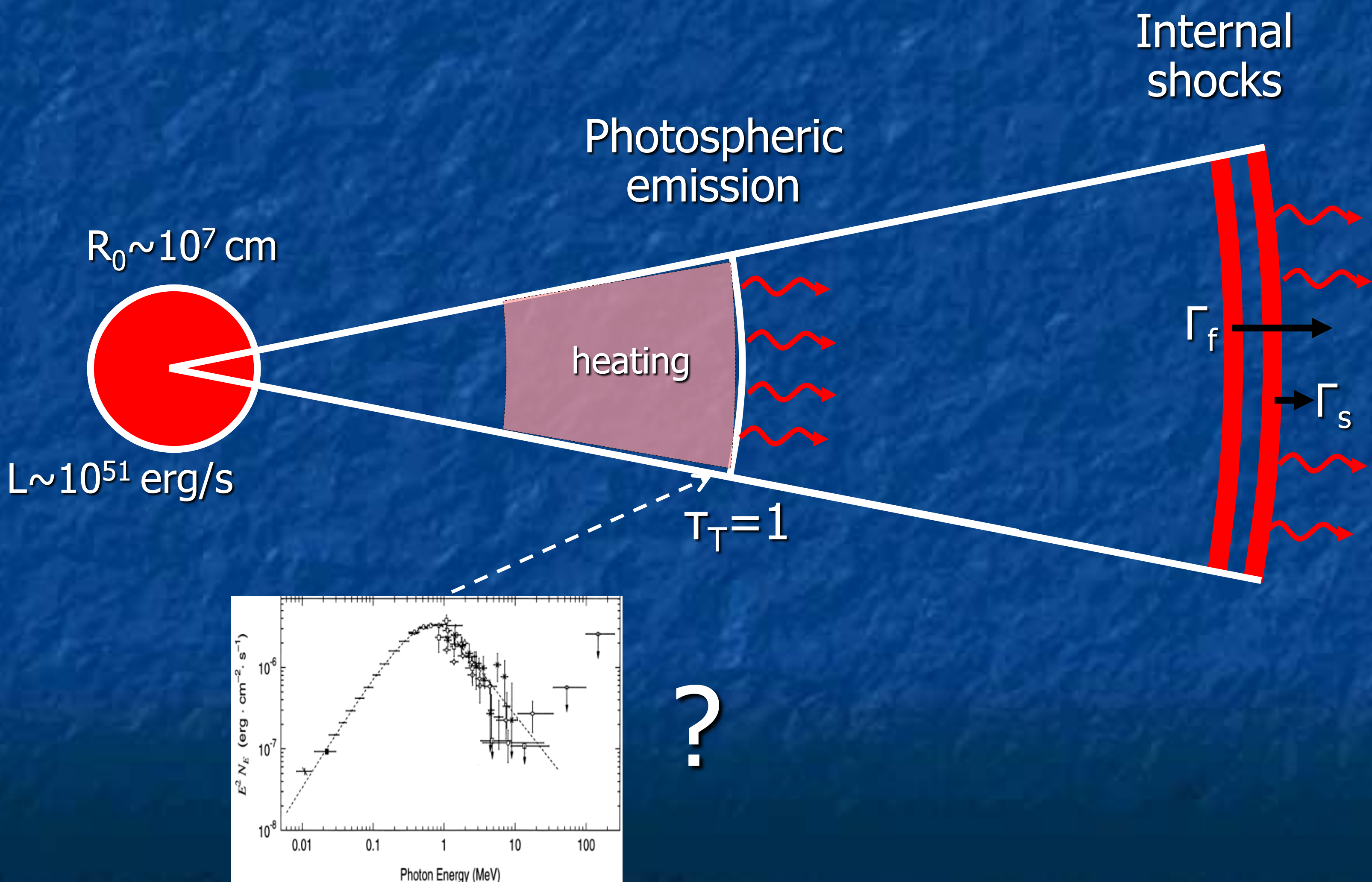
Outline

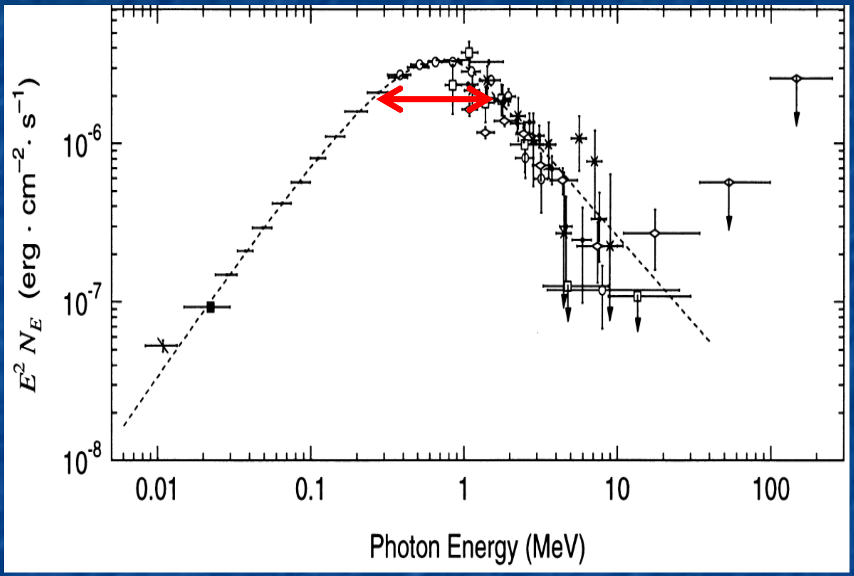
- Prompt emission
  - Photospheric emission from dissipative jets
    - Photon number and spectral peaks
    - Non-thermal spectra
- GeV (+optical+TeV) flashes
  - Forward shock in a pair-loaded progenitor wind
  - Examples: 080916C, 130427A

GRB prompt emission: optically thin vs. thick

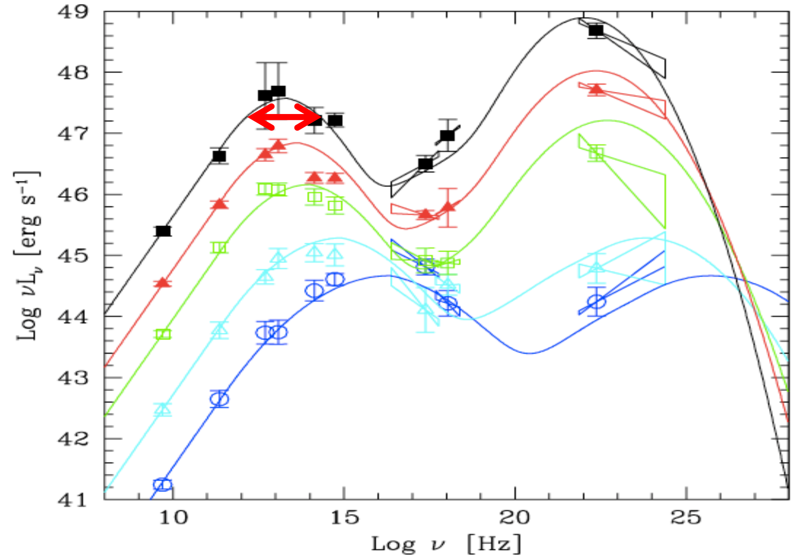


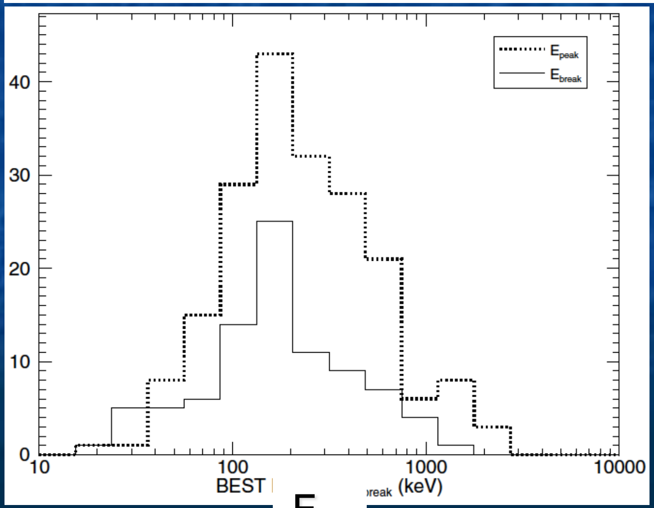
Peak sharpness and position

GRB 990123 — Briggs et al. (1999)



Blazars — Ghisellini (2006)





E_{pk}

Goldstein et al. (2012)

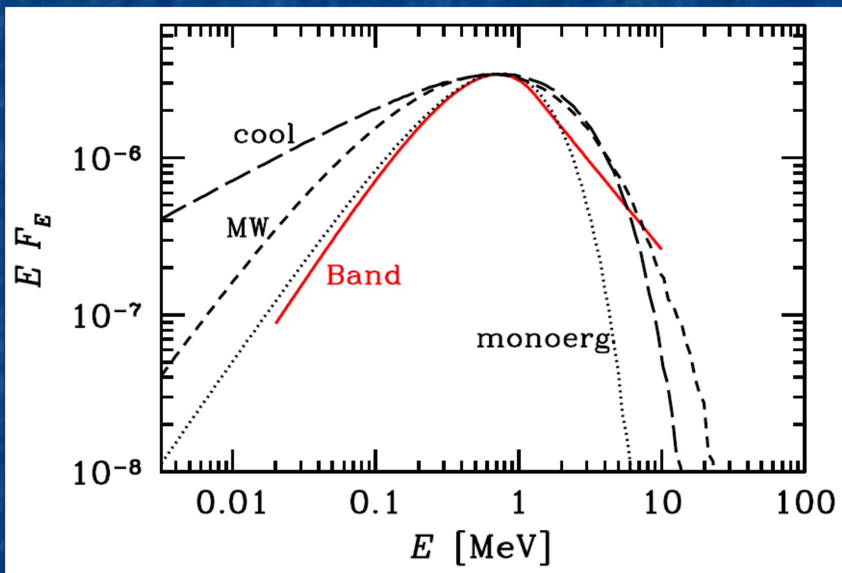
- Spectra narrowly peaked
- Peak energies cluster

Synch. peak

$$E_{peak} \propto \frac{\Gamma \gamma_{peak}^2 B}{(1+z)}$$

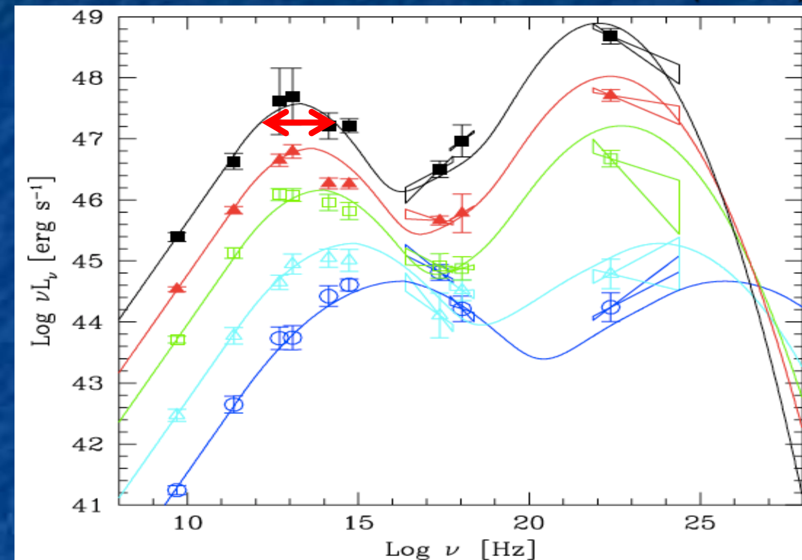
Peak sharpness and position

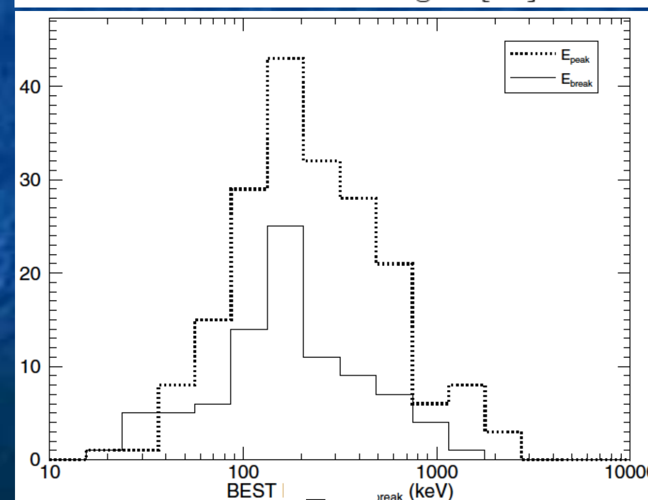
GRB 990123



Blazars

Ghisellini (2006)





E_{pk}

Goldstein et al. (2012)

- Spectra narrowly peaked
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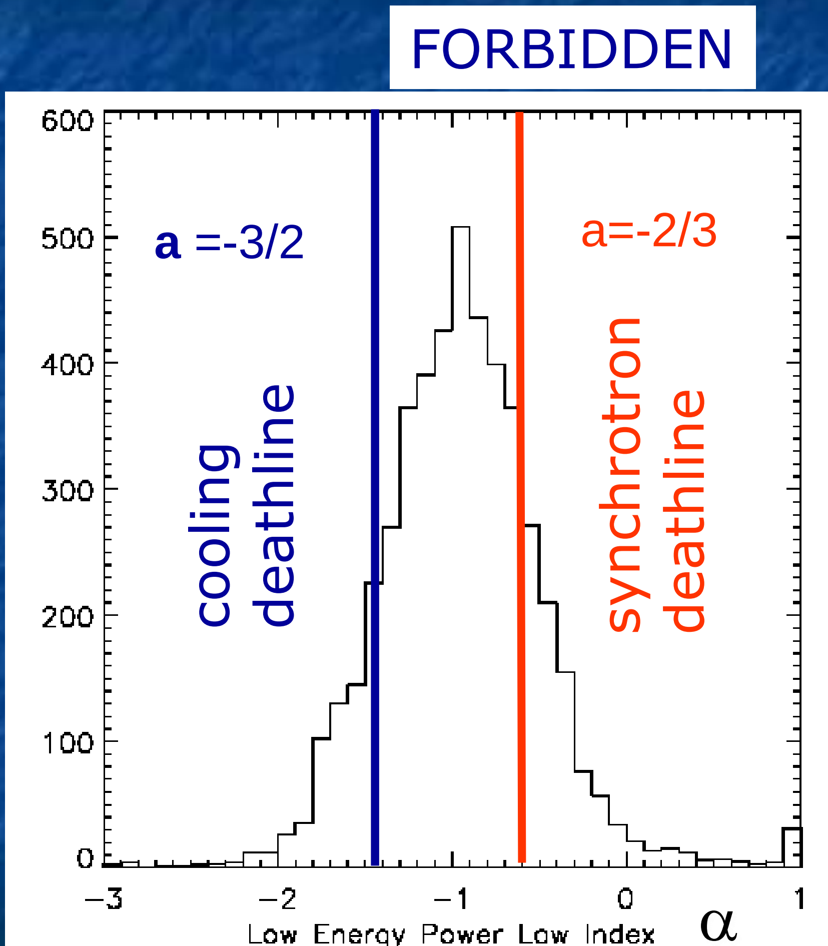
Synch. peak

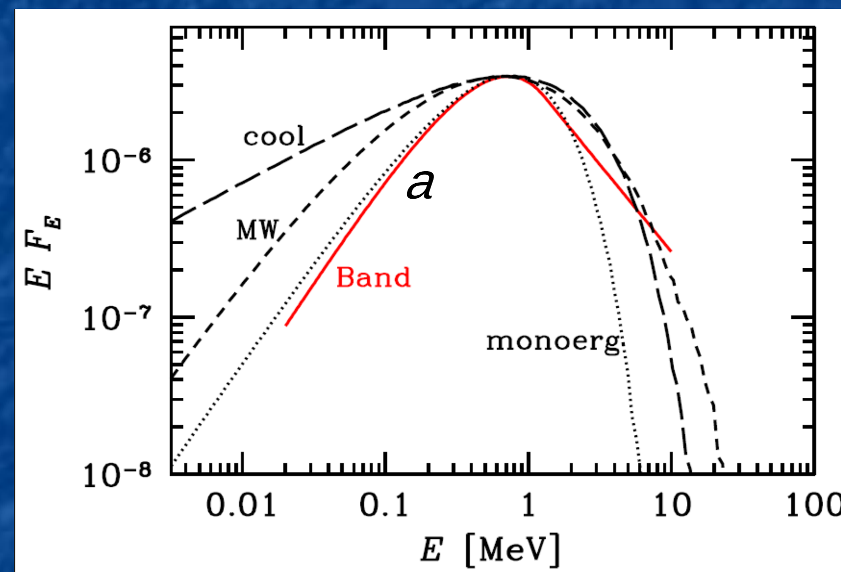
$$E_{peak} \propto \frac{\Gamma \gamma_{peak}^2 B}{(1+z)}$$

Low-energy slope



Preece et al. (2000)

$$N_\nu \propto F_\nu / \nu \propto \nu^\alpha$$



- Optically thin + radiatively efficient

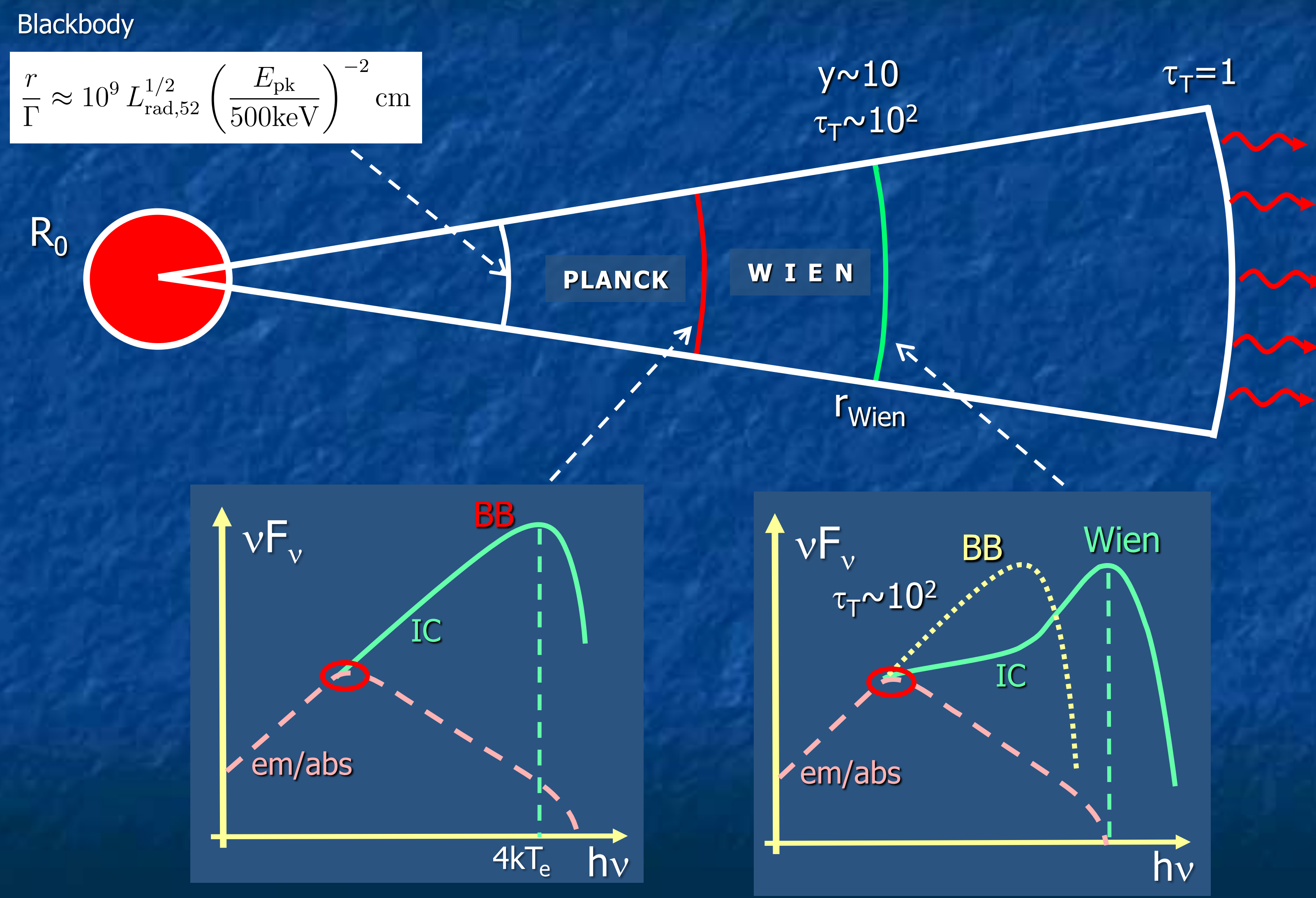
  ⇒ $\alpha > -1.5$ (synch. or IC)

Photospheric emission

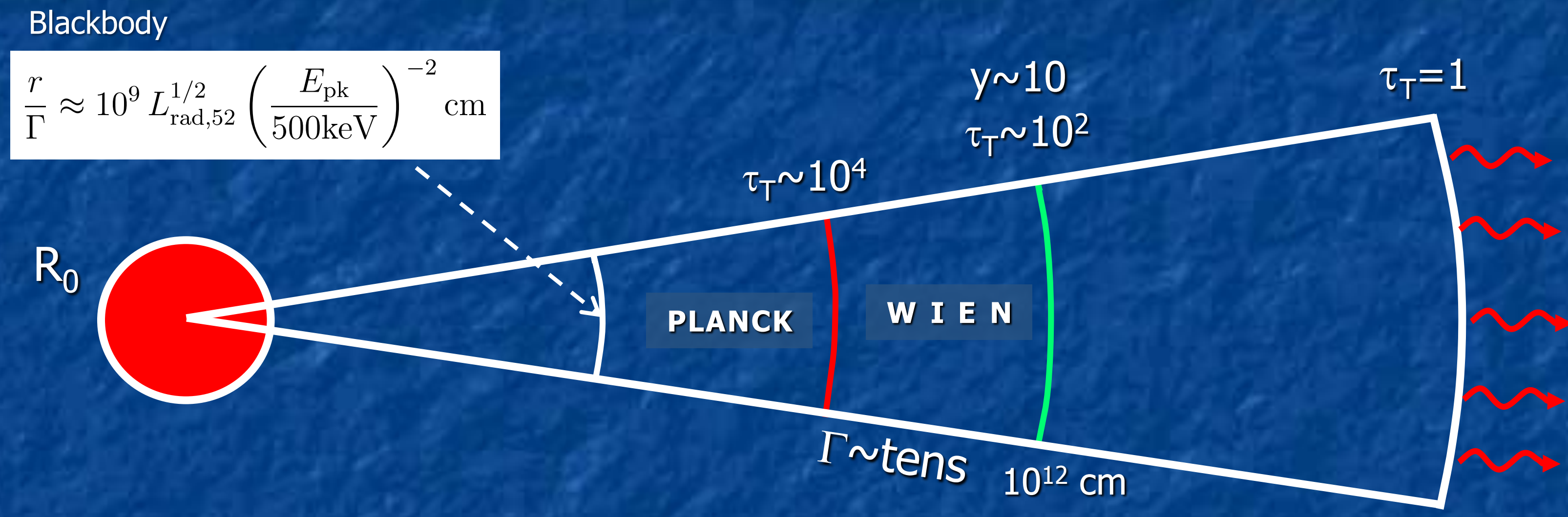
- Spectral peaks
  - Narrow: *can* be as narrow as Planck
  - Position
    - Natural scale $\overline{E}_{\rm ph} \sim 3kT_0\, L_{52}^{1/4} r_{0,7}^{-1/2} \sim 5\,{\rm MeV}$
    - Observed $\overline{E}_{\rm pk} \sim 500\,{\rm keV}$ $\Longrightarrow$ photon production
- Non-thermal shape

Dissipation

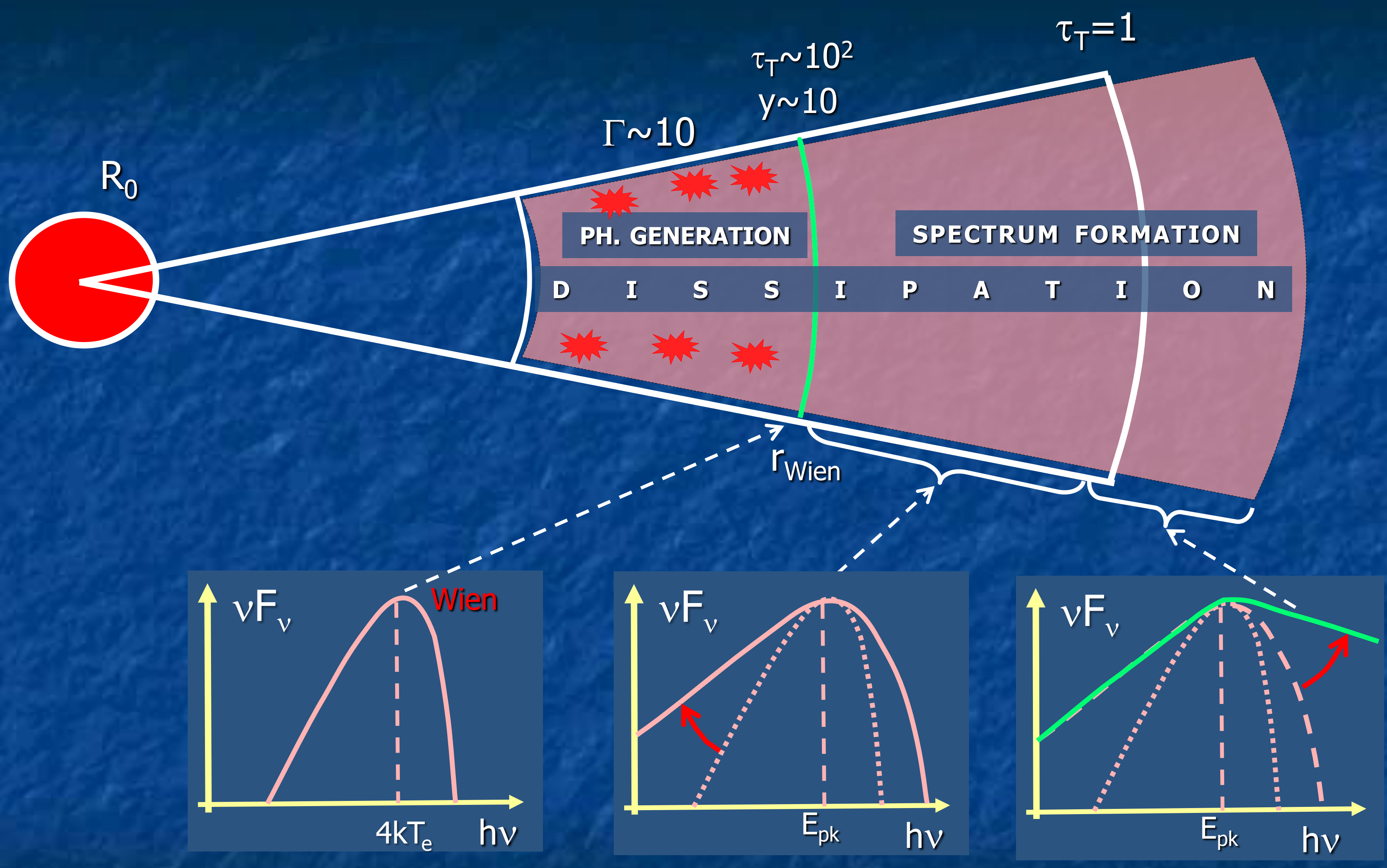
Photon production



Photon production



- Number of photons at the peak established below/near the Wien radius
- Most efficient mechanism: synchrotron
- Observed E_{pk} -s $\Leftrightarrow$ modest Γ ~ a few tens at r~10^{11} - 10^{12} cm



$\tau_T=1$
$\tau_T \sim 10^2$
$y \sim 10$
$\Gamma \sim 10$
R_0
PH. GENERATION
SPECTRUM FORMATION
D I S S I P A T I O N
r_{Wien}
νF_ν
Wien
$4kT_e$
$h\nu$
νF_ν
E_{pk}
$h\nu$
νF_ν
E_{pk}
$h\nu$

Radiative transfer

$$\frac{\partial I_\nu}{\partial \ln R} = (1-\mu)\left(\frac{\partial I_\nu}{\partial \ln \nu} - 3I_\nu\right) - (1-\mu^2)\frac{\partial I_\nu}{\partial \mu} + \frac{(j_\nu - \kappa_\nu I_\nu)\,R}{(1+\mu)\,\Gamma}$$

I_ν - intensity μ - photon angle

Processes: Compton, synchrotron, pair-production/annihilation

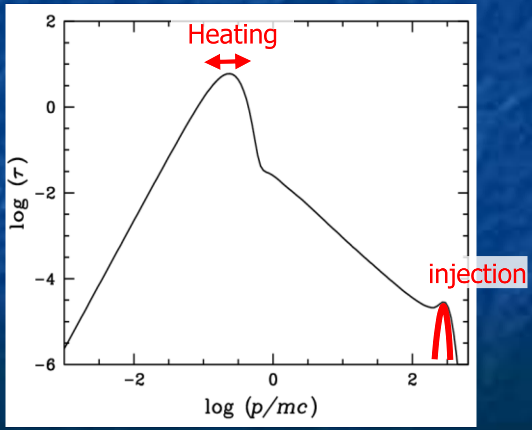
- Continuous dissipation throughout the jet
  - Thermal and non-thermal channels
- Acceleration:

$$\frac{d\ln\Gamma}{d\ln r} = \frac{1}{2+\Gamma/\eta}\left[2\,(1-\Gamma/\eta) - 4\,\frac{d\varepsilon_{\rm h}}{d\ln r}\right]$$

- Magnetization:

$$\epsilon_B \sim 10^{-3} - 10^{-1}$$

$e_\pm$ pairs



Dissipation mechanism: example

- Neutron-proton collisions (Beloborodov 2010)
  - Internal (radiation mediated) shocks: Neutrons penetrate through
  - Proton and neutron flows decouple at $\tau_T \approx 20 \Rightarrow$ drift
  - Nuclear collisions:
    - Elastic: Thermal heating of $e_\pm$ via Coulomb collisions
    - Inelastic: Injection of relativistic $e_\pm$ with $\gamma \sim 300$ via pion production and decay

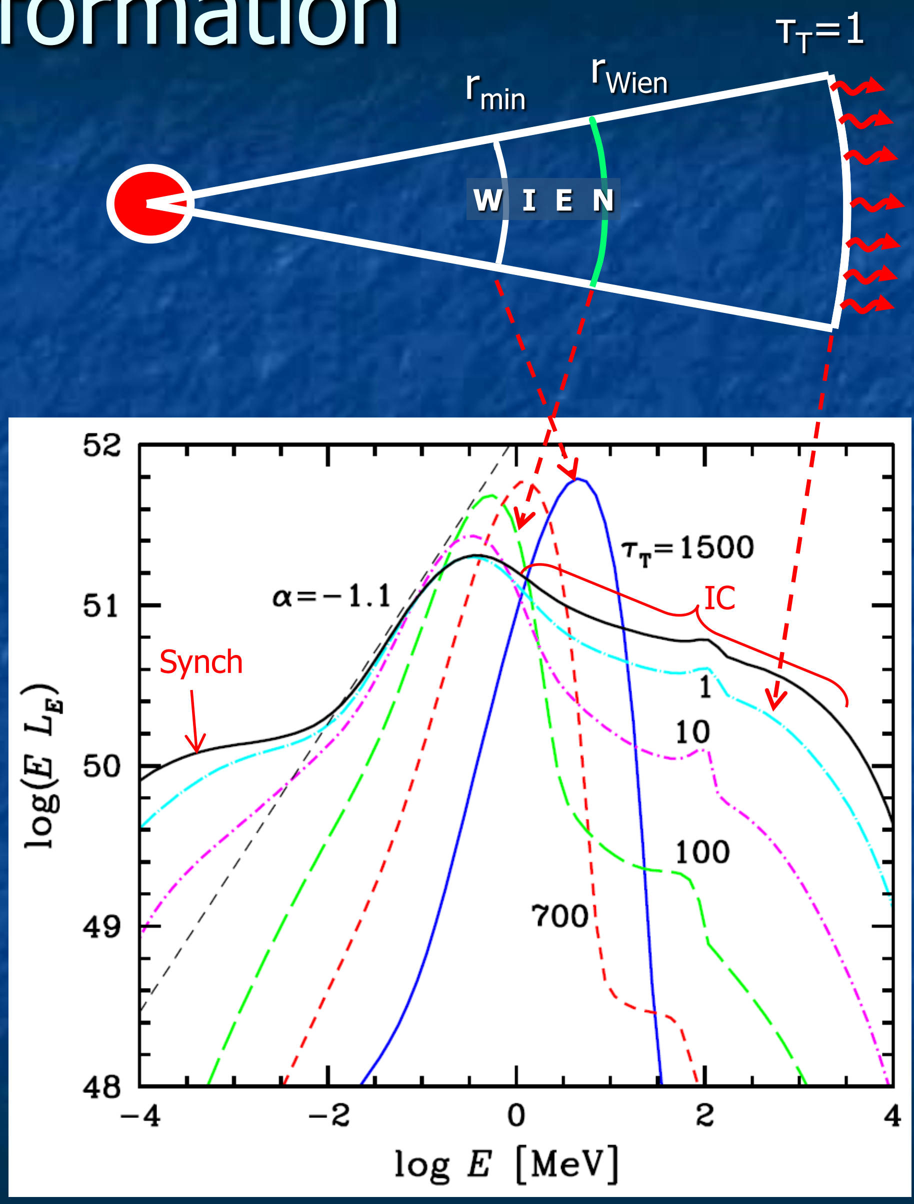
π^+, π^-, π^0 $\qquad m_\pi c^2 \approx 140\ \mathrm{MeV}$

$$\pi^+ \to \mu^+ + \nu_\mu;\ \ \pi^- \to \mu^- + \bar{\nu}_\mu;\ \ \pi^0 \to \gamma + \gamma$$

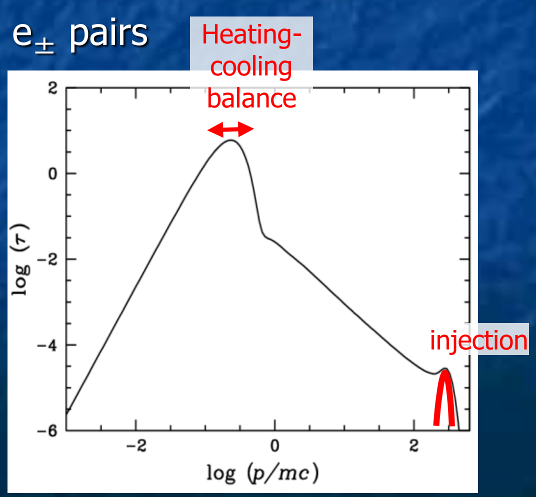
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu;\ \ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

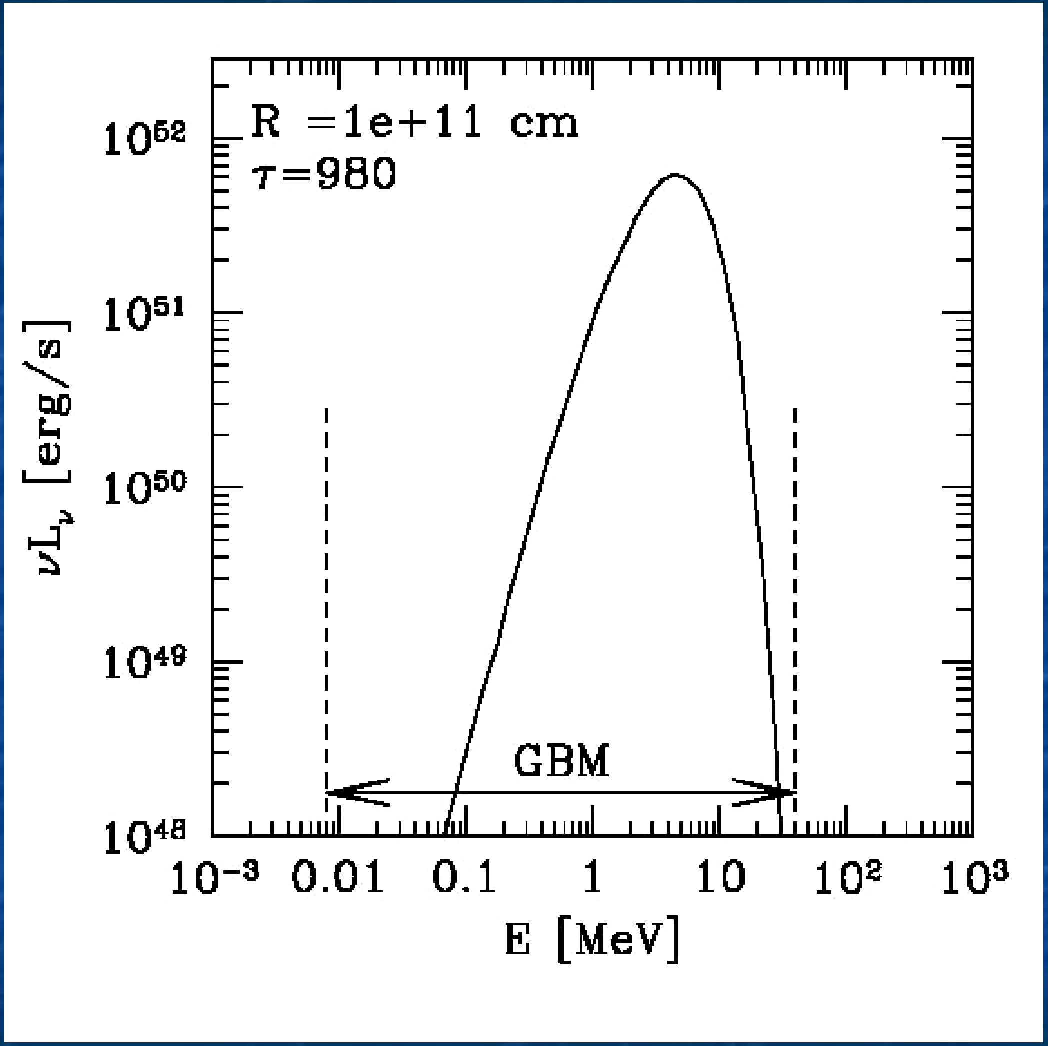
Spectral formation

- Initial spectrum: Wien
- Peak shifted to lower energies due to photon production
- Broadening starts near Wien radius, proceeds through the photosphere
- Final spectrum: Band



Spectra at different stages of expansion





$$L_{jet} = 10^{52} \text{ erg s}^{-1}$$

$$h = 300$$

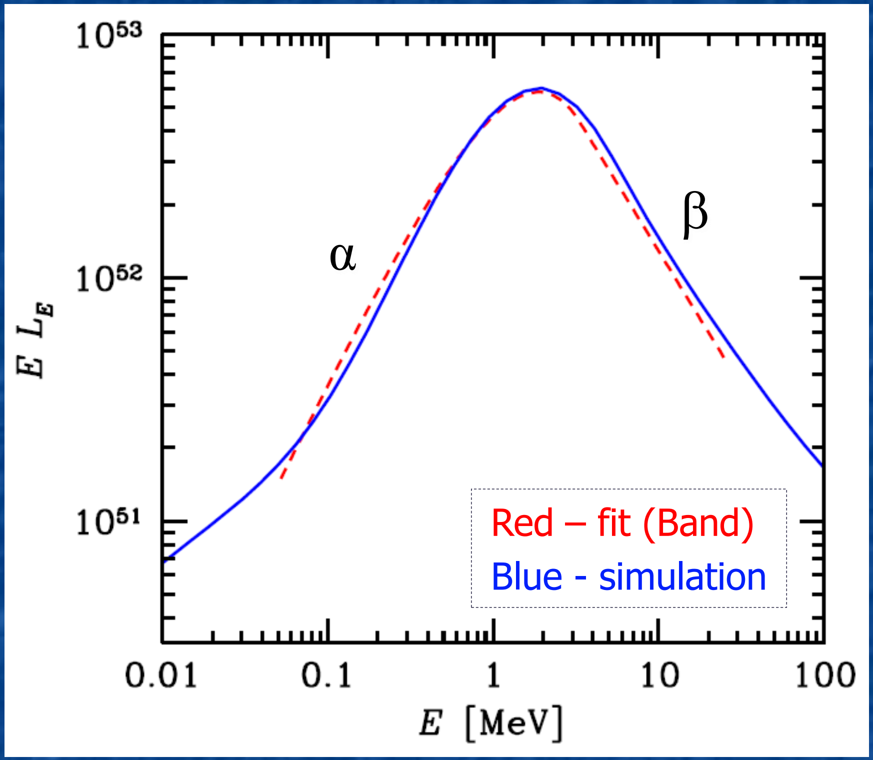
$$e_B = 0.01$$

$$\frac{dL_{\text{heat}}}{d\ln R} = const$$

‘Fits’ to data: GRB 990123

- Simulation parameters:
  - Initial $\Gamma(r_{min})$ = 80; r_{min}=3 x 10^{10} cm
  - Final Lorentz factor Γ_f = 600
  - ε_B = 0.03

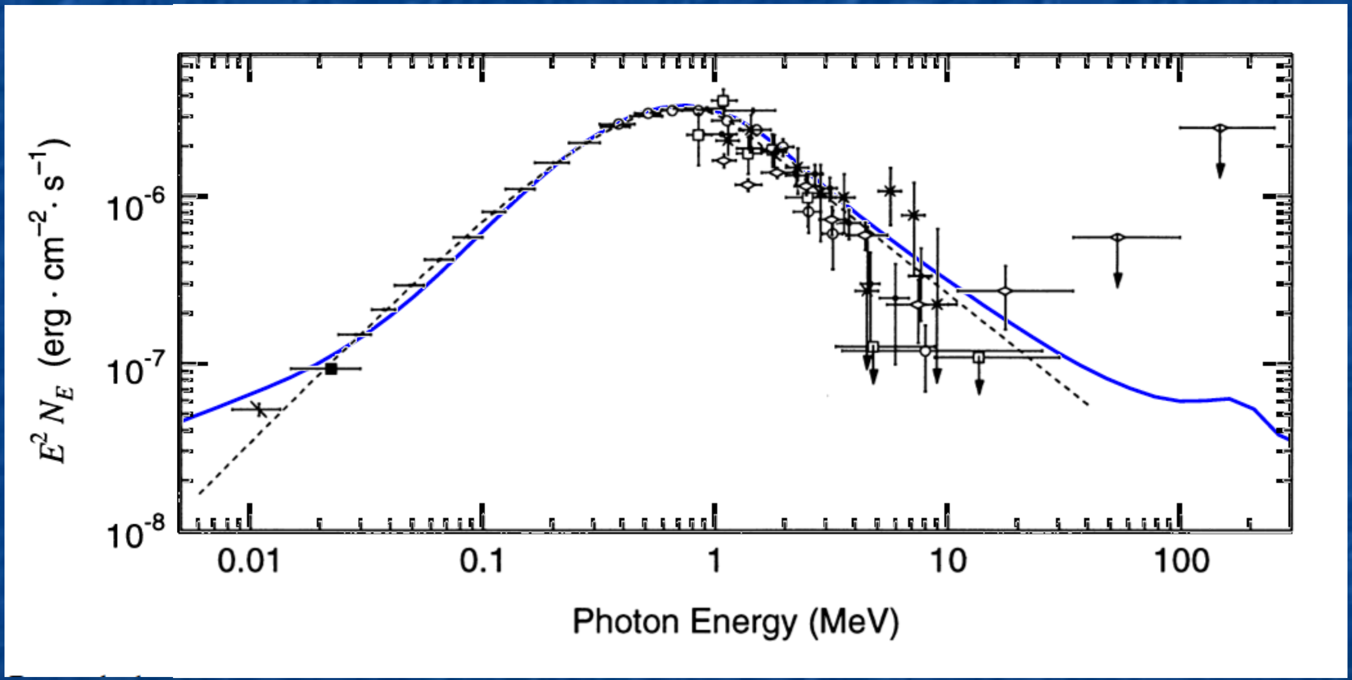
Spectrum (cosmological rest frame)



Fit: Band (Briggs et al. 1999)

α = -0.6; β = -3.11

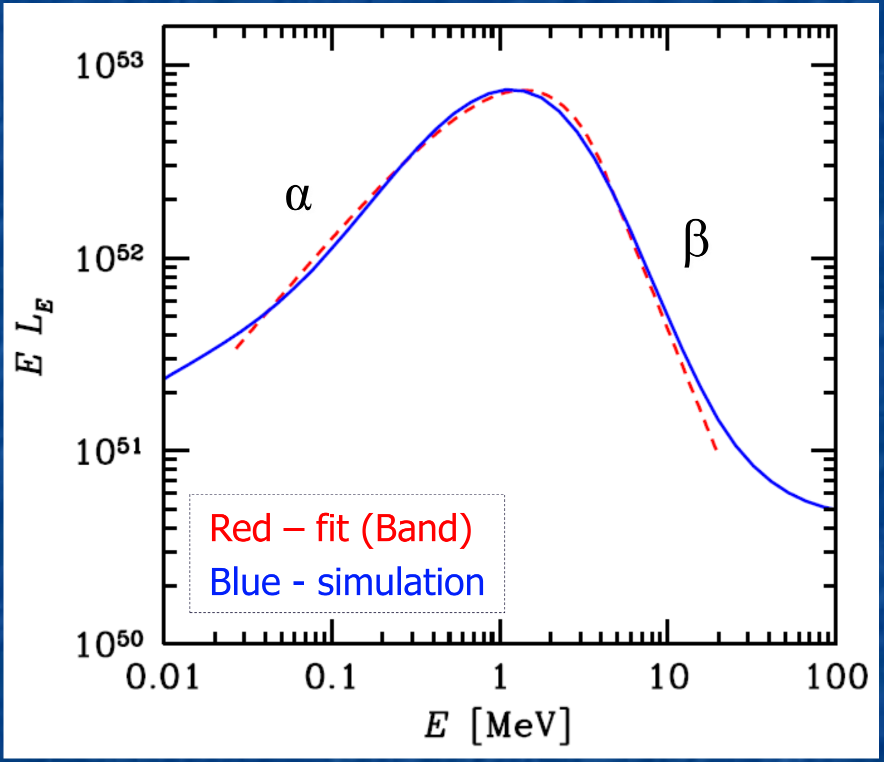
E_{pk}=720(1+z) keV; z = 1.6


$E^2 N_E$ (erg · cm^{-2} · s^{-1})
10^{-6}
10^{-7}
10^{-8}
0.01
0.1
1
10
100
Photon Energy (MeV)

‘Fits’ to data: GRB 130427A

- Simulation parameters:
  - Initial $\Gamma(r_{min})$ = 100; r_{min}=3 x 10^{10} cm
  - Final Lorentz factor Γ_f = 450
  - ε_B = 0.03
  - Heating at τ<1, passive at τ>1

Spectrum (cosmological rest frame)



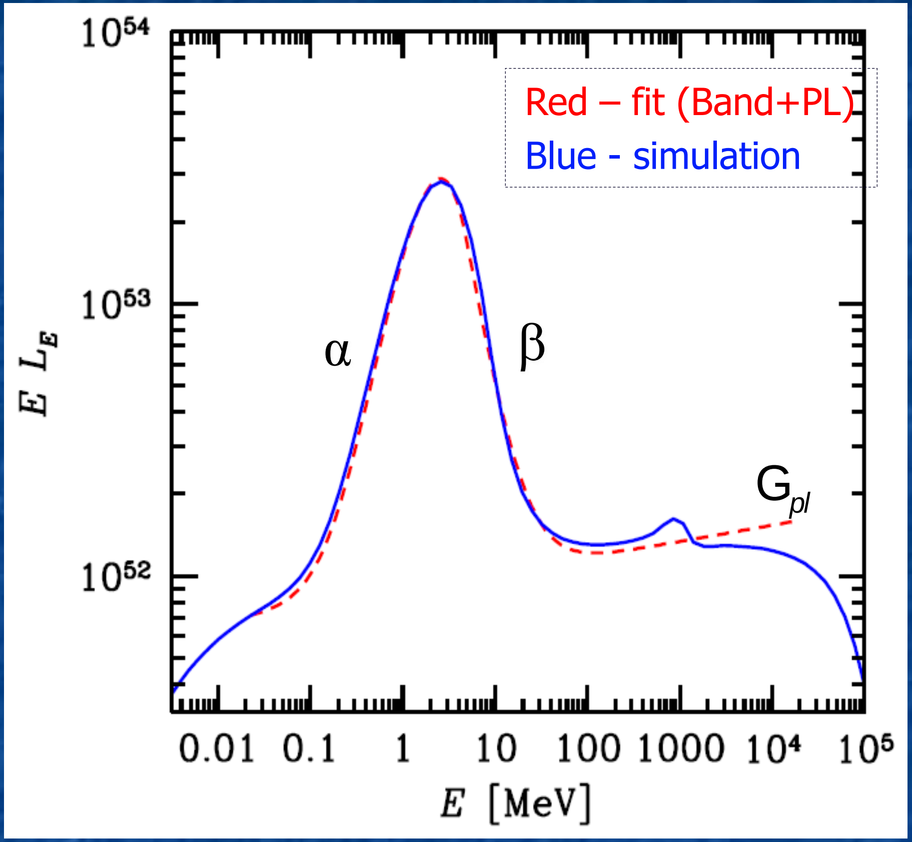
Fit: Band (Golenetskii et al 2013)

α = -0.96; β = -4.17

E_{pk}=1.028(1+z) MeV; z = 0.34

‘Fits’ to data: GRB 090902B

- Simulation parameters:
  - Initial $\Gamma(r_{min})$ = 70; r_{min}=3 x 10^{10} cm
  - Final Lorentz factor Γ_f = 1200
  - ε_B = 0.02
  - Strong non-thermal heating



Fit: Band + power-law (bin b, Abdo et al. 2009)
α = 0.07; β = -3.9; Γ_{pl} = -1.94
E_{pk}=908(1+z) keV; z = 1.8

Summary

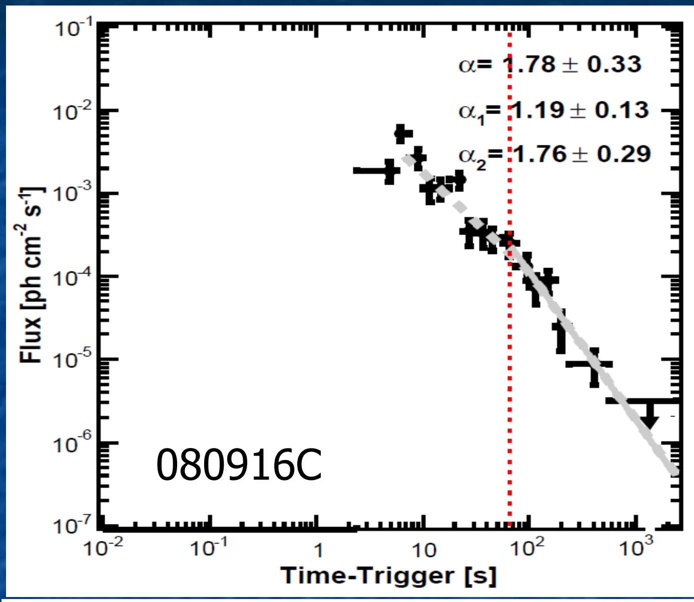
- Photospheric emission from dissipative jets
  - Naturally lead to Band-like spectra
  - Different heating histories result in a variety of spectral shapes
  - Only way to generate narrowly peaked spectra
- Typical E_{pk} -s require
  - efficient dissipation at $r \sim 10^{11}$ cm
  - bulk Lorentz factor $\Gamma \sim$tens at the same radii
  - At least moderate magnetization $\varepsilon_B > 10^{-3}$

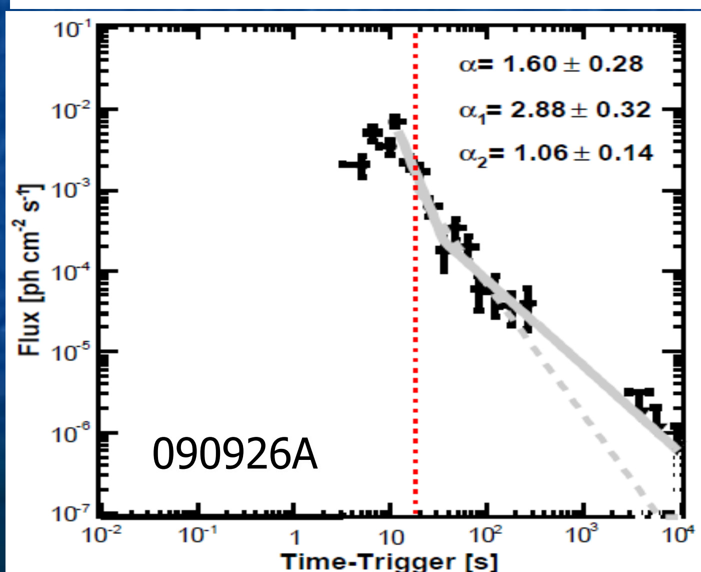
Continuous dissipation throughout the jet?

GeV (+optical) flashes

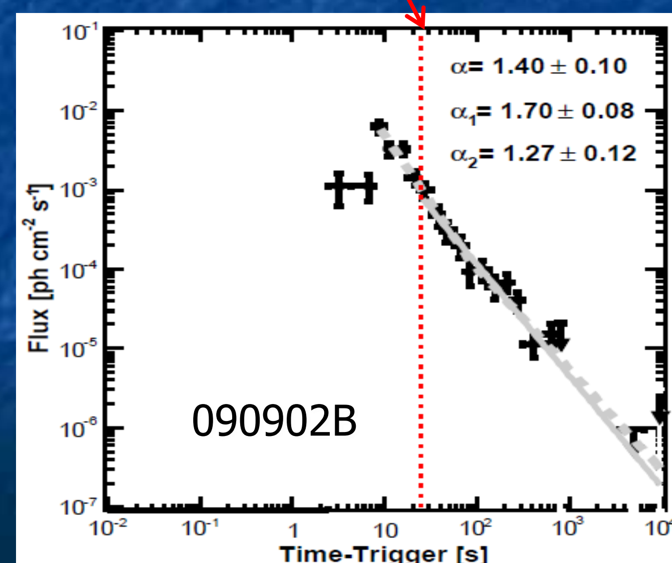
Observations: LAT lightcurves

- 'Regular' behaviour:
  - Delayed rise
  - Peaks <u>during</u> the prompt: likely not assoc. with deceleration
  - Extended monotonic decay (lasts well beyond T_{95}
- External origin (forward shock)?





T_{95} (GBM)



Fermi LAT collaboration (2013)

Emission mechanism

- Synchrotron?

Kumar & Barniol Duran (2009)
Asano et al. (2009)
Razzaque et al. (2010)
Ghisellini (2010)

  - Theoretical limit: a few 10 MeV (comoving)
    ⇒ ~ 10 GeV (observed); limit tighter at late times

    e.g. Nakar & Piran (2010)

  - Observed: 95 GeV @ 243 s, 32 GeV @ 34 ks (GRB 130427A)

- Inverse Compton

Bosnjak et al. 2009
Toma et al. 2011

  - GeV peak during prompt ⇒ intense IC cooling by prompt radiation

Number of IC photons

Bright GeV flashes: $N_{\rm GeV} \sim 10^{57}$

No. of emitted IC photons (w.o. Pair loading):

$$N_{\rm GeV} = Z_{\pm}\mathcal{M}\frac{\dot{M}R}{\mu_{\rm e}m_{\rm p}w} \sim 10^{53}\, Z_{\pm}R_{16}\dot{M}_{-5}$$

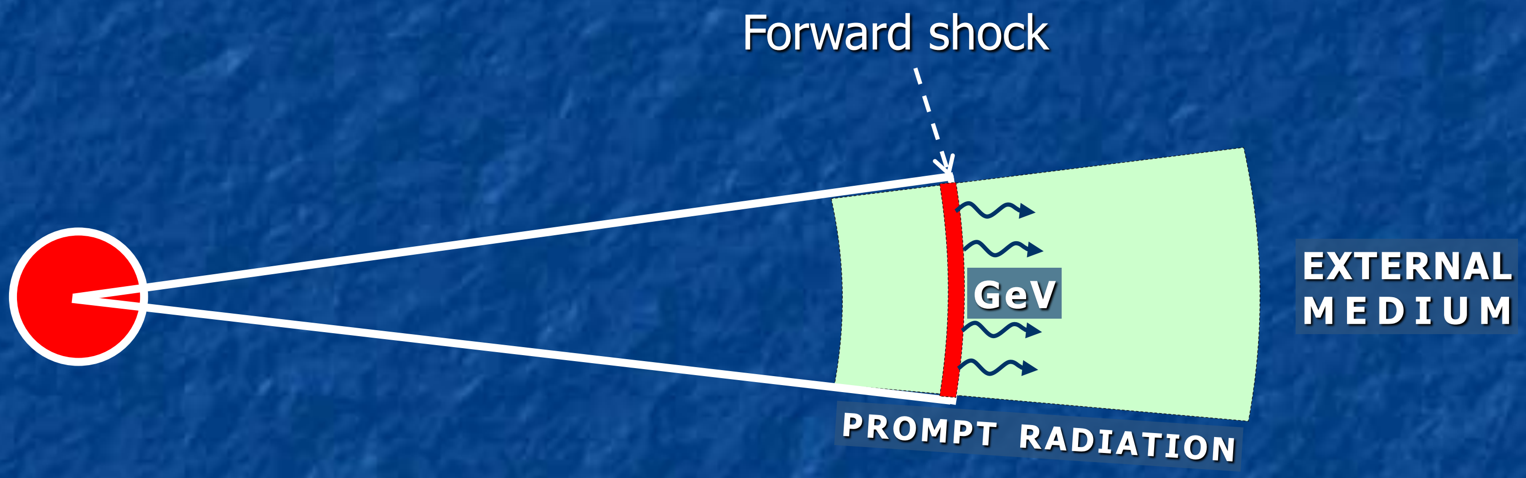
No. of emitted IC photons per single electron:

$$\mathcal{M} \sim \frac{\Gamma m_{\rm e}c^2}{(E_{\rm pk}E_{\rm IC})^{1/2}} \sim 10$$

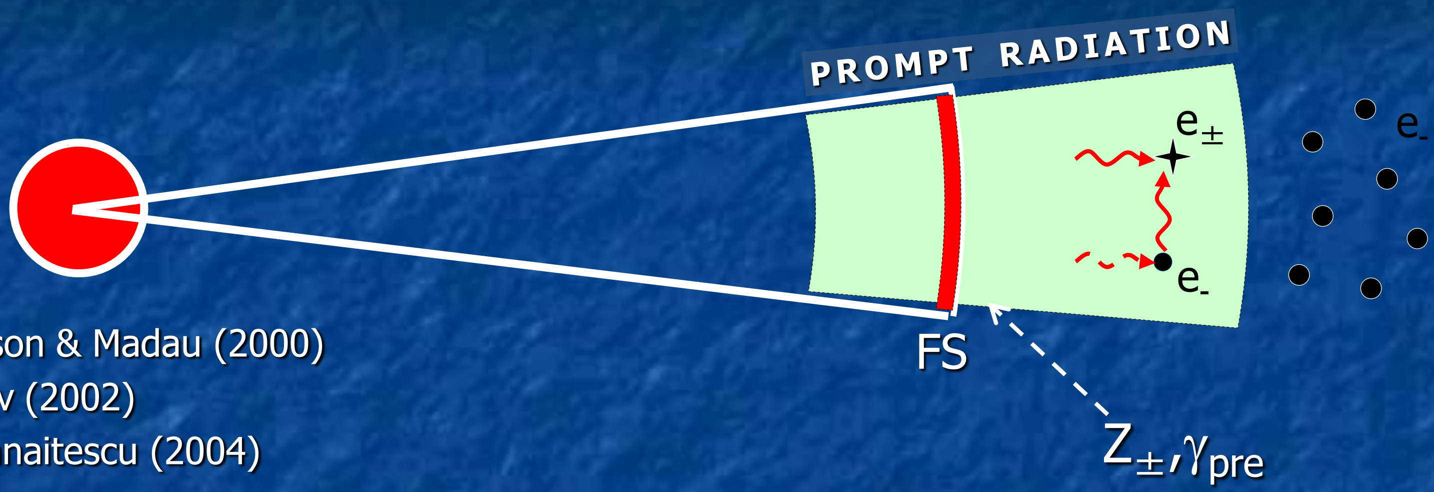
Wind velocity $w \sim 2\times 10^8\ {\rm cm\ s^{-1}}$

Required pair multiplicity: $Z_{\pm} \sim 10^4$

Proposed mechanism: inverse Compton scattering of prompt MeV radiation in the forward shock in a pair-enriched external medium



Pair-enrichment of the external medium



e.g Thompson & Madau (2000)
Beloborodov (2002)
Kumar & Panaitescu (2004)

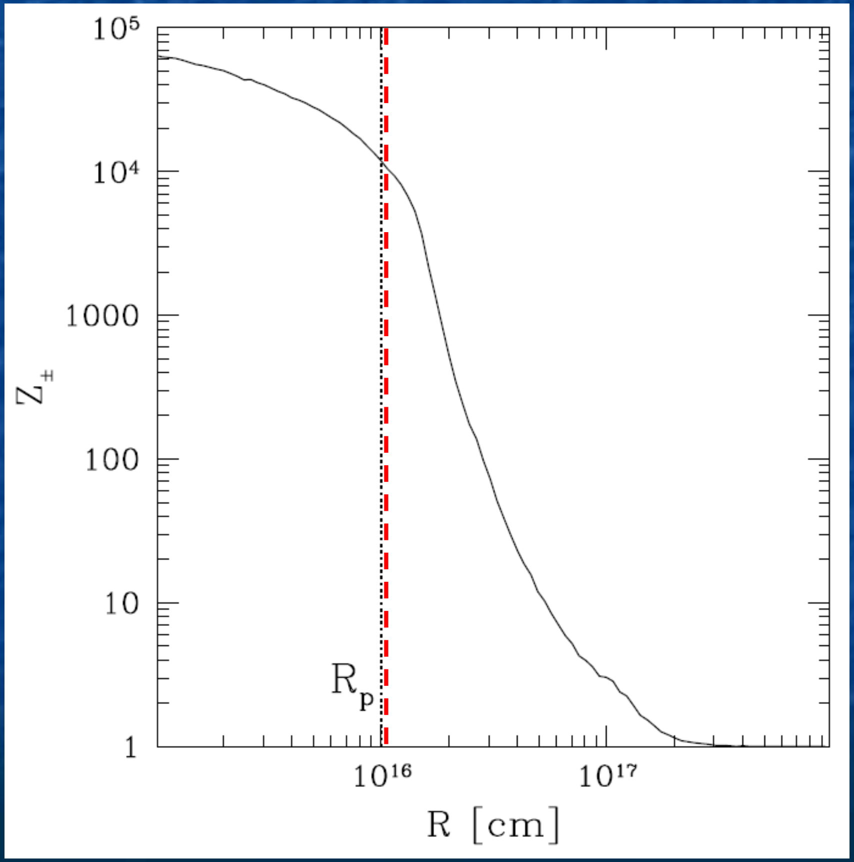
1. ISM particle scatters a prompt photon
2. Scattered photon pair-produces with another prompt photon
3. New pairs scatter further photons etc.

Prompt radiation pair-loads and pre-accelerates the ambient medium ahead of the FS

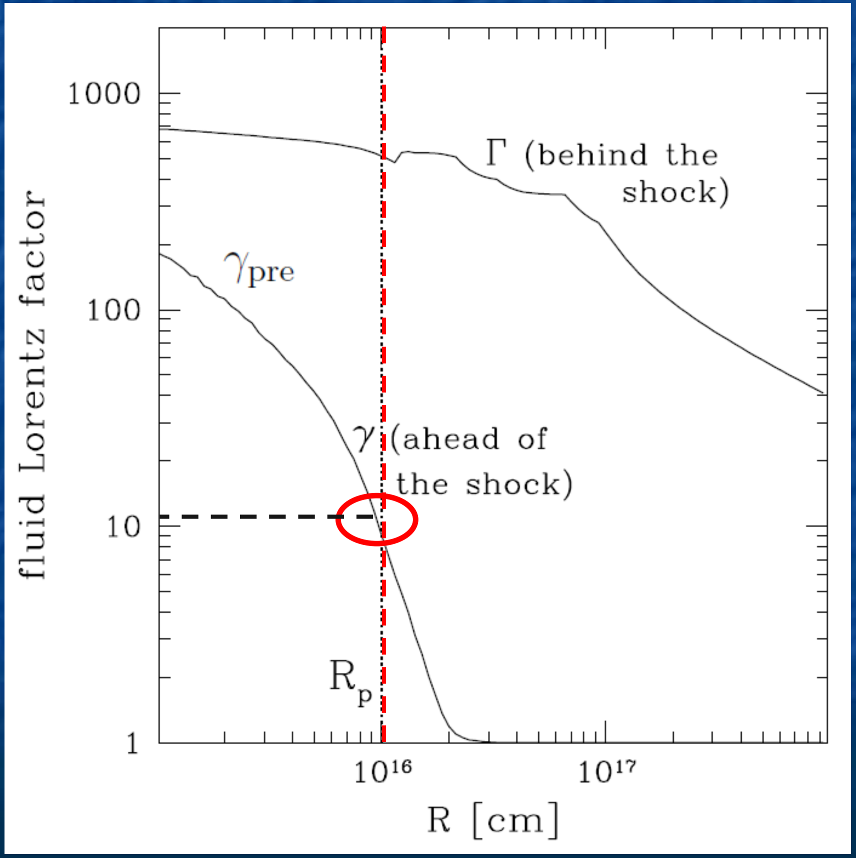
Loading and pre-acceleration controlled by the column density of prompt radiation

GRB 080916C: pair-loading and pre-acceleration

Pair loading at the forward shock

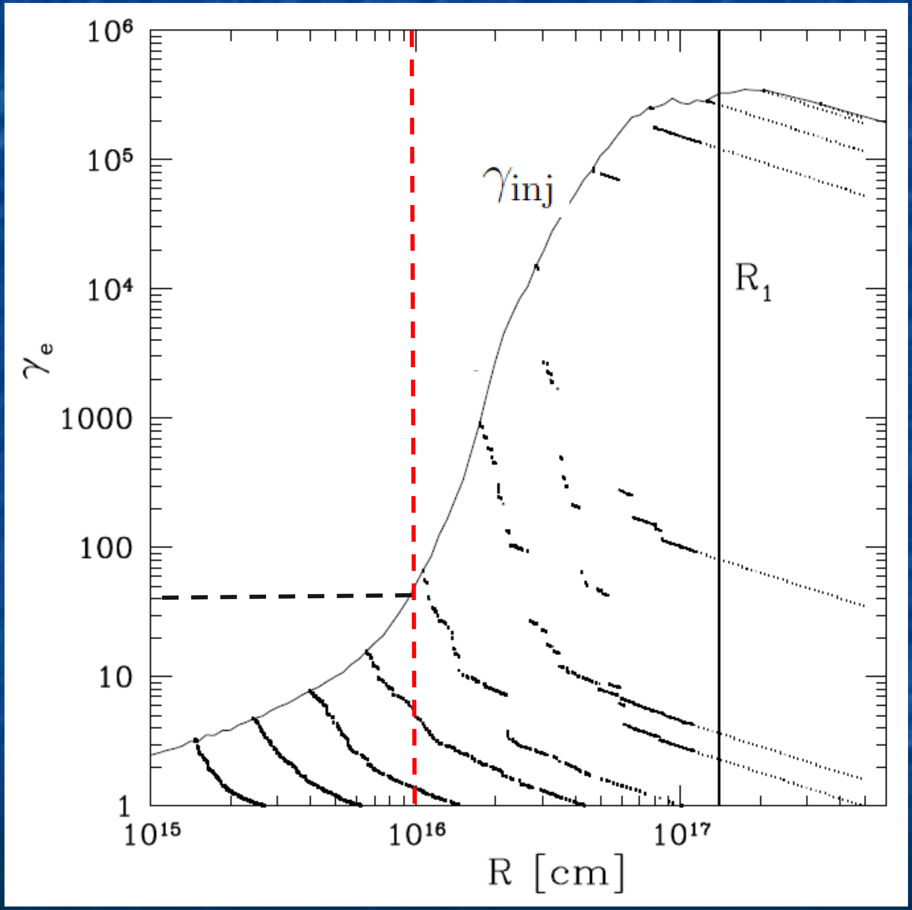


Pre-acceleration and blastwave Lorentz factors



Beloborodov, Hascoet, IV (2013)

GRB 080916C: thermal injection Lorentz factor



$$\gamma_{\rm inj} \sim \frac{\Gamma}{\gamma_{\rm pre}}$$

- Flash peaks when:

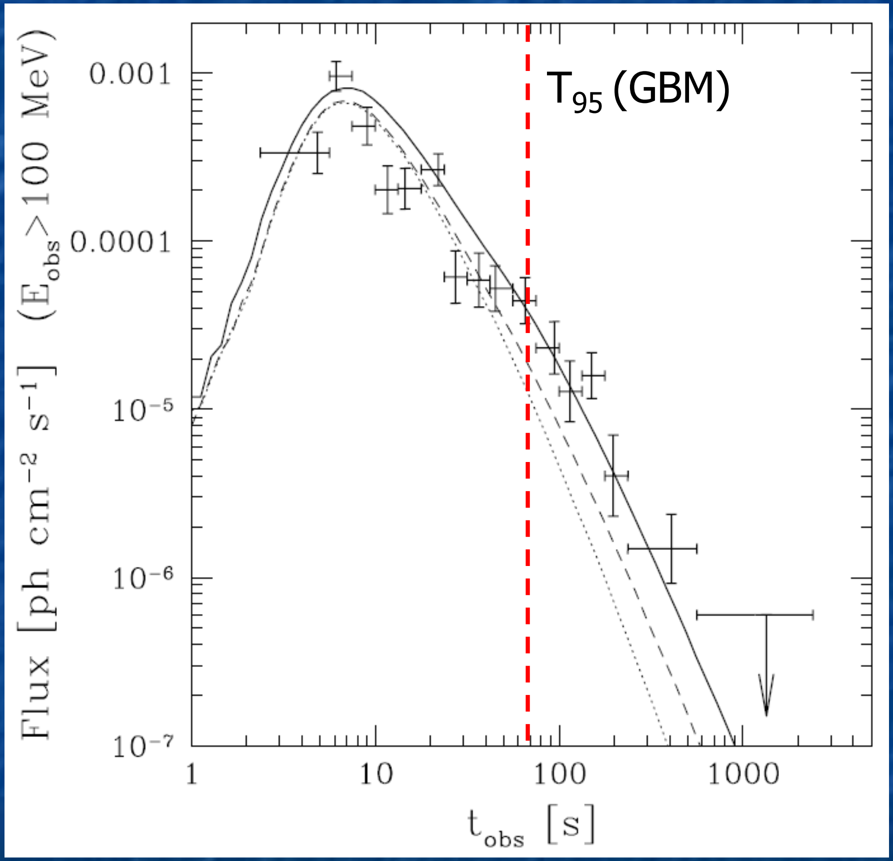
$$\gamma_{\rm inj} \approx \sqrt{\frac{E_{\rm GeV}}{E_{\rm MeV}}} \approx 30$$

$$Z_{\pm} \sim 10^4$$ - pair loading

- Early decay due to fast evolution of γ_{inj} and $Z_{\pm}$

GRB 080916C: light curve

Flux above 100 MeV



Beloborodov, Hascoet, IV (2013)

- Delayed rise
- Peak during the prompt
- Persists well after T_{95}

External medium:

Progenitor wind

$$\dot{M} = 10^{-5} M_{\rm Sun} / \rm yr$$

Wind parameter

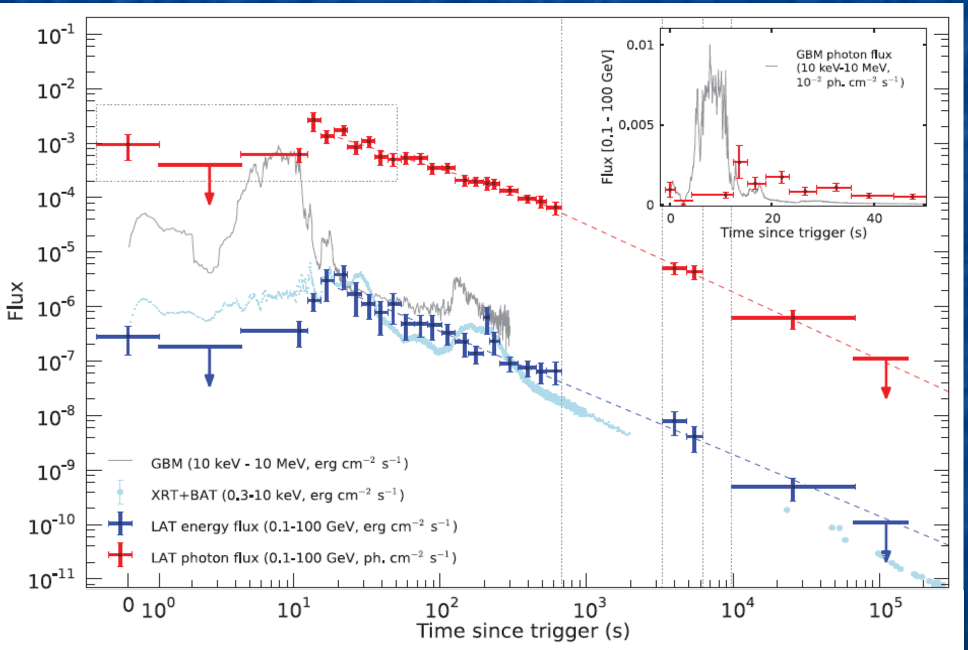
$$A \approx 2.5 \times 10^{11}\ \rm g\ cm^{-1}$$

$$r = \frac{A}{r^2}$$

Non-thermal particle acceleration NOT required

Extended GeV emission: GRB 130427A

- GeV lasts up to a day
- Seed photons for IC: transition from prompt (EIC) to afterglow (SSC)
- Fast cooling ⇒ smooth transition

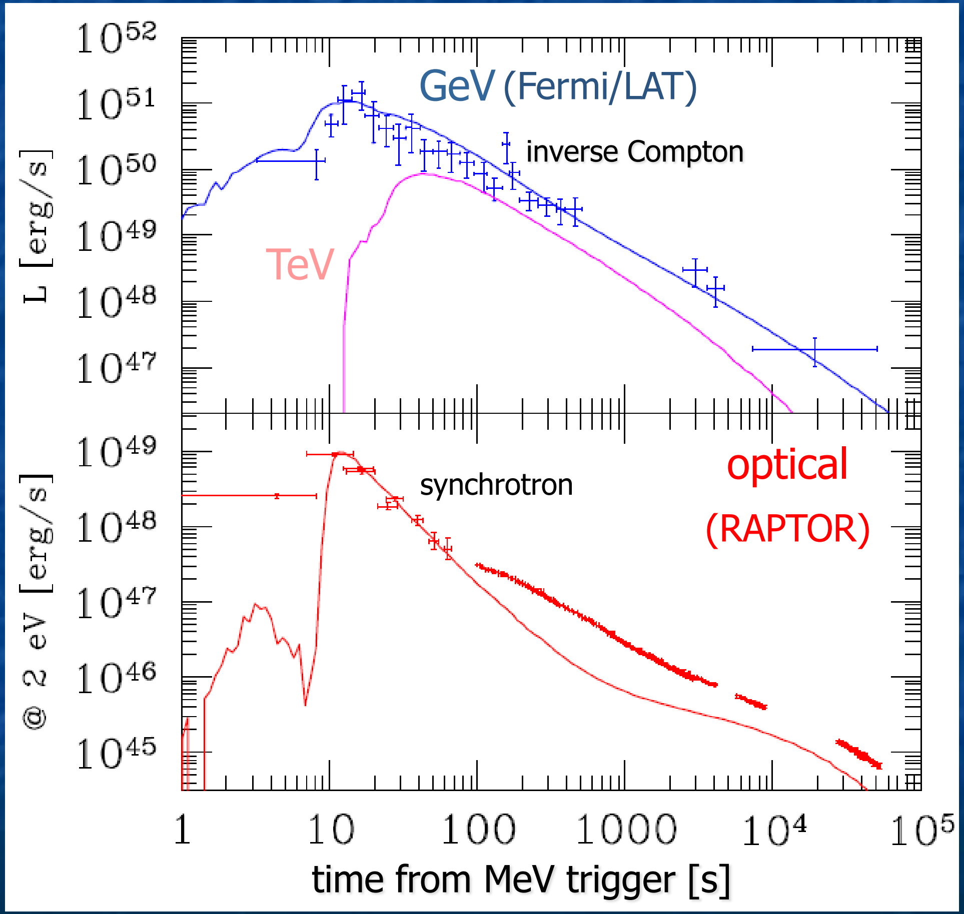


Ackermann et al. (2014)

GRB 130427A: GeV + optical flash

- GeV-emitting particles also radiate optical via synchrotron
  - Optical peaks simultaneously with GeV (Vestrand et al. 2014)
  - Yields forward shock magnetization: $\varepsilon_B = 2 \times 10^{-4}$

130427A

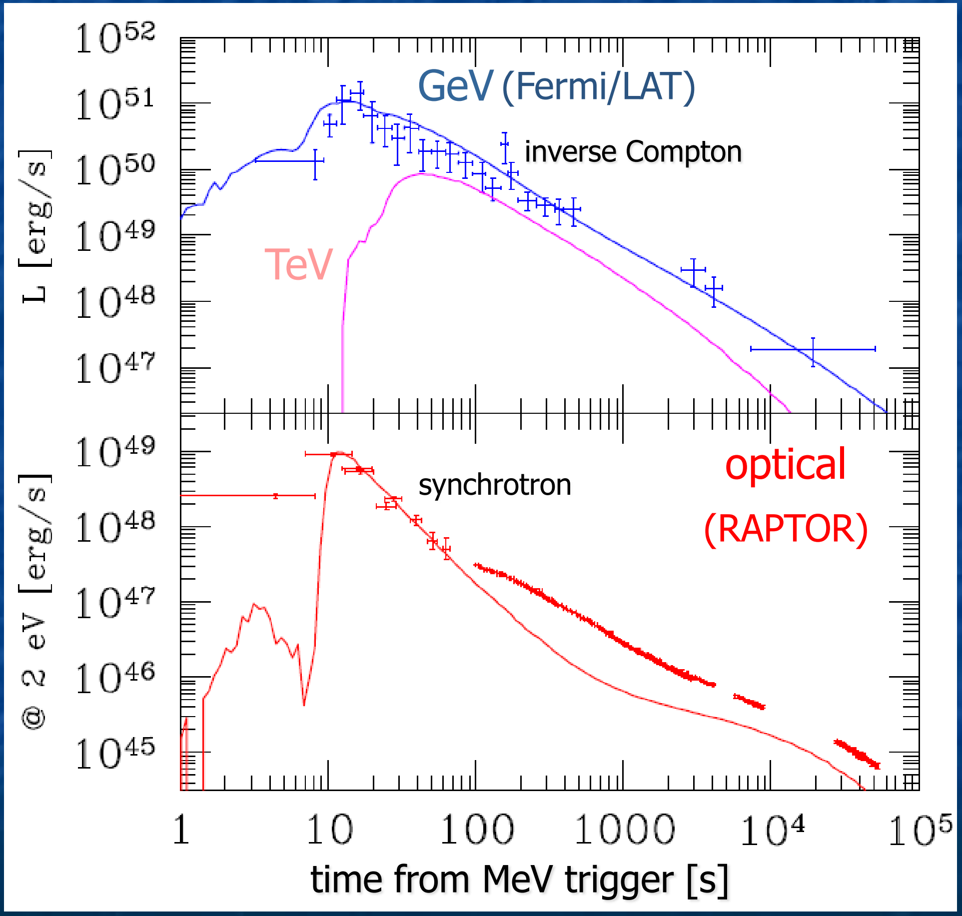


IV, Hascoet, Beloborodov (2014)

GRB 130427A: TeV flash

- TeV emission
  - Peak T~1 min
  - $E \sim 10^{51}$ erg
  - Detectable by current Cerenkov observatories
  - Veritas upper limit at 1 day consistent with model

130427A



IV, Hascoet, Beloborodov (2014)

GeV (+optical) flashes: summary

- GeV/TeV flash:
  - Forward shock in a pair-loaded Wolf-Rayet wind
  - Radiative mechanism: inverse Compton of prompt and/or afterglow radiation
  - Emitting particles quasi-thermal (even for TeV)
  - Can infer Γ_{bw} and external medium density
- Optical flash:
  - Peaks simultaneously with GeV
  - Radiative mechanism: synchrotron
  - Yields ε_B in the FS