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Neutrino astronomy in the IceCube era

Todor Stanev

Bartol Research Institute, University of Delaware, Newark, DE, USA

E-mail: stanev@udel.edu

The IceCube Neutrino Observatory is build to detect high energy neutrinos generated in different powerful astrophysical objects in the Universe. We describe the observatory, different types of events it has detected, and some of the sources of the detected neutrinos.

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1. Introduction

IceCube is a huge experiment for detection of high energy neutrinos built in the ice cover at the South Pole of the Earth. It is shown on the first figure of this manuscript. Just the fact that this experiment was build is amazing and it deserves the Nobel Prize. The person who contributed mostly to it is Dr. Francis Halzen from the University of Wisconsin in Madison. He gave a presentation to the US Congress which convinced the politicians that building a physics experiment deserves the very large amount of money that it costs. When the building of IceCube was approved many other countries joined the effort and contributed with finances and personal. Francis Halzen is still the leader of IceCube. IceCube, which is shown in Fig. 1, consists of 80 strings at distance

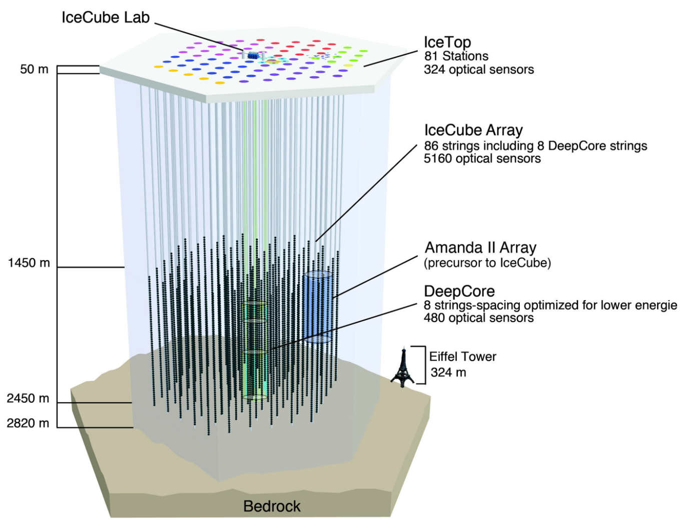

Figure 1: IceCube

of 125 meters, which are 1 km long and start at 1450 m under the top of the ice. Each one of them contains 60 optical modules, which detect the light generated by the neutrino induced cascades or the muons produced in the neutrino interaction. The distance of 1450 meters from the top of the ice is chosen to increase the energy of the events detected by the experiment. Very few of the neutrinos produced by cosmic rays in the atmosphere reach the detector. On top of the ice is the air shower detector IceTop. It is used as a typical air shower detector, but also to veto air showers that appear like cascade events. Additional eight strings, called Deep Core, have optical modules at seven meters at the maximum depth.

If you want to know more about IceCube, you can go to the website 'Icecube.wisc.edu' that has a longer (and probably better) description of the experiment and also description of its studies and discoveries.

The two types of IceCube events have different characteristics. The cascades, as shown in the next figure, allow the researchers to estimate the energy of the event very well, within several percent. The direction of the detected neutrino is not that well determined.

The muon track events have generally the opposite characteristics. The direction of the events is generally determined with an error not exceeding one degree, while the energy determination is

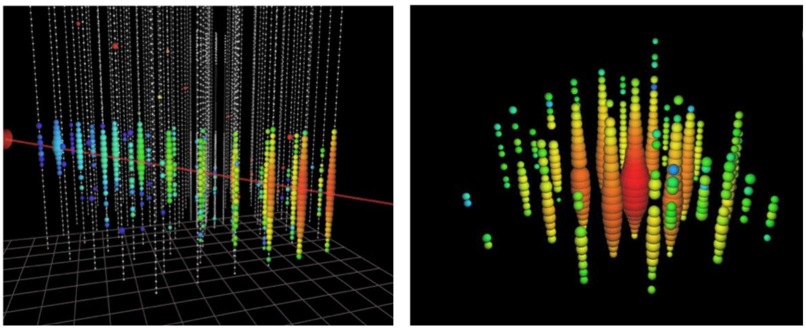

Figure 2: Muon track and cascade events

much worse. One of the reasons for that is also the fact that it is known how long the muon has propagated before reaching the detector. This is true for all muons that are not propagating down vertically within several degrees.

2. Neutrino sources

The reason for building IceCube was the search for sources of high energy neutrinos. These sources should also generate high energy γ-rays. The gamma rays, however interact much more than the neutrinos do. For this reason neutrinos, which much smaller interaction cross-section can propagate from much distance sources and with them we are observing most of the Universe.

The first neutrino source detected was the blazar TXS0506-056 [1, 2]. This started with the observation of a 290 TeV neutrino coming from its direction while the blazar was also active in generating γ-rays. The accuracy in direction at that time was already very good, less than 0.3 degrees for such high energy events. A careful look at older neutrino events, when the direction

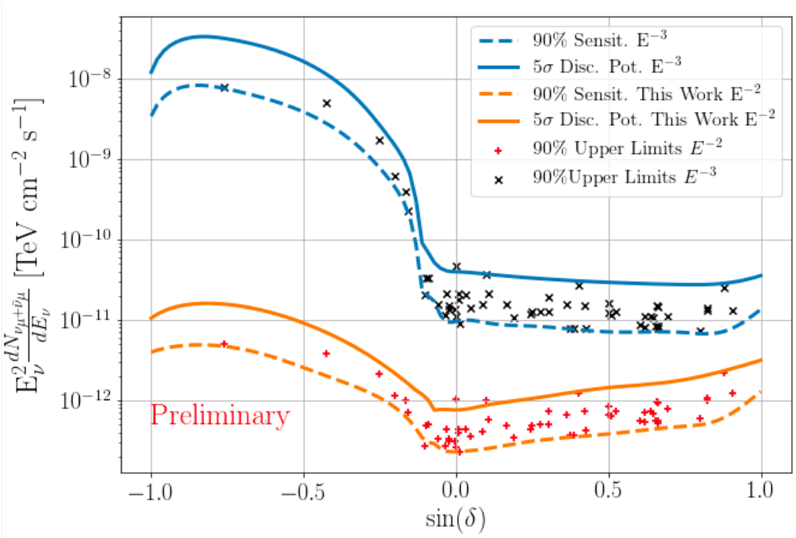

Figure 3: Neutrino source search

accuracy was lower, were also coming from the direction of this blazar when it was active in production of γ-rays. After that IceCube was convinced that the results have established a high energy neutrino source.

Finding the sources of the detected high energy neutrinos is, of course, much easier when the accuracy in determining the neutrino direction is better. IceCube discovered several more sources of high energy neutrinos among which are NGC 1068 and PKS 1424+240.

NGC 1068 is an active galaxy from which IceCube has detected 79 +/-20 high energy neutrinos between 2011 and 2020. The error of 20 events is due to the fact that the exact direction of the different neutrino events are not determined equally well. These 20 events have a chance of coming from the source, but it is not certain.

PKS 1424+240 is a distant luminous and high frequency blazar, which is source of high energy gamma-rays reaching almost one TeV. After the detection of high energy neutrinos coming from it, there are many papers discussing the production of gamma rays and neutrinos on similar objects.

The two objects discussed above are not one only neutrino sources discovered by IceCube. One should at least mention the sources TXS9596 and GB9, which created similar numbers of high energy neutrinos.

A summary of the high energy neutrino alert events detected by the IceCube was published at the end of 2023 [3]. It shows the location of the 275 very high energy neutrino alert events that are label as 'gold' or 'bronze'. Gold events are those that have more than 50 percent chance to come from universal neutrino sources. For 'bronze' events that percentage is 30. The next figure shows the directions of these events.

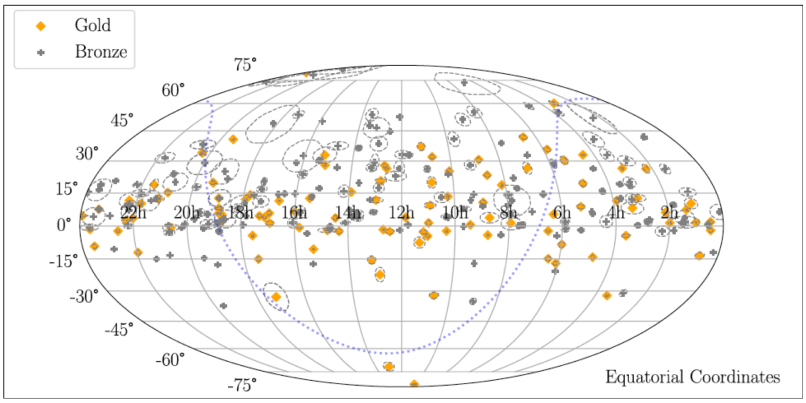

Figure 4: The 275 high energy events direction

There are about 100 new papers on the topics I mentioned here and some other related ones in the publications presented at the International Conference on Cosmic Rays in 2023.

IceCube did not only discover sources of high energy neutrinos. The only existing huge neutrino detector observed, for example, another unusual event, that is very rare: A W resonance of energy 6.3 PeV (6.3 million GeV). The interpretation of this event was the interaction of an antielectron neutrino with an electron. As is seen on the picture it is not totally contained in IceCube, but the energy estimates are very close to the predicted energy. The IceCube event is shown on the figure below.

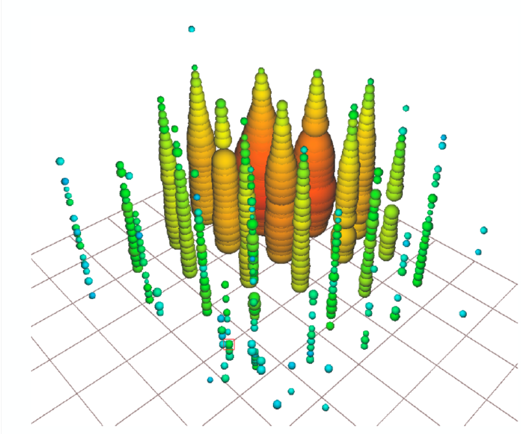

Figure 5: The Glashow resonance

3. Future

The success of the IceCube detector in the discovery and study of neutrino sources leads to the idea of building a bigger detector, which will be able to discover and study more neutrino sources. This project is called IceCube_Gen2. It suggests using sensors slightly better than the ones of IceCube at 250 meters from each other. When built it would generate eight times the volume of IceCube.

References

[1] **IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, VLA/17B-403** Collaboration, M. G. Aartsen et al., *Science* **361** (2018) eaat1378.

[2] **IceCube** Collaboration, M. G. Aartsen et al., *Science* **361** (2018) 147–151.

[3] **IceCube** Collaboration, R. Abbasi et al., *Astrophys. J. Suppl.* **269** (2023) 25.