33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

A search for neutrinos from long-duration GRBs with the ANTARES underwater neutrino telescope

C.W.JAMES[1] ON BEHALF OF THE ANTARES COLLABORATION.
[1] *ECAP, University of Erlangen-Nuremberg, Erwin-Rommel-Str 1, 91058 Erlangen, Germany*
clancy.james@physik.uni-erlangen.de

Abstract: ANTARES is an underwater neutrino telescope located at a depth of 2475 m off the coast of Toulon, France. In this contribution, a search for neutrino events observed by ANTARES in coincidence with gamma-ray bursts (GRBs) is described. The observed properties of 296 long-duration GRBs visible to ANTARES from Dec. 2007 to Dec. 2011 are used to construct neutrino-selection criteria which are optimised to discover the expected prompt neutrino emission. In particular, the numerical 'Neutrinos from Cosmic Accelerators' (NeuCosmA) method is used for the calculation of the expected neutrino fluxes. Using these predictions, a search is performed using data from the Fermi and Swift satellites to select neutrino candidate events coincident in time and direction with the GRBs. The result of this search is presented, and used to place limits on the predictions of neutrino production from various GRB models.

Keywords: neutrinos, gamma-ray bursts, methods: numerical.

1 Introduction

Gamma-ray bursts (GRBs) are intense flashes of gamma rays which are usually divided into two classes: short (duration $\lesssim 2$ s) and long (duration $\gtrsim 2$ s) bursts [1]. The latter class has been associated with Type 1b/c supernova events [2], and their emission is commonly treated in terms of the 'fireball' model [3]. In this model, the gamma rays result from a highly relativistic jet formed during the collapse of the massive star. Shocks associated with the jet — internal shocks, and any resulting from the jet interacting with material previously ejected by the star — will accelerate electrons, thus producing the observed gamma-ray emission via the synchrotron self-Compton process [4]. Any co-acceleration of protons in these shocks would lead to interactions with the local photon field, producing an accompanying neutrino flux via e.g. the decay of charged pions [5] produced in these interactions. The detection of a neutrino flux associated with GRBs would thus be a clear signature of hadronic acceleration in these sources.

In these proceedings, a search for a neutrino flux in coincidence with GRBs is presented using data from the ANTARES neutrino telescope taken from late 2007 to 2011. A numerical treatment ('NeuCosmA') of the neutrino flux from GRBs is used in Sec. 3 to model the predicted flux from a sample of 296 candidate GRBs (described in Sec. 2), which indicates that the expected flux of neutrinos using the fireball model of GRBs is not currently limited by observations. In Sec. 4, the NeuCosmA predictions are used to optimise the sensitivity of a neutrino-search for each GRB individually. The results of this analysis after unblinding are given in Sec. 5.

2 Data selection

The ANTARES underwater neutrino telescope is located at a depth of 2475 m off the coast of Toulon, France [6, 7]. It primarily detects charged-current (anti) muon-neutrino interactions by observing the passage of the subsequent relativistic muons through the seawater near the detector. When the resulting Cherenkov light is detected by ANTARES' array of photo-multiplier tubes, the initial direction of the primary neutrino can be estimated. Due to the number of down-going muons coming from cosmic-ray interactions with the atmosphere above the detector, only up-going muons (those coming from below the local horizon) are selected for analysis, and stringent quality-cuts are used to reject mis-reconstructed down-going events (see e.g. Ref. [6] for a description of this methodology). The instantaneous sky coverage of ANTARES is therefore 2π sr; its latitude of 43° thus makes it more likely to observe GRBs occurring in the Southern Hemisphere.

For the results presented here, data primarily from *Fermi* and *Swift* are used to select long-duration GRBs which were visible to ANTARES from Dec. 2007 to Dec. 2011. A complete description of the data-selection process, and the final table of all relevant GRB parameters used to model these events as described in Sec. 3, is given in Ref. [8]. Requiring that the detector was operating under normal conditions for the entire burst duration leads to 296 events located below the ANTARES horizon being chosen for this analysis. From the observed beginning and end times of the bursts, this amounts to a total coincidence window of 6.55 hr. The coordinates of these bursts are shown in Fig. 1.

3 The NeuCosmA model

The most commonly used method to estimate the neutrino-emission from long-duration GRBs in the context of the fireball model is that of Waxmann & Bahcall [9], adapted as per Guetta *et al.* [10] to account for individual GRB properties. This calculation models Δ-resonance interactions of Fermi-accelerated protons with the GRB photon field — neutrinos result from the subsequent decay of charged pions and muons. This method predicts a doubly broken power-law spectrum for the ν_μ flux. The recently-published limit by the IceCube collaboration on the $\nu_\mu + \bar{\nu}_\mu$ flux from GRBs lies significantly below the prediction from this two-break model [11]. Accounting for the different maximum

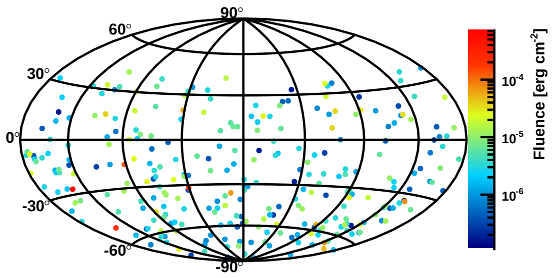

Figure 1: Sky distribution of the selected 296 gamma-ray bursts in equatorial coordinates (colour indicates measured gamma-ray fluence).

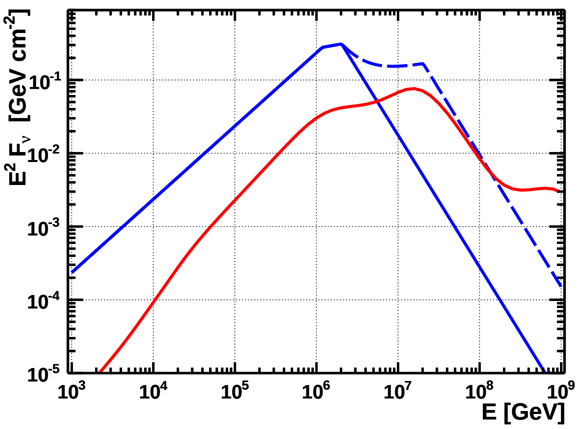

Figure 2: Expected $\nu_\mu + \bar{\nu}_\mu$ spectra from GRB110918, using both the two-break (solid blue) and three-break (dotted blue) treatments of the model of Guetta *et al.*, and the NeuCosmA model (red).

break energies for the ν_μ and $\bar{\nu}_\mu$ fluxes within the model of Guetta *et al.* produces a combined spectrum that has three break energies. This was the method used for the previously published limits from ANTARES on the neutrino flux from GRBs using 2007 data [12]. For comparison, the predictions for the combined flux of ν_μ and $\bar{\nu}_\mu$ from one GRB (GRB110918) from both the 'two-break' and 'three-break' treatments of the Guetta model are shown in Fig. 2 as the solid and dotted blue curves respectively. It is likely that applying the three-break treatment to the IceCube predictions would still result in the limit lying below the expected flux.

A full account of all the physical processes relevant for neutrino production within the fireball model requires a detailed numerical calculation. The NeuCosmA (Neutrinos from Cosmic Accelerators) code [13, 14] was developed to include the full photo-hadronic cross-sections as given by the Monte-Carlo code SOPHIA [15], the energy-losses of secondary particles produced in such interactions, and the effects of neutrino-mixing in the final calculation of the expected neutrino spectrum from GRBs (among other details). As discussed in Hümmer *et al.* [13], the resulting predictions for the GRB neutrino flux lie an order of magnitude below those of the simplified Guetta model, with the addition of a high-energy component due to K^+ decays — see e.g. Fig. 2 (red curve) for a comparison in the case of GRB110918. It should be emphasised that predictions from the NeuCosmA model arise simply through a more thorough application of known physics to the same GRB fireball model as used by previous predictions, and thus

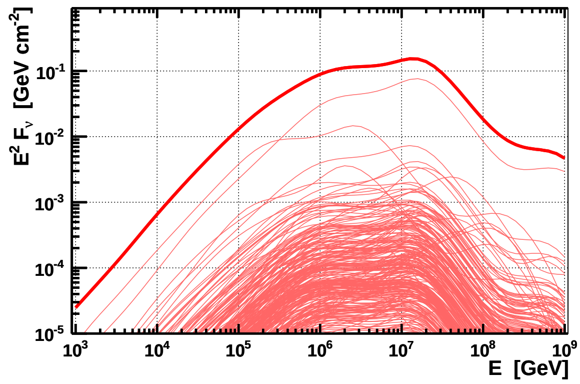

Figure 3: $\nu_\mu + \bar{\nu}_\mu$ NeuCosmA spectra of the 296 GRBs (thin lines) and their sum (thick line).

suffer from no more — and no less — error due e.g. to uncertainty in GRB parameters such as the jet gamma-factor. Therefore, we used the NeuCosmA model to estimate the ν_μ and $\bar{\nu}_\mu$ flux from the 296 GRBs in the chosen sample for the purposes of optimising data-selection, as described in the next section. The predicted spectrum from each event, and the combined total, is shown in Fig. 3. Observe that GRB110918 contributes approximately half the total predicted flux in the energy-range above 1 TeV, where ANTARES has the greatest sensitivity.

4 Search methodology

The primary criteria used to search for a neutrino flux coming from the sample of GRBs are timing and spatial coincidence of observed up-going muons with the gamma-ray signal. For each GRB, only up-going muons arriving within the observed GRB duration and with reconstructed origin less than 10° from the GRB direction are considered. For this purpose, the algorithm used in this analysis to reconstruct the direction of observed muon tracks returns two parameters: the Λ parameter, reflecting the quality of the track fit (high values are better), and β, giving the estimated uncertainty in the reconstructed direction (low values are better). See Ref. [16] for a more detailed description of the event-reconstruction procedure. A cut of $\beta < 1°$ was used as per Ref. [16], while the values of $\Lambda_{\rm cut}$ used to select events with $\Lambda > \Lambda_{\rm cut}$ vary from source to source and are optimised as follows.

To determine if an observation of neutrinos in coincidence with a given GRB is significant, the 'extended maximum-likelihood ratio' [17] is used to define a test-statistic Q. This is the log-likelihood ratio of observing a given spatial-distribution of events with an estimated number of source events $n_s^{\rm est}$ and expected background contribution μ_b as a function of the observed angular offsets δ between the events and the source:

$$Q(n_s^{\rm est}) = \max_{\hat{n}_s \in [0, n_{\rm tot}]} Q(\hat{n}_s) \quad (1)$$

$$Q(\hat{n}_s) = \sum_{i=1}^{n_{\rm tot}} \log \frac{\hat{n}_s \cdot S(\delta_i) + \mu_{\rm b} \cdot B(\delta_i)}{\mu_{\rm b} \cdot B(\delta_i)} - (\hat{n}_s + \mu_{\rm b})$$

where $n_s^{\rm est}$ is chosen as the value of $\hat{n}_s$ which maximises Q. Here, $S(\delta_i)$ and $B(\delta_i)$ represent the likelihoods of event i (with reconstructed direction δ_i degrees from the GRB direction) being of signal (GRB) and background (atmospheric

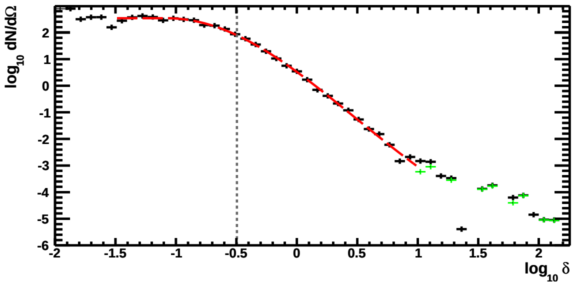

Figure 4: Point-spread function $S(\delta)$ (red), ν_μ and $\bar{\nu}_\mu$ events (black), and shower events (green) for the GRB 11091889 with $\Lambda_{\rm cut} = -5.5$.

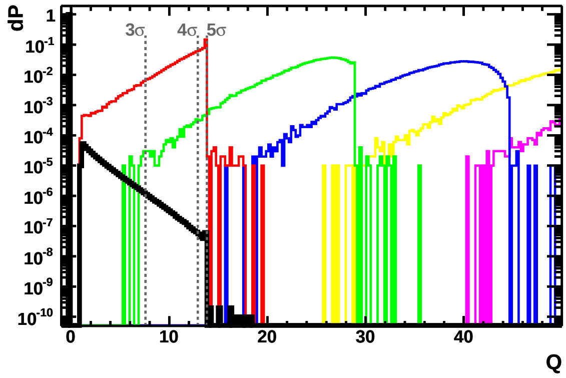

Figure 5: Probability distributions of Q-values $h_{n_s}(Q)$ for (left to right) $n_s = 0, 1, 2, 3\ldots$ for GRB110918 and $\Lambda_{\rm cut} = -5.5$; $\mu_b = 3.7 \cdot 10^{-4}$. Grey vertical lines indicate the threshold values $Q_p^{\rm thresh}$ for different levels (3σ, 4σ, 5σ) of significance after accounting for a trial factor of 296 as calculated from $h_0(Q)$. The three distinct components $h_0(Q)$ (black) are due to the random number of background events n_b (Poisson mean μ_s) taking values 0, 1, and 2.

cosmic ray) origin respectively. S is thus the ANTARES point-spread function (PSF) in the direction of the GRB, and $S(\delta_i)$ takes a separate value for each of the $n_{\rm tot}$ events passing the selection criteria. From hereon, 'Q' will be used as shorthand for '$Q(n_s^{\rm est})$'. The distributions S and B are themselves functions of cuts on the Λ parameter used to discriminate signal from background; their determination is described below.

4.1 Signal simulation and background estimation

In order to determine S, each GRB is simulated using $4 \cdot 10^9$ incident ν_μ and $\bar{\nu}_\mu$ sampled from the spectrum from the NeuCosmA model using the standard ANTARES Monte-Carlo simulation chain [16]. A preliminary simulation of 150 neutral-current 'shower' events from neutrinos of all flavours (Fig. 4, green points) demonstrates that, using methods currently available, their reconstructed directions correlate poorly with their arrival directions, and thus these events are not used in the fit to S. For each simulated event, δ is the angular offset between the reconstructed direction and the source direction. The distribution $S(\delta)$ (the point-spread function) is modelled for each possible cut value $\Lambda_{\rm cut}$. The fitted function used for $S(\delta)$ is given in Eq. 2:

$$\begin{aligned} S(\delta) &\equiv \frac{dN(\delta)}{d\Omega} \qquad (2) \\ \log_{10} S &= \begin{cases} C_1 & \delta \leq \delta_0 \\ C_1 - C_2\left(1 - e^{-\frac{(\log\delta - \log\delta_0)^2}{2\sigma^2}}\right) & \delta > \delta_0 \end{cases} \end{aligned}$$

where C_1, C_2, δ_0 and σ are fitted parameters. An example of this fit, which is performed for each combination of GRB and $\Lambda_{\rm cut}$ value, is given in Fig. 4. The grey vertical line gives the median value $\bar{\delta}$.

The distribution of background events B is taken to be constant over the narrow time-windows and small regions of sky about each GRB. The expected number of background events μ_b is taken from data, and is calculated as per Eq. 3:

$$\mu_b = 1.5\, T_s r_{\bar{t}}(\Omega) \left(1 + \frac{r_{\bar{\Omega}}^{90}(t)}{\bar{r}}\right) \qquad (3)$$

Here, T_s is the duration of the search-time window, $\bar{r}$ is the long-term all-sky mean background rate, $r_{\bar{\Omega}}^{90}(t)$ is the 90% upper limit on the observed all-sky background rate around the time t of the GRB, and $r_{\bar{t}}(\Omega)$ is the long-term background rate observed in the direction of the GRB in detector-coordinates Ω. The extra factor of 1.5 is included to ensure that all observed rates are below the estimates, i.e. under the conservative assumption that all fluctuations are real rather than statistical [8].

4.2 Threshold calculation and MDP optimisation

The test-statistic Q (Eq. 1) is defined such that high values are evidence against the background-only (null) hypothesis — i.e. evidence for a neutrino signal from GRBs. The significance of an observation $Q^{\rm obs}$ is characterised by the p-value, defined as the probability of observing a Q-value $Q > Q^{\rm obs}$ in the case of background only. In general, for any true number of signal events n_s (as opposed to the estimate $n_s^{\rm est}$) and expected number of background events μ_b, Q has the distribution $h_{n_s}(Q)$. The distributions $h_{n_s}(Q)$ are calculated using 'pseudo-experiments'. Firstly, n_b background events are Poisson-sampled from the mean μ_b. Then, for these and the n_s signal events, random values of δ according to the distributions S and B are generated. Since an accurate determination of $h_0(Q)$ is critical for determining the discovery threshold $Q^{\rm thresh}$, 10^{10} pseudo-experiments are used to estimate each $h_0(Q)$, 10^5 are used for $h_{n_s>0}(Q)$, yielding enough statistics for the optimisation procedure.

Given $h_0(Q)$, the critical threshold value of $Q^{\rm thresh}$ required for a discovery can then be calculated from a required value of p via:

$$\int_{Q_p^{\rm thresh}}^{\infty} h_0(Q)\, {\rm d}Q = p. \qquad (4)$$

A global probability of $2.7 \cdot 10^{-3}$ (3σ) is chosen for the optimisation — this corresponds to $p = 2.7 \cdot 10^{-3}/296 = 9.1 \cdot 10^{-6}$ per source. After defining $Q^{\rm thresh}$, the probability to discover a model predicting an expected source flux of μ_s events (from which n_s are actually observed, according to Poisson statistics) is given by the 'model discovery potential' *MDP*:

$$MDP = \sum_{i=0}^{\infty} P(Q > Q^{\text{thresh}}|n_s)P(n_s|\mu_s) = \sum_{n_s=0}^{\infty} \int_{Q_p^{\text{thresh}}}^{\infty} h_{n_s}(Q)\text{d}Q \cdot \frac{\mu_s^{n_s} e^{-\mu_s}}{n_s!}. \quad (5)$$

The value of Λ_{cut} chosen for each source is thus that which maximises the *MDP*. Applying this procedure, a set of Λ_{cut}, Q^{thresh}, S, B, and μ_b are determined for all 296 sources. Table 1 gives the expected source and background counts, and the cut parameters, for the ten most-promising GRBs. In total, 0.06 signal events are expected from the NeuCosmA model, and 0.5 from the Guetta model, against a background of 0.05 events.

GRB†	Λ_{cut}	μ_{b}	μ_s^{NCA}	$\delta(^\circ)$	T_{s}(s)
110918	-5.5	$3.7{\cdot}10^{-4}$	$3.5{\cdot}10^{-2}$	0.32	73.4
080607	-5.4	$5.5{\cdot}10^{-4}$	$6.5{\cdot}10^{-3}$	0.33	164.3
111008	-5.5	$3.6{\cdot}10^{-4}$	$2.2{\cdot}10^{-3}$	0.35	75.4
101014	-5.1	$4.1{\cdot}10^{-4}$	$1.2{\cdot}10^{-3}$	0.89	723.1
100728	-5.6	$2.0{\cdot}10^{-4}$	$9.6{\cdot}10^{-4}$	0.49	268.6
090201	-5.4	$5.4{\cdot}10^{-4}$	$7.0{\cdot}10^{-4}$	0.39	126.6
111220	-5.2	$1.4{\cdot}10^{-4}$	$6.2{\cdot}10^{-4}$	1.13	66.5
090829	-5.4	$1.7{\cdot}10^{-4}$	$3.9{\cdot}10^{-4}$	1.02	112.1
110622	-5.4	$1.7{\cdot}10^{-4}$	$4.3{\cdot}10^{-4}$	1.42	116.6
081009	-5.5	$1.3{\cdot}10^{-4}$	$3.5{\cdot}10^{-4}$	0.94	70.2
All GRBs		$5.1{\cdot}10^{-2}$	$6.1{\cdot}10^{-2}$		23500

Table 1: Sample parameters (see text) of the ten GRBs with the highest discovery probabilities as estimated from the NeuCosmA ('NCA') model, and the total (where relevant) over all 296 GRBs.

5 Results

With search parameters defined as in Sec. 4, the data from Dec. 2007 to Dec. 2011 were unblinded and analysed for evidence of a neutrino signal correlating with the 296 GRBs in the data-sample. No events passing quality cuts are found within the specified time-intervals and 10° search windows. Hence, all Q-values are zero, and we find no evidence for a neutrino signal from any of the analysed GRBs. A 90% confidence limit on the total flux of neutrinos from all GRBs predicted by each of the NeuCosmA and Guetta models is then placed by scaling the flux predictions to obtain $\mu_s = 2.3$ (since, from Poisson statistics, $P(n_s > 0|\mu_s = 2.3) = 0.9$). The resulting limits on both the NeuCosmA and Guetta (two-break) fluxes are shown in Fig. 6 (red and blue dotted lines). Neither prediction is constrained by the observations presented here, with the predictions for the NeuCosmA flux lying a factor of 38 below the limit. While this analysis improves the previous limit set by ANTARES [12], which used a smaller sample of 40 GRBs and the three-break treatment of the Guetta model, the IceCube limit [11] (set using the two-break Guetta model) is not improved-upon due to the larger effective volume of the IceCube detector. Note that both the relative sensitivities to particular GRBs, and the GRB samples used, in these previous searches differ significantly from those presented here, which is particularly relevant given the importance of individual bright events such as GRB110918. We have also shown that the more detailed calculation of the expected neutrino flux from long-duration GRBs using NeuCosmA indicates that current

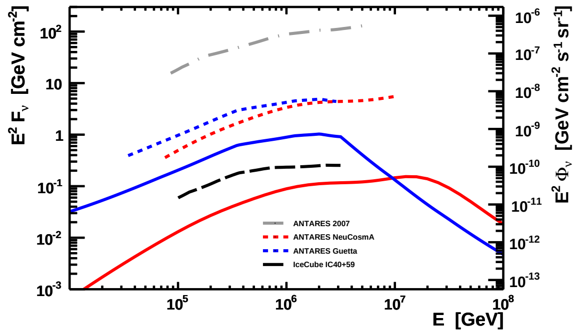

Figure 6: Comparison of 90% confidence limits (dashed) with expected fluxes (solid) for the summed $\nu_\mu + \bar{\nu}_\mu$ spectra of the 296 GRBs used in this analysis, using the NeuCosmA (red) and 'two-break' Guetta (blue) models. Limits from a previous IceCube (black dashed) and ANTARES (grey dash-dotted) are also shown for comparison.

limits on neutrino emission from GRBs are completely consistent with expectations.

Acknowledgment: We would like to thank Philipp Baerwald for producing the NeuCosmA neutrino-flux predictions, and Walter Winter for helpful discussions and making the NeuCosmA model available. This work is supported by the German government (BMBF) with grant 05A11WEA.

References

[1] C. Kouveliotou *et al.*, ApJ Letters 413 (1993) 101–104 doi:10.1086/186969.
[2] T.J. Galama *et al.*, Nature 395 (1998) 670–672 doi:10.1038/27150.
[3] P. Meszaros and M.J. Rees, ApJ 405 (1993) 278–284 doi:10.1086/172360.
[4] P. Mészáros, Reports on Progress in Physics 69 (2006) 2259–2321 doi:10.1088/0034-4885/69/8/R01.
[5] E. Waxman, Phys.Rev.Lett. 75 (1995) 386–389 doi:10.1103/PhysRevLett.75.386.
[6] M. Ageron *et al.*, NIMPR A 656 (2011) 11–38, doi:10.1016/j.nima.2011.06.103.
[7] A. Kouchner (The ANTARES Collaboration), 33rd ICRC Rio de Janeiro, Brazil (2013) ID 27; Brazillian J. Phys (2013).
[8] S. Adrián-Martínez *et al.* (in preparation).
[9] E. Waxmann, J. Bahcall, Phys.Rev.Lett 78 (1997) 2292–2295, doi:10.1103/PhysRevLett.78.2292.
[10] D. Guetta, D. Hooper, J. Alvarez-Muñiz, F. Halzen, E. Reuveni, Astropart.Phys. 20 (2004) 429–455 doi:10.1016/S0927-6505(03)00211-1.
[11] R. Abbasi *et al.*, Nature 484 (2012) 351–354 doi:10.1038/nature11068.
[12] S. Adrián-Martínez *et al.*, JCAP 3 (2013) 6 doi:10.1088/1475-7516/2013/03/006.
[13] S. Hümmer, M. Rüger, F. Spanier and W. Winter, ApJ 721 (2010) 630–652 doi:10.1088/0004-637X/721/1/630.
[14] S. Hümmer, P. Baerwald and W. Winter, PRL 23 (2012) 231101 doi:10.1103/PhysRevLett.108.231101.
[15] A. Mücke, R.R. Engel, R.J. Protheroe, J.P. Rachen, T. Stanev, Nuc.Phys.B Proc.Supp 80 (1998) C809.
[16] S. Adrián-Martínez *et al.*, ApJ 760 (2012) 53 doi:10.1088/0004-637X/760/1/53.
[17] R. Barlow, NIMPR A 297 (1990) 496–506 doi:10.1016/0168-9002(90)91334-8