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Recent high-energy results from IceCube

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Summary. — In 2013 the cubic-kilometre Cherenkov detector IceCube has detected an astrophysical flux of PeV neutrinos. This talk gives an overview over some of the measurements that followed the initial discovery and summarizes the current status of the high-energy neutrino flux measurement.

1. – Introduction

High-energy neutrinos provide a window to energetic astrophysical processes which is complementary to electromagnetic and cosmic-ray observations. Due to their low interaction cross-section they reach Earth from much more distant sources and point back directly to the primary hadronic interaction in which they were created, unlike high-energy photons which are absorbed by the extragalactic background light and often reprocessed once they reach Earth. Additionally, neutrinos are not deflected by magnetic fields which in principle makes them usable for pointing studies. These unique properties largely motivated the construction of the IceCube experiment, a high-energy neutrino detector which has been running in full operation since 2011 [1]. IceCube consists of over 5000 photomultipliers (PMTs) submerged in a depth between 1.5 and 2.5 km in the Antarctic ice at the geographic South Pole. The PMTs detect Cherenkov light emitted from charged secondary particles created in the neutrino interactions. Typical event topologies are either cascade-like (from charged-current ν_e interactions or neutral-current interactions) or track-like (charged-current ν_μ interactions). The background for astrophysical neutrinos comes from atmospheric neutrinos and muons originating from cosmic-ray interactions in the atmosphere.

2. – Starting events

The first strong evidence (4σ) of an astrophysical neutrino flux came in 2013 with an analysis focussing on neutrinos interacting within the instrumented volume of the

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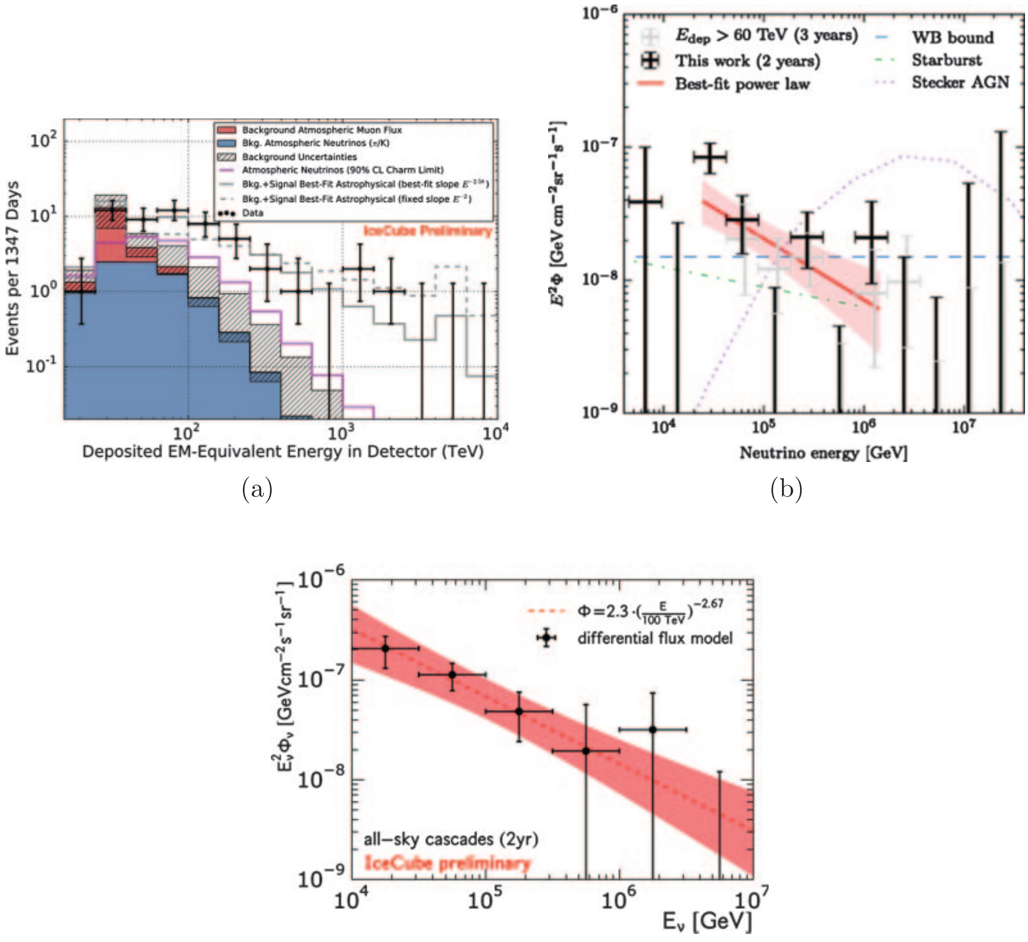


(a) (b)

(c)

Fig. 1. – Energy spectra for different starting-track/cascade analysis. (a) Latest HESE analysis [2]: observed events *vs.* energy. (b) Energy flux for a starting-event analysis extended towards lower energies [3]. (c) Energy flux for a cascade analysis with partially contained events at the detector boundary [4].

detector [5]. This High-Energy Starting-Event (HESE) analysis crucially used the outer detector layer to discard cosmic-ray-induced background events from both cosmic-ray muons and neutrinos. Neutrinos are normally an irreducible background, but can be identified for downgoing directions by accompanying muons from the same parent air shower [6].

3. – Further developments of starting events 2013-2016

Over the coming years this search has been repeated with more data. In the currently published version it uses 4 years of data and detects the astrophysical flux with over 7σ (see fig. 1(a)).

The spectral index of this latest measurement is found to be -2.58 ± 0.25. Another

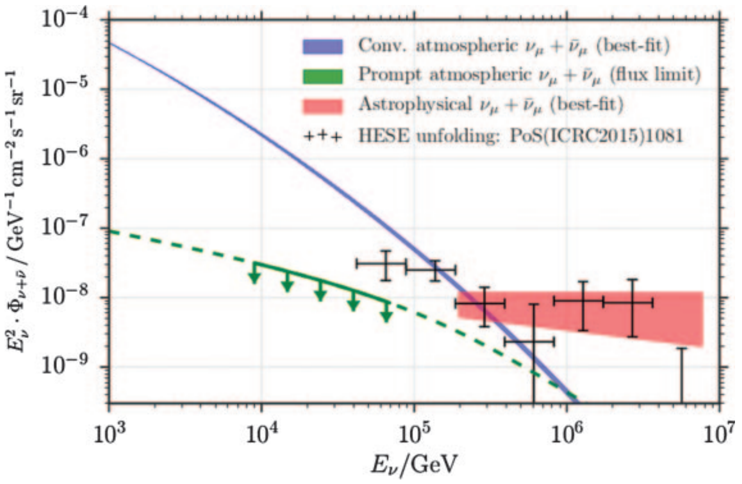


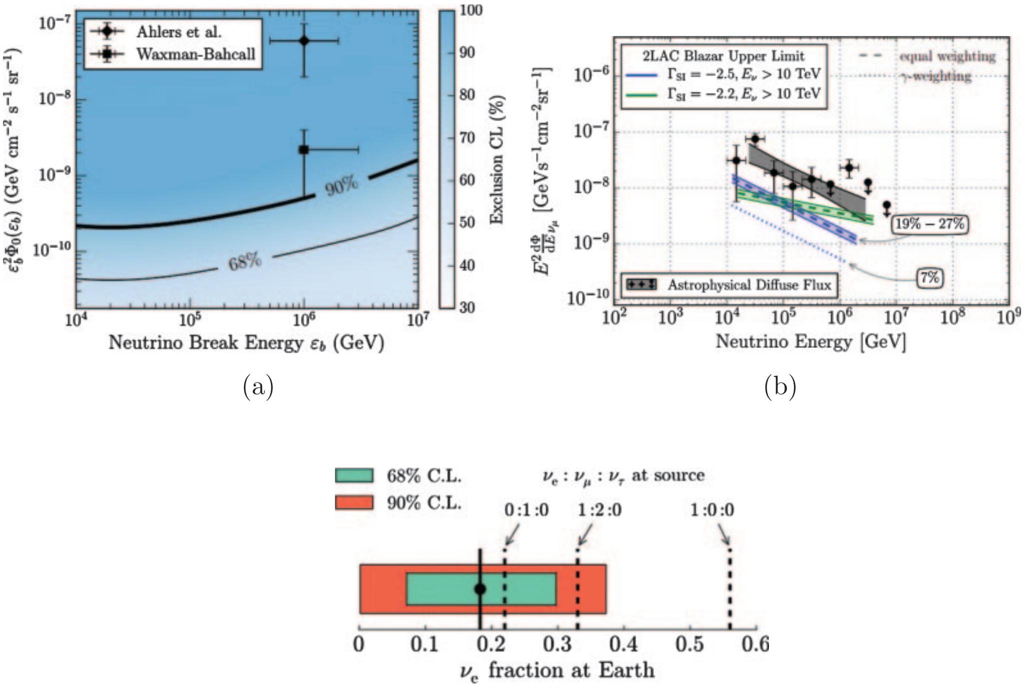
Fig. 2. – Energy spectrum from the 6-year throughgoing muon analysis [7] (red) together with the starting-track HESE spectrum [2] (black crosses). Conventional and prompt best-fit values are shown in blue and green, respectively.

analysis has extended the neutrino veto to lower energies (see fig. 1(b)) which increases the statistics and leads to a more precise measurement of the astrophysical flux spectral index of -2.46 ± 0.12, even though it only uses 2 years of data. Yet a third direction has been to focus on a slightly different event selection using cascade-like topologies only, but also including cascades at the boundary of the detector [4]. The best-fit spectrum of this slightly different selection is also soft, with a spectral index of -2.67 ± 0.12.

To summarize, a soft spectral index is the common feature of all these analyses. While tempting, a prompt component from charmed mesons is insufficient to explain this feature given current cosmic-ray interaction models.

4. – Throughgoing tracks

Complementary searches to starting events using through-going tracks have been performed as well, most recently using 6 years of data [7]. The significance of this latest track sample yields a 5.6σ exclusion of the background-only hypothesis and thereby confirms the astrophysical flux with an independent dataset. Figure 2 shows the result from the starting event search [2] in combination with this 6-year track analysis. The astrophysical index is determined to be around -2.13 ± 0.13, which is in slight tension with the starting event searches. However, the low-energy threshold is much higher at around 200 TeV, compared to the 1–60 TeV in the starting event searches. It is therefore possible that the flux hardens at higher energies, while both measurements remain valid in their respective energy regimes. More data will confirm or exclude this spectral change in the future. If the high-energy spectral index is as hard as -2, a value which is compatible with the through-going muon measurement, it cannot continue forever but has to cut off around 50–100 TeV due to constraints from a recent all-flavor high-energy analysis [8].



(a) (b)

(c)

Fig. 3. – Constraints for the astrophysical flux. (a) Flux Upper Limit (Normalization, break energy) for over 800 prompt GRBs [9]. (b) Upper limit on *Fermi* LAT 2LAC blazar emission compared to the astrophysical flux [10]. (c) ν_e flavor contribution to the astrophysical flux [11].

5. – Probing the source class

Several searches have been performed to extract more information than just the spectrum. A galactic plane scan [2] with the same dataset as in the 4-year starting search yielded a p-value of 2.3% , indicating no significant deviation from isotropy. A dedicated point-source search using 7 years of throughgoing muon-track data [12] which scanned every point in the sky also saw no significant deviation from background.

Other analyses looked for overfluctuations studying entire populations of objects. A GRB search [9] looking at over 800 bright prompt GRBs saw nothing which provides upper flux limits for the population of GRBs assuming all GRBs emit equally. Comparing the upper limit (fig. 3(a)) with the HESE flux shows that the bright GRBs of this sample contribute at most a few percent to the signal. Another search studying all 862 blazars in the 2LAC gamma-ray catalog [10] for quasi-steady neutrino emission also observed no overfluctuation in 3 years of IceCube data. Here, the unknown source count distribution for the flux of these objects is accounted for and a model-independent upper limit for the flux from these objects shows that these blazars contribute less than 27% to the astrophysical diffuse flux. Yet another strategy to probe potential source environments is to study the composition of neutrino flavors observed in the detector. Using neutrino oscillation physics one can then calculate the flavor composition in the sources. The most sensitive flavor-determination was performed in [11] which can exclude pure electron-neutrino sources at 3.7σ.

6. – Conclusion

IceCube detected an astrophysical diffuse neutrino flux in 2013. Since then, several other analyses have either extended the measurement with more data of starting events or confirmed it using an independent measurement with through-going muon tracks. Some of these searches have been outlined here. The flux is consistent with isotropy and a power-law spectrum without any significant indication of a cutoff at the moment. To the contrary, the spectral index of this power-law spectrum is soft at low energies (about -2.5) and seems to harden as suggested by the muon-track analysis above 200 TeV to about -2.1. The significance of this difference in spectral indices is currently at the level of 2–3σ, and more data is required to confirm this spectral change.

Several sources could be excluded as an origin so far. The dominant contribution is extragalactic due to compatibility with isotropy. However, the brightest GRBs in the years 2010-2013 and the brightest GeV blazars are at most sub-dominant contributers, both of which are extragalactic source populations. Also, pure ν_e-sources as the dominant contribution are excluded at 3.7σ.

The fact that the standard point-source all-sky scan does not see anything indicates that the total flux is not dominated by the bright flux-end of the overall source count distribution, *i.e.* the flux comes from a large population of faint objects. A comparison with *Fermi* LAT data suggests that sources must be optically thick GeV-gamma ray emission if the low-energy end of the spectrum continues with such a steep spectrum of around -2.5. Potential source candidates that are still compatible with experimental constraints to be dominant contributers are, among others, Starforming galaxies [13] or Type-IIn supernovae [14].

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