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Detecting TeV γ-rays from GRBs with km^3 neutrino telescopes

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Abstract. Observing TeV photons from GRBs can greatly enhance our understanding of their emission mechanisms. Under-sea/ice neutrino telescopes—such as ANTARES in the Mediterranean Sea or IceCube at the South Pole—can also operate as a γ-ray observatory by detecting downgoing muons from the electromagnetic cascade induced by the interaction of the photons with the Earth's atmosphere. Theoretical calculations of the number of detectable muons from single GRB events, located at different redshifts and zenith distances, have been performed. The attenuation by pair production of TeV photons with cosmic infrared background photons has also been included.

Keywords. astroparticle physics, gamma-ray burst: general, elementary particles, methods: analytical

The ANTARES neutrino telescope is currently operating in the Mediterranean Sea, 40 km offshore Toulon (France) at a depth of 2475 m. With an instrumented volume of ~ 0.01 km^3, it is the largest neutrino telescope in the Northern Hemisphere. Although optimized to detect upgoing neutrino-induced muons, it can also detect downgoing photon-induced muons and thus operate as a gamma-ray telescope. Because of its large collecting area, wide field of view, and high duty cycle, there is a potential then for ANTARES to detect TeV photons emitted from gamma-ray burst (GRBs).

TeV photons from GRBs are produced from electron Inverse Compton emission or π^0 decay from $p\gamma$ interactions (Asano & Inoue, 2007). Searching for these photons could help us not only in understanding the mechanisms of GRB emission but also in identifying the possible source of Ultra High-Energy Cosmic Rays (UHECR).

Along their path from the source to the Earth, TeV photons interact with ambient IR photons. They annihilate themselves, creating pairs of electron–positron in the process. The transparency of the universe to TeV photons depends on the photons's energy and the distance to the source. Once the surviving TeV photons reach the top of the Earth's atmosphere, they will interact with atmospheric particles and initiate particle showers. Muons are produced from these showers mainly (Halzen *et al.* 2009) through 1) photoproduction, in which TeV photons interact with atmospheric nuclei and produce pions, followed by the decay of the pion into a positive muon and a muon antineutrino; and 2) direct muon-pair production, where muons are created directly via the channel $\gamma + N \rightarrow N + \mu^+ + \mu^-$, where N is a nucleus of the atmosphere.

Muon production through the first channel dies away with increasing energy, but the cross section of muon-pair production increase with photon energy. At TeV regime it is thus the dominant muon-producing channel. As the muons travels downward toward the detector at the bottom of the sea, they lose their energy through ionization and radiative

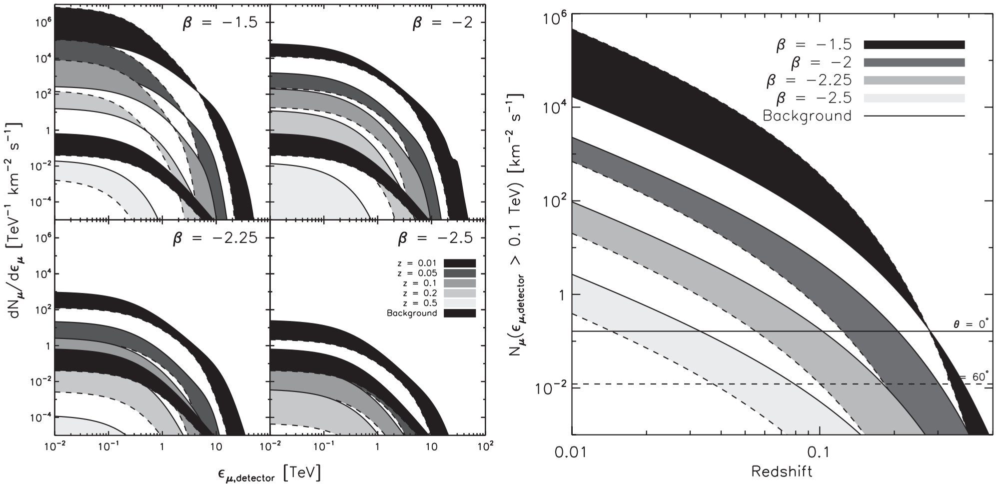

Figure 1. Left: The muon flux at detector depth (2475 m) for single GRBs emitted from different redshifts as indicated by the color coding on the legend. The black horizontal lines show the background flux from cosmic ray-induced muons parametrized by Gaisser (1991), assuming a search cone with an opening angle of 1°. For each color, the muon flux drawn by the dashed-line is the flux from zenith distance $\theta = 60°$ while that drawn by the solid line is the flux straight from the zenith (i.e. $\theta = 0$). The filled-area then defines all the possible flux from all zenith distances between $\theta = 0$ and $\theta = 60°$. Attenuation is determined by using a model by Finke *et al.* (2010). Each square is a plot for different high-energy photon spectral index β of the GRB. **Right:** The number of muons with energies $\epsilon_{\mu,\mathrm{detector}} > 0.1$ TeV per km^2 per seconds for GRB sources with various high-energy photon spectral index β. The muon counts are plotted as a function of the redshift of the GRB. The two horizontal lines are the background levels at $\theta = 0$ and $\theta = 60°$.

processes (Barrett *et al.* 1952). There is thus a minimum energy threshold for the muons to survive its journey to the bottom of the sea: For a vertical depth of 2475 m, the surface energy of the muons must be larger than ~ 1 TeV.

Consequently, only the very nearby GRBs can be detected significantly. To obtain at least 3σ detection significance, a GRB has to be located at redshift $z \lesssim 0.07$ if the detector's muon effective area is $A^{\mu}_{\mathrm{eff}} \sim 0.01$ km^2, or $z \lesssim 0.15$ if the muon effective area is $A^{\mu}_{\mathrm{eff}} \sim 1$ km^2 (Astraatmadja, 2011). The annual probability that such an event will occur (Wang & Dai, 2011) is very small ($P \sim 2 \times 10^{-4}$) but nevertheless it has occured in the past (Butler *et al.* 2007, 2010).

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