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Neutrino astronomy with IceCube and beyond

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Abstract. With the recent discovery of high-energy neutrinos of extra-terrestrial origin by the IceCube neutrino observatory, neutrino astronomy is entering a new era. Here we review current results on astrophysical high-energy neutrinos from IceCube, as well as present plans for a major extension of the project – IceCube-Gen2.

1. Introduction

The first evidence of astrophysical neutrinos was announced by the IceCube collaboration in 2013 [1], and more data and refined analyses have since then pushed the significance of the observation to a level that we can now speak of high-energy neutrinos as a new cosmic messenger [2, 3, 4]. Hence, more than 50 years after the idea was born [5], astronomy with high-energy neutrinos is finally becoming reality. The promise of neutrino astronomy rests on the unique property of the neutrino - interacting only weakly, they escape even the densest and most energetic environments in the Universe. As such, they can provide insight into a range of phenomena, from the accretion of matter on super massive black holes to the explosions of stars. Cosmic neutrinos are expected to be produced in the interaction of cosmic rays with ambient photons or matter. However, unlike charged cosmic rays, neutrino propagate through the cosmos without being deflected by magnetic fields and hence point back to their sources. Furthermore, they are not attenuated by background radiation, in contrast to gamma-rays, which above 10 TeV, are absorbed on extra galactic distance scales via interaction with the cosmic microwave background and other sources of radiation. Accordingly, neutrinos offer a new window on the high-energy Universe. In this contribution, we review results on astrophysical high-energy neutrinos from the IceCube neutrino observatory, and present plans for an extension of the project – IceCube-Gen2. A separate contribution [6] covers IceCube's measurements of neutrino properties derived from the observation of atmospheric neutrinos.

2. IceCube and the observation of astrophysical neutrinos

The South Pole is home to the currently largest operating neutrino detector, the IceCube neutrino observatory. The instrumented volume of the array comprises a cubic kilometre and is installed between 1450 and 2450 m depth in the icecap. It was deployed between 2005 and 2010 and consists of 86 strings with 5160 Digital Optical Modules, each containing a 10 inch Hamamatsu PMT. The inter-string distance is 125m, resulting in an energy threshold of about 100 GeV. A more densely instrumented sub-array called DeepCore is located at the bottom center of IceCube and has a lower energy threshold of 10 GeV. The deployment of IceCube strings



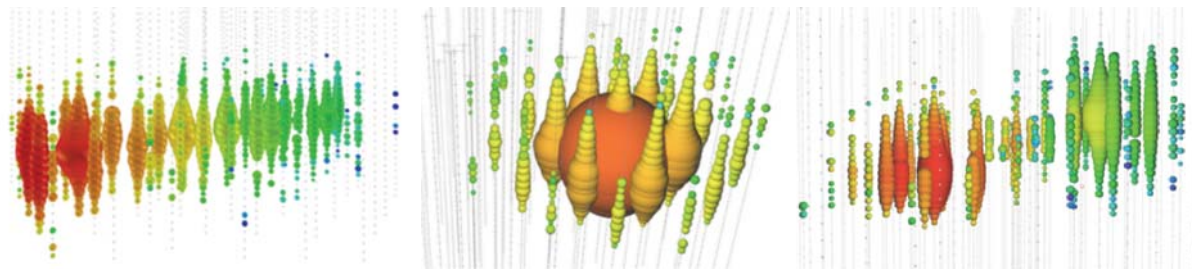


Figure 1. Typical event signatures observed by IceCube, a track-like event (left), a shower-like event (middle) and a double-bang event (right). Each colored sphere marks a DOM that records Cherenkov light. The first and second are events observed by IceCube while the third is a simulation. The size of the spheres represents the amount of light that was observed. The colors indicate the relative time of the photons with respect to each other. Early photons are red, late photons are blue.

required melting holes into the antarctic ice. Once the instrumented holes are frozen again, the ice provides a remarkably stable environment to operate a detector. This is demonstrated by only 32 sensors failing since commissioning more than 5 years ago, and an uptime exceeding 99%. The deep-ice detector is complemented by a km²-sized air shower array on the surface.

IceCube has been taking data in its complete configuration since 2011. The majority of the $\sim 10^5 \text{ yr}^{-1}$ neutrino events detected are produced in the atmosphere via cosmic ray interaction. However, events have been identified that stand out above the background of atmospheric neutrinos and reach energies of up to several PeV [7, 2, 3, 4]. The evidence for astrophysical neutrinos comes from different detection channels, including contained events in the detector (mainly the signature of electron- and lower energy tau-neutrinos), starting events as well as through-going events. In the latter two cases, a muon is produced in a charged current muon-neutrino interaction that either starts inside or before the detector. Tau neutrinos have not yet been identified [8]. At higher energies they produce a characteristic double-bang signature, where the interaction and decay vertex — separated on average by 50 m $E_\tau / 1 \text{ PeV}$ — can be resolved (see Fig. 1 for displays of cascade, track and double bang events). The combined analysis of all available IceCube data until 2014 results in a spectrum above 20 TeV consistent with an unbroken power law with best-fit spectral index of -2.50 ± 0.09 [9], while the most recent analysis of high-energy muon tracks above 200 TeV prefers a spectral index of -2.13 ± 0.13 [4], suggestive of a spectral hardening (see Fig. 2, left). The possibility of a spectral hardening is intriguing, since it implies a second population or at least a second production mechanism, that starts taking over at higher energies. Note that the softer part of the spectrum can not be explained as due to charmed particles produced and decaying in the atmosphere, since the angular and energy distribution appear to be inconsistent with the hypothesis.

The neutrino flavor ratio at Earth can be predicted by assuming neutrino production with subsequent neutrino mixing over very long baselines that result in any energy/distance dependent oscillation probabilities being averaged out. The flavor ratio obtained from the combined analysis of various cascade and track searches appears to be consistent with the expectation from the decay of pions and subsequent decay of muons (with the resulting flux ratio at source $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$) as well as with the case where the muon decay contribution is suppressed ($\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$). The possibility that cosmic neutrinos are produced through the decay of neutrons, leading to a pure electron neutrino beam ($\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$), is in tension with the data [9, 10] (see Fig. 2, right).

Fig. 3 (left) shows a sky map of IceCube track events, displaying their probability to point back to a point source above the isotropic background of atmospheric neutrinos (Northern

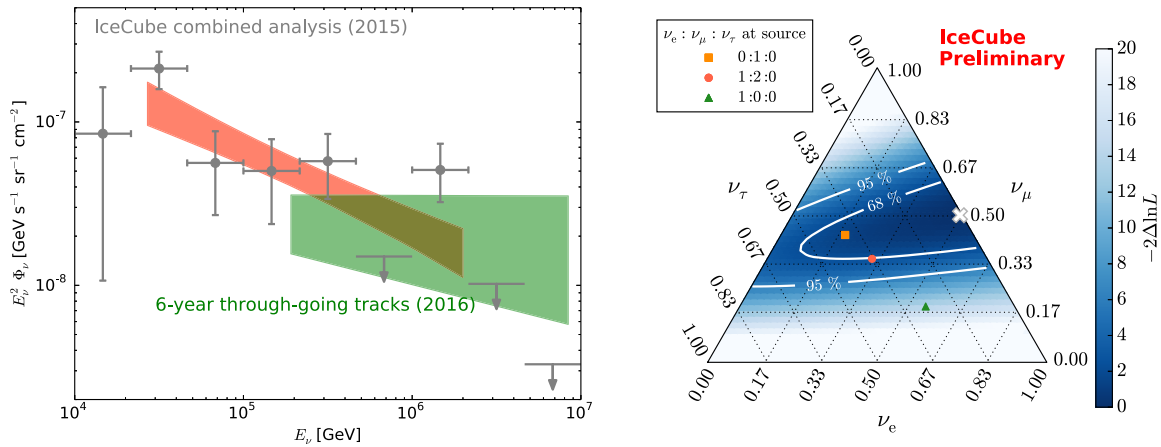


Figure 2. Left: Spectrum of cosmic neutrinos measured in a combined analysis of all detection channels (grey points, red bar). A new measurement based on 6 years of through-going muons (green bar) that is sensitive at higher energies indicates a harder spectrum above few hundred TeV. Right: Flavor constraints on the cosmic neutrino flux from the combined analysis in comparison to different scenarios expected for neutrino production in astrophysical sources.

hemisphere) and muons (Southern hemisphere). It contains more than 400.000 neutrinos accumulated over 7 years of data (2008-2015) but there is no evidence yet for individual point sources or the emergence of a galactic component. Although the sources of the observed high-energy neutrinos have remained unidentified, important clues have been extracted from the data nevertheless: 1) The sources of the cosmic neutrinos are predominantly of extra-galactic origin. This conclusion can be drawn from the event sample dominated by astrophysical neutrinos, which appear largely isotropic and predominantly not aligned with the galactic plane [3, 4]. 2) Two leading contenders for the sources of IceCube’s neutrino events can only explain a small fraction of the observed neutrino flux. A search for neutrinos in spatial and temporal coincidence with GRBs observed with gamma rays resulted in a strict upper bound of 1% as the maximum contribution from GRBs to the diffuse flux observed by IceCube [11]. And by not observing a coincidence with a large catalog of Blazars, the IceCube collaboration computed an upper bound of 27% as the maximum contribution from Blazars to the diffuse astrophysical flux [12] (but consistent with a sub-dominant contribution saturating only the highest energies, see e.g. [13, 14]).

Further constraints can be derived by relating the diffuse flux of neutrinos to that of gamma rays. Since gamma-rays and neutrinos are produced in the same hadronic interaction, one can expect that any astrophysical sources of high-energy neutrinos that is transparent to GeV gamma-rays should at best saturate the diffuse flux of gamma-rays, where the most detailed observations come from the Fermi satellite. However, careful modeling indicates that the measured spectrum of astrophysical neutrinos would be associated with an overproduction of gamma-rays unless the sources are dark in gamma-rays, e.g. so called hidden sources [16]. This connection to gamma-rays constrains the contribution of gamma-transparent sources such as Starburst galaxies, effectively ruling them out as the sole source of IceCube’s extraterrestrial neutrinos.

Hence, just three years after their discovery, the sources of the astrophysical high-energy neutrinos are already severely constrained. The source classes avoiding the constraints mentioned above are core-collapse Supernovae (SNe), where the region of neutrino (and gamma ray)

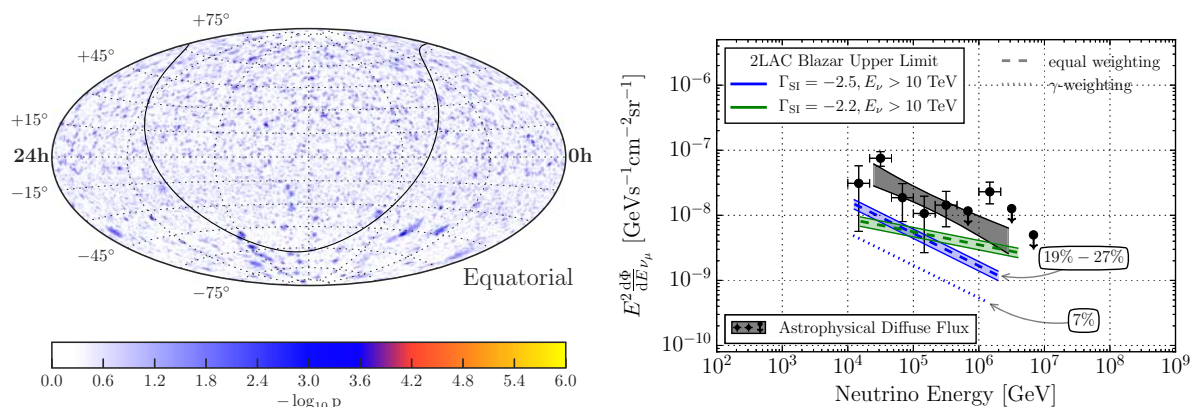


Figure 3. Left: sky map of p-values representing the local probability that an excess of events at a given position is due to a background fluctuation [15]. The Northern part of the sky is dominated by atmospheric neutrinos while the Southern sky is dominated by atmospheric muons - no significant excess over background is observed. Right: Flux upper limit for the FERMI-2LAC catalog of Blazars [12]. The constraints are shown as a function of energy for two different spectral indices Γ and different weighting schemas. The quoted percentages refer to the upper limit flux in units of the observed astrophysical, diffuse flux.

production is hidden by a stellar envelope or thick circumstellar medium, special classes of Gamma-Ray Bursts (GRBs), the core regions of Active Galactic Nuclei (AGNs) as well as potentially the class of Tidal Disruption Events (TDE), where stars are being torn apart by the supermassive Black Hole at the center of normal galaxies.

How would we move forward? At least for transient and highly variable source classes we can expect significant gains in sensitivity over the coming years through dedicated multi-messenger searches, e. g. combining the neutrino information — ideally in realtime — with that from electromagnetic [17] or gravitational wave messengers [18]. To probe some of the other sources classes, a larger, more sensitive neutrino detector appears necessary.

3. IceCube-Gen2 - a next generation neutrino observatory at the South Pole

To fully exploit the scientific opportunities and answer the pressing questions about the high-energy Universe raised by IceCube will require a detector larger than the existing one. This can be achieved by utilizing the transparent ice at the South Pole and employing several detection technologies.

The planned IceCube-Gen2 facility will integrate the operating IceCube detector with three new components: (1) the IceCube-Gen2 main array complemented by (2) the surface array, and (3) the low-energy core [23, 24]. It will increase the number of observed cosmic neutrinos ten-fold and be able to detect sources five times fainter compared to IceCube. This gain in sensitivity is possible — within a budget comparable to that of IceCube — through an increase in spacing between strings, more instrumentation per string and new sensor technology. IceCube-Gen2 is optimized to address the questions that emerge from current observations and that can not be answered by any other means. In particular, it is optimized for energies > 10 TeV, where IceCube has detected its signal and where gamma rays from cosmological distances start being attenuated. With its much improved point source sensitivity IceCube-Gen2 should be able to distinguish between the prospective sources classes, thus resolving the mystery surrounding the sources of cosmic neutrinos. It will also have sensitivity to neutrinos from the Galactic plane,

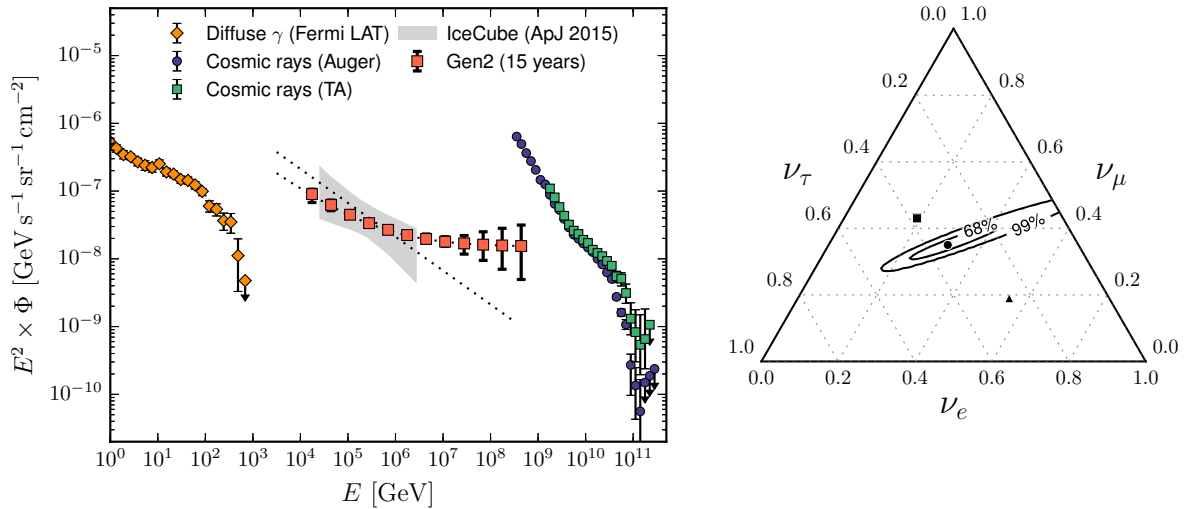


Figure 4. Left: the high-energy astrophysical neutrino spectrum, compared to the extragalactic γ -ray spectrum measured by Fermi-LAT [19] and the ultrahigh energy cosmic ray spectrum measured by Telescope Array [20] and the Pierre Auger Observatory [21]. The grey band is the range of neutrino fluxes obtained by IceCube [9], and the dotted lines represent two extrapolations to higher energies. The orange points are the median flux levels and 68% confidence intervals that would be obtained with 15 years of Gen2 data, assuming that the flux continues as E^{-2} (initial version of figure adapted from [22]). Right: expected constraints on the flavor composition of the diffuse astrophysical flux with 15 years of Gen2 data. (See Fig. 2 for a comparison to current constraints.)

thereby probing cosmic ray propagation within the Milky Way¹.

With its 10-fold increase in statistics, IceCube-Gen2 will expand the measurement of cosmic neutrinos spectrum by 1-2 decades in energy (see Fig. 4), allowing the measurement to connect directly to the highest energy cosmic rays. These cosmic rays are assumed to be of extragalactic origin, their sources unknown but in principle identifiable through observation of the associated neutrinos. Furthermore, observation of the flavor composition over a large range of energies will allow to probe the environment in which high-energy cosmic neutrinos and cosmic rays are being produced. Moreover, probing neutrino oscillations on cosmic baselines and detecting neutrinos with \gg PeV energies provides significant opportunities for detecting physics beyond the Standard Model. The range extends from the otherwise hard to identify pseudo-Dirac scenario [26, 27] to neutrino decay [28, 29], two name just two examples.

4. Conclusion

IceCube is opening a new window to the Universe. The observed flux of neutrinos is surprisingly large. In terms of energy density it is comparable to that of extra galactic gamma-rays and the highest energy cosmic rays. This appears to imply a close connection between the sources. Yet, the bulk of the gamma rays originate from Blazars, in tension with the upper bounds on the IceCube neutrino flux coming from the Blazars observed by the Fermi satellite. This implies that the sources might not be the same, and as a consequence, a class of neutrino sources that are

¹ for selected galactic sources a detector such as KM3NeT [25] in the Mediterranean sea, or GVD in lake Baikal will be better positioned

dark in gamma rays. On the other hand, the suggestion of a spectral hardening of the observed diffuse flux is indicative of a superposition of several source classes, which await discovery. To exploit the full scientific potential, plans are underway for a larger, more sensitive detector. Our goal is to have IceCube-Gen2 fully operational by the end of the next decade, allowing it to play an essential role in shaping the new era of multi messenger astronomy.

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