High Energy Neutrino Emission from GRBs

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1.Introduction

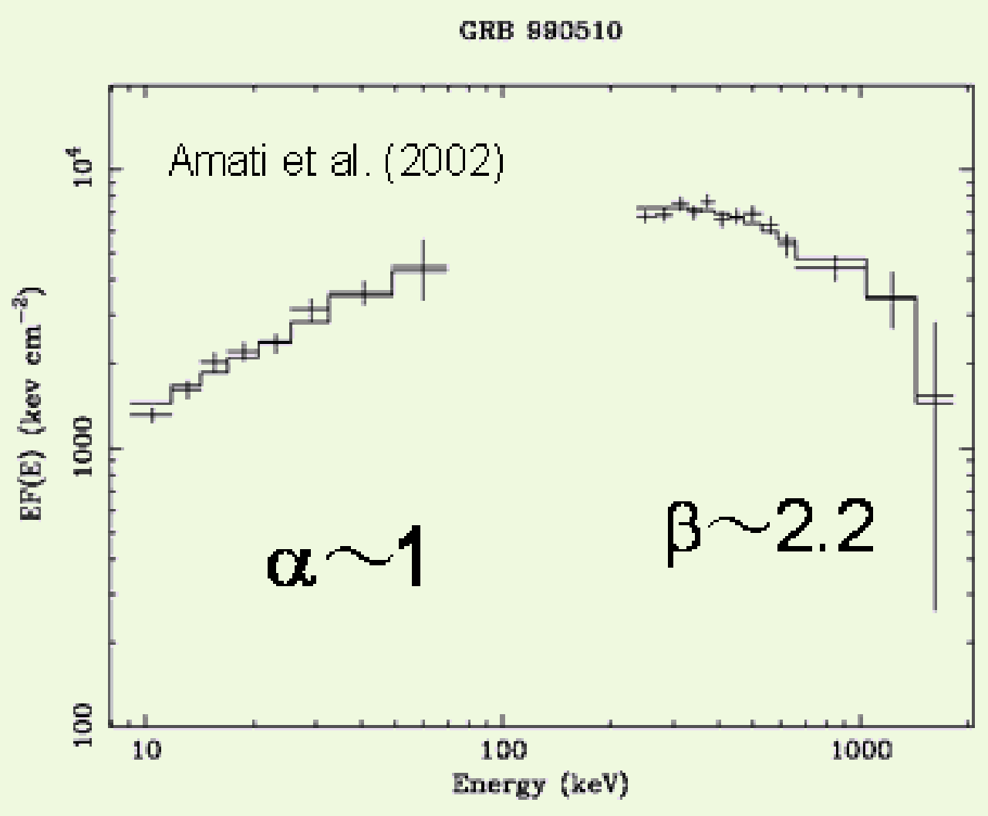
Gamma-ray bursts (GRBs) are the most powerful phenomena in the universe. In the standard model, we can expect the strong magnetic field in the fireball, in which protons can be accelerated as well as electrons. Protons accelerated to the very high energy can react with surrounding photons and produce mesons such as pions and kaons. These Mesons decay and can generate high energy (TeV - PeV) neutrinos. If there are many accelerated protons, emitted neutrinos may be detected by large neutrino detectors such as IceCube. If they can detect, neutrino observations will give us information independently of gamma-ray observation. We calculate neutrino spectra quantitatively taking into account inelasticity and multiplicity by executing the simulation kit GEANT4. We also study various dependences on various parameters. We also calculate a diffuse neutrino background assuming that the GRB rate traces the star formation rate.

2.Gamma-Ray Burst

rapid variability $\Delta t > 10$ ms gamma-ray observation ➡ $\Gamma > 100$

spectra ➡ broken power law

$$\frac{dn}{d\varepsilon} \propto \begin{cases} \varepsilon^{-\alpha} & (\varepsilon < \varepsilon_b) \\ \varepsilon^{-\beta} & (\varepsilon > \varepsilon_b) \end{cases} \qquad \varepsilon_b \sim 250 \text{ keV}$$



An example of spectra

isotropic equivalent energy $E_\gamma^{iso} \sim (10^{52} - 10^{54})$ ergs ➡ geometrically corrected energy $E_\gamma = \frac{\theta^2}{2} E_\gamma^{iso} \sim 10^{51}$ ergs

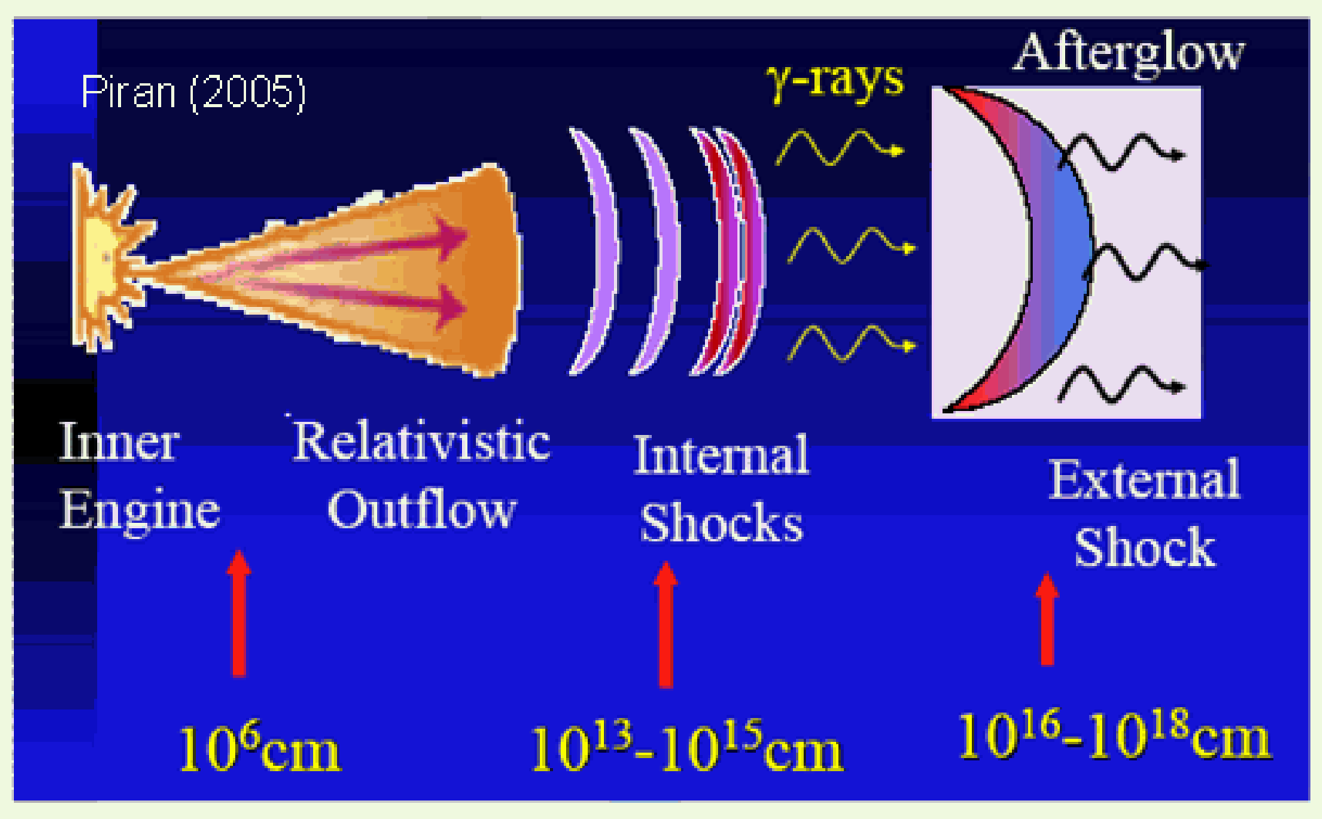
•Internal Shock Model

Many subshells collide with each other. Their kinetic energy is converted to radiation in the shock.

distance $r \sim (10^{13} - 10^{15})$ cm

$U_B = \xi_B U_\gamma$ ➡ $B \sim (10^4 - 10^7)$ G

number of shell $N_{sh} \sim 10 - 100$

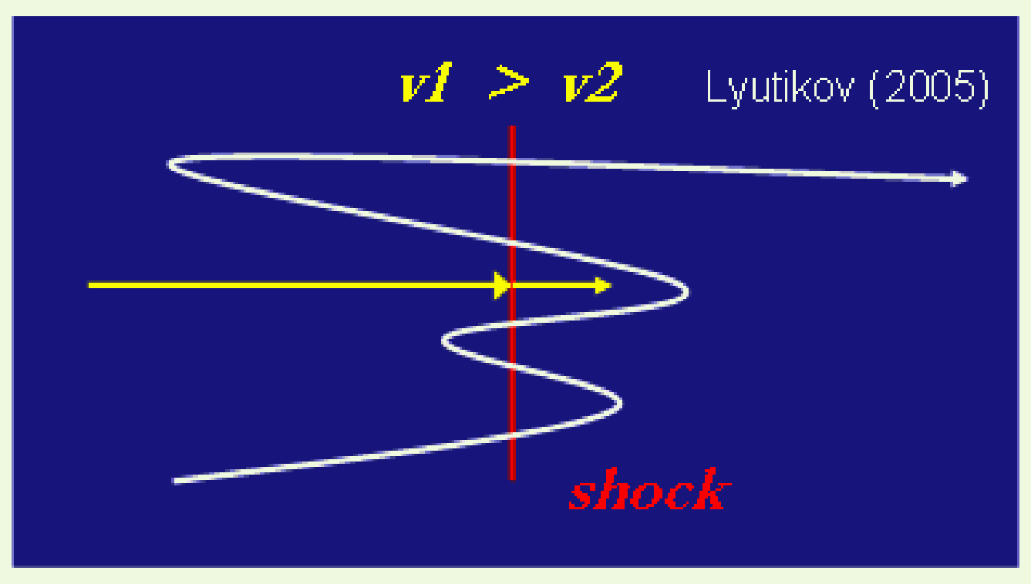


The standard model

3.Acceleration and Cooling of Proton

•Fermi Acceleration Mechanism

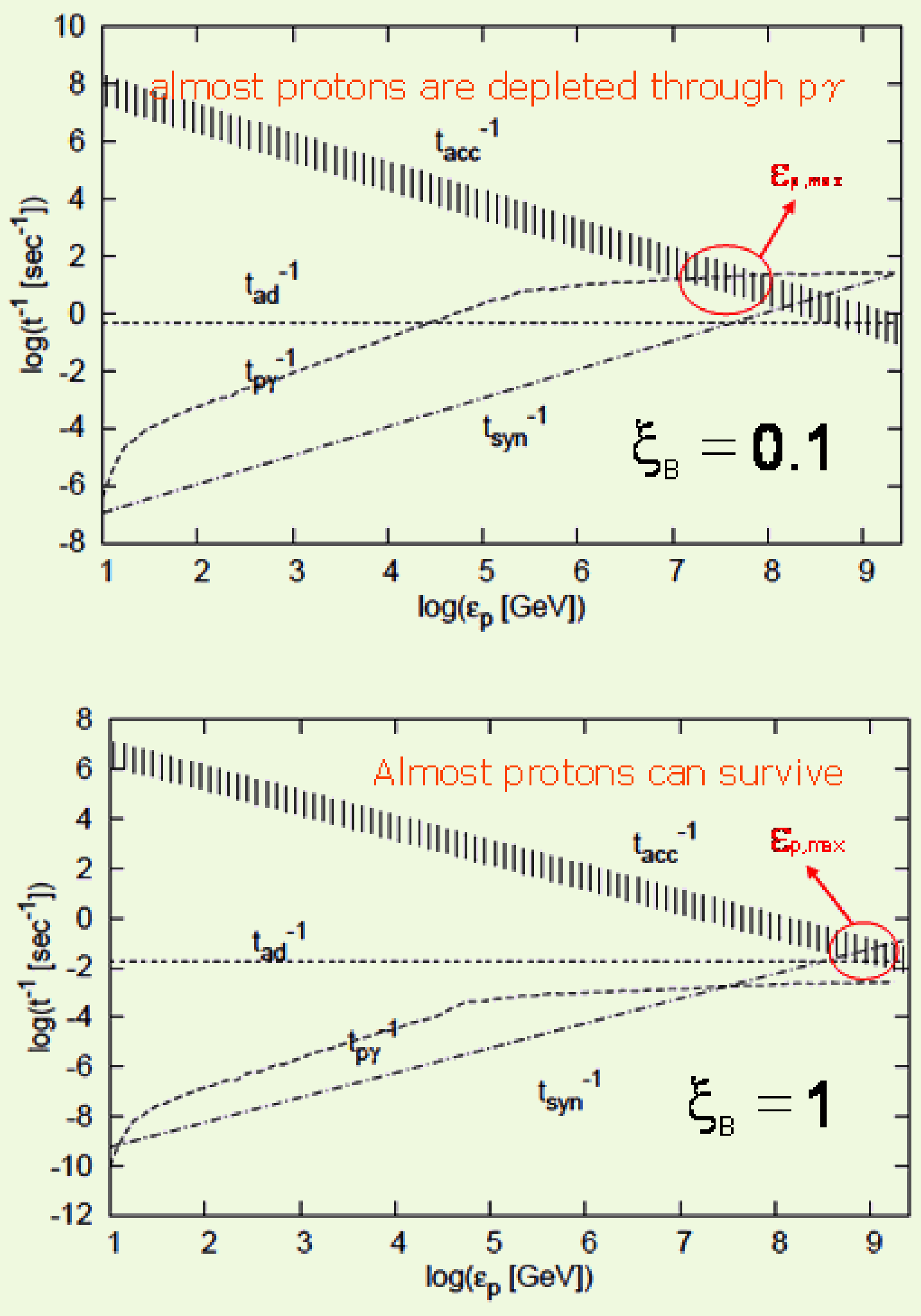
scatterings by plasma waves → spectral index ~2



Shock acceleration

mildly relativistic shock, optimistic case

$$t_{acc} = \eta \frac{\varepsilon_p}{eBc} \qquad (\eta \sim 1 - 10)$$



Acceleration time and cooling time

Criterion of Acceleration

$t_{acc} < t_{cool}$

(+Hillas condition)

$\varepsilon_{p,max} \sim 10^{18} - 10^{20}$ eV

Cooling Process
- •photomeson production
- •synchrotron radiation
- •adiabatic cooling

baryon-loading factor (unknown)

$U_p = \xi_p U_\gamma$ ➡ assuming a baryon-rich fireball $\xi_p \sim 10 - 100$

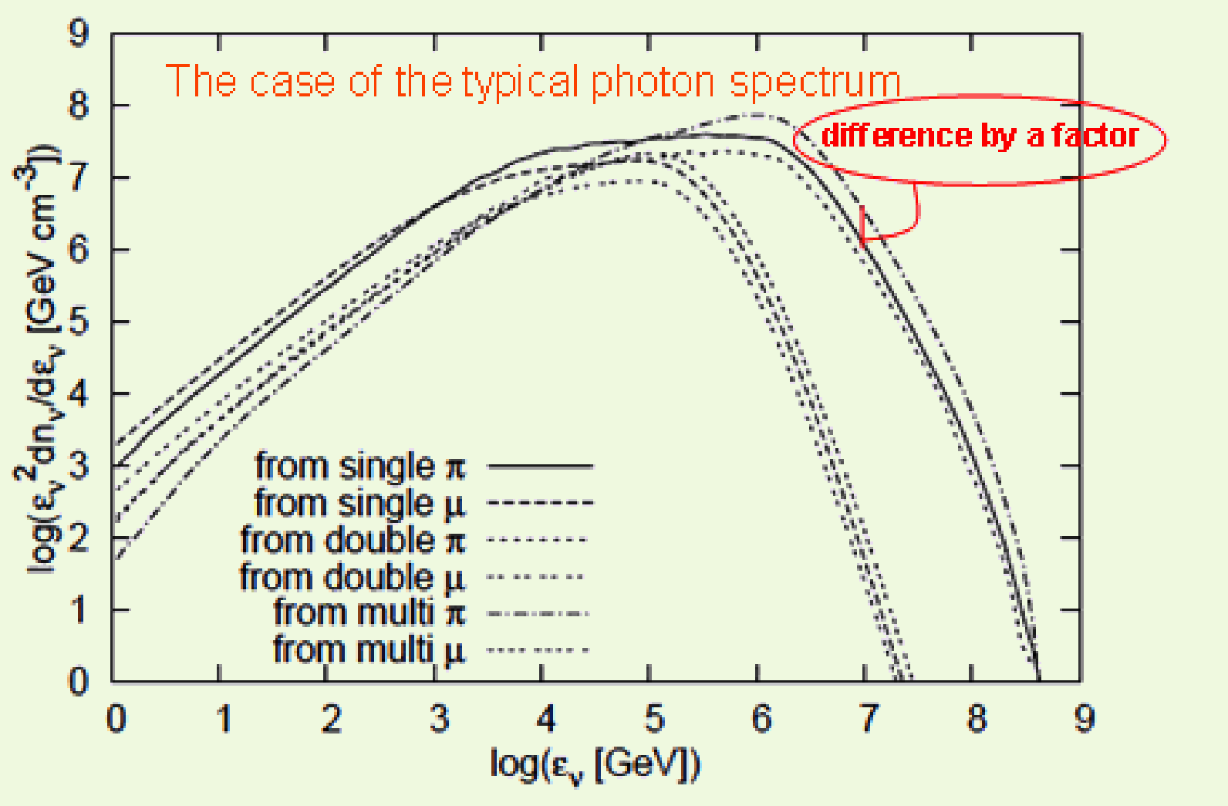
- •The effect of inelasticity and multiplicity is important in the high energy region.
- •Photomeson reaction can be important at smaller radii, and other cooling processes are important at larger radii.

4.Neutrino Emission

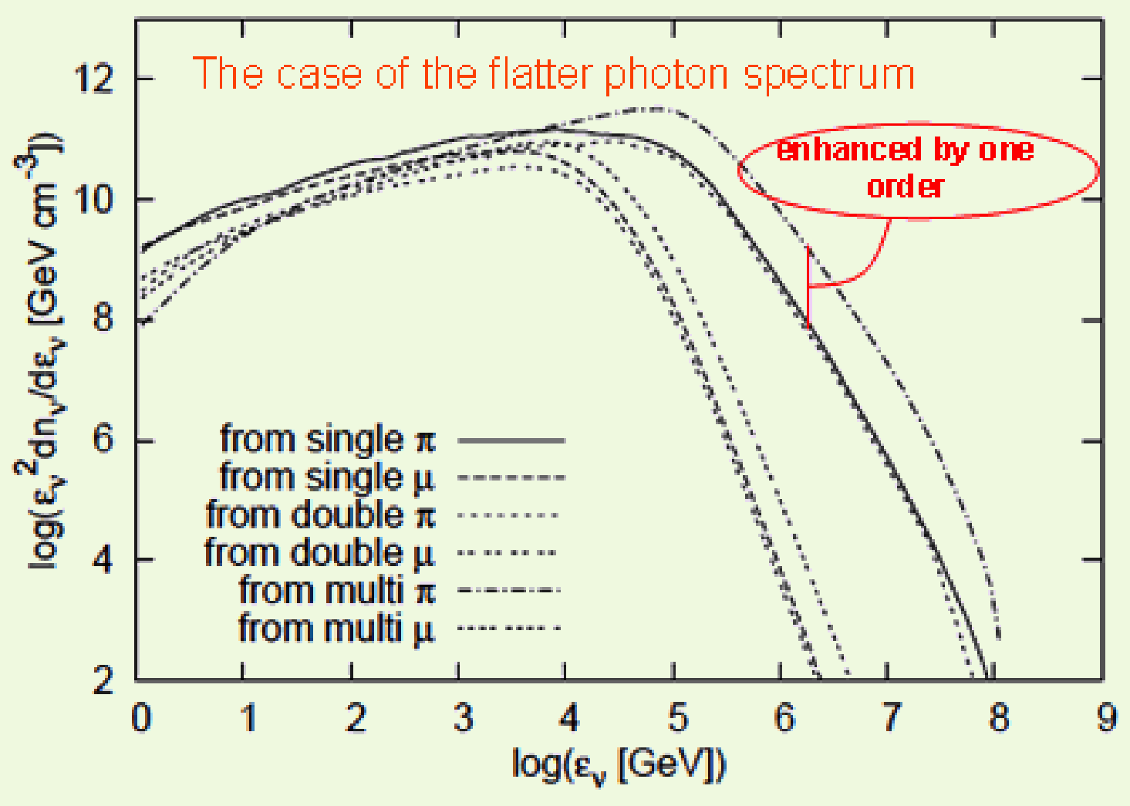
•Photomeson production

Δ-resonance approximation is valid for many cases $p + \gamma \rightarrow \Delta \rightarrow n + \pi^+ \quad \kappa_p \sim 0.2$

but, $\gamma_p > 10^{6-7}$ multi-pion production can be important $p + \gamma \rightarrow N\pi^{\pm} + X \quad \kappa_p \sim 0.5 - 0.9$



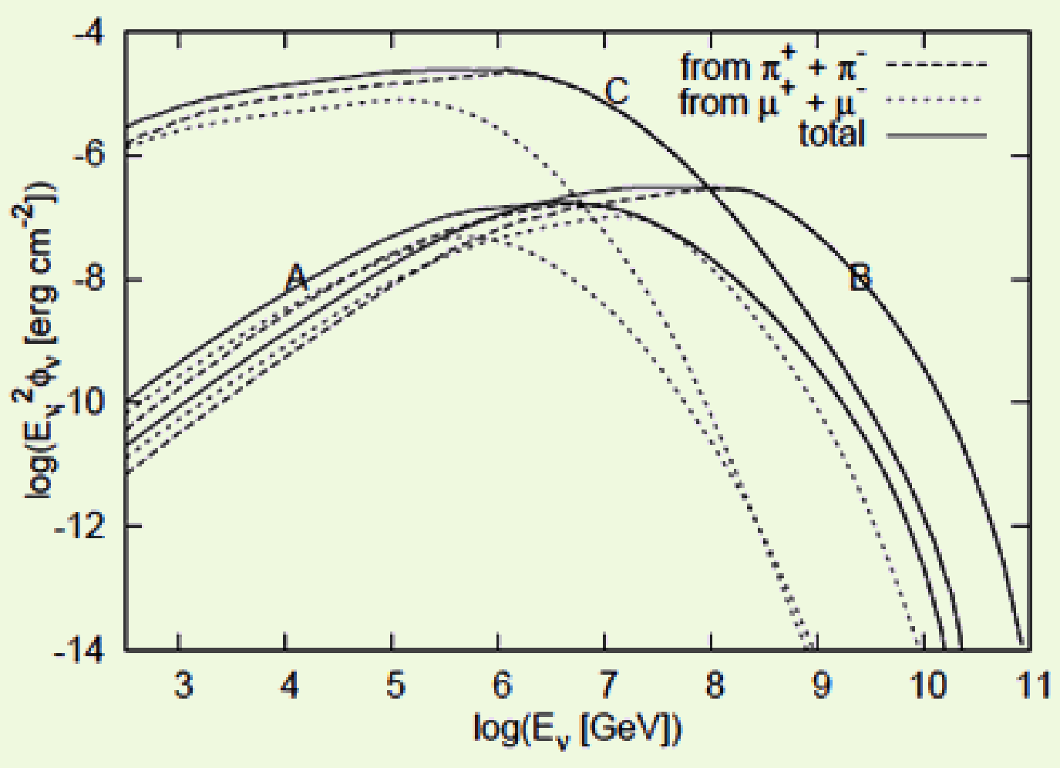
The case where multi-pion production isn't so important



The case where multi-pion production is important

•Pion Decay

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu$$



Neutrino spectra from one burst

Pions and muons cool down by cooling processes before they decay.

➡ fluxes are suppressed at $t_{\pi,\mu} > t_{syn}$, t_{ad}

- •The effect of multiplicity raises flux by a factor for the typical spectrum, and by one order for the flatter spectrum.
- •Only energetic and near bursts can be detected by IceCube.

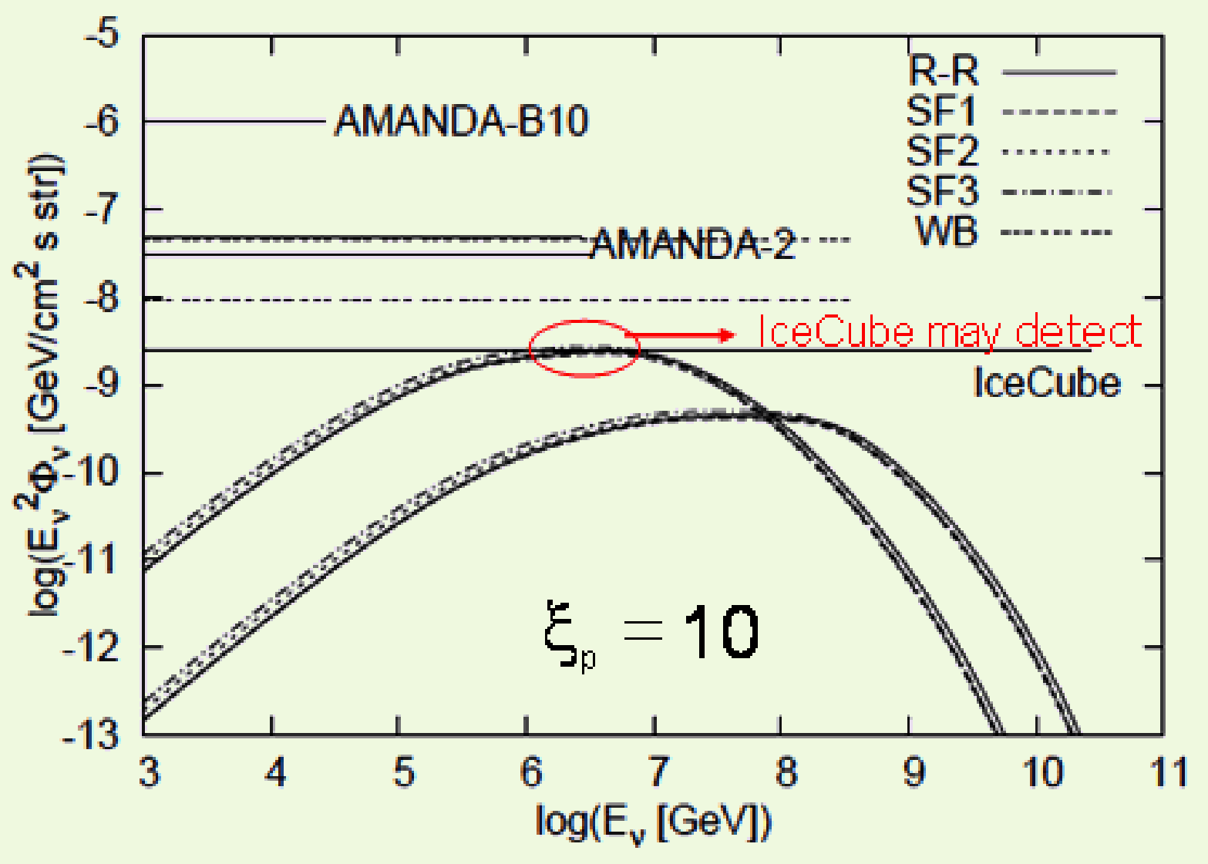
5.Neutrino Background

Inner engine of GRBs is unknown

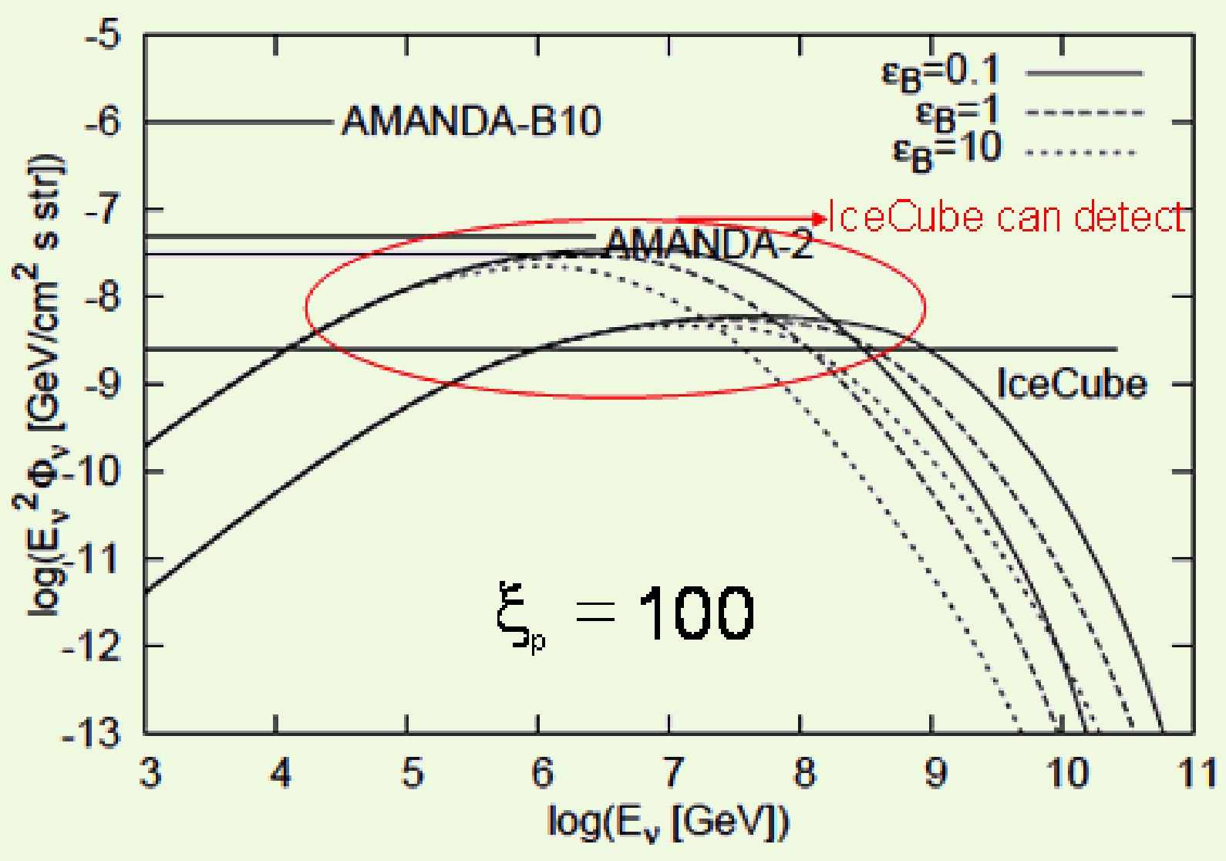
association with long GRBs and supernovae ➡ **death of massive stars (e.g. collapsar)**

•assumption $R_{GRB} \propto R_{SF}$ ➡ GRB rate $R_{GRB} \sim (20 - 40)\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$

We calculate a neutrino background by integrating with respect to z for some parameter sets.



Diffuse neutrino background(1)



Diffuse neutrino background(2)

- •If photon density in subshells is enough large, neutrino signals can be detected by IceCube without assuming GRBs are not main sources of UHECRs even when the nonthermal baryon loading factor is ~10. In such cases, we can expect higher flux than previous works if the nonthermal baryon loading factor is enough large.
- •If photon density is lower, which condition is caused when internal shocks occur at larger radii, we can expect detections only when GRBs are the main sources of UHECRs.

6.Discussion

- •If a fireball is baryon-rich, high-energy gamma-rays will affect assumed photon spectra by electromagnetic cascades. → GLAST observartion
- •The nonthermal baryon-loading factor can be constrained by the flux of UHECRs. It can also be constrained if we know the unknown explosion energy.
- •We need to reveal the validity of internal shock model and the distribution of many GRB parameters for more plausible evaluations.
- •The GRB rate may trace not the star formation rate but metallicity.
- •We need to consider the effect of neutrino oscillation in future.

7.Conclusion

•The effect of multi-pion production and high-inelasticity that is often neglected so far can be important in cooling protons and resulting neutrino spectra for some cases.

•We evaluated a diffuse neutrino background spectra assuming that the GRB rate traces the star formation rate. If the internal shock model is true and there are enough many accelerated protons, IceCube can detect high energy neutrinos from GRBs. If they are detected in future, we can obtain the evidence that protons are accelerated in GRBs and some information about parameters of GRBs from neutrino observation.

References

Asano, ApJ, 623, 967 (2005), Bahcall & Waxman, Phys. Rev. D, 64, 023002 (2000), Dermer & Atoyan, Phys. Rev. Lett., 91, 071102 (2003), Guetta et al., ApJ, 619, 412 (2005), Halzen & Hooper, Rep. Prog. Phys., 65, 1025 (2002), Mucke et al., Nucl. Phys. B, 80 (2000), Piran, Rev. Mod. Phys., 76, 1143 (2005), Totani, ApJ. Lett., 486, L71+ (1997), Waxman & Bahcall, Phys. Rev. Lett., 78, 2292 (1997)