Neutrino Astronomy and IceCube

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Understanding cosmic acceleration mechanisms, such as jet formation in black holes, star collapses or binary mergers, and the propagation of accelerated particles in the universe is still a 'work in progress' and requires a multi-messenger approach, exploiting the complementarities across all possible probes: ultra-high energy cosmic rays (UHECR), gamma-rays and neutrinos. In this report the IceCube results concerning searches for astrophysical neutrino point sources and diffuse fluxes from populations of sources widely distributed in the sky or from the GZK cut-off will be summarized. The results to other Neutrino Telescopes and to astrophysical models of neutrino production in sources will be compared.

1 Introduction

The IceCube Neutrino Observatory will be composed of a deep array of 86 strings holding 5,160 light sensors (PMTs) deployed between 1.45 and 2.45 km below the surface of the South Pole ice. The strings are typically separated by about 125 m with PMTs separated vertically by about 17 m along each string. IceCube construction started with a first string installed in the 2005–6 season and will be completed in the austral summer of 2010–11. Eight of the strings in the final detector, six of which use higher quantum efficiency PMTs with respect to the others, are at smaller spacing (about 70 m horizontally and 7 m vertically). Together with seven standard strings they make up DeepCore, designed to enhance the physics performance of IceCube below 1 TeV such as Dark Matter searches. The observatory also includes a surface array, IceTop, for extensive air shower measurements on the composition and spectrum of CRs. PMTs detect the Cherenkov light induced by relativistic charged particles passing through the ice sheet. Direction of events can be reconstructed using the time of hit PMTs and the amplitude as well, and the energy can be inferred exploiting the stochastic energy loss properties of muons and the charge measurement.

2 Astrophysical diffuse fluxes of neutrinos

Unlike gamma and proton astronomy, neutrino astronomy can access the entire universe, probe cosmological sources and sources opaque to photons. The generic neutrino and comic ray (CR) source can be envisaged as an engine that accelerates protons and possibly magnetic fields confine them in the accelerator region. If protons attain sufficient energy, they can interact with radiation and produce neutrons that can escape the accelerating region before interacting. Subsequently, neutron decay can give rise to the observed cosmic ray flux, gamma rays, and yet unobserved neutrinos. These conditions together define an optically thin source [1]. From

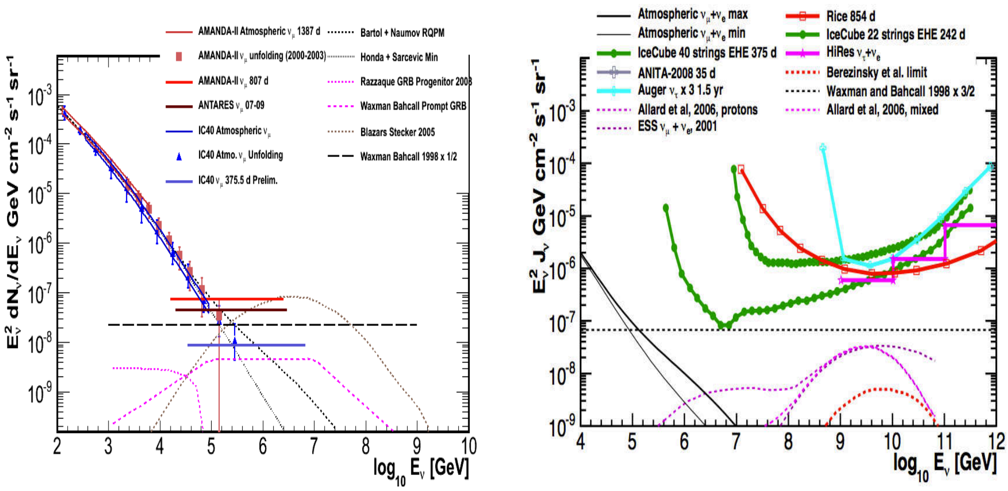

Figure 1: *On the left:* The measured flux of atmospheric $\nu_\mu + \bar{\nu}_\mu$ measured by AMANDA-II (squares) [4] and two independent analyses with 40 strings of IceCube (an unfolding of the spectrum - triangles [5] and a forward folding [6]) is compared to a combination of conventional (from π's and K's) and prompt (from charmed mesons) ν models that approximately indicate the theoretical uncertainty [7]. Horizontal lines are 90% c.l. upper limit to an E^{-2} muon neutrino flux for AMANDA-II [4] (807 d), ANTARES (334 d with 9-12 line configurations) [8] and 40 strings of IceCube (375.5 d). The WB limit [2] is shown together with some models on GRBs [2, 9] and an example of an AGN model [10] rejected at 5σ c.l. by the 40 string limit. *On the right:* 90%c.l. differential upper limits for experiments sensitive to all-ν flavors (for experiments sensitive to < 3 flavors the applied correction factor is given): PAO, HiRes, RICE [12] and IceCube (the 22 string limit and the preliminary 40 string one [11]) are shown. At low energies the region of predictions of $\nu_e + \nu_\mu$ is shown too [7]. At higher energy cosmogenic neutrino models are shown [13] and the limit on the cosmogenic neutrino flux (ankle model) calculated using the Fermi-LAT extragalactic γ-ray background [14].

the measured Ultra-High Energy CR (UHECR) flux above 10^{18} eV the power required for a population of sources to generate the energy density in CRs can be inferred. This hints to active galactic nuclei (AGNs) and gamma-ray bursts (GRBs) as best candidate sources. The result is the Waxman & Bahcall (WB) upper limit for optically thin sources shown in Fig. 1 (on the left). It is extrapolated to lower energies than the UHECR region assuming a proton injection spectrum of E^{-2} [2] resulting from Fermi acceleration mechanism in shocks and $p-\gamma$ interactions that produce a Δ-resonance. The limit also assumes that magnetic fields in the universe do not affect the observed CR spectrum. It has been divided by a factor of 2 to account for mass neutrino oscillations. The upper bound applies as well to $p - nucleon$ interactions since it is likely that the energy fraction of the protons transferred to pions is even less than for $p-\gamma$ [2] but can be much higher at lower energies than 10^{16} eV assuming a 10% contribution of an extragalactic source of protons between the measured galactic component. The experimental limits exclude this option. It should be noted that if the injected CR spectrum from extragalactic sources include heavier nuclei than protons, then the upper bound and the cosmogenic neutrino fluxes [13] would be lower than for the assumed proton case [3].

A search dedicated to EHE events has been performed using the data of 333.3 d of 22 strings of IceCube and 375.5 d of 40 strings [11]. Upper limits are shown in Fig. 1 (on the right). Models predict between 2 and 24.5 neutrino events (WB upper bound with z evolution of sources [2]) in 3 yrs of the full detector. The search uses a zenith dependent cut of the total charge released in the detector.

3 Searches for Point Sources and Dark Matter

An unbinned likelihood method that compares the signal and the signal plus atmospheric muon and neutrino background hypotheses has been applied to look for emissions of neutrinos from point like sources. The method uses the reconstructed direction and energy of events and can use also time for time-dependent emission searches [15]. As a matter of fact events would cluster around the point source with an error that we measure to be less than $1.2°$ for 50% of the events with $E_\nu \in [10, 100]$ TeV and less than $0.6°$ for 50% of the events with $E_\nu \in [1, 10]$ PeV. Moreover, as discussed above, neutrino signal from sources is expected to have a harder spectrum ($\sim E^{-2}$) compared to atmospheric muon and neutrinos produced in the meson decays in atmospheric showers ($\sim E^{-3.7}$ for $\gtrsim 500$ GeV).

The search for the 40 string configuration has been conducted on a data sample of 36,900 events collected during 375.5 d of livetime: 14,121 from the northern sky, mostly muons induced by atmospheric neutrinos and 22,779 from the southern sky, mostly high energy atmospheric muons. A zenith-dependent energy proxy cut has been implemented to prevent that the large background of atmospheric muons overwhelms the IceCube sensitivity to hard-spectrum neutrino sources in the southern sky in the sub-PeV energy region. The sensitivity is at least a factor of two better than previous searches (depending on declination), with 90% c.l. muon neutrino flux upper limits between $E^2 dN/dE \sim 2 - -200 \times 10^{-12}\mathrm{TeV\,cm^{-2}\,s^{-1}}$ in the northern sky and between $3 - -700 \times 10^{-12}\mathrm{TeV\,cm^{-2}\,s^{-1}}$ in the southern sky. A comparison with some models is shown in Fig. 2 (on the left).

The absolute pointing has been confirmed by the Moon shadow detection, initially reported in [16], at the level of 6.76σ for 14 lunar cycles during the 40-string configuration.

Indirect detection of neutrinos from the annihilation of dark matter eventually trapped in celestial bodies like the Sun is extremely promising. Being the Sun rich in H the limits set by IceCube are of interest with respect to direct detection experiments (see Fig. 2 on the right). While the limit begins to touch the region of the MSSM not excluded by direct detection experiments, IceCube with DeepCore will probe an interesting fraction of the parameter space.

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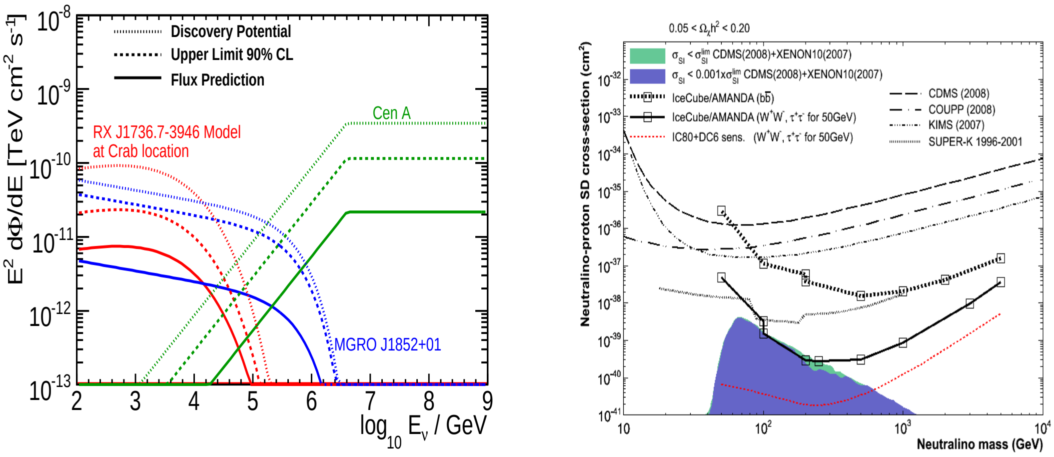

Figure 2: *On the left:* Differential flux for three theoretical models shown with the IceCube 40-string upper limit (90% CL) and discovery potential in each case. Shown are the ν_μ predictions of for SNR RX J1713.7-3946 but moved to the location of the Crab Nebula, for MGRO J1852+01, and for Cen A with the optimistic condition that protons have a spectral index $\alpha_p = 3$ (references in order in [17]). *On the right:* 90% c.l. limits on the spin dependent p-neutralino cross section in the Sun vs the neutralino mass for the 22 string configuration summed to the AMANDA-II result for two annihilation channels. The darkened regions represent MSSM parameter scans. All references for other experiments and the description of IceCube analysis are in [18].

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