

Neutrino astronomy with the AMANDA and IceCube detectors

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Abstract

IceCube is a 1 km³ neutrino detector which is now under construction at the South Pole. IceCube will search for neutrinos from astrophysical sources, with energies from 100 GeV up to 10¹⁹ eV. In addition to detecting astrophysical neutrinos it will also search for neutrinos from WIMP annihilation in the Earth and the Sun and look for low-energy (MeV) neutrinos from SuperNovae. AMANDA, the predecessor of IceCube, has been taking data in its final configuration since 2000. This smaller detector has a denser spacing of optical modules and is therefore sensitive to neutrinos of lower energies. Results will be shown from the analysis of 7 years of AMANDA data and from preliminary analyses of data taken with IceCube in 2007, in its configuration with 22 strings. In the near future, AMANDA will be replaced by the Deep Core detector, a purpose-built, low-energy extension of IceCube.

1 Introduction

Astronomical observations traditionally exploit a wide range of the wavelengths of the electromagnetic spectrum. Photons are abundantly produced in astrophysical processes, and relatively easy to detect. However, they are absorbed by interstellar matter and in interactions with infrared radiation or the cosmic microwave background and therefore do not reach us from the interior of stars or from far away regions of the universe. Gamma rays with TeV energies travel distances of about 100 Mpc, but at PeV energies they barely reach us from the edge of our galaxy.

High-energy cosmic rays constitute another probe of the universe. Cosmic rays consist mostly of protons with a small admixture of helium and heavier nuclei [1]. They were discovered by Victor F. Hess in 1912 [2] and since then have been studied extensively with space-borne and ground-based detectors. At a given energy the range of protons is larger than that of photons. However, protons are deflected by the intergalactic and interstellar magnetic fields and the information on the direction back to their sources is lost. Figure 1 shows the measured all-particle cosmic-ray energy spectrum, extending over more than 30 decades out to about 10²⁰ eV. The feature around 5×10^{15} eV is called the ‘knee’ and indicates a change in slope from $E^{-2.7}$ to $E^{-3.1}$. A flattening called the ‘ankle’ is observed at about 3×10^{18} eV. A cut-off is finally expected because of interactions with the cosmic microwave background radiation (CMB). For protons this occurs through the resonant reaction $p + \gamma \rightarrow \Delta^+ \rightarrow N + \pi$. For nucleons, the so-called Greisen–Zatsepin–Kuzmin (GZK) cut-off [3] is around 5×10^{19} eV. Although all Ultra High Energy Cosmic Ray (UHECR) experiments have detected events of energy above 10²⁰ eV, the spectral shape above the ankle is still not well determined [4].

Considering the broken power-law shape of the cosmic-ray energy spectrum, it is commonly believed that the mechanisms causing the acceleration of these charged particles might be connected to diffuse shock phenomena, with different types of sources contributing to fluxes with different spectral indices. Enrico Fermi realized that charged particles crossing back and forth over a moving shock-front can get accelerated to very high energies due to stochastic scattering processes of moving magnetized plasma-clouds, and showed that the resulting energy spectrum follows a power law [5]. It is generally assumed that cosmic rays in the energy range below the knee are of galactic origin, accelerated in shocks originating in supernova explosions. For energies above the knee, galactic magnetic fields are not strong enough to confine the cosmic rays and it is likely that the sources of these particles are to be found beyond the Milky Way. Actually, at the very highest energies proton astronomy might be possible since

the magnetic deflection decreases with energy. Unfortunately, these protons are extremely rare (fewer than 1 per km² per year) and their range is limited by the GZK cut-off. In November 2007, however, the Auger Collaboration reported [6] a correlation of the arrival directions of the highest energy cosmic rays with Active Galactic Nuclei (AGN) at distance less than 75 Mpc. Twenty of 27 events with energy above 6×10^{19} eV arrive at an angle less than 3.1° from the position of a nearby AGN.

High-energy neutrinos emerge as extremely interesting cosmic messengers. Unaffected by intergalactic magnetic fields and weakly interacting, neutrinos should be able to penetrate regions opaque to protons and photons, and point straight back to their sources. They are the only available long-range directional carrier of information about the origin of cosmic rays. There are many potentially interesting astrophysical sources of high-energy neutrinos. Extra-galactic objects like AGN or Gamma Ray Bursts (GRB), and galactic objects like micro-quasars or SuperNova Remnants (SNR), are characterized by the presence of violent shock waves in which particles are accelerated. Ultra-high energy (UHE) neutrinos originate in decays of pions and kaons produced when protons, accelerated to ultra-high energies by these ‘cosmic accelerators’, interact with radiation or matter in the vicinity of the sources. For these processes one expects the neutrino spectrum to follow a power law of the form $dN/dE \sim E^{-2}$.

For the detection of neutrinos with energies in the TeV to EeV range observatories of cubic kilometre scale are needed. Pioneering experiments like BAIKAL [7] demonstrated the detection technique, while prototypes such as AMANDA [8] and ANTARES [9] are exploring the possibilities of using Antarctic ice or deep water to build large telescopes reaching astrophysical sensitivity. With the construction of IceCube going on, the technological obstacles confronting cubic-kilometre neutrino detectors have been overcome, and high-energy astrophysics enters an era of opportunity and discovery, as the sensitivity of the detectors approaches astrophysically relevant fluxes.

2 The AMANDA and IceCube detectors

The IceCube detector at the South Pole [10] is the largest neutrino detector in history. Its mission is the observation of high-energy neutrinos from extra-terrestrial origin. The detection of muon neutrinos is based on the measurement of the track of the muon produced when the neutrino interacts through a charged current (CC) process in or just below the instrumented volume. Electron and tau-neutrinos will yield cascade-like events. For very-high-energy tau-neutrino events the neutrino interaction is far enough from the tau-lepton decay vertex and a double-bang structure is observed. At relativistic energies the charged lepton produces Cherenkov light along its path. This light pattern is recorded by an array of photomultiplier tubes. The arrival times of the Cherenkov photons determine the direction and angle of the muon, while the number of photons registered is related to the muon energy.

The IceCube design employs 80 uniformly distributed strings, each one equipped with 60 digital optical modules (DOMs) (Fig. 2). The DOMs are installed in the Antarctic ice-cap at depths between 1.5 and 2.5 km. The strings are placed at distances of 125 m from each other, matching the light absorption length of about 100 m. In 2008, data were taken with 40 strings, while in the 2008/2009 austral summer 19 more strings were deployed. The full completion of the detector is foreseen for early 2011.

The AMANDA detector [8], (Fig. 2), the predecessor of IceCube, is completely embedded in IceCube, and contains 677 optical modules spread over 19 strings of 500 m length. AMANDA was deployed in several phases, and during 1997 and 1999 it consisted of between 10 and 13 strings (AMANDA-B10 detector). AMANDA has been taking data in its final configuration since 2000. Because of the denser spacing of optical modules, AMANDA has a lower threshold, of the order of 30 GeV.

The third component of the detector is IceTop [10], (Fig. 2), an air shower array located at the surface of the ice-cap. IceTop uses the same DOMs as the in-ice device, and consists of four DOMs in two ice tanks on top of each IceCube string. Combining IceTop data with data from the in-ice array allows the study of the cosmic-ray composition on the region of the ‘knee’ (Fig. 1), extending earlier measurements performed with the AMANDA and SPASE detectors [11].

The expected high-energy neutrino signal rates are of the order of a few (tens) events per km² per year. The detector will trigger mainly on atmospheric muons originating in the Southern sky (downgoing muons), and muons induced by atmospheric neutrinos originating in the Northern sky (upgoing neutrino-induced muons). The atmospheric muons originating in the Northern sky will be absorbed by the Earth. In order to reduce the sensitivity for downgoing atmospheric muons, the DOMs are placed with the sensitive cathode oriented towards the bottom of the detector. The IC40 trigger rate is around 1300 Hz, while the data volume amounts to a few 10⁹ events per year, corresponding to about 10 Tbyte.

IceCube is being deployed in deep clear ice, where the absorption length is around 100 m and the scattering length ranges from 20 m to 40 m. Vertically the ice is characterized by different dust layers related to climate changes in the last glacial period in the late Pleistocene. Knowledge of the dust concentration is essential to model the detector response in the simulation. For this purpose the PHOTONICS software package [12] was developed.

3 Main results

IceCube is designed to identify and reconstruct all three flavours of neutrinos: ν_μ , ν_e , and ν_τ . Figure 3 shows examples of these three topologies. The events are reconstructed using algorithms designed to select these events based on their different topologies: long tracks for muons, blob-like cascade events, τ double-bang events, etc. Here we shall focus on muon reconstruction. The reconstruction of muon tracks is performed on the basis of the arrival times of the light signals at the hit PMTs. At energies above 1 TeV, the angle between the neutrino and the reconstructed muon is less than 1 degree (see Table 1). For track-like events the energy resolution is of the order of 0.3–0.4 in $\log_{10} E$. For electron and tau events the direction of the neutrino cannot be well reconstructed, but the energy can be measured with a resolution of 0.18 in $\log_{10} E$, see Table 1. Muons are initially reconstructed with a first-guess algorithm which fits the photon arrival times. Later reconstruction methods use maximum-likelihood fits which use probability distribution functions which account for the photon scattering and absorption. These functions are depth dependent to account for the varying optical properties of the ice.

Icecube and AMANDA study a wide range of physics topics: searches for point sources of ν_μ , for diffuse fluxes of extra-terrestrial ν_μ, ν_e, ν_τ , for neutrinos from GRBs, for neutrinos from Weakly Interacting Massive particles (WIMPs) accumulated in the Earth and the Sun; studies of atmospheric ν ; searches for MeV neutrinos from SuperNova collapse; and searches for a variety of exotic signals.

The results obtained with the AMANDA and IceCube telescopes were recently summarized in Ref. [13].

In all the neutrino studies the background is very large. The ratio of downgoing atmospheric muons to upgoing neutrino-induced muons from atmospheric neutrinos is about 10⁶ : 1, so stringent cuts are required to eliminate background. Cuts are applied to the reconstructed zenith angle, likelihood of the fit, and on the quality of the track reconstruction. Figure 4 shows the zenith angle distribution of data obtained with the IC22 detector and the expectations from Monte Carlo simulation. The data and simulation are in good agreement; after all cuts the upward sample is dominated by atmospheric neutrinos.

3.1 Atmospheric neutrinos

As outlined above, several filtering steps are needed to obtain a rejection power of about 10⁶. After these filtering steps a rather pure sample of upgoing atmospheric muon-neutrino events remains. The energy distribution of the atmospheric neutrinos observed with AMANDA II in 2000–06 is shown in Fig. 5, together with the predictions from two popular models [14, 15]. The data were obtained from 1387 days of livetime; at the final filtering level, the atmospheric ν_μ sample consisted of 5511 events and had a purity of approximately 99%. The estimate of the muon energy was given by the number of OM hits, or N_{ch} . The fact that the observed spectrum is consistent with the two model predictions for the atmospheric

flux at low energies allows us to place a limit on the magnitude of any possible diffuse muon neutrino flux with a harder spectrum, for example due to the prompt decay of charmed particles in atmospheric air showers or to a population of unresolved astrophysical sources (see Section 3.2).

3.2 Diffuse neutrino flux

The summed flux of extra-terrestrial neutrinos, not ascribable to individual sources, is called ‘diffuse’. The observations integrate over the full Northern sky and over long time periods. The most important background to the astrophysical neutrinos consists of the atmospheric neutrinos. This background has a spectrum which varies like $E^{-3.7}$ while the extra-terrestrial neutrinos are expected to have a harder, E^{-2} , spectrum. Hence one expects the energy spectrum to contain an excess at high energies. The search for a diffuse flux of high-energy neutrinos was conducted in the following way.

- The high-energy end of the atmospheric muon-neutrino spectrum was analysed to estimate a possible excess (see Section 3.1).
- TeV to PeV muon-neutrinos were searched for using upgoing well-reconstructed muon tracks.
- Neutrinos from all flavours were searched for with an analysis dedicated to TeV–PeV cascade events.
- At very high energies (PeV–EeV) the neutrino cross-section becomes very large and the Earth becomes opaque for upgoing neutrinos; hence a dedicated search was performed for downgoing and horizontal cascade events.

For all analyses the selected events were compared statistically to the expected background. No excess above the background expectation was found and upper limits were set on possible neutrino fluxes, as shown in Fig. 6. The results are discussed in Ref. [17].

3.3 Point sources

The primary goal of AMANDA and IceCube is the detection of astrophysical sources of high-energy neutrinos. Potential sources include Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRBs). An all-sky search was performed for localized sources in the Northern sky. An unbinned maximum likelihood search was performed using a sky map of 6595 upward-going neutrino events collected by AMANDA over 7 years (3.8 years of livetime). With these data, a significance of the deviation from a background uniform in right ascension (α) was calculated for all points with declinations (δ) between -5° and 83° . The results are shown in Fig. 7 [18]. The most significant point in the sky has a significance of 3.38σ , at $\delta = 54^\circ$, $\alpha = 11.4$ h. The chance probability of observing a maximum significance of at least 3.38σ is determined by performing the search on sky maps randomized in right ascension and is found to be 95%. A similar search was performed with the data taken with the IC22 detector in 2007. Searches were also performed for neutrinos from directions corresponding to catalogued gamma-ray sources. No statistically significant excess was found. More details can be found in Ref. [13]. The AMANDA and IceCube sensitivities for neutrinos from point sources and measured flux limits are shown in Fig. 8.

3.4 Indirect dark matter searches

AMANDA has been used to search for indirect evidence of WIMPs that have accumulated in the gravitational wells of the Earth and the Sun. This search is complementary to those conducted by direct detection experiments because such experiments constrain models with spin-independent neutralino–nucleon scattering, while neutralino capture in the Sun is mainly sensitive to spin-dependent processes. Searches for neutralino-induced muons from the centre of the Earth were performed with the data taken with AMANDA B10 collected between 1997 and 1999 (536 days livetime). In a more recent analysis

the AMANDA-II data taken in 2001–03 (689 days livetime) were searched for a similar signal with emphasis on neutralino masses below 250 GeV, by exploiting a dedicated low-energy trigger (the string trigger) [23]. No evidence for a signal was found and 90% C.L. upper limits were set on hypothetical muon fluxes from neutralino annihilations, see Fig. 9. The AMANDA-II data taken in 2003 (150 days livetime) were searched for neutralino-induced muons originating in the Sun [24]. A similar analysis was performed with data taken by the IceCube-22-string detector in 2007 (104 days livetime) [25]. There was no evidence for a signal and upper limits were set on possible muon fluxes, see Fig. 10. Because of the sparser spacing of the DOMs in IceCube, the latter analysis was limited to neutralino masses of 250 GeV and higher.

Figures 9 and 10 show the AMANDA and IceCube upper limits on the muon flux from neutralino annihilations into hard neutrinos in the Earth and the Sun, together with the results from other indirect searches [26]. The limits have been rescaled to a common muon energy threshold of 1 GeV using DARKSUSY [27]. Also shown are the cosmologically relevant MSSM models [28] allowed (markers) and disfavoured (dots) by the direct search results from CDMS [29] and XENON10 [30]. In the near future, improvement in sensitivity is expected from extending the search to the full 2000–06 AMANDA data set. After five years of data taking in its final configuration, IceCube will be sensitive to fluxes from neutralino annihilations in the Earth and the Sun which are a factor 5–10 smaller than the present limits (see Figs. 9 and 10). We plan to extend the detector with Deep Core, a densely instrumented array placed in deep very clear ice [31]. This will allow us to extend the sensitivity for dark matter searches with IceCube down to 50 GeV (see Figs. 9 and 10).

4 Outlook

The construction of the IceCube detector will be completed in the 2010/11 austral summer. In the near future, AMANDA will be replaced by the Deep Core detector [31], a purpose-built low-energy extension of IceCube, see Fig. 2. This densely instrumented array will consist of six strings of 60 high quantum efficiency DOMs and will be installed in deep very clear ice, where the scattering length is around 40 m. The first two Deep Core strings were deployed during the 2008/09 austral summer. In order to extend the sensitivity of IceCube towards very high energy it is envisaged to add radio and acoustic detectors in the ice [32], [33].

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Table 1: Best values obtained for AMANDA and expected for IceCube observables

Track-like events	IceCube	AMANDA
Angular resolution	$< 1^\circ$	$2^\circ\text{--}3^\circ$
Energy resolution ($\log_{10} E$)	0.3–0.4	0.3–0.4
Field of view	2π	2π
Cascade-like events	IceCube	AMANDA
Energy resolution ($\log_{10} E$)	0.18	0.18
Field of view	4π	4π

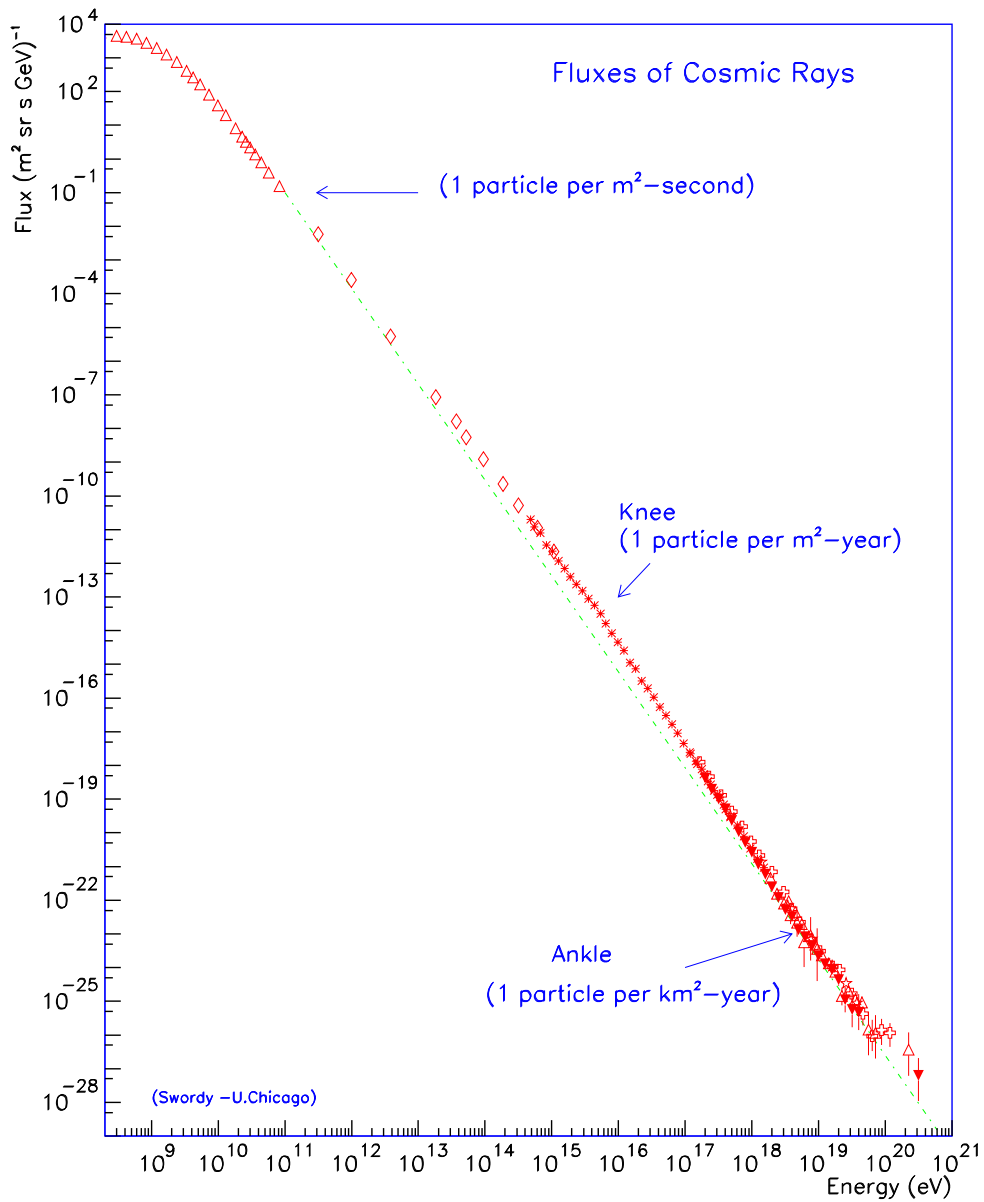


Fig. 1: All-particle cosmic-ray spectrum. From a compilation by S. Swordy for J. Cronin, T.K. Gaisser, and S.P. Swordy, *Sci. Amer.* **276** (1997) 44

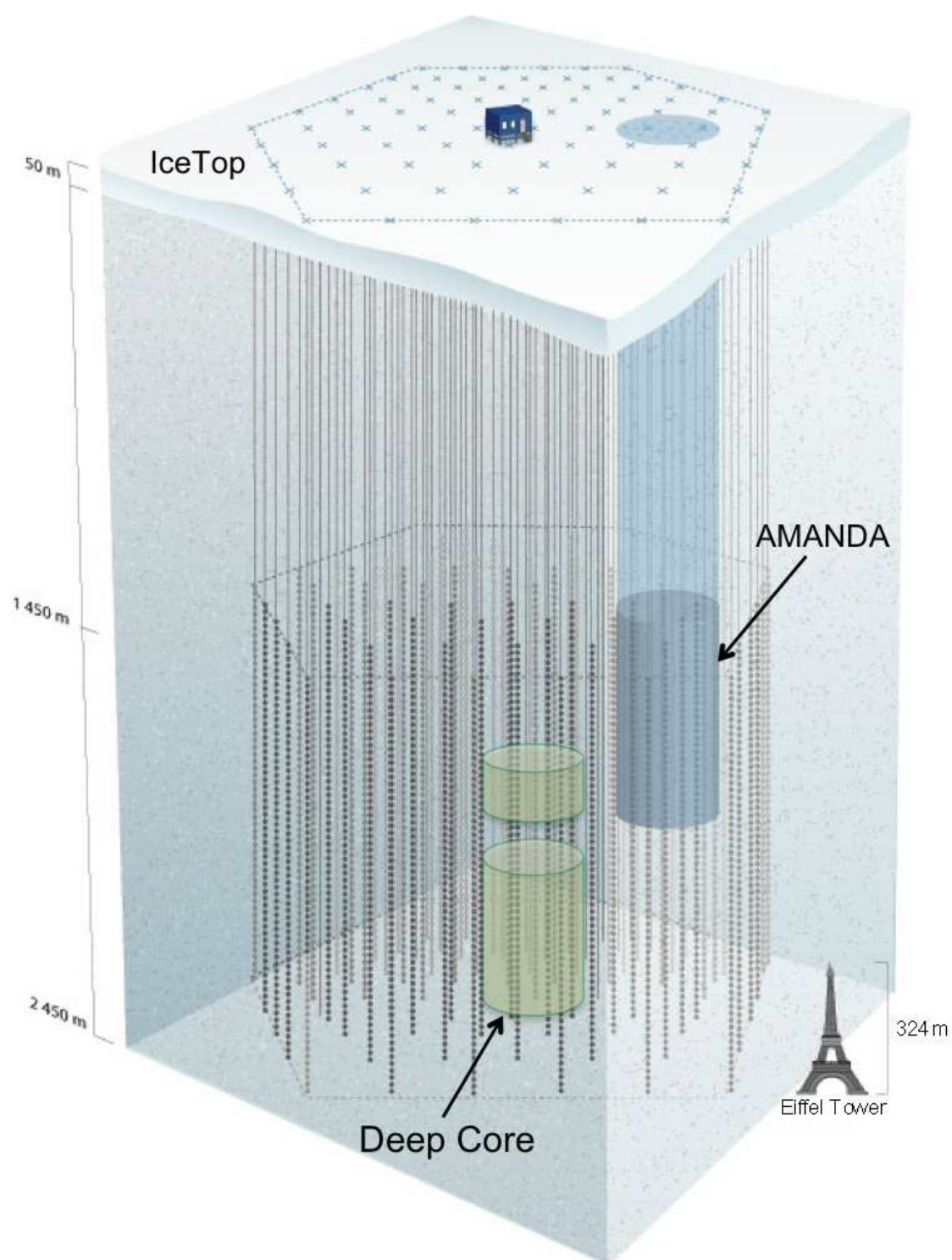


Fig. 2: Schematic view of the IceCube detector with 80 in-ice strings and, on the surface, 80 IceTop stations, one above each string location. The grey cylinder represents AMANDA. The grey cylinder at the bottom represents the Deep Core detector.

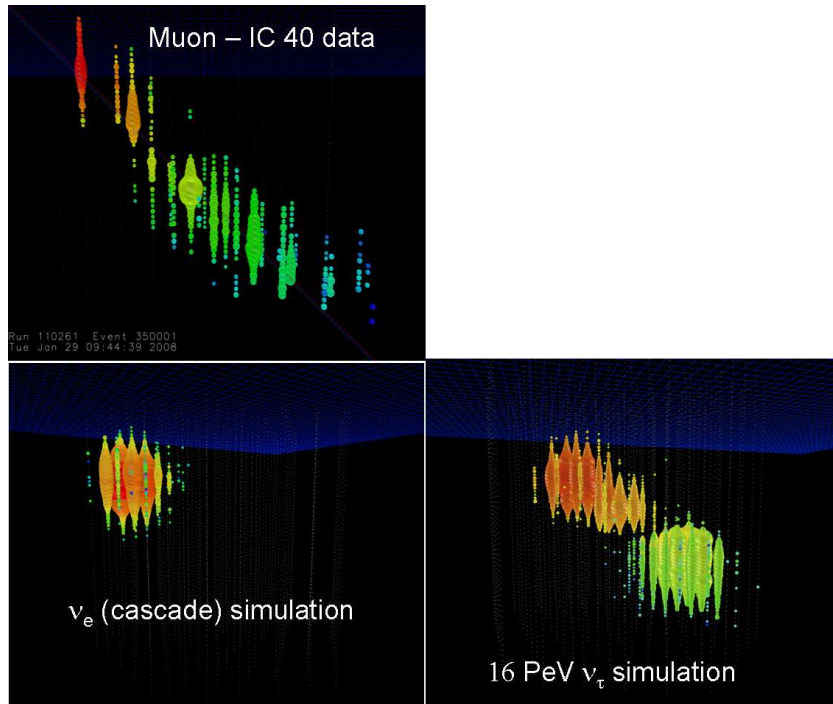


Fig. 3: Event displays for (top) an actual muon (or muon bundle) in the IceCube 40-string detector (IC40), (middle) simulated ν_e event and (bottom) simulated double-bang ν_τ event. The colours indicate times, from red (earliest) to blue (latest).

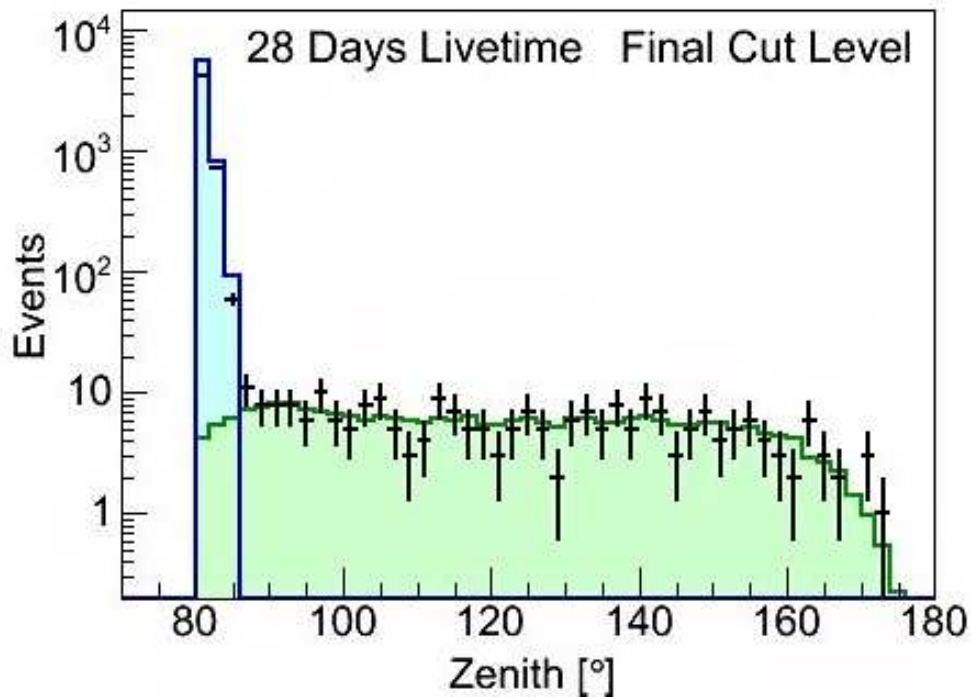


Fig. 4: Zenith angle distribution of atmospheric muon-neutrinos in the IceCube 22-string detector (IC22). The crosses represent data taken in 2007, the shaded histogram shows the prediction from simulated atmospheric neutrinos, and the open histogram the prediction for atmospheric muons.

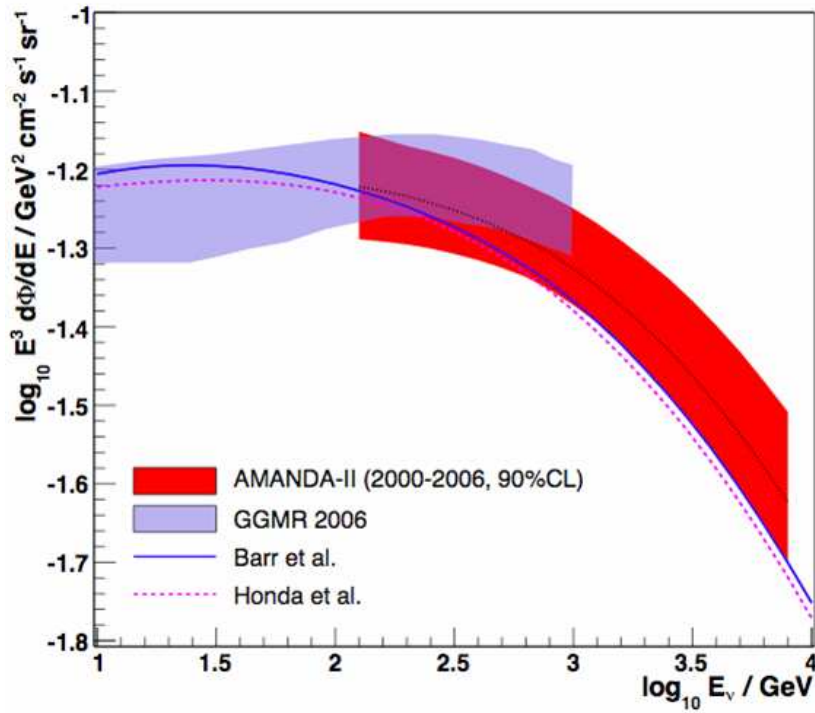


Fig. 5: Angle-averaged $\nu_\mu + \bar{\nu}_\mu$ atmospheric neutrino flux (solid band, 90% C.L.). The dotted line shows the central best-fit curve. Also shown is a previous result from Super-Kamiokande data (GGMR [16]). The full and dashed lines show the calculations from two theoretical models, see text.

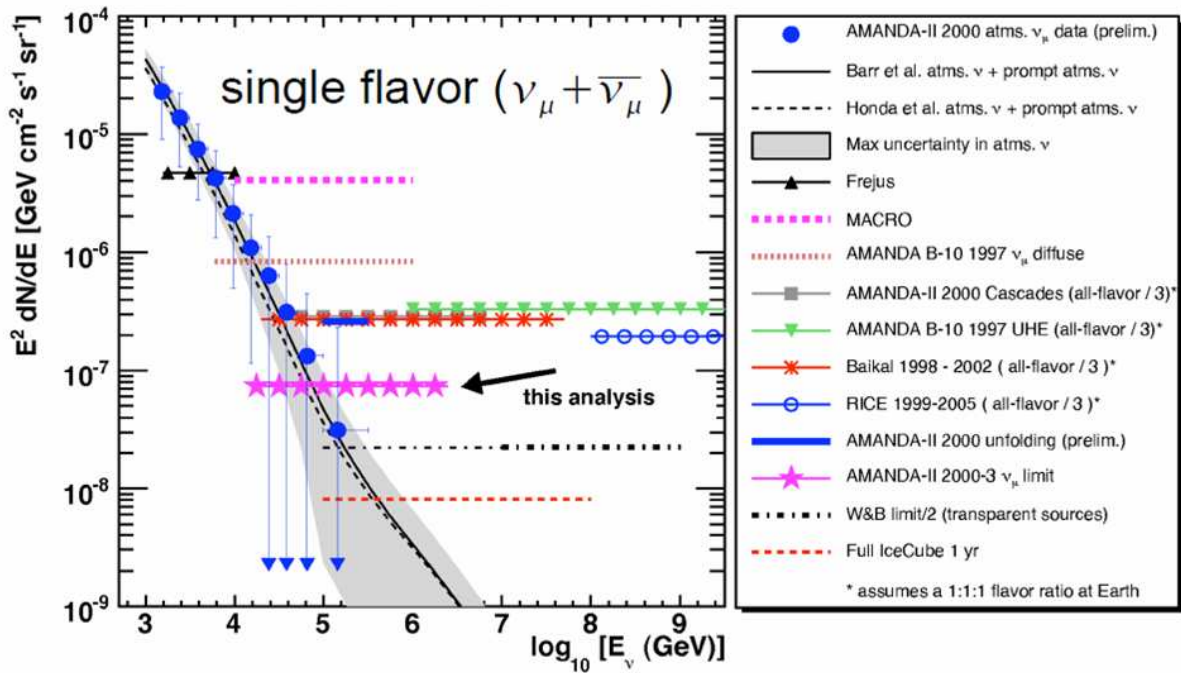


Fig. 6: Summary of existing experimental limits on the diffuse neutrino flux versus the logarithm of the neutrino energy

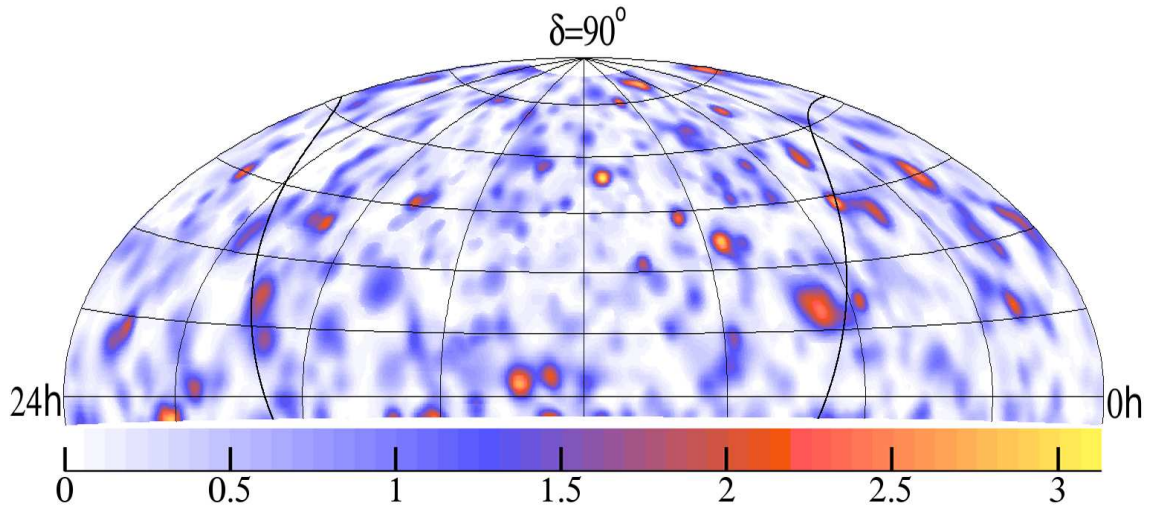


Fig. 7: Map (equatorial coordinates) of pre-trial significances obtained from an unbinned point source search using the 2000–06 AMANDA data set (3.8 yr livetime)

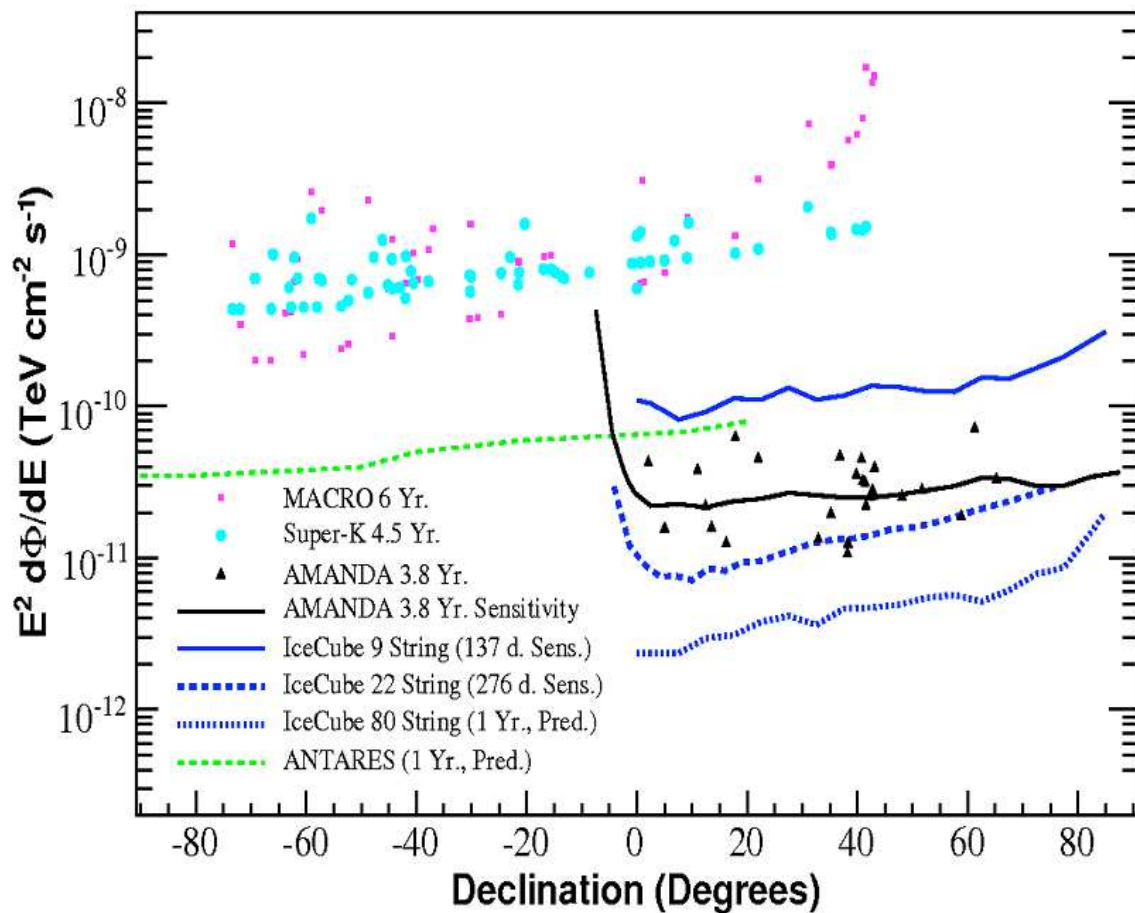


Fig. 8: $E^{-2} \nu_{\mu}$ flux limits from final AMANDA analysis (3.8 yr livetime), from MACRO [19], and Super-Kamiokande [20]; $E^{-2} \nu_{\mu}$ sensitivity for final AMANDA analysis (3.8 yr livetime) and from IceCube-9-string analysis [21]; predicted sensitivity for ANTARES [22] and IceCube (80 strings). The AMANDA and IceCube ν_{μ} and ν_{τ} limits are divided by 2 for comparison with limits on only ν_{μ} .

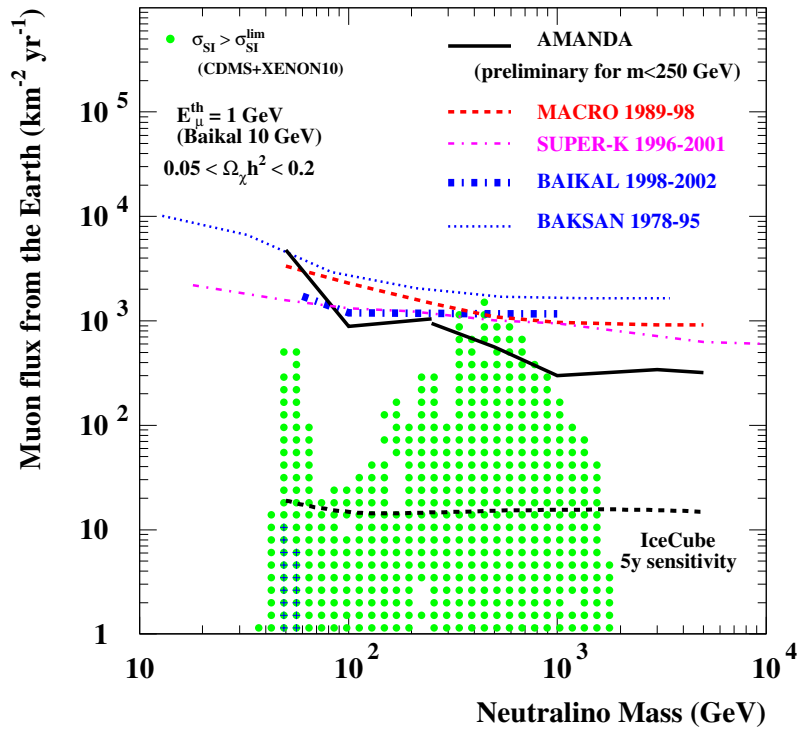


Fig. 9: 90% C.L. upper limits on the muon flux from hard neutralino annihilations in the centre of the Earth, compared to other indirect searches and to direct searches, see text

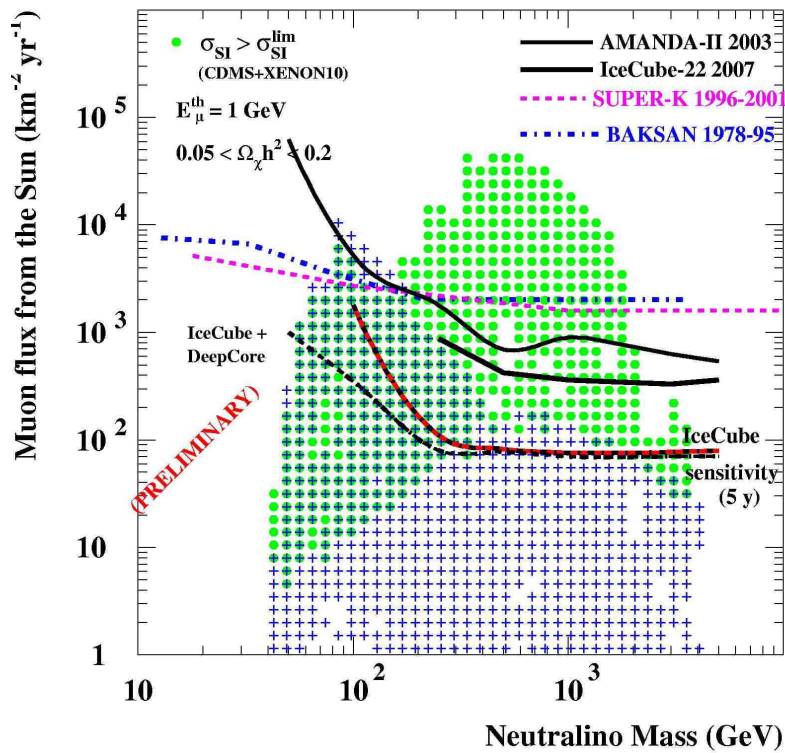


Fig. 10: 90% C.L. upper limits on the muon flux from hard neutralino annihilations in the Sun, compared to other indirect searches and to direct searches, see text