

# IceCube: Multiwavelength Search for Neutrinos from Transient Point Sources

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**Abstract.** In this paper we discuss the strategy developed in order to associate neutrinos with their cosmic sources using historical light curves. Periods of very intense photon activity are selected through a novel analysis approach. The statistical method called *Maximum Likelihood Blocks* is applied for the first time on light curves of high frequency blazars. In order to avoid any possible bias in the selection of periods with intense photon activity, the arrival time and incoming direction of the neutrinos are kept blinded. Following the approach here reported, neutrino fluxes below the atmospheric neutrino background level can become accessible. We report as well on a first step to establish a target-of-opportunity program based on neutrinos detected in IceCube which are used as alerting messenger particles.

## 1. Introduction

We report here on the inclusion of the photon flux time evolution, measured in one or more photon wavebands, in the search for HE neutrino sources. We illustrate this approach by a discussion of blazars. In the framework of *hadronic models* [5, 6], blazars are HE neutrino sources and they are dominated by a highly variable component of non-thermal radiation [3]. Blazar broad-band spectra consist of two prevalent components which appear in the spectral energy distribution like two broad humps. The low-energy component can peak at various frequencies between optical and X-ray and the high-energy is proportionately shifted from X-rays up to very high energy (VHE)  $\gamma$ -rays. The synchrotron radiation coming from primary electrons as well as from electrons produced in proton-induced cascades contributes to the low-energy component. In hadronic models, high-energy radiation arises from photo-meson interaction and from proton and muon synchrotron radiation [6]. The  $\gamma$ -ray production by pion photo-production is accompanied by neutrinos, created in the decay of charged pions.

So, assuming that neutrino production follows the same time behaviour like the electromagnetic activity, the transient nature of the energetic emission can be used to improve the association between highly energetic neutrinos and non-thermal sources. If the enhancement of the neutrino signal is concentrated in a short period of time, neutrino flares not evident in a time-integrated point source search like the one reported in [1], might be detectable. A first analysis following this approach has been discussed in [7, 8]. In this paper, we concentrate on the statistical interpretation of measured light curves.

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## 2. Collection and Interpretation of Light Curves: Periods Selection

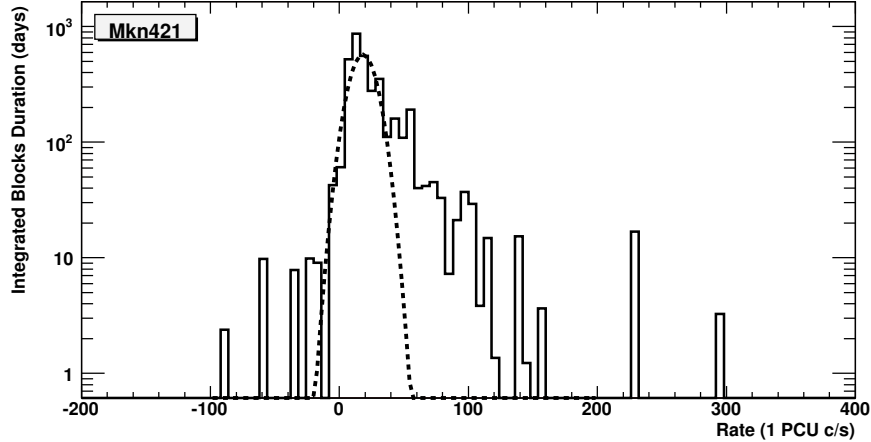
IceCube Collaboration has started a comprehensive collection of historical light curves. For now, most of our efforts are concentrated on X- and VHE  $\gamma$ -ray wavebands which corresponds to the two humps of the spectral energy distribution for high frequency blazar (HBL). The two instruments used for X-ray data are All-Sky Monitor (ASM) [9] and the Proportional Counter Array (PCA) installed on board of the Rossi X-ray Timing Explorer (RXTE). RXTE standard data products are collected directly from the HEASARC database and then transformed in *root* format. A large set of data has been collected by VHE  $\gamma$ -ray experiments [10]. Moreover, optical data has been as well taken for few sources and reported in [11].

In order to utilize the transient character of the electromagnetic emission for HE neutrino search, we have first to separate variable periods (*flares*) and steady state periods of a source. Periods of no variable activity are often defined in the literature as *quiescent* but an apparent *quiescent* level can be due to a superposition of numerous unresolved flares or to a limited sensitivity of the instrument [14]. We call the level of activity in which the source stays for the longest period of time its *characteristic* level. We do not attempt to interpret this level in phenomenological terms. Often data are affected by large uncertainties or the data spacing is rather inhomogeneous. In order to improve the interpretation of photon data, a simple and model-independent approach has been applied. The method aims at dividing the light curves in time intervals in which the source emission is compatible with a constant level. An algorithm based on Bayesian statistics that provides such a segmentation of data of different nature was presented in [13] and a modified version based on Maximum Likelihood was recently employed in studies of stellar X-ray light curves [14]. We will refer to this algorithm as the method of Maximum Likelihood Blocks (MLBs); its first application to blazars X- and VHE  $\gamma$ -ray light curves has been reported in [15].

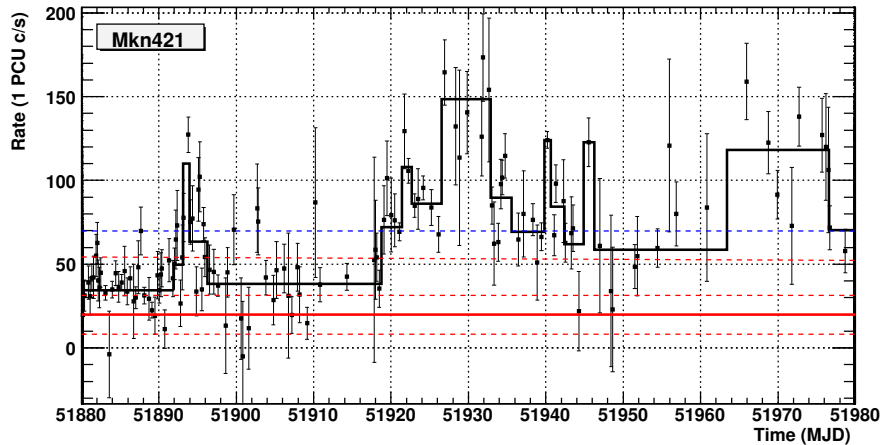
The MLBs sub-divides the light curve into constant-flux intervals or *blocks*. The confidence level at which the algorithm splits the light curve is given as input to the algorithm (in this work 99%). From this interpretation of the data we can extract various information about the source like the time a source pass in a particular activity state, if there are favorite flux levels and the periods in which the source is in *flare* state. For a visualization, the flux value of the single block is histogrammed and the duration of the block is used as a weight for the single entry. In Fig. 1, the histogram of ASM blocks are reported for the Mkn421 as example. The peak of the distribution is quite naturally interpreted as the *characteristic* level. The tail at higher flux values represent the flaring activity of the source; the tail at negative flux indicates measurement errors in the ASM data. Mean value and the standard deviation of a fitted Gaussian are then interpreted as the *characteristic* level  $R_{char}$  and  $\sigma_{char}$ , respectively. An example of such interpretation is shown in Fig. 2. With this interpretation of the light curve, the periods of time when the source is in *flare* can be selected requiring that the photon flux deviates from the characteristic level for a certain number of standard deviations. In this way, a uniform selection of *flares* is obtained on years-long light curves. A similar procedure applied on VHE data failed in the identification of a possible VHE  $\gamma$ -ray characteristic level. Nevertheless, an arbitrary flux threshold can be placed in order to select flaring periods on VHE light curves. Considerations about the VHE data are reported also in [10, 11].

A comparison of the time behaviour of different wave length bands may lead to a particularly interesting classification of periods for the neutrino search, as will be described below. Nearly simultaneous X- and VHE  $\gamma$ -ray data are collected from organized multi-wavelength campaigns. The time and flux correlation between the X- and  $\gamma$ -ray components have been investigated [12]. In most of the cases, a time-correlation between the two components has been observed as

expected in the framework of *leptonic models*. So called orphan flares, where an increasing TeV flux is not accompanied by an increase of the X-ray flux, have been seen in at least two sources: 1ES 1959+650 and Mkn 421. A study of the correlation between these two wavebands using the high statistic light curves collected is under way and results will be reported elsewhere.



**Figure 1.** Duration of maximum likelihood blocks for Mkn421, based on ASM flux. This represents the measurement of the integrated time a source stays at a given flux level. In particular, the flux of the peak is the flux level in which the source stays for the longest time and therefore corresponds to the characteristic level. Negative blocks are due to systematic errors in ASM.



**Figure 2.** Mkn421, sub-period of 100 days of ASM light curve (10 years total time of observation), blocks (99% C.L.). The continuous red line corresponds to the *characteristic level*  $R_{char}$ , the dotted line represent  $1 \sigma_{char}$  and  $3 \sigma_{char}$  deviation from  $R_{char}$ . The blue line corresponds to  $R_{char} + 5 \sigma_{char}$ . The X-ray units are normalized to 1 PCU count/second (1 Crab  $\approx$  3000 counts/sec/detector).

### 3. Toward a Multi-messenger Approach

The use of historical light curve to improve the search for HE neutrino sources is limited by the low duty cycle of  $\gamma$ -ray telescopes and rare long term observations. Neutrino telescopes, on the contrary, like IceCube are characterized by a very wide field of view and very high duty cycle. HE neutrinos are produced exclusively by hadronic mechanisms and are expected to be time-correlated with the related photon emission. In order to improve the synchronous measurement of both photons and neutrinos, the idea to develop a *hadronic* trigger or target of opportunity (ToO) using HE neutrino candidates has been born within the IceCube Collaboration [8]. The ToO under discussion concerns transient phenomena of particularly interesting targets, as well as unpredictable sudden astronomical events. HE neutrino candidates are reconstructed on-line at the South Pole as up-going muon tracks. Information on these events can be transferred north via satellite and, in principle, be used as the alert messengers for other telescopes. The technical realization of such alerts is under investigation and results are encouraging. The first telescope already reacting to neutrino ToO program is the MAGIC VHE  $\gamma$ -ray telescope. A test run started on September 27 (2006) is based on AMANDA data acquisition system and will last for a few months. The test is focused on technical aspects, such as the recording and real time reconstruction of the neutrinos at the South Pole, the reception of the triggers by MAGIC and the communication between the two instruments.

To date, no indication of HE cosmic neutrinos has been found in the performed analysis of AMANDA data. Contrary to other ToO programs, the alert in the case of the neutrino ToO is issued on the basis of a non clear detection. Non-trivial statistical issues related to the interpretation of possible coincidences are under careful investigation and will be reported elsewhere. Beyond that, once a significant accumulation of HE neutrinos will be observed in IceCube, the simultaneous photon data provided by ToO programs will lead to a mature phenomenological picture of the astronomical object observed.

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