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# High-energy neutrino astronomy

**Teresa Montaruli**

DPNC, Université de Genève, 1211 Genève, Suisse, formerly at University of Wisconsin - Madison

E-mail: `teresa.montaruli@unige.ch`

**Abstract.** Neutrino astronomy, conceptually conceived four decades ago, has entered an exciting phase for providing results on the quest for the sources of the observed highest energy particles. IceCube and ANTARES are now completed and are scanning in space and time possible signals of high energy neutrinos indicating the existence of such sources. DeepCore, inside IceCube, is a playground for vetoed neutrino measurement with better potential below 1 TeV. A larger and denser detector is now being discussed. ARA, now in test phase, will be composed by radio stations that could cover up to $\sim$ 100 km$^2$ and aims at the highest energy region of cosmogenic neutrinos. The non observation of cosmic events is on one side a source of disappointment, on the other it represents by itself an important result. If seen in the context of a multi-messenger science, the combination of photon and cosmic ray experiment results brings invaluable information. The experimental upper bounds of the cubic-kilometer telescope IceCube are now below the theoretical upper bounds for extragalactic fluxes of neutrinos from optically thin sources. These are responsible for accelerating the extragalactic cosmic rays. Such limits constrain the role of gamma-ray bursts, described by the fireball picture, as sources of ultra-high energy cosmic rays. Neutrino telescopes are exciting running multi-task experiments that produce astrophysics and particle physics results some of which have been illustrated at this conference and are summarized in this report.

## 1. Introduction

Astroparticle physics concerns fundamental questions on the universe evolution, its constituents, particle interactions, verification of general relativity, and life science. I will focus here on some selected topics and on Cherenkov neutrino telescopes, large extensive air shower arrays having been covered elsewhere at this conference [1]. Indirect dark matter detection will not be covered here since it has been covered at this conference in [2]. The topic is of high interest also in view of the fact that current LHC limits are pushing new physics in the high energy region, where indirect detection is competitive with respect to direct measurements.

IceCube was completed during the austral summer 2010–11, hence the first cubic kilometer detector is operative at the South Pole measuring a muon rate of $\sim$ 2.7 kHz. At the time of writing, fall 2011, the running livetime is 99%. The completion of IceCube on schedule [3] and the operation of ANTARES in the Mediterranean sea in its final configuration since May 2008 [4] are two important milestones for neutrino astronomy. Currently, there is high momentum in the European community for the construction of a detector in the Mediterranean sea of better sensitivity than IceCube for galactic sources [5]. The IceCube Observatory is an ensemble of detectors at the South Pole composed by: a cubic-kilometer neutrino telescope deep in the ice sensitive to neutrinos with $E_\nu \gtrsim 100$ GeV; the extensive air shower array IceTop and the recently added DeepCore [6], a denser array with the aim of improving the performance at energies $\lesssim 1$ TeV for dark matter, neutrino oscillation and SN collapse neutrino searches. Since April 2011 IceCube takes data in its full configuration. The deep ice hosts 5160 optical modules, glass spheres enclosing 10-inch photomultipliers (PMTs) and associated electronics for waveform digitization. Dubbed Digital Optical Modules (DOMs), they are autonomous small computers that communicate with the surface laboratory. The time and the amount of photons that reach the ns-precision DOMs make the reconstruction of particle direction and energy possible. After almost 7 years from the installation of the first string, 98.5% of the DOMs are in stable operation. IceTop is composed of stations of 2 tanks of frozen water seen by 2 DOMs separated by about 10 m at the top of each string. It can be used in coincidence with the deep-ice detector for cosmic ray (CR) composition studies, angular and energy reconstruction cross calibrations and to veto background muons produced in atmospheric showers. A coincident CR induced event through IceTop and IceCube is shown in Fig. 1 (left).

Occasionally, neutrinos interact with matter in the proximity of the detector or inside its instrumented volume. The Earth can be used as a filter to reduce the main background to the neutrino measurement: atmospheric muons. Upgoing muons are a signature of neutrinos since they are the only particles that can cross the entire Earth. Since the neutrino cross section increases almost linearly with energy, at energies above $10^5$ GeV the interaction length becomes comparable to the Earth diameter. Hence, only downgoing or horizontal ultra-high energy neutrinos can be detected. At analysis level atmospheric neutrinos contribute about 200 upgoing neutrino events per day in the full IceCube. A muon neutrino charged current interaction produces a muon that propagates through the detector for a distance that depends on energy. A neutrino-induced upgoing muon event releasing about 10 TeV in the detector and a 50 TeV candidate electron neutrino cascade are shown in Fig. 1 (left).

Electron and tau charged current interactions and all-flavor neutrino neutral current interactions produce cascade events that have an approximately isotropic distribution of light and are ‘point-like’ on the scale of the distance between PMTs. Light propagates from the interaction vertex up to some hundreds of meters. The 1.5 km layer of ice above IceCube reduces the atmospheric muon flux by about 4 orders of magnitude. Further reduction of 2 orders of magnitude can be obtained using the 3 external rings of strings of IceCube that surround DeepCore and 40 horizontal layers of DOMs above it as veto. Since the ratio between the atmospheric muon and neutrino fluxes at trigger level in IceCube is about $10^6$, the veto is effective to reduce backgrounds to neutrino detection level and to identify neutrinos with vertex contained in the instrumented region [6]. An analysis using this veto and additional containment and reconstruction quality cuts has been shown at this conference using 79-string data of IceCube that ran the season before completion [8]. For the first time, cascade events with the vertex inside a fiducial volume due to all flavor neutral current and charged current electron neutrino interactions have been measured.

## 2. Life science and particle physics related observations

Cherenkov neutrino telescopes are built in poorly explored media, sea abyss, the depth of Lake Baikal or the deep ice of Antarctica. Some observations are connected with actual themes such as global warming, environmental conditions and animal life. Science [9] and the Economist (Dec. 2010) published the news on the detection of dolphins in the Catania gulf with an acoustic station of 4 hydrophones (NEMO-O$\nu$DE) operating in the range 30–43 kHz at 2000 m depth and 25 km offshore. It is served by the test infrastructure for the cubic-kilometer in the Mediterranean of the NEMO project and it explores the possibility for high energy acoustic neutrino detection. Ongoing analysis is obtaining evidence for sperm and cuiver’s beaked whale sounds, and information on their sex and their migration routes. ANTARES hosts a variety of instruments, including seismographs that clearly detected the March 2011 earthquake in Japan, acoustic hydrophones, sensors for oceanographic parameters (sea currents, oxygen, temperature, salinity) and video cameras for studies of bioluminscence. Video cameras are also installed in IceCube to observe the refreezing process after drilling and the quality of the ice around DOMs.

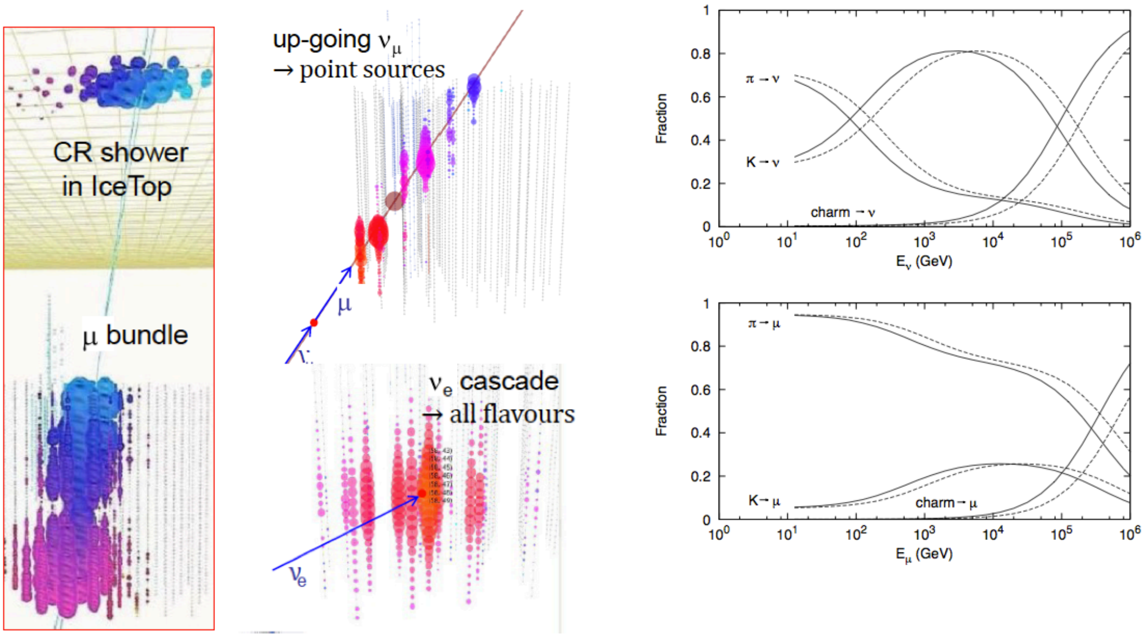

**Figure 1.** Left: An event detected by IceTop and IceCube in coincidence and two high energy muon and electron neutrino events. The color code (from red to blue) is proportional to the DOM hit time and the DOM size is proportional to the deposited charge. Right: shown at the top is the fraction of muon-neutrinos from pion, kaon and charm decay as a function of neutrino energy. At the bottom: same for muons. Solid lines are for vertical and dashed lines for $60^o$. (figure from [11]). IceCube response function for atmospheric neutrinos peaks at around 1 TeV for vertical events and at about 1 PeV for horizontal events [7].

The muon rate in IceCube shows a seasonal dependency of about ±10% due to the density variation of the atmosphere. The temperature increase produces a reduction in the interaction rate and the shorter decay length for kaons and pions. Charm decay contribution, still unmeasured, would not be affected by such variations since charmed mesons and baryons decay before interacting [11]. The current sensitivity is of the order of few Hz/$^o$C [12]. A long term monitoring of temperature variations is possible including the observation of sporadic processes such as the ozone hole split in Sep. 2002 observed by the precursor of IceCube, AMANDA, as a muon rate sudden increase [10]. In Fig. 1 (on the right) the fraction of neutrino and muon events due to the different channels is shown. For $\nu_\mu + \bar{\nu}_\mu$ the flux is described by:

$$\frac{dN_{\nu_\mu}}{d\ln E} = A_{\rm tot} E^\gamma \sum_{i=\pi,K,{\rm charm}} \left[ \frac{A_{\nu i}}{1 + B_{\nu i} E \cos\theta^* / \epsilon_i} \right] \quad (1)$$

where $A_{\rm tot}E^\gamma$ is the primary spectrum, each term in the sum represents the contribution of pion, kaon and charm decays, $\theta^*$ is the neutrino zenith angle that takes into account the Earth curvature, and $\epsilon_i$ are characteristic energies [11]. They are related to the critical energy below which all mesons decay and the spectrum has the same slope as the primary one. At higher energy the flux steepens asymptotically for pions and kaons by one power due to the interaction and decay competition. Figure 1 (right) shows the relative contribution of various particles to the atmospheric muon and neutrino flux. It depends on the fraction of primary energy taken by muon and neutrino secondaries and so on the ratio of the muon mass to the primary particle mass. The energy taken by muons is much lower for kaon decays than for pion decays. From the measurement of the correlation of the muon rate variation with the stratospheric temperature of the atmosphere above Antarctica it is possible to infer the $K/\pi$ ratio which was found by IceCube to be $0.09 \pm 0.04$ at primary particle energy of about 20 TeV. It is lower than the nominal value of 0.149 [12]. This can be reconciled by reducing the amount of associated production $p + \text{air} \rightarrow \Lambda + K^+ + X$. An update on the muon charge ratio $\mu^+/\mu^-$ was presented at this conference by the OPERA collaboration [14]. The ratio is observed to increase from its value of 1.27 around 100 GeV to $\sim 1.37$ above 1 TeV. The amount of this increase depends on the increasing importance of associated kaon production, favored because secondaries have constituents in common with the proton valence quarks. This process makes the charge ratio larger for kaons than for pions [11]. The amount of this rise is consistent with the $K/\pi$ measurement and it is not clear that the decrease at energies above 10 TeV can be due to a charm component. As a matter of fact, at some energy, perhaps around 100 TeV, the decay of charmed hadrons will become the main source of all atmospheric leptons. IceCube found no evidence for this component with data belonging to the 40-string configuration [15]. Figure 2 shows the expected distributions for atmospheric neutrinos and for an arbitrary normalization astrophysical $E^{-2}$ signal in the configuration currently under analysis [13].

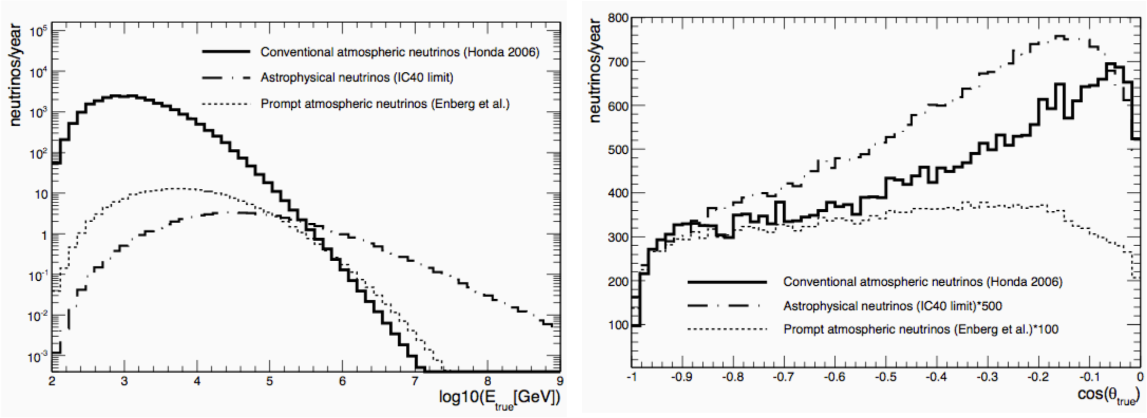

**Figure 2.** Energy estimator (left) and zenith (right) distribution for detectable neutrinos from pion and kaon decays, from prompt and for an astrophysical $E^{-2}$ neutrino signal corresponding to 90% CL upper limit in [15] for the simulated data of 59-strings (from [13]).

## 3. Multi-messenger astronomy with IceCube

An astronomical messenger has to point back to its cosmic source. Neutrinos are neutral and so undeflected by magnetic fields in the Galaxy and in the intergalactic space. Potentially, they are the most sensitive messengers because they are weakly interacting particles and hence they probe the interior of sources and reach us from cosmological distances. As illustrated by the well known Hillas' diagram [16], the maximum energy of an accelerated particle of charge $Ze$ depends on the size of the accelerating region, the magnetic field and eventually on the jet Lorenz factor. Energy losses and the age of the accelerating process have to be accounted for to define a minimum efficiency for accelerating ultra-high energy cosmic ray (UHECR). Candidate efficient accelerators are extragalactic sources such as gamma-ray bursts (GRBs) and black hole jets in Active Galactic Nuclei (AGN).

Since the most powerful engines of the universe host intense magnetic fields, they can be 'optically thick'. In these sources, protons and nuclei are accelerated and interact in radiation fields and matter in the source but only neutrinos can emerge. On the other hand, in 'optically thin' sources neutrons produced in proton interactions can escape the magnetic fields and produce both the cosmic rays that we observe in large extensive air shower arrays and the neutrinos observed by neutrino telescopes. Hence, there is an intimate relationship between the energy we observe in the UHECR spectrum and expected neutrino fluxes. From this reasoning, Waxman & Bahcall (W&B) derived an upper limit on the diffuse neutrino emission from extragalactic optically-thin sources from which CRs escape [17]. This upper limit is estimated in the assumption that UHECRs are protons with $E^{-2}$ injection spectrum and is normalized on the UHECR measured in large extensive air shower arrays. The CR production rate used in Ref. [17] of $E^2 dN/dE = 10^{44}$ erg Mpc$^{-3}$ yr$^{-1}$ was recently updated due to the results of HiReS and Auger that superseded the originally used AGASA data. This produced a decrease of a factor of about 2 in the normalization [18] to which another factor of 2 of reduction has to be added due to astrophysical neutrino oscillations. The resulting bound is about $10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This normalization procedure is affected by the indetermination of the energy at which extragalactic CRs begin to dominate over galactic ones between $10^{17} - 10^{19}$ eV. Moreover, the resulting neutrino flux depends on the composition of extragalactic CRs, on the maximum energy of the primary injection spectrum and on the assumed cosmological source evolution. In Fig. 3 (left) the grey band indicates the region between the revised W&B upper limit [18] to predictions for GRBs [18]. It can be seen that the 90%CL upper limit of 1/2 of the full IceCube begins to explore the relevant region for steady emissions of optically-thin sources.

Recent results on GRBs using neutrino-induced muon events for the 40-string configuration were published in [19] and 59 string data were combined providing considerably better limits discussed at this conference in [20]. A total of about 300 GRBs were searched for neutrino emission with complementary analyses that should have seen between 8 and 27 events. In the absence of a signal, the limits are combined and are a factor 0.22 of the model in [21] that consider neutrino fluxes for specific bursts. The model in [17], that applies to the average of BATSE GRBs, predicts 14.2 events. It should be noted that primary protons may not escape the intense magnetic fields in the fireball. Hence, the CRs observed by giant extensive air showers could originate from the decay of secondary neutrons from $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$ that can escape B-fields. In this second case, the upper limit would be higher by about a factor of 3–6 since the CR flux is normalized on secondary and not primary nucleons. At this conference the impact of the upper limit of IceCube on fireball predictions was discussed in [20]. For the case in which GRBs are the dominant sources of CRs, neutrino fluxes can be lowered by reducing the proton content below the level required to explain the CR spectrum, or the threshold for pion production can be increased by increasing the boost factor of the shocks.

If GRBs were the sources of CRs, UHECRs would be proton dominated since nuclei would not survive in the fireballs. No correlation between UHECRs and neutrino events could be observed since neutrinos cannot arrive in temporal coincidence with protons that would take a much longer time to reach us. IceCube data provide no evidence for an excess on top of the background in the direction of UHECRs in Auger and HiReS [24]. The composition measurement and the observation of anisotropies for UHECR and the detection of UHE neutrinos would help understanding the nature of extragalactic sources. Pure proton or pure iron composition would produce similar spectral shape in the GZK cut-off region. Nonetheless, if iron dominates, expected neutrino fluxes from iron photo-disintegration would be orders of magnitude smaller than for pure proton composition and could be unaccessible to current detectors [1]. Moreover, if the composition would be dominated by high mass elements anisotropies become improbable

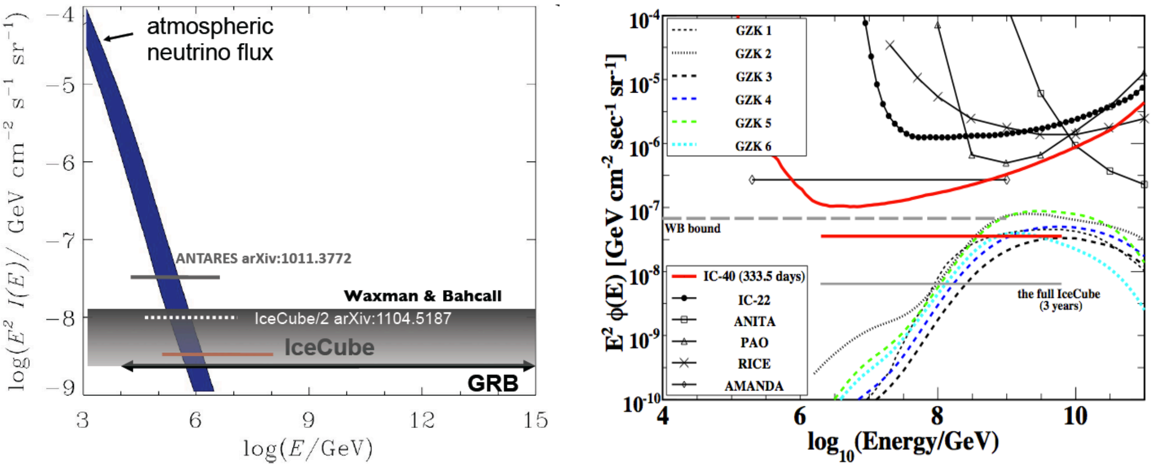

**Figure 3.** Left: 90% c.l. upper limits on the diffuse muon neutrino flux of $E^{-2}$ neutrinos for ANTARES [4] and 40-strings of IceCube [15] and a prediction for the full IceCube. The horizontal band represents the region between the revised W&B upper limit and the region relevant for GRB fluxes and the oblique band atmospheric neutrinos. Right: All flavor neutrino flux differential limit (90% c.l.) and $E^{-2}$ spectrum integrated limit for IceCube (red solid lines) and for 3 yr of the full detector (lowest horizontal line) [22]. The minimum of the differential flux limits indicates the region of maximum sensitivity of the detector. Various model predictions (assuming primary protons) are shown for comparison. The gray dashed horizontal line indicates the W&B flux bound with cosmological evolution [17]. References are in [22].

unless B-fields are much lower than what we believe. The EHE search in IceCube for a diffuse flux of neutrinos selects downgoing and horizontal events with energies $\gtrsim 10^6$ GeV based on the charge released in the detector as a function of the zenith angle [22]. No event survived the analysis cuts for a livetime of 333.5 d of the 40 string configuration and upper limits are shown in Fig. 3 (right) together with some models (references in [22]). The upper limit to the neutrino flux from optically thin sources [17] modified to include oscillations and including evolution of sources corresponds to 4.5 neutrino events/yr in 40 strings and 24.5 in 3 yrs of the full detector. The model GZK6, that includes the constraints from the Fermi-LAT diffuse gamma flux and the UHECR as measured by HiReS and Auger, would produce 4.8 events in 3 years of the full detector. A radio detector for ultra-high energy neutrinos ($\gtrsim 10^{17}$ eV), ARA, is now under test and a proposal for a 100 km$^2$ radio detector is submitted [23].

Other searches dedicated mainly to AGN flares have been developed in IceCube [25, 24] and ANTARES [4] to look for flares in coincidence with other X-ray or gamma detectors, such as Fermi and Imaging Cherenkov Telescopes. None found evidence of correlated neutrino emission. This ‘triggered’ search reduces the trial factor by using X-ray and $\gamma$-ray information, but relies on the assumption that flares of neutrinos are in coincidence with flares in photons as a result of an enhanced acceleration power in the source. In order not to miss any signal from a flare if neutrinos are not in coincidence with photons, IceCube also uses an untriggered approach looking for clusters of high energy neutrino events in space and time. For a neutrino flare of 1 s (1 day) the discovery potential is about a factor of 4 (3) better than the time-independent search [7, 24]. This analysis did not find a significant flare in the data taken with 40 strings [25]. The recently unblinded results with 59 strings of IceCube revealed a 1.4% significant flare of reconstructed duration of $\sim$ 10 days with about 14 signal-like events that contributed to this significance. Given the large trial factor this flare did not reach the threshold required for discovery in IceCube of $5\sigma$.

Time independent likelihood approaches have been used by ANTARES and IceCube [26, 7, 24] to detect the presence of a signal from any point in the sky among a large background of atmospheric neutrino upgoing events. In this region, the sensitivity for an $E^{-2}$ flux of neutrinos is peaked around some tens of TeV. The background is mainly due to atmospheric neutrinos with a few percent contamination of mis-reconstructed atmospheric muons for IceCube and 40% for ANTARES. IceCube extended the search to the full sky including the southern sky that is dominated by downgoing atmospheric muons. A zenith-dependent energy cut selects high energy muons to reduce the high statistics that would prevent the application of this likelihood method. Hence, in the southern hemisphere IceCube sensitivity is peaked at higher energies between PeV and EeV. Muon events are used for this search, since their pointing accuracy is $\sim 1^\circ$.

The likelihood approach uses the main features that distinguish signal from atmospheric muon and neutrino backgrounds: clustering around a direction in the sky and harder spectrum (typically $\sim E^{-2}$ spectra are expected for neutrinos directly accelerated in non-relativistic supernova shocks or in relativistic jets). The technique uses scrambled data samples, since the background is uniform in time and hence in right ascension and the signal is assumed to be small compared to backgrounds. Since data and not simulation are used to calculate the background test statistics distribution, the post-trial p-value for the hottest spot in the sky is solid since it comes from the comparison of the data outcome to the scrambled data maps. When unblinded, the 40 + 59 string data of IceCube showed nothing incompatible with the atmospheric backgrounds [24]. The skymap of significances is shown in Fig. 4 (left). Similar result has been presented by ANTARES. An update of the published result [26] improved the sensitivity by a factor of 2.5 bringing it to the level of $E^2 dN/dE \sim 3\text{–}9 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ TeV (90% CL) between declination values of $-85^\circ \div -40^\circ$. IceCube preliminary sensitivity in the declination range $5^\circ - 85^\circ$ is $1.3 - 6 \times 10^{-12}$ and in the Northern hemisphere, where it overlaps with ANTARES, it rises from 1.7 to $58 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ TeV (90% CL) between $-85^\circ$ and $0^\circ$.

IceCube limits are not only challenging models for extra-galactic sources, but also most optimistic models for galactic sources. In Fig. 4 (right) the case of the Crab Nebula [27] is taken as a benchmark to understand where our limits stand with respect to gamma-astronomy observations. Nonetheless, it for sure accelerates photons to TeV energies. IceCube 90% CL limit for the configuration of 40 strings (1/2 of IceCube) is only a factor of 3.4 higher than the luminosity observed in TeV photons by H.E.S.S. For the Kappes *et al.* model the IceCube 90% CL limit is a factor of 6 higher (references of models are in [27]). This model derives from parent protons the gamma spectrum observed by H.E.S.S. and the muon neutrino one that is reduced by oscillations at Earth by about a factor of two.

Another multi-messenger search is the SN collapse search with neutrinos that should proceed the photon signal. While water is a uniform medium and ice is difficult to model since its optical properties are depth-dependent, the optical background level in IceCube is much smaller than in sea water. The average level of 540 Hz, is adequate for supernova (SN) collapse searches [28]. Most of this rate is due to radioactive decays of Th and U, and also of $^{40}$K in the glass spheres, while about 16 Hz is due to atmospheric muons. The data acquisition reduces the background rate to about 286 Hz at the cost of introducing a 13% deadtime for the signal. A SN similar to SN1987A at 10 kPc from us will produce mostly inverse-$\beta$ reactions in IceCube and in less than 1 s about one million events will be recorded with time precision of 2 ms. The significance for a SN in the Galaxy will be larger than 25 $\sigma$ and between 3–10 $\sigma$ for a SN in the Large Magellanic clouds (pre-trial). Since the trial factor is large for this search (it depends on the time search bin), IceCube is in a network of detectors, SNEWS [29]. Coincident detection between other neutrino telescopes such as Super-Kamiokande and LVD, and consequent observation of an optical counterpart will make the discovery unequivocal.

The diversity of the physics reach of IceCube is being demonstrated by the intriguing

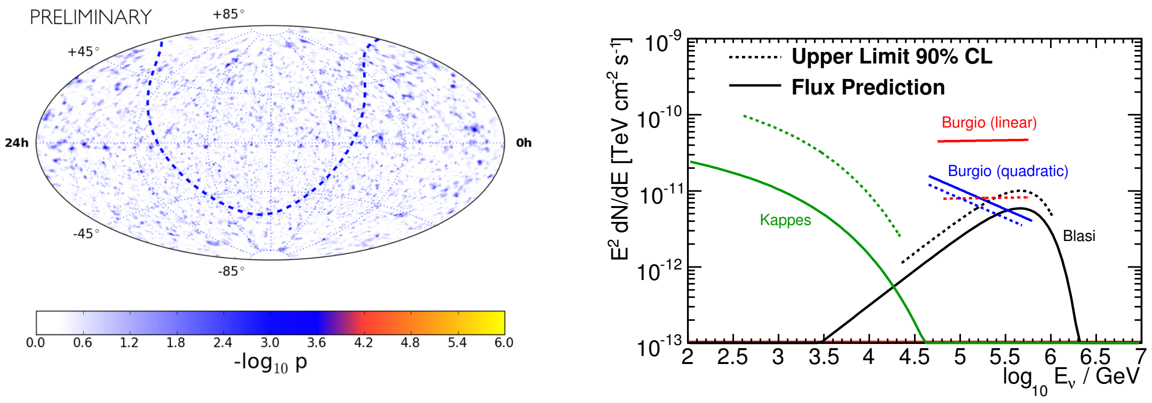

**Figure 4.** Left: equatorial coordinate hammer-aitoff projection map of the 40 + 59 string IceCube samples. The dashed line represents the Galactic plane. Right: Predicted fluxes from the Crab (solid lines) and 90% c.l. upper limits (dashed lines) for 1/2 of IceCube (Ref.s in [27]).

observation of anisotropies using more than 10 billion events. It was found that the arrival direction distribution of cosmic rays at several TeV exhibits significant large scale anisotropies [30]. Once dipole and quadrupole moments are subtracted, the data include several localized regions of excess and deficit at scales $10° - 30°$. The large large-scale anisotropy observed at median energies around 20 TeV seem not to be present at 400 TeV, where the anisotropy shows substantial differences with respect to that at lower energy.

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