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Neutrinos from Starburst-Galaxies – A source stacking analysis of AMANDA II and IceCube data

J. Dreyer[1,2], J. K. Becker[1], W. Rhode[2], and the IceCube Collaboration[3]

[1]Theoretische Physik IV, Fakultät für Physik und Astronomie, Ruhr-Universität Bochum, 44780 Bochum, Germany
[2]Experimentelle Physik Vb, Fakultät Physik, TU Dortmund, 44221 Dortmund, Germany
[3]http://icecube.wisc.edu/

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Abstract. A stacking analysis performed with data from the IceCube neutrino observatory is presented in this paper. In general, the stacking technique is sensitive to a cumulative signal from a generic source class. This can lead to a significant signal for the most luminous sources of the class, even if the individual sources cannot be detected. Here, the final data set of the AMANDA-II experiment, which is the predecessor of the IceCube, is used for an analysis. In a second analysis, data from a quarter of the IceCube detector is used. IceCube consists of so called stings, these are steel cables with photo multipliers hooked up which are deployed into the Antarctic ice to depths between 1450 m and 2450 m. This analysis covers data taken with 22 strings of IceCube (IC-22) within one year. For the first time, a sample of Starburst Galaxies was analyzed. In addition, several AGN catalogs are used as well as a catalog of pulsars. The analysis did not reveal a significant neutrino signal for any of the analyzed source classes, neutrino flux limits were improved. The strongest limit was received for the class of Gigahertz Peaked / Compact Steep Spectrum sources (GPS/CSS), $E_\nu^2 dN_\nu/dE_\nu|_{\mathrm{GPS}} < 8.2\cdot 10^{-12}$ GeV/s/sr per source, assuming an E_ν^{-2}−shaped spectrum. This corresponds to an improvement of a factor of 2.5 compared with the average point source limit for single sources.

1 Introduction

One of the main questions in astrophysics concerns the origin of cosmic rays. Their origin cannot be derived from the arrival direction, since they are deflected and scrambled by cosmic magnetic fields. One method to identify the sources of cosmic rays is to measure high-energy neutrinos. In photon-hadron interactions, or in interactions of the cosmic rays with matter in the vicinity of the source, neutrinos are mainly produced via charged pion decays. Neutrinos are dominantly produced in hadronic interactions and are not expected to come from leptonic interactions. Therefore, a neutrino detection from an extraterrestrial source is an unambiguous sign for cosmic ray acceleration. Several sources and source classes have been proposed as neutrino emitters, see e.g. Becker (2008). The IceCube experiment is currently being constructed close to the geographic South Pole, using the Antarctic ice for neutrino detection. IceCube uses digital optical modules (DOMs) to detect Cherenkov light emitted by muons which where produced in neutrino-nucleon interactions in the ice. When completed in 2011 IceCube will consist of 5160 DOMs arranged along 86 strings deployed in depths between 1450 m and 2450 m in the antarctic ice. The seven source classes presented in this analysis were analyzed aiming for a high energy neutrino signal.

Correspondence to: J. Dreyer
(dreyer@icecube.wisc.edu)

2 Catalogs

Six extragalactic source classes and one galactic class were analyzed. Detailed information on the selection procedure can be found in Dreyer (2010) and Ackermann et al. (2006). The final catalogs are the following:

1. Starburst Galaxies, catalog presented by Becker et al. (2009). Sources were selected according to their far-infrared emission.

2. Fanaroff-Riley I galaxies, from Ackermann et al. (2006). Sources were selected according to their radio emission.

3. Fanaroff-Riley II galaxies, from Ackermann et al. (2006). Sources were selected according to their radio emission.

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4. Compact Steep Spectrum Sources and Gigahertz Peaked Sources, catalog presented by O'Dea et al. (1998). Sources were selected according to their radio emission.

5. Flat Spectrum Radio Quasars, selected according to their gamma-ray detection by the Fermi satellite, see Abdo et al. (2009).

6. Blazars, selected according to their gamma-ray detection by the Fermi satellite, see Abdo et al. (2009).

7. Pulsars, selected according to their gamma-ray detection by the Fermi satellite, see Abdo et al. (2009).

Most of the catalogs were predefined astronomical source lists. The selection of the Starburst Galaxies was done from several catalogs, and we therefore describe it in more detail in Sect. 3. The presented analysis uses data obtained in 7 years of operation of IceCube's predecessor AMANDA and data obtained in 276 days of operation of IceCube in its configuration with 22 strings. In a stacking analysis signal and background inside a defined search bin around the source are summed up, the signal significance increases since it grows faster than the square-root of the background. The number of sources to stack and the size of the search bin are determined using simulated data. The results of the analyses are presented in Sect. 4.

3 Starburst Galaxies

3.1 Definition of Starburst Galaxies

Starburst Galaxies differ from late type galaxies through their enhanced star formation rate (SFR). An area with higher than average star formation activity is labeled as a starburst region. The SFR can be derived from various measurements, from the HCN emission for example. The SFR calculated out of the HCN luminosity was determined to (Gao et al., 2004)

$$SFR_{\mathrm{HCN}} \approx 1.8 \cdot 10^{7} \left(L_{\mathrm{HCN}} \frac{\mathrm{s}}{\mathrm{K\,km\,pc^{2}}} \right) \frac{\mathrm{M_{\odot}}}{\mathrm{yr}} \,. \tag{1}$$

In (Gao et al., 2004) the fraction of HCN to CO luminosity $L_{\mathrm{HCN}}/L_{\mathrm{CO}}$ is proposed as an indicator for Starburst Galaxies. For galaxies investigated in (Gao et al., 2004) the authors find $L_{\mathrm{HCN}}/L_{\mathrm{CO}} \approx 0.1-0.25$. The HCN and other molecular luminosities are measured through rotation-vibration line emission at radio wavelengths. Galaxies also have abundant far-infrared (FIR) emission, which is due to dust. This dust is heated by stars, often mostly young stars. As was noted in the mid-eighties, this thermal dust emission correlates rather well with the non-thermal radio emission in Starburst Galaxies. The correlation in its most simple form is just a proportionality between far-infrared and non-thermal emission. As reference wavelengths, 60 μm and 100 μm are used for the far-infrared. Frequencies between 1.4 GHz and 5 GHz are used as typical for the radio regime. This FIR-radio correlation is typically explained by a calorimetric model, in which non-thermal electrons lose their entire energy in the galaxy (Völk, 1989). However, observations of the radio spectral index indicate that most electrons actually escape the source before losing their kinetic energy (Becker et al., 2009). The energy carried by cosmic rays might play a crucial role in the understanding of the FIR-radio correlation. Most recently, the Starburst Galaxies M82 and NGC253 were detected at GeV and TeV energies (Acciari et al., 2009; Acero et al., 2009; Abdo et al., 2010). The signal is explained by interactions of cosmic rays with ambient matter. However, only a few percent of all cosmic rays appear to interact before they escape, speaking against a calorimetric model as well. The detection of neutrinos from hadronic interactions in Starburst Galaxies could help to get a clearer view on the energetics of Starburst Galaxies.

3.2 A local sample

For the analysis presented here a sample of local (redshift $z < 0.03$) Starburst Galaxies is collected from various references, see Becker et al. (2009) as well as Dreyer (2010) and references therein. To ensure that the galaxies in the sample are indeed Starbursts the ratio between integrated FIR flux and integrated radio flux is required to be larger than 30. A negligible contamination with Seyfert galaxies is still present. However, since Seyfert-II cores are usually connected to host galaxies with high star formation, it is useful to keep sources like NGC1068 in the sample. It is further required that the FIR flux at 60 μm is larger than 4 Jy and the radio flux at 1.4 GHz is larger than 20 mJy, in order to remove selection effects i.e. having a selection which depends on the sensitivity of the measurements. By applying these cuts the sources which are just at the edge of the sensitivity of the instruments are removed leaving only the region where the instruments can detect all sources with the given flux. From 309 previously selected sources 124 are left after applying the cuts. Figures 1 and 2 show the distance-luminosity diagram and illustrate the cuts for the FIR and radio wavelengths respectively. The observed distribution lines up smoothly with the dashed sensitivity curve, indicating that the selection is unbiased. The lack of sources at large distances is due to the applied distance cut. For the analysis, it is assumed that the neutrino signal is proportional to the FIR emission.

4 A stacking analysis for Starburst Galaxies, AGN classes and Pulsars with AMANDA and IceCube

This analysis makes use of the stacking approach which is an analysis technique sensitive to generic source classes. The source classes as well as a signal hypothesis have to be defined carefully beforehand. Apart from the catalog of Starburst Galaxies defined above, several classes of AGN as well

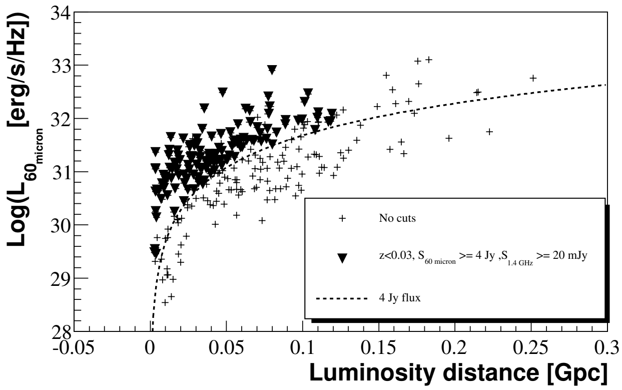

Fig. 1. The luminosity-distance diagram for the FIR flux, the dashed line shows the applied 4 Jy cut.

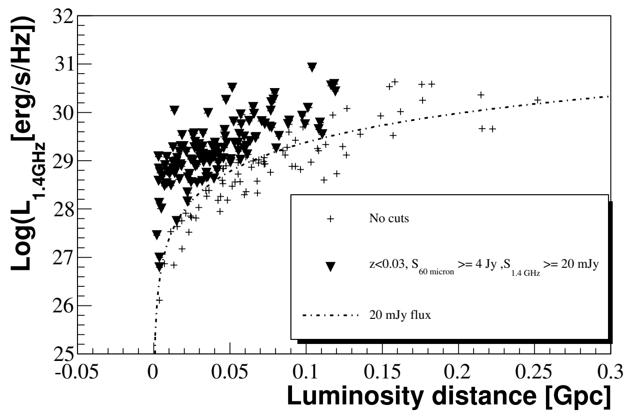

Fig. 2. The luminosity-distance diagram for the radio flux, the dashed line shows the applied 20 mJy cut.

as pulsars are analyzed as specified in Sect. 2. The analysis is performed with seven years of AMANDA-II data (Abbasi et al., 2009a) and data obtained in 276 days with IceCube in its 22 string configuration (IC-22) (Abbasi et al., 2009b). The analysis is first performed on a blind data set, i.e. directions are scrambled in right ascension for the optimization of the analysis parameters. Table 1 summarizes the final parameters for the stacked sources. After optimization is finalized and the scrambled data set was shown to be consistent with no signal, the results are applied to the actual data set. Neither of the two analyses showed a significant signal. Upper limits for the neutrino flux from the different source classes are derived, assuming that the expected flux follows an E_ν^{-2} spectrum. The results for the analysis performed with AMANDA data are shown in Fig. 3, the results for the IC-22 analysis are shown in Fig. 4. The improvement of the neutrino flux limits is more visible in the AMANDA analysis than it is in the IceCube 22 strings analysis. The reason for this difference is most likely the different geometrical properties of AMANDA and IceCube in the 22 string configuration. While AMANDA shows a cylindrical shape, IceCube-22 has a more irregular shape. IceCube's sensitivity is therefore more dependent from the source position than AMANDA's sensitivity. The effects of the different geometries shows particularly in the optimal number of sources that are stacked, which is systematically lower for IceCube-22. While the AMANDA analysis performs best with around $\sim$10 sources, the IceCube-22 analysis typically shows best results for less than 10 sources, except the FR-I galaxies. In particular, blazars and FR-II sources show an optimum number of only two sources for stacking, and pulsars only three. In those cases, the result is expected to be close to the point source sensitivity, just as it is observed. The optimal number of sources and the optimal bin size are determined using simulated data and pick the number of sources and the bin size that yields the best sensitivity.

Table 1. Final parameters for the stacking analysis with the final AMANDA-II and the IceCube-22 data sets.

catalog	#(sources) AMANDA	bin size AMANDA	#(sources) IC-22	bin size IC-22
Starbursts	13	2.4°	8	2.5°
FR-I	14	2.4°	16	2.4°
FR-II	15	2.2°	2	2.7°
CSS/GPS	7	2.7°	7	2.5°
FSRQs	12	2.4°	9	2.5°
Blazars	11	2.6°	2	2.7°
Pulsars	4	2.9°	3	2.6°

5 Conclusions and Outlook

This paper presents the final results of a source stacking analysis with seven years of AMANDA-II data and 276 days of IceCube data in the 22 string configuration. In particular, a sample of Starburst Galaxies is presented here, selected in order to search for a neutrino signal from Starburst Galaxies. The sample contains Starburst Galaxies closer than $z = 0.03$, with a FIR flux at 60 μm larger than 4 Jy and a radio signal at 1.4 GHz of > 20 mJy, in order to work with a relatively complete sample. The final sample contains 124 sources, and as a signal hypothesis, it is assumed that the neutrino intensity scales with the FIR signal. In addition to the sample of Starburst Galaxies, five catalogs of Active Galactic Nuclei and a catalog of pulsars are used to look for a neutrino signal. Two different data samples are used, seven years of AMANDA-II data and one year of IceCube data with 22 strings. No significant signal is found and upper limits to the expected neutrino flux from the source classes are set. For AMANDA-II, point source limits can be improved up to a factor of ~ 2 with respect to the binned single point source analysis. A similar improvement can be achieved with the

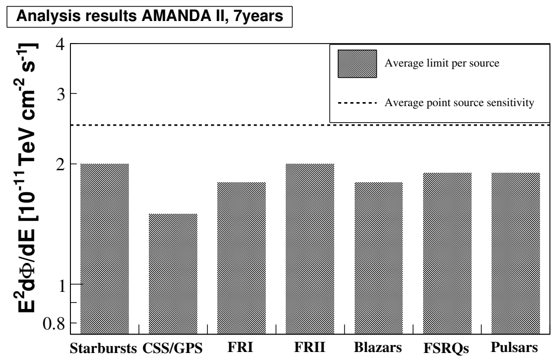

Fig. 3. Results of the AMANDA analysis: Differential neutrino flux limits per source class in units of $10^{-11}\,\mathrm{TeV}^{-1}\,\mathrm{s}^{-2}$ multiplied by E_ν^2. The dashed line shows the average point source sensitivity, the flux limits are improved for all source classes.

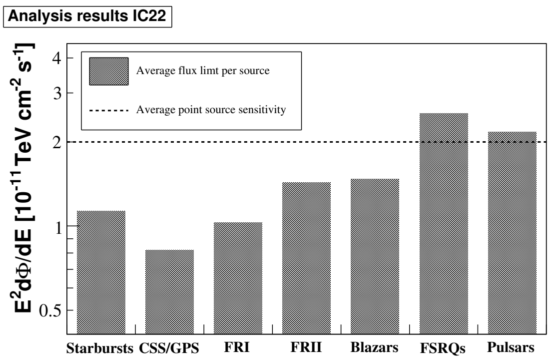

Fig. 4. Results of the IceCube analysis: Differential neutrino flux limits per source class in units of $10^{-11}\,\mathrm{TeV}^{-1}\,\mathrm{s}^{-2}$ multiplied by E^2. The dashed line shows the average point source sensitivity, the flux limits show an improvement for all source classes except the FSRQs and Pulsars.

IceCube-22 data sample, however, only for source classes where the selected number of sources is large enough. The IceCube detector is planned to be completed before February 2011. In the final configuration, it will consist of 86 strings, instrumenting 1 km^3 of Antarctic ice. The final configuration will be similarly symmetric as AMANDA-II, which will result in a source selection for a binned stacking analysis, which is basically independent of the location of the sources. A significant improvement of sensitivity compared to a binned single point source analysis is therefore expected. With IceCube, statistics for the stacked sources will be sufficiently high to perform the unfolding of the energy spectrum Abbasi et al. (2010), to look for significant deviations from the atmospheric spectrum for the stacked sources. The binned stacking search will be complemented by an unbinned search, which can further improve sensitivities, see Karle et al. (2009). Further, the southern hemisphere can be explored in a stacking approach at very high energies as described in Abbasi et al. (2009c). The improved techniques in combination with a more sensitive detector will give the opportunity to investigate the level of neutrino emission from different source classes, either by setting strong limits to the emission or by a detection.

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