

Neutrino Events at IceCube and the Fermi Bubbles

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Abstract. The IceCube Neutrino Observatory announced thirty-seven candidate events observed with deposited energies above ~ 30 TeV with three-year dataset, more than expected from atmospheric backgrounds. We discuss the detectability of the Fermi Bubbles (FB) by IceCube and show that up to 6 – 7 of the 37 events could originate from the FB. If the observed gamma rays from the FB are created due to baryonic mechanism, high-energy ($> \text{GeV}$) neutrinos should be emitted as a counterpart. These neutrinos should be detectable as shower- or track-like events at a Km^3 neutrino detector. For a hard primary cosmic-ray proton spectrum, $E^{-2.1}$, and cutoff energy at or above 10 PeV, the FB flux substantially exceeds the atmospheric backgrounds. For a steeper spectrum, $E^{-2.3}$, and/or lower cutoff energy, detection with high significance will require a longer running time.

1. Introduction

The IceCube Neutrino Observatory located at the South Pole, was designed to search for high energy neutrinos from extraterrestrial origin. IceCube recently found strong evidence for high energy astrophysical neutrino flux at the level of $10^{-8} \text{ GeV/cm}^2/\text{s/sr}$ in three years of data [1]. Except the first 28 neutrinos announced before [2, 3], an additional 9 neutrino candidates from the third year of data has been reported [1]. These total 37 events with observed energy of 30 TeV – 2 PeV more than expected background of 15 events from atmospheric muons and neutrinos, indicate a 5.7σ rejection of purely atmospheric hypothesis. Of these events, 9 are identified with visible muon tracks. The remaining 28 events are cascades or showers, caused by neutrino interactions other than ν_μ charged current.

The origin of these high energy neutrinos at IceCube is still mysterious [4]. Although the prompt atmospheric neutrino may contribute significantly with energy between 10 and 100 TeV [5, 6], the isotropic distribution of these events indicates astrophysical sources are the most natural explanation. Many scenarios have been discussed in the literature, including cores of active galactic nuclei [7, 8], γ -ray bursts [9] and their lower-powered counterparts [10, 11], galaxies with intense star-formation [12–14], active galaxies [15], flat-spectrum radio quasars [16] and intergalactic shocks [17]. Due to the weak cluster of events near the Galactic Centre, some analyses implied that Galactic sources may be responsible for a fraction of the signals [18, 19]. The IceCube events may originate from the Galactic Centre (GC) [20], the FB [21],

Galactic Halo [22], or Galactic plane [23, 24]. Some studies suggested that the origination could also be from PeV dark matter decay as well [25–27].

In this paper, we investigate the possibility that IceCube might be observing signals from the FB. The two gamma-ray bubbles, observed by Fermi-LAT [28], are symmetrically located above and below the Milky Way’s galactic center, extending up to 50° in Galactic latitude. These bubbles are mostly made of energetic gamma rays emanating from the galactic core. The origin of the FB is still unknown. There are two main hypothesis, the supermassive black hole activity [28] or high rate of star formation in the GC [29, 30]. The emitted gamma rays from the FB are produced either via leptonic model, which is the Inverse Compton scattering of low energy photons by highly relativistic electrons, or via hadronic model, i.e., decays of π^0 created from interactions of energetic baryons with gas in the FB. In the hadronic model, a neutrino counterpart with similar magnitude as gamma ray flux from the FB is produced [29, 31], which could be detected as muon tracks or showers at KM3NeT, ANTARES, or IceCube [31–33]. The ANTARES collaboration has placed an upper limit for this neutrino flux, as seen in figure 3 [32]. Later, we will quantitatively present the down-going muon track as well as shower events from the FB at IceCube, not only as a possible interpretation of IceCube events, but also as a prediction for future searches.

2. Neutrino Fluxes

The Fermi Bubbles are seen as extended sources in the southern sky, see figure 1, subtending a 0.808 sr solid angle [28]. Their gamma ray flux is fairly uniform over the extent of the bubbles [28], and it is expected the neutrino flux has the same feature [31]. We compare the coordinates of the 37 IceCube all-sky search events and their median angular errors [2] with the bubbles coordinates, see figure 1. Note that event 32 produced by a pair of background muons is not labeled in figure 1, because it cannot be reconstructed with a single direction and energy [1]. It appears at least 5 events, number 2, 12, 14, 15, 36 are strongly correlated with the FB whose central position values are inside the bubbles. In addition, events 17, 22, 24, 25, are weakly correlated with the FB whose values, within errors, are compatible with the bubbles. Among these 9 correlated events, event 14, has ~ 1 PeV deposited energy [2]. figure 2 displays the time correlation of these 8 events with errors on the observed energy.

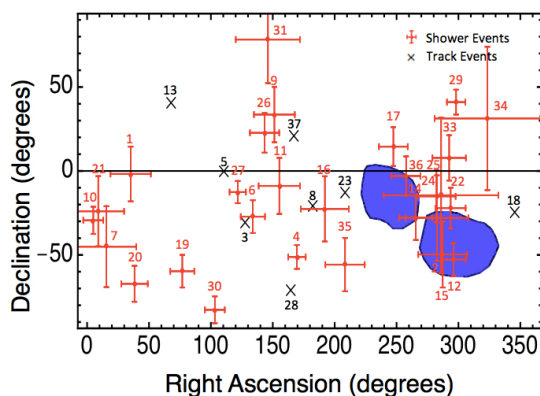


Figure 1. IceCube events distribution in equatorial coordinates, with their median angular errors, from [2]. The corresponding FB regions are shown with shaded contours.

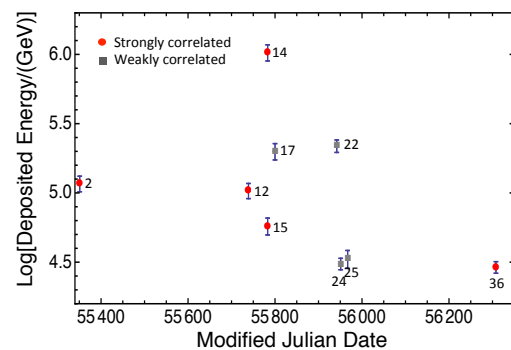


Figure 2. Events 2, 12, 14, 15, 17, 22, 24, 25, 36 (spatially correlated with bubble) are shown with errors on energy in modified Julian time and deposited energy distribution.

We adopt the FB neutrino fluxes from Ref. [31], to calculate the expected event rate at IceCube due to FB. In the model, the cosmic ray protons from supernova remnants are driven by the high velocity bipolar wind from galactic center to fill the bubbles. The neutrino fluxes are produced from the interactions of these cosmic rays with the ambient gas. This proton spectrum has the form of $dN/dE \propto E^{-k} \exp(-E/E_0)$, where E_0 is the cutoff energy, motivated by the maximum energy that accelerated protons may reach, varying from 1 - 100 PeV [34]. By fitting the gamma ray data of the FB, the spectral index $k = 2.1$ is taken as our default model; meanwhile, due to the limited number of gamma ray data points, a steeper spectrum with $k = 2.3$ is also compatible with observation, as seen in figure 3. These two sets of fluxes depending on E_0 differ significantly above ~ 200 GeV. The flux with cutoff energy of $E_0 = 30$ PeV is the most optimistic one, which is approximately 20% higher than the normalization of the whole flux, allowed by the uncertainty in the gamma ray data. The IceCube best-fit astrophysical flux of $E^2 dN/dE = 0.95 \times 10^{-8}$ GeV/cm²/s/sr is shown as well [1], see figure 3.

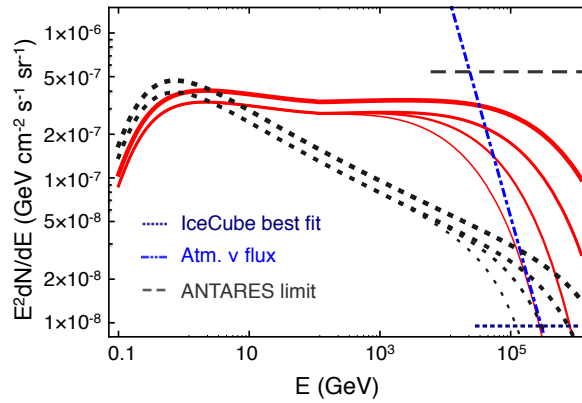


Figure 3. The pre-oscillated ν_μ and $\bar{\nu}_\mu$ flux from the FB, as a function of the energy, normalized to the gamma ray flux, for spectral indices $k = 2.1$ (solid, red) and $k = 2.3$ (dotted, black). For each index, the curves from thick to thin correspond to $E_0 = 30, 10, 3, 1$ PeV. The dash-dot curve presents the atmospheric neutrino flux [35] averaged over 25° - 95° zenith angle. The dotted line is the ANTARES upper limit [32]. The dashed line is the estimated IceCube best-fit diffuse flux expected for the FB region [2]. This figure has been taken from Ref. [36]

The neutrino fluxes initially produced at the FB of all flavors are in a composition of ν_μ : ν_e : $\nu_\tau = 2 : 1 : 0$. After oscillations, the flavor ratios are close to ν_e : ν_μ : $\nu_\tau = 1 : 1 : 1$, with deviations up to $\sim 30\%$ at $E \sim 1$ PeV.

The atmospheric muons and neutrinos are the two main backgrounds at IceCube, with an expectation of 8.4 and 6.6 events respectively for a 988-day running time [1]. The atmospheric muon level is depending on the detector veto, more details can be found in [2]. For the atmospheric neutrinos, we adopt the ν_μ flux model from Ref. [35], which is a good fit of IceCube's atmospheric data [37], extrapolated at high energies. In our calculation, we consider the flux to be symmetric in $\cos\theta_z$ [38], take the ν_μ / ν_e ratio of 14 [39], and neglect flavor oscillation due to the short propagation distance [40], as shown in figure 3.

3. Event Rate

The expected number of atmospheric neutrino backgrounds and signals for $k = 2.1, 2.3$ in 10 years, above the energy threshold E_{th} is estimated, as shown in figure 4. Taking into account of the angular resolution 1° and 10° for tracks and showers respectively at IceCube [2], we calculate

the number of atmospheric shower events over a larger solid angle than that of FB (0.808 sr). To do this, we encase each bubble in a rectangle in the θ and ϕ coordinates (see figure 1), and enlarge the area by 15° on each side. On the other hand, we take FB solid angle for track events, due to the angular resolution less than 1° . As seen in figure 4, the atmospheric shower (thick, dashed) and track (thin, dashed) events are comparable. This can be explained that the predominant atmospheric ν_μ flux compensates for the smaller effective area for tracks. For a harder spectrum ($k = 2.1$), the signal is above the background with cutoff energy $E_0 \gtrsim 10$ PeV. With $E_0 = 30$ PeV, the signal is approximately 2 orders of magnitude higher. For $E_{th} = 40$ TeV, we find 23 signals and 3 background events, indicating a $\sim 4\sigma$ excess due to the FB. It would be quite promising to discover the FB with the use of detailed statistical analyses of the spatial correlation. For $E_0 \sim 1$ PeV, the signal is even lower than the background for some thresholds, and with lower event rate as well. For a steeper spectrum ($k = 2.3$), even with $E_0 = 30$ PeV, the signal is still not significant, comparable to the background.

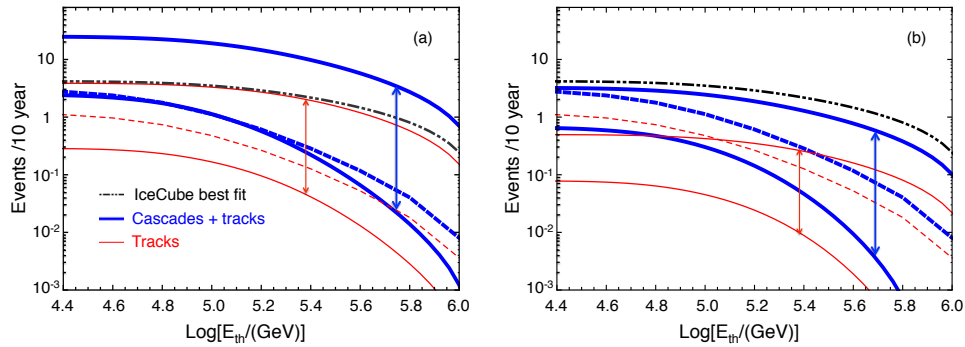


Figure 4. Expected number of events at IceCube for 10 years, as a function of energy threshold E_{th} , for the spectral indices of $k = 2.1$ (a) and $k = 2.3$ (b), from Ref. [36]. The total FB (atmospheric neutrino) signals of showerlike and tracklike events are presented as thick solid (dashed) curves. The tracklike FB (atmospheric neutrinos) signals are thin solid (dashed) curves. The arrows indicate the variation of the primary spectrum cutoff in the interval $E_0 = 1 - 30$ PeV. The estimated total showerlike and tracklike events from IceCube best-fit diffuse flux.

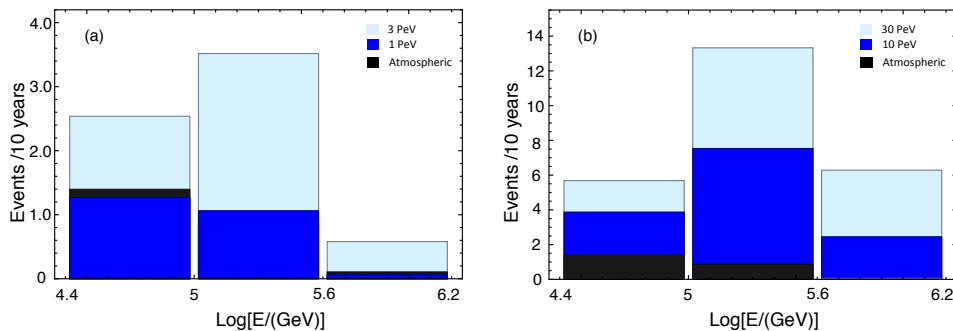


Figure 5. The expected number distribution of shower and track events per decade in each energy bin for atmospheric background and signal with $k = 2.1$ and cutoff energy $E_0 = 1, 3$ PeV (a) and $E_0 = 10, 30$ PeV (b), from Ref. [36].

The distribution of number of signal and background events per decade in neutrino energy bins is given in figure 5. As confirmed from figure 4(a), for $E_0 = 1$ PeV, the signal is comparable

Table 1. The expected number of shower and track events from the atmospheric background and from the FB in three neutrino energy bins, with different cutoff energy E_0 , for a 988-day IceCube livetime. The number of tracklike events are in brackets.

E (GeV)	$10^{4.4} - 10^5$	$10^5 - 10^{5.6}$	$10^{5.6} - 10^{6.2}$	Total
$E_0 = 1\text{PeV}$	0.34 [0.03]	0.29 [0.04]	0.02 [0]	0.65 [0.08]
$E_0 = 3\text{PeV}$	0.69 [0.07]	0.95 [0.14]	0.16 [0.03]	1.8 [0.24]
$E_0 = 10\text{PeV}$	1.05 [0.1]	2.04 [0.32]	0.66 [0.14]	3.75 [0.56]
$E_0 = 30\text{PeV}$	1.54 [0.15]	3.61 [0.57]	1.7 [0.35]	6.85 [1.08]
Background	0.38 [0.11]	0.24 [0.09]	0.03 [0.01]	0.64 [0.21]

to the background, and the most events are distributed in the energy of $10^5 - 10^{5.6}$ GeV due to the rise in the effective area below ~ 1 PeV [2].

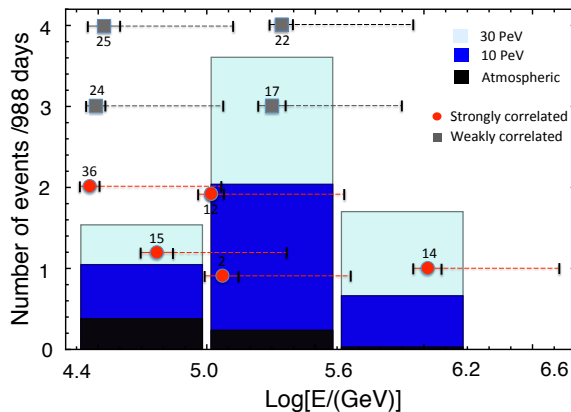


Figure 6. The same as figure 5(b) for the IceCube 988-day running time. Four strongly (red dot) and four weakly (grey square) correlated with the FB events at IceCube are shown. The solid and dashed error bars present the errors on the observed energy and a factor of $\sim 3-4$ difference between neutrino energy and deposited energy for neutral current events [41], respectively. Their coordinates on the vertical axis present the number of events for which the central value of the observed energy falls in the corresponding bins.

For comparison with IceCube data, we rescale the event rate with a 988-day running time [1], as seen in table 1 and figure 6. The total shower and track background events is less than one in the energy of $10^{4.4} - 10^{6.2}$ GeV. For $E_0 > 3$ PeV, it is expected more than 2 signals from FB with a livetime of 988 days. Especially, for $E_0 = 30$ PeV, $N \sim 5$ and $N \sim 2$ events are estimated below and above $E = 10^{5.6}$ GeV $\simeq 400$ TeV of neutrino energy respectively. Which is intriguingly close to the number of 5 events that has strongly spatial correlation to the FB.

4. Discussion

In this work, we present the possibility that IceCube may have detected the FB. With a hard spectrum and the most optimistic neutrino flux model $E_0 = 30$ PeV, we predict that up to 5 of IceCube observed events may due to the FB. Especially, 9 IceCube events are spatially correlated with the FB (figure 1), which might be the conservative upper limit for the number of events. To have a significant detection of the FB, the statistics not only depends on the backgrounds, but also on the level of the other neutrinos sources. However, as seen in figure 4, if with the most promising flux model, in seven to ten running years, the signals will be well identified.

The observation of a neutrino flux from the FB will provide clues to the mechanism of the FB, which will strongly support the hadronic origin of gamma rays from these structure. It will give a hint to the maximum limit of particle acceleration in supernova remnants, and to the time scale of the activity of the Galactic center as well.

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