ICECUBE AS A DISCOVERY OBSERVATORY FOR PHYSICS BEYOND THE STANDARD MODEL

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Construction of the cubic-kilometer neutrino detector IceCube at the South Pole has been completed in December 2010. It forms a lattice of 5160 photomultiplier tubes monitoring a gigaton of the deep Antarctic ice for particle induced photons. The telescope is primarily designed to detect neutrinos with energies greater than 100 GeV from astrophysical sources. Beyond this astrophysical motivation IceCube is also a discovery instrument for the search for physics beyond the Standard Model. Owing to subfreezing ice temperatures, the photomultiplier dark noise rates are particularly low which opens up tantalizing possibilities for particle detection. This includes the indirect detection of weakly interacting dark matter, direct detection of SUSY particles, monopoles and extremely-high energy phenomena.

1 Introduction

The physics questions that can be addressed with neutrino telescopes are manifold. They cover the internal mechanisms of cosmic accelerators, the cosmological evolution of sources, particle physics at center of mass energies far beyond the TeV scale and the search for new particles and physics beyond the Standard Model.

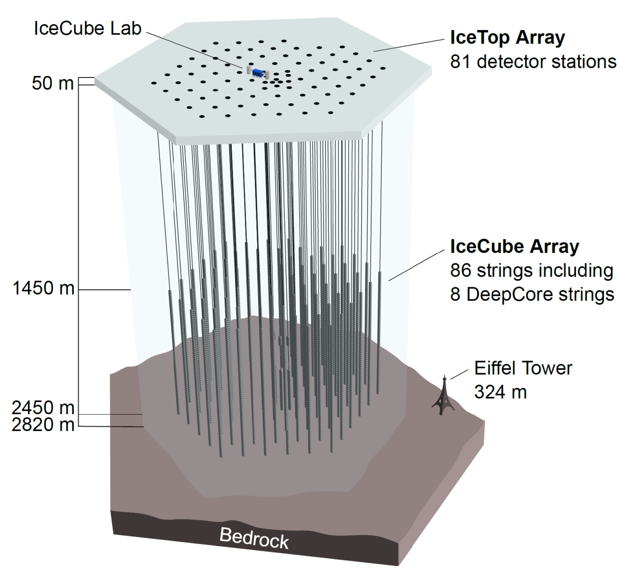

Figure 1: The IceCube observatory.

1.1 The detector

The IceCube Neutrino Observatory at the geographic South Pole has been completed in December 2010. The detector comprises 5160 digital optical modules (DOMs) deployed in a three-dimensional array approximately one cubic-kilometer in size and centered 2 km deep in the clear Antarctic ice (Fig. 1). Each DOM consists of a photo-multiplier tube and electronics for digitization of waveforms and communication with neighboring DOMs and the

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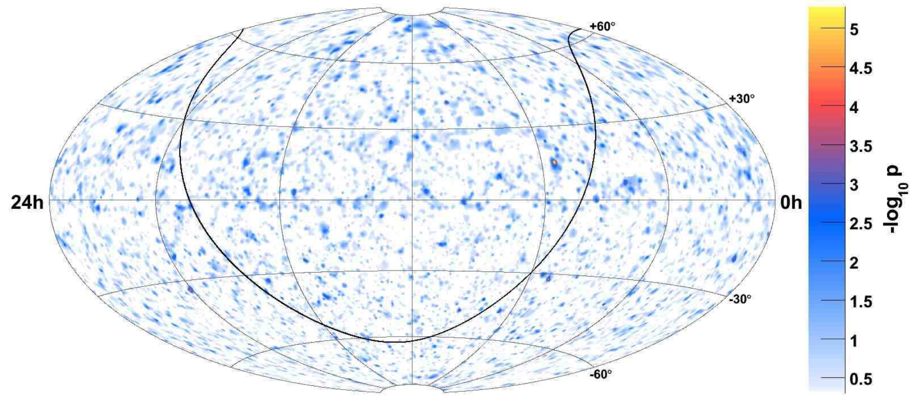

Figure 2: Equatorial skymap (J2000) of pre-trial significances (p-value) of the all-sky point source scan. The galactic plane is shown as the solid black curve.

surface. Cherenkov light from the passage of a relativistic charged particle through the ice creates a pattern of "hit" DOMs in the array, and the position and timing of the hits is used to reconstruct the path of the particle.

The vast majority of these particles are muons, arriving from cosmic ray air showers occurring in the atmosphere above the site. IceTop, the surface component above IceCube, is an air shower array with an area of 1 km^2 at a height of 2830 m above sea level. It consists of 162 ice Cherenkov tanks, grouped in 81 stations. IceTop is primarily designed to study the mass composition of primary cosmic rays in the energy range from about 10^{14} eV to 10^{18} eV by exploiting the correlation between the shower energy measured in IceTop and the energy deposited by muons in the deep ice.

2 Astronomy

2.1 Neutrino sky

IceCube's principal mission is to detect high energy neutrinos from astrophysical sources. Ultra-high energy cosmic ray (UHECR) experiments have shown that particles with energies up to a few times 10^{20} eV arrive at Earth. Since the cosmic rays are hadrons also ultra-high energy (UHE) neutrinos should be produced at these cosmic accelerators. These neutrinos propagate undeflected through galactic and inter-galactic magnetic fields and their measurement allows to point back to the source. Due to the low predicted neutrino fluxes, target masses of cubic kilometers of water or ice need to be instrumented with photomultiplier tubes for detection of these neutrinos.

The detection principle for high energy neutrinos is the measurement of the Cherenkov light in transparent media which is emitted by charged leptons produced in neutrino interactions in and around the detector. The most promising detection channel is muons since muons can propagate up to several kilometers through the medium. The results of an all-sky scan [1] performed with the half-completed IceCube detector (IC40) are shown in the map of the pre-trial p-values in Fig. 2. The most significant deviation from background is located at 113.75° r.a., 15.15° dec. The best-fit parameters are 11.0 signal events above background, with spectral index $\gamma = 2.1$. The pre-trial estimated p-value of the maximum log likelihood ratio at this location is $5.2 \cdot 10^{-6}$. In trials using data sets scrambled in right ascension the resulting post-trial p-value was found to be 18% – consequently, the excess is not claimed. While no TeV neutrinos from astrophysical sources have been identified yet unambiguously, the partially completed IceCube detector has

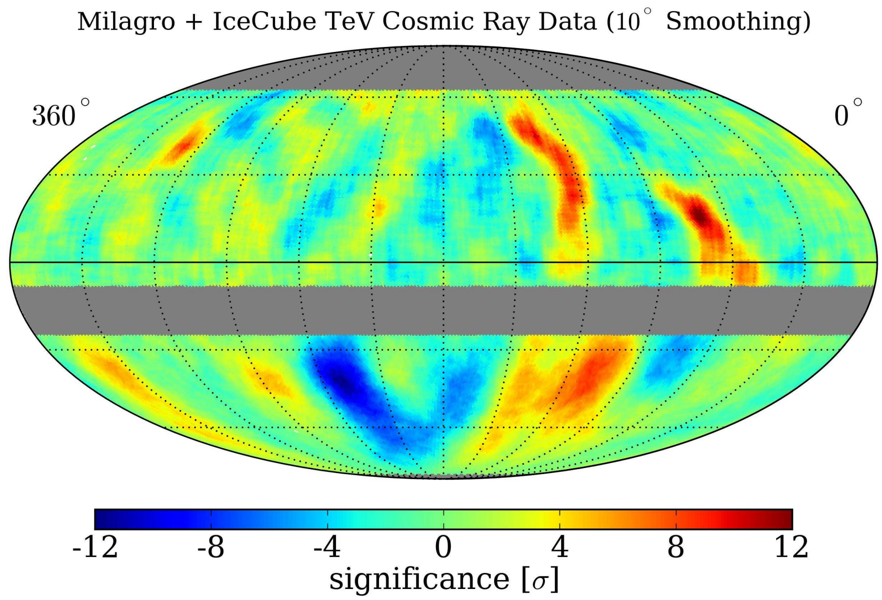

Figure 3: Combined map of significances in the cosmic ray arrival direction distribution observed by Milagro in the northern hemisphere and IceCube in the southern hemisphere.

set the most stringent upper limits to date.

2.2 Cosmic rays

Between May 2009 and May 2010, the IceCube neutrino detector consisted of 59 data taking strings recording 32 billion muons. The muons are generated in air showers produced by cosmic rays with a median energy of 20 TeV. With this data the southern sky was probed for per-mille anisotropies in the arrival direction distribution of cosmic rays. The arrival direction distribution is not isotropic, but shows significant structure on several angular scales [3]. In addition to a large-scale structure in the form of a strong dipole and quadrupole, the data show small-scale structures. Fig. 3 shows the combined skymap of significances in the cosmic ray arrival direction distribution observed by Milagro in the northern hemisphere [2] and IceCube in the southern hemisphere on scales between 15° and 30°. It exhibits several localized regions of significant excess and deficit in cosmic ray intensity. The most significant excess is localized at right ascension 122.4° and declination −47.4° and has a post-trials significance of 5.3σ. The origin of this anisotropy is unknown.

3 Searches for non Standard Model particles

Supersymmetry (SUSY) is currently the most extensively studied amongst theories beyond the Standard Model (SM). The most direct constraints on SUSY particle masses have been obtained at LEP and the Tevatron. While cryogenic dark matter detectors presently have the best sensitivity for spin independent WIMP-nucleon scattering, indirect searches with IceCube constrain the spin-dependent cross-sections for neutralino-proton scattering.

Direct detection channels for SUSY particles are only now being investigated with the parameter space being largely complementary to that covered by LHC experiments and WIMP searches – especially in scenarios where the gravitino is the lightest SUSY particle. Also, studies of high light yield exotic signatures from particles like magnetic monopoles have been performed.

3.1 Indirect WIMP searches

A search for muon neutrinos from neutralino annihilations in the Sun has been performed with the combined data set of AMANDA and IC22. No excess over the expected atmospheric background has been observed. Upper limits have been obtained on the annihilation rate of captured neutralinos in the Sun and converted to limits on the WIMP-proton cross-sections. These results are the most stringent limits to date on neutralino annihilation in the Sun. In Fig. 4 the limits on the spin-dependent WIMP-proton cross-section are compared with direct search experiments [5,6,7] and Super-K [8]. Soft WIMP models (annihilation into $b\bar{b}$) are indicated by the dashed lines, whereas hard models (W^+W^-) are shown in solid lines. Our limits also present the most stringent limits on the spin-dependent WIMP-proton cross-section for neutralino masses above 100 GeV. The full IceCube detector with the densely instrumented DeepCore extension is expected to test viable MSSM models down to 50 GeV. IceCube is also able to constrain the dark matter self-annihilation cross section by searching for a neutrino signal from the Galactic halo [9].

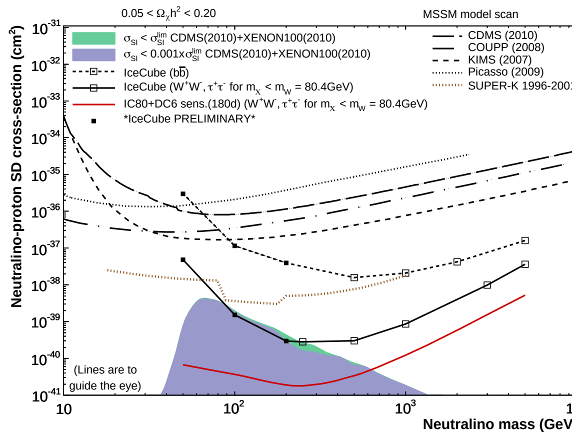

Figure 4: Limits on the spin-dependent WIMP-proton cross-section.

3.2 Direct SUSY searches

The main phenomenological features of SUSY models arise from the choice of the symmetry breaking mechanism. Within the minimal supersymmetric extension of the Standard Model (MSSM) the most extensively studied mechanisms are gravity mediated supersymmetry breaking and gauge mediated supersymmetry breaking. In both scenarios the gravitino may be the lightest supersymmetric particle (LSP). This scenario however, has not been widely addressed at collider experiments (except in terms of future concepts) and also WIMP searches usually assume the neutralino to be the LSP. In that respect a direct search for SUSY with the gravitino being the LSP is complementary to both ongoing collider experiments and also to indirect searches.

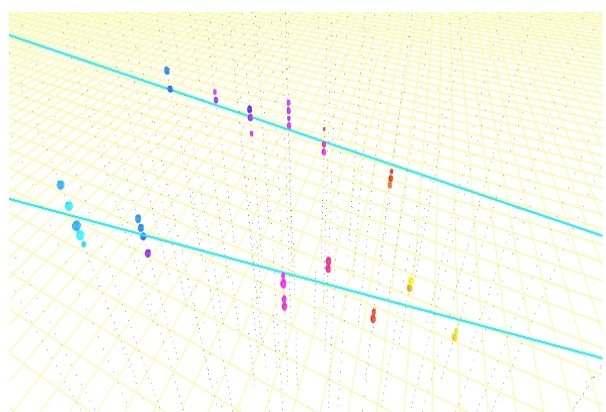

Figure 5: Two faint tracks in IceCube from a simulation of parallel staus

In models where the lightest supersymmetric particle (LSP) is the gravitino, typically the next to lightest SUSY particle (NLSP) is a long lived meta stable slepton (typically a stau). Being charged the stau is detected by its Cherenkov radiation in the neutrino telescope. Staus have a small cross section for interactions with "normal" matter. In interactions in the Earth of cosmic neutrinos of typically PeV energies and above SUSY particles can be produced which eventually decay into a pair of staus. This pair of staus of a few hundred GeV mass can propagate through the whole Earth [10], leaving the very distinct signature of two parallel, up-going tracks separated by several hundred meters when they pass a neutrino telescope (see Fig. 5).

This detection signature is quasi background free: Because of the down-going nature of air shower events, the up-going double stau tracks are distinguishable e.g. from the high-p_T muon events. Upgoing muon pairs can be created in neutrino-nucleon interactions in the earth involving charm production and decay [11]: $\nu N \rightarrow \mu H_c \rightarrow 2\mu\nu_\mu H_x$. The track length of these muons is however much shorter than that of staus. Hence their track separation is smaller as they need to be produced closer to the detector. Algorithms to identify such stau signatures are currently being developed for IceCube based e.g. on the track separation and the low brightness.

3.3 Magnetic monopoles

Generally, cosmic rays and the big bang are the most likely sources of massive monopoles, since accelerator energies are likely insufficient to produce them. The predictions for the mass and charge of monopoles depend strongly on the choice of the unified group and its symmetry breaking pattern in the early Universe. The non-observation of the partner to electric charges may be explained by inflation diluting the primordial monopole abundance.

Monopole detectors have predominantly used either induction or ionization and Cherenkov radiation. Ionization experiments rely on a magnetic charge producing more ionization than an electrical charge with the same velocity. The MACRO and Ohya experiments are examples for the ionization technique [12,13].

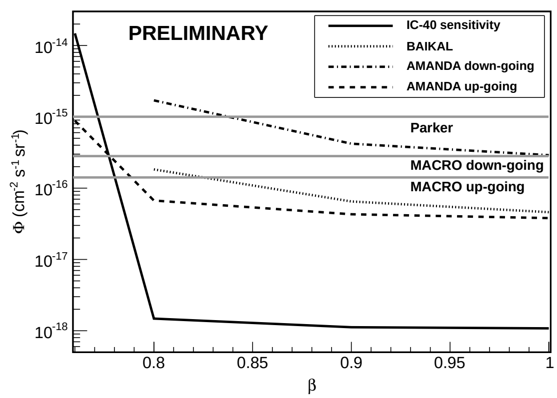

Figure 6: Monopole limits and the expected sensitivity of the half completed IceCube.

Large scale Cherenkov telescopes deployed in naturally occurring transparent media like sea water or glacial ice can detect magnetic monopoles with both the ionization and Cherenkov radiation from magnetic monopoles: For relativistic monopoles moving at a speed above the Cherenkov threshold the light yield is excessive (several thousand times more) compared to Standard Model particles. But even at velocities below the Cherenkov threshold monopoles are observable through delta rays and ionization, again exceeding the light yield of other particles of the same velocity. Moreover, some GUT theories predict that monopoles catalyze the decay of nucleons which would be observed by a series of light bursts produced along the monopole trajectory.

Searches for relativistic monopoles with Cherenkov neutrino telescopes have already been performed with the AMANDA and BAIKAL detector and are being investigated with the IceCube detector [14,15]. Fig. 6 shows that sensitivities well below the so called Parker bound [16,17] have been reached for relativistic monopoles. Parker pointed out that the abundance of magnetic monopoles cannot be as high as to deplete galactic magnetic fields. Strategies to identify non-relativistic monopoles in IceCube are currently being developed. In conclusion, IceCube is entering the interesting region of sensitivities for monopole searches spanning a wide range of relativistic and sub-relativistic velocities.

4 Extremely-high energy neutrinos

Cosmogenic neutrinos may give a unique picture of the Universe in the highest energy regime. With the Greisen-Zatsepin-Kuzmin (GZK) process the highest energy cosmic-rays interact with the cosmic microwave background producing these neutrinos [19,20]. Hence, cosmogenic neutrinos carry information about the sources of the highest energy cosmic-rays, such as their location, cosmological evolution, and cosmic-ray spectra at the sources.

On the other hand, tiny departures from Lorentz invariance have effects that increase rapidly with energy and can kinematically prevent cosmic-ray nucleons from undergoing inelastic collisions with CMB photons. With charged cosmic-rays alone it is impossible to differentiate between a true GZK cutoff or the fading spectrum of cosmological accelerators.

Underground neutrino telescopes, such as IceCube, can detect EHE neutrino interactions through the strong Cherenkov radiation emitted by the charged secondary particles. In a neutrino telescope, an EHE neutrino interaction is identified by the extremely high number of Cherenkov photons deposited in the detector. Fig. 7 shows the search for neutrinos with energies above 10^{15} eV using data collected with the half-completed IceCube detector in 2008−2009 [18]. Our limits are competitive up 10^{19} eV.

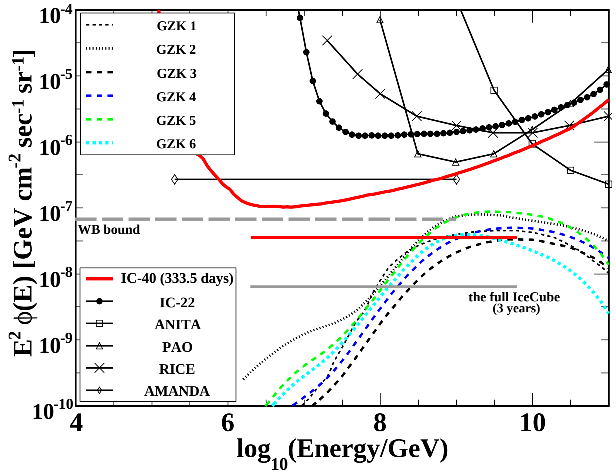

Figure 7: Quasi-differential model-independent 90% CL limit normalized by energy decade and E^{-2} spectrum integrated limit on all flavor neutrino fluxes from the 2008-2009 IceCube EHE analysis (red solid lines). The systematic errors are included. Various model predictions (assuming primary protons) are shown for comparison.

4.1 Extensions of IceCube

Besides the GZK process, neutrinos at ultra-high energies are also a valuable tool to study the neutrino-nucleon cross section at high center of mass energies. For energies above 10^{16} eV the Standard Model cross section rises roughly with a power law $\sigma_{SM} \propto E_\nu^{0.36}$ in the energy of the neutrino [23]. Naively, the cross section for black hole creation scales with the Schwarzschild radius $\sigma_{BH} \propto r_S^2 \propto E_{cm}^2 \propto E_\nu$ eventually exceeding the Standard Model processes. For a more refined discussions also addressing extra dimensions see for example [24].

The detection of the small neutrino flux predicted at the highest energies (E $>$ 10^{17} eV) requires detector target masses of the order of 100 gigatons, corresponding to 100 km^3 of water or ice. The optical Cherenkov neutrino detection technique is not easily scalable from the 1 km^3-scale telescopes to such large volumes. Several techniques have been studied to realize such huge detection volumes. Radio Cherenkov neutrino detectors search for radio Askaryan pulses in a dielectric medium as the EHE neutrino signature [21]. Acoustic detection is based on the thermo-acoustic sound emission from a particle cascade depositing its energy in a very localized volume causing a sudden expansion that propagates as a shock wave perpendicular to the cascade [22].

Within IceCube the properties of the South Pole ice for acoustic [25,26,27] and radio [28] detection have been studied with respect to signal attenuation, refraction and the noise environment . The results turn out to be very favorable promising longer signal attenuation lengths than for the optical detection, allowing for a sparse instrumentation of the Antarctic ice. Consequently, the installation of a 80 km^2 radio array dubbed ARA has commenced [30]. Studies to augment the radio detection with acoustic sensors show that it may be possible to bootstrap detection strategies for the large effective volumes by building a hybrid detector [29]. A signal seen in coincidence between any two of the three methods (radio, acoustic, optical) would be unequivocal. The information from multiple methods can also be combined for hybrid reconstruction, yielding improved angular and energy resolution.

Another addition pursued is the RASTA detector which will complement the IceTop air-shower detector with an extended surface array of radio antennas [31]. Besides the additional capabilities for cosmic-ray composition studies, this combination also enhances IceCube's optical high-energy neutrino sensitivity by vetoing the air-shower background.

Acknowledgments

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