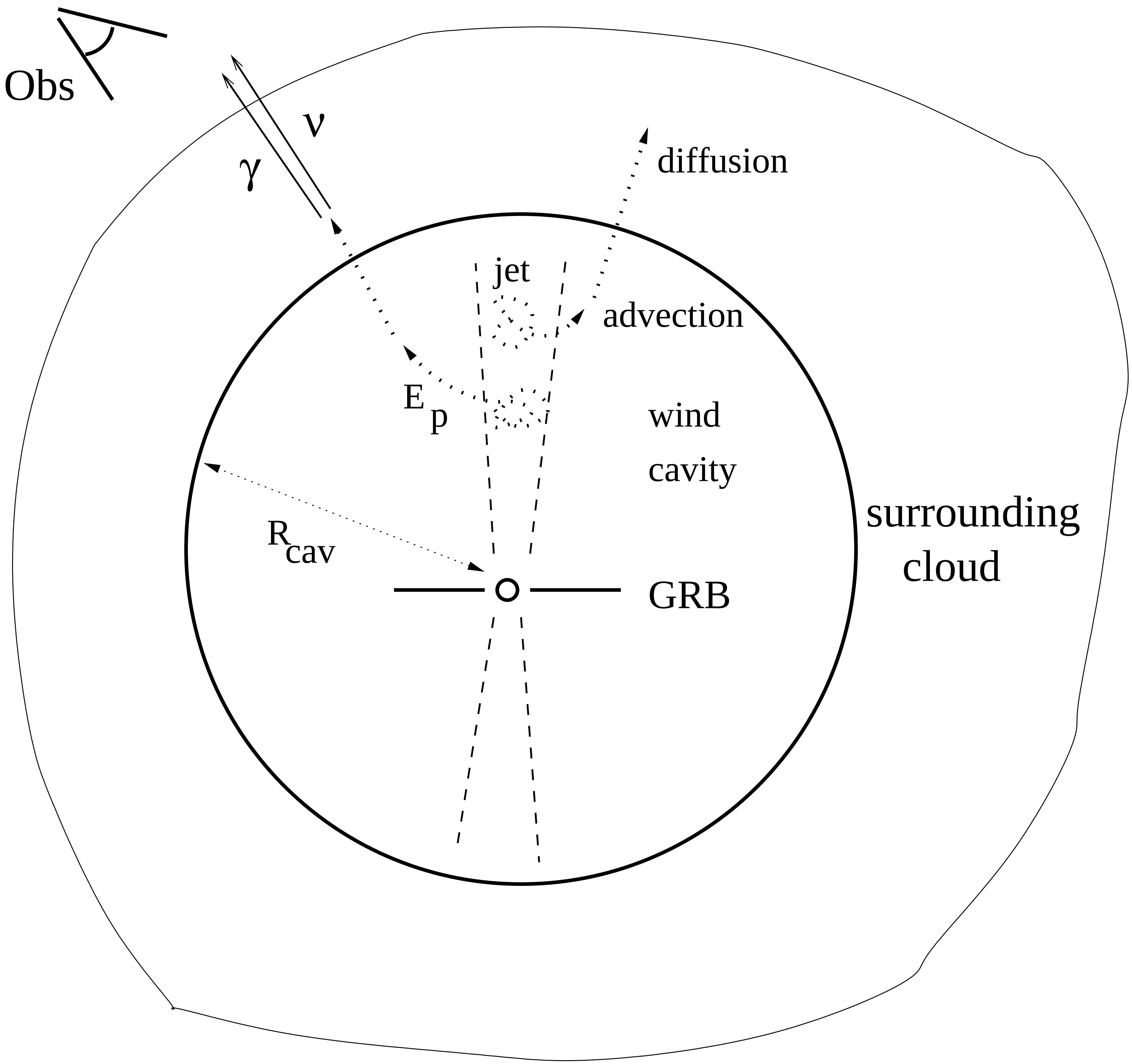
Very High Energy Neutrino afterglows from Dense Clusters Surrounding GRBs

W. Bednarek[1] & A. Śmiałkowski[2]

[1]Department of Astrophysics, [2]Department of Theoretical Physics
The University of Łódź, Łódź, Poland

GRB progenitor within massive cloud



1) Massive star in giant cloud

2) Wind cavity

3) GRB –> jet

4) Acceleration of protons in the jet

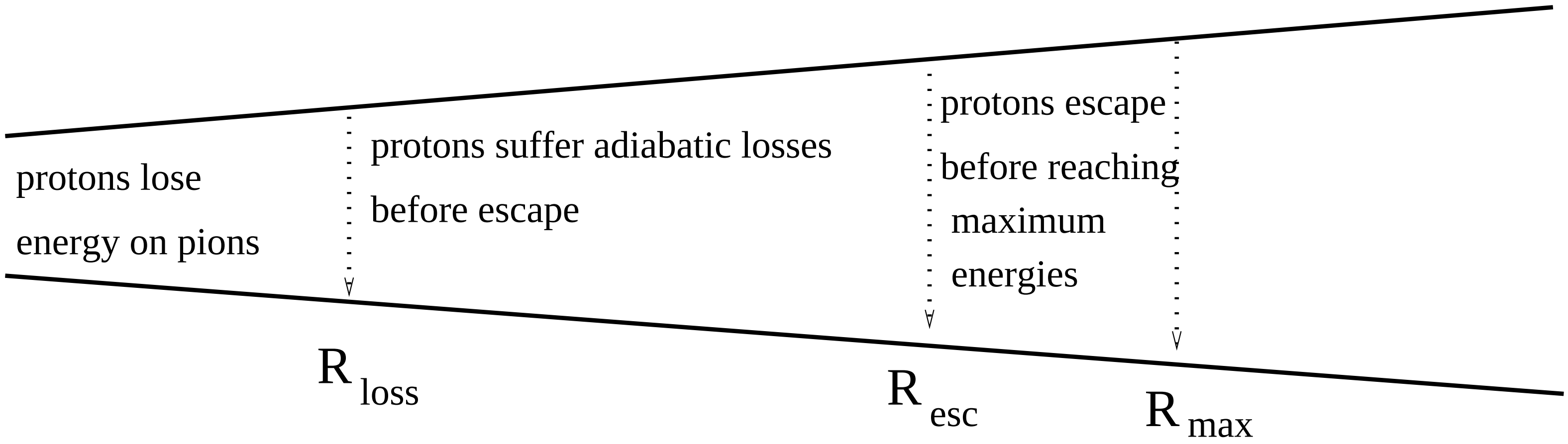
5) Protons escape from the jet

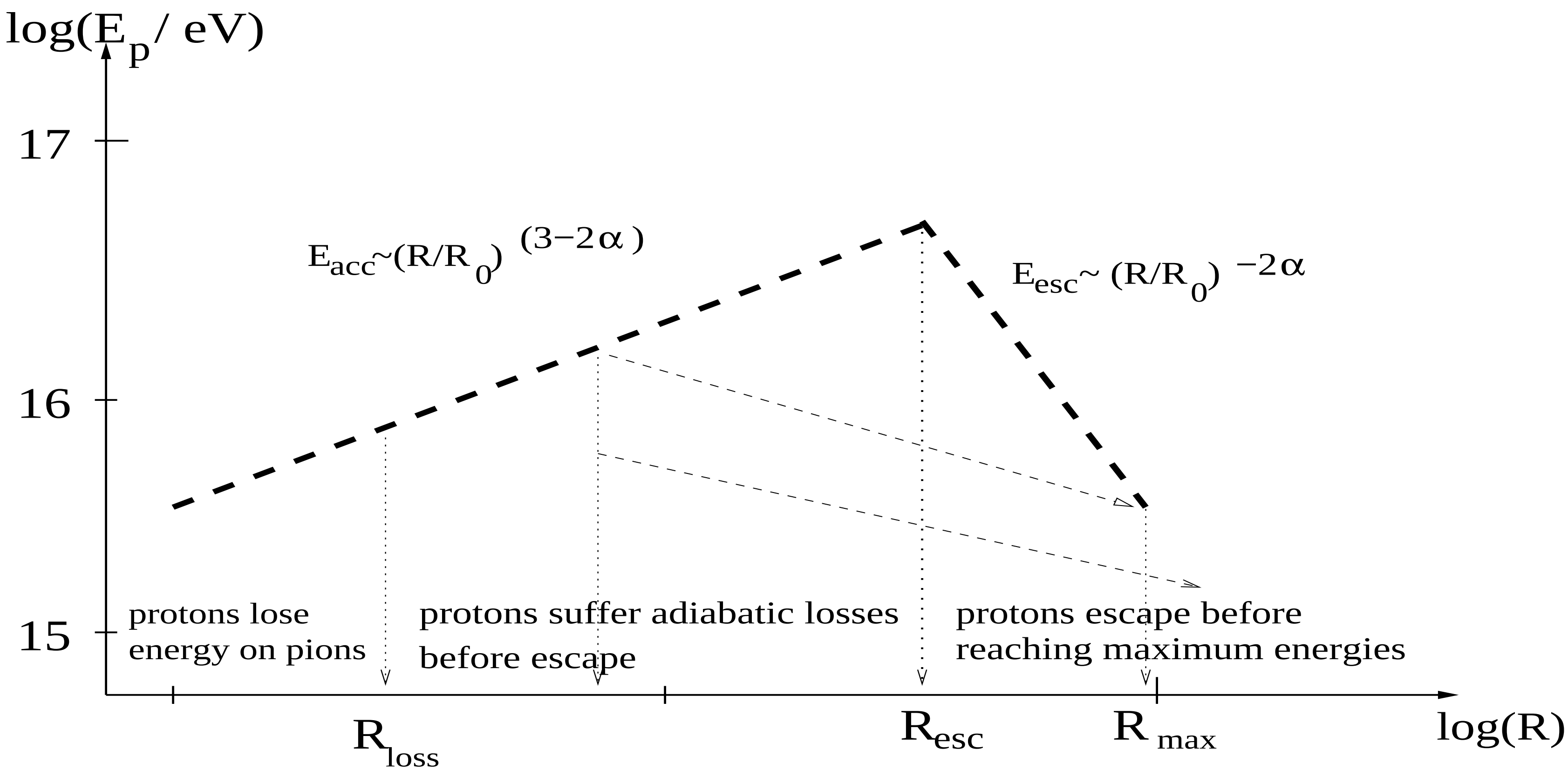
6) Propagation in the wind cavity

7) Interaction with matter in the cloud

8) p + p –> π –> ν

Acceleration of protons in the decelerating GRB jet





Propagation of protons in the jet

- The Lorentz factor of decelerating jet (e.g. Sari 1997)

$$\Gamma(R) = \Gamma_0(R/R_0)^{-3/2}. \tag{1}$$

Distance from the jet base as a function of time t,

$$R = 8c\Gamma_0^2 t_0 (t/t_0)^{1/4} = R_0 (t/t_0)^{1/4}, \tag{2}$$

where $R_0 = 8c\Gamma_0^2 t_0 \approx 6 \times 10^{16} t_0 \Gamma_{2.7}^2$ cm.

- Energy gains of protons versus their adiabatic energy losses,

$$E_{\rm ad}(R) \approx 3.6 \times 10^3 (\Gamma_{2.7} t_0 B/\eta_1)(R/R_0)^{5/2} \quad \text{TeV}. \tag{3}$$

Magnetic field in the jet (e.g. see Razzaque et al. 2004),

$$B = \left(\frac{2\varepsilon_{\rm B} L_{\gamma,iso}}{R^2 c \Gamma^2 \varepsilon_{\rm e}}\right)^{1/2} \approx \frac{27\beta L_{52}^{1/2} T^{\alpha/2}}{\Gamma_{2.7}^3 t_0^{(\alpha/2+1)} (R/R_0)^{(2\alpha-0.5)}} \quad {\rm Gs}, \tag{4}$$

- Energy losses in the inner jet ($p\varepsilon \to \pi\ldots$). $\rm R_{loss}$ determined from,

$$\tau_{\rm p\varepsilon} = \sigma_{\rm p\varepsilon} n_\varepsilon R/\Gamma = 1. \tag{5}$$

- Protons diffuse out of the jet when they reach energy,

(comparison of diffusion scale scale through the perpendicular dimension of the jet)

$$E_{\rm esc}(R) \approx 1.5 \times 10^8 \alpha_{-1}^2 \Gamma_{2.7}^3 t_0 B (R/R_0)^{-1/2} \quad {\rm TeV}. \tag{6}$$

This happens above the distance from the base of the jet,

(protons escape before reaching maximum energies allowed by adiabatic losses)

$$R_{\rm esc} = 34.7 R_0 (\Gamma_{2.7} \eta_1 \alpha_{-1})^{1/3}. \quad (7)$$

- Protons accelerated close to the base suffer adiabatic losses and escape with energy,

$$E_{\rm inj}(R_{\rm inj}) \frac{R_{\rm inj}}{R_{\rm fin}} = E_{\rm fin}(R_{\rm fin}), \quad (8)$$

- Protons accelerated with the power law spectrum up to $E_{\rm ad}$ or $E_{\rm esc}$.

  (spectral index -2)

Spectra of protons from the GRB jet

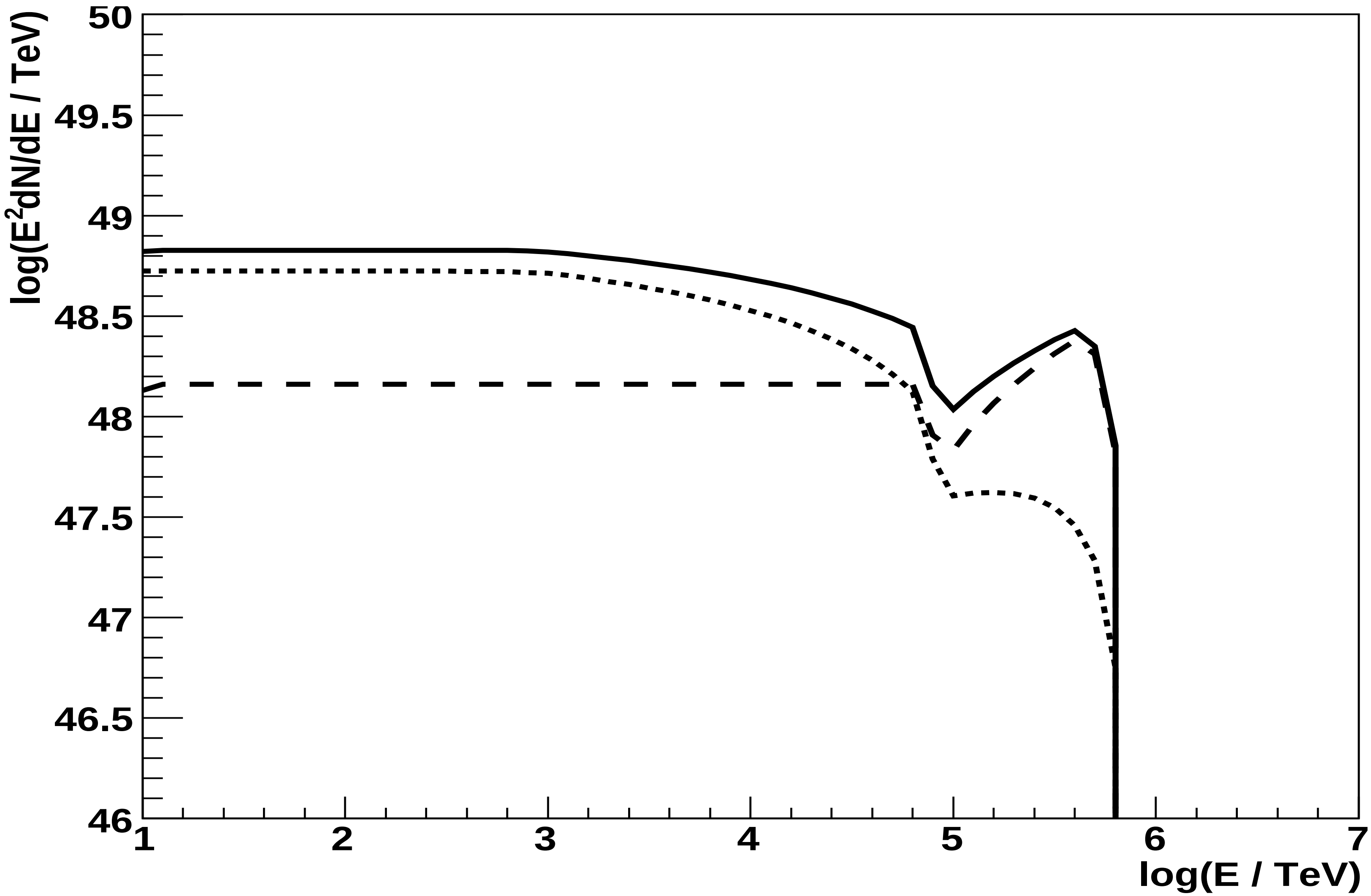


Figure 1: SED of protons injected from jet below R_{esc} (dotted curve), above R_{esc} (dashed), and the total spectrum (solid) calculated for the parameters of the GRB 130427A.

Spectra of protons from the GRB jet (cont.)

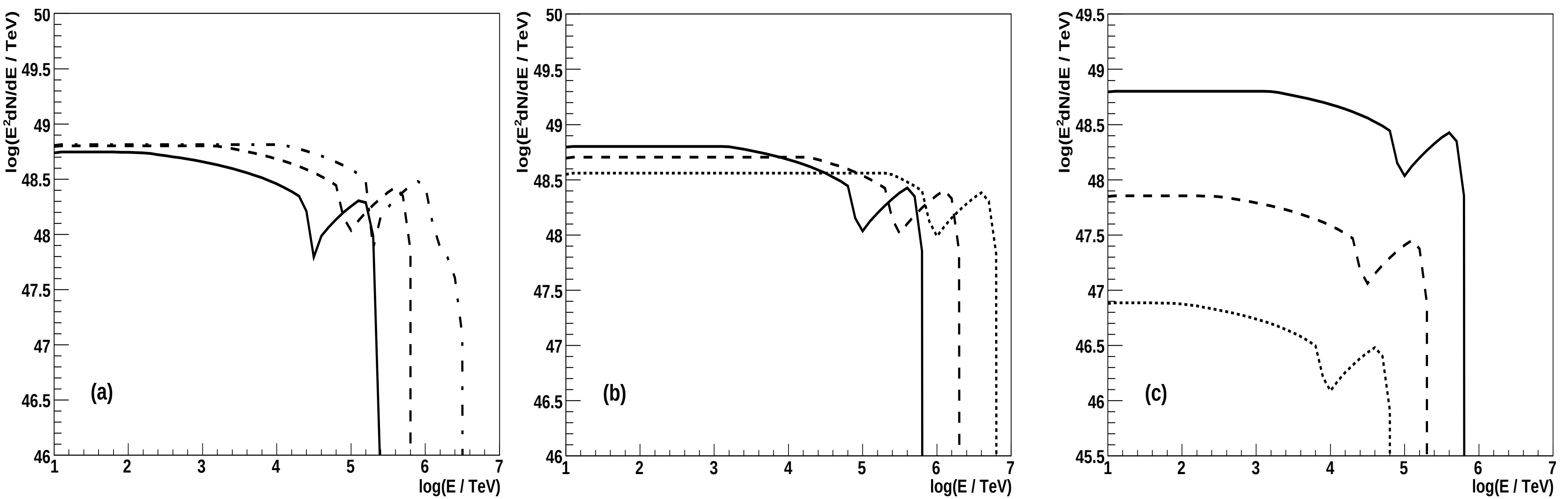


Figure 2: SED of relativistic protons escaping from the GRB jet into a progenitor wind region. (a) Dependence on the initial jet Lorentz factor: $\gamma_0 = 1000$ (solid), 500 (dashed), and 300 (dot-dashed). The other parameters are $L_\gamma = 10^{52}$ erg s^{-1}, magnetization of the jet $\varepsilon_{\rm B} = 10^{-3}$. (b) dependence on the jet magnetization parameter: $\varepsilon_{\rm B} = 10^{-3}$ (solid), 0.01 (dashed), and 0.1 (dotted) for $\Gamma_0 = 500$ and $L_\gamma = 10^{52}$ erg s^{-1}; (c) dependence on the jet γ-ray power $L_\gamma = 10^{52}$ erg/s (solid), 10^{51} erg/s (dashed), 10^{50} erg/s (dotted) for $\Gamma_0 = 500$ and $\varepsilon_{\rm B} = 10^{-3}$.

Propagation of protons in the progenitor wind

- Density of the wind

$$n_{\rm w} \approx 3.7 \times 10^{-3} \dot{M}_{-6}/(R_{\rm pc}^2 v_3) \quad {\rm cm}^{-3}, \tag{9}$$

where the wind velocity $v_{\rm w} = 1000 v_3$ km s^{-1}, and the mass loss rate $\dot{M}_{\rm WR} = 10^{-6} M_{-6}$ M$_\odot$ yr^{-1}, and $R = 1 R_{\rm pc}$ pc is the distance from the star in parsecs.

- Magnetic field in the wind,

$$B(R) = 3 \times 10^{-5} B_3/R_{\rm pc} \quad {\rm Gs}. \tag{10}$$

- Condition for capturing of protons in the wind,

$$R_{\rm inj} = R_{\rm Lar} = E_{\rm p}/eB \approx 3 \times 10^{-5} E_{\rm TeV} R_{\rm pc}/B_3 \quad {\rm pc}. \tag{11}$$

- Protons with energies lower than $E_{\rm fin}$ are captured in the wind,

$$E_{\rm fin} \approx 3 \times 10^4 B_3 \quad {\rm TeV}. \tag{12}$$

- Energies of protons escaping to the cloud,

(after adiabatic losses in the wind)

$$E_{\rm cav} = E_{\rm fin} R_{\rm fin} / R_{\rm cav}. \tag{13}$$

- The wind cavity radius,

$$R_{\rm cav} = 18 (M_{-6} V_3 / n_2)^{1/5} t_3^{3/5} \quad {\rm pc}, \tag{14}$$

where $t = 3t_3$ Myr is the age of the star up to the explosion, and $n_{\rm cl} = 100 n_2$ cm^{-3} is the density of the giant cloud.

Propagation and interaction of protons in the cloud

- Diffusion time of protons in the cloud,

$$T_{\rm dif} = R_{\rm cl}^2/2D_{\rm dif} \approx 1.35 \times 10^{16} R_{30}^2 B_{-4}/E_{\rm TeV} \quad {\rm s}, \tag{15}$$

where the Bohm diffusion coefficient is,

$$D_{\rm dif} = R_{\rm L}c/3 \approx 3 \times 10^{23} E_{\rm TeV}/B_{-4} \quad cm^2\ s^{-1} \tag{16}$$

- The optical depth for protons (p+p$\longrightarrow \pi$) is,

$$\tau_{\rm int} \approx T_{\rm dif} c n_{\rm cl} \sigma_{\rm pp} \approx 1.2 \times 10^3 R_{30}^2 B_{-4} n_2/E_{\rm TeV}. \tag{17}$$

(transition, for $\tau_{\rm int} = 1$, occurs for protons close to $\sim$PeV energies)

- Protons with low energies interact frequently but only protons with high energies interact partialy.

Spectra of neutrinos from the cloud

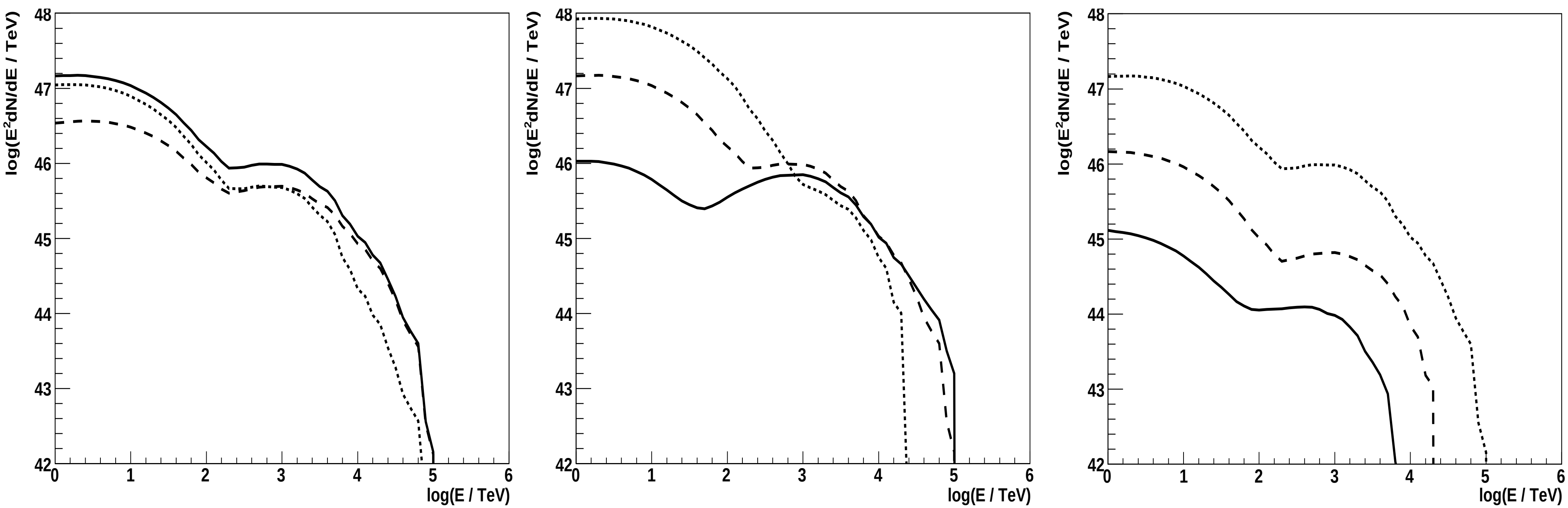


Figure 3: Spectral Energy Distribution (SED) of neutrinos (all flavour) produced by protons accelerated in the GRB jet and escaping from the surrounding projenitor wind region. The spectra of protons accelerated in different parts of the jet, i.e. below and above $R_{\rm esc}$ are shown in (a) by the dotted and dashed curves, respectively. The total spectrum is shown by the solid curve. The spectra for different Lorentz factors of the blob, i.e. $\Gamma_{\rm j} = 1000$ (dotted curve), 500 (dashed), and 300 (solid), are shown in (b). The spectra for different γ-ray luminosity of GRB, $L_\gamma = 10^{52}$ erg s^{-1} (dotted), 10^{51} erg s^{-1} (dashed), and 10^{50} erg s^{-1} are shown in (c). Unless specified, the following parameters of the model have been used: $\Gamma_{\rm j} = 500$, $L_0 = 10^{52}$ erg s^{-1}, $\varepsilon_B = 10^{-3}$, $\varepsilon_p = 0.1$, $\alpha = 0.1$, $R_{\rm cl} = 18$ pc, ...

Neutrino emission delayed after GRB flash

- Protons propagate in the wind before interacting within the cloud.
- Their advection time scale in the wind is,

$$\tau_{\rm adv}^{wind} \approx R_{\rm cav}/v_{\rm w} \approx 10^3 R_{\rm pc}/v_3 \quad {\rm yrs}, \tag{18}$$

and the ballistic time scale (for the most energetic protons) is,

$$\tau_{\rm bal} = R_{\rm cav}/c \approx 3.3 R_{\rm pc} \quad {\rm yrs}. \tag{19}$$

- The diffusion time scale of protons in the cloud

$$T_{\rm dif} = R_{\rm cl}^2/2D_{\rm dif} \approx 4.5 \times 10^8 R_{30}^2 B_{-4}/E_{\rm TeV} \quad {\rm yrs}. \tag{20}$$

Neutrino emission from GRBs persists for very long time on a low level

$\Downarrow$

GRBs remnants: weak, persistent sources of ∼TeV-PeV neutrinos

Conclusions

- **Relativistic protons escape from the outer jets of GRBs**
- **They suffer energy losses in the jet and the projenitor cloud**
- **protons interact in the giant cloud producing neutrinos**

$\Downarrow$

- **Neutrinos produced isotropically by protons from GRBs**
- **Neutrinos delayed $\rightarrow$ cannot be related to historical GRB**
- **Two component spectra (below and above $\sim$PeV)**
- **Higher energy component insensitive on the Lorentz factor of the jet ($\Gamma_{\rm j}$)**
- **Higher energy component shifts to lower energies for weaker GRBs**
- $\sim$**8**$\times 10^{47}$ **ergs in ν injected from GRB 130427A**

Comments

- about 0.002 ergs in neutrinos detected by IceCube times the number of GRBs/yr
- number fo GRBs/yr/collimation factor (all GRBs should contribute ν to observer)/energy of ν
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