Robust Statistics in IceCube Initial Muon Reconstruction

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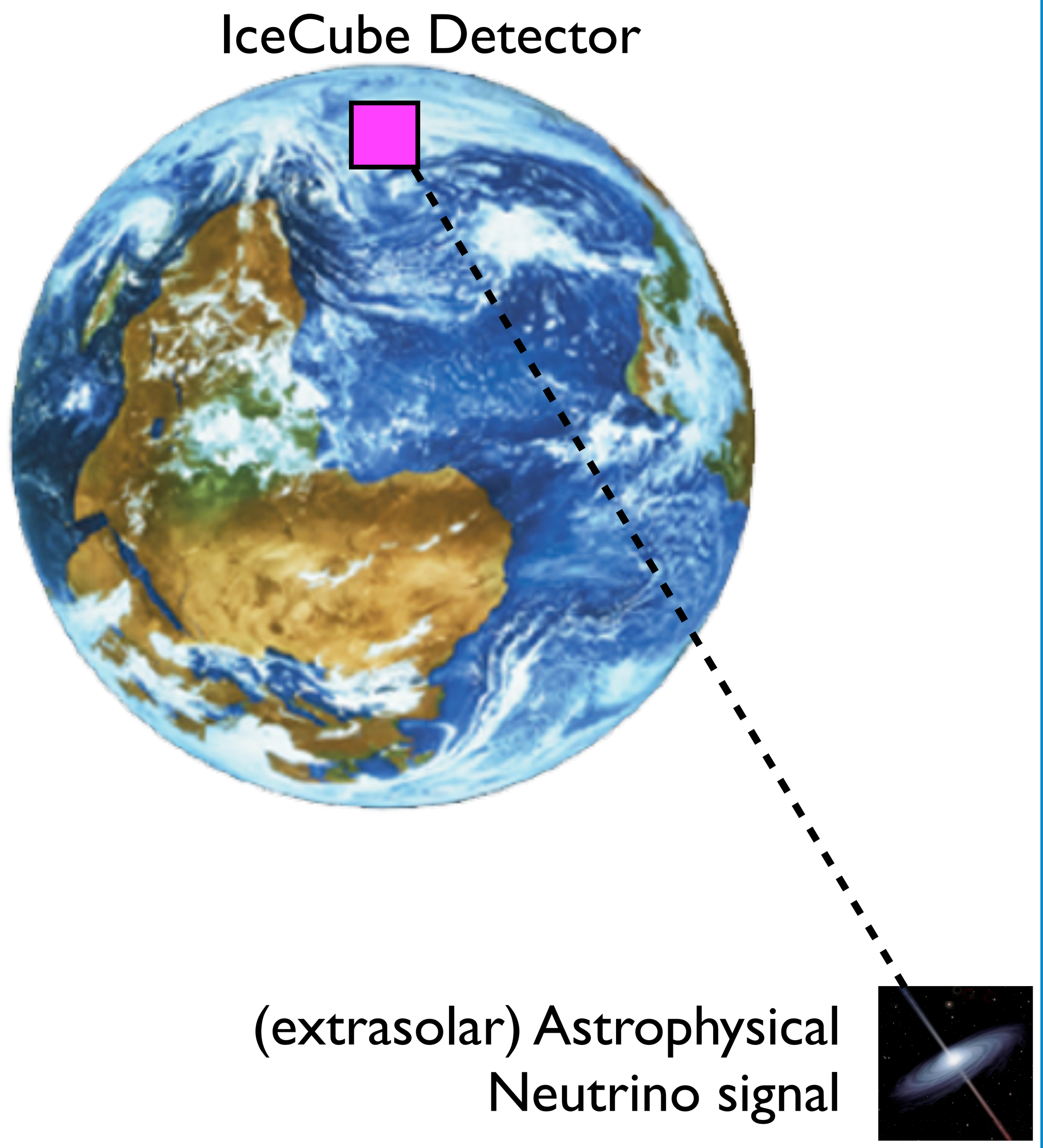
Abstract

In the IceCube Neutrino Detector, muon tracks are reconstructed from the muon's light emission. The initial track reconstruction serves as a starting point for more sophisticated track fitting, using detailed knowledge of the ice and the detector. The new approach described here leads to an improvement of the accuracy in the initial track reconstruction for muons. Our approach is to couple simple physical models with robust statistical techniques. Using the metric of median angular accuracy, this solution improves the accuracy in the reconstructed direction by 13%.

Motivation

The IceCube neutrino detector searches for neutrinos that are generated by the universe's most violent astrophysical events: exploding stars, gamma ray bursts, and cataclysmic phenomena involving black holes and neutron stars.



A neutrino source being detected.

The IceCube telescope is a tool to search for dark matter, and could reveal the new physical processes associated with the enigmatic origin of the highest energy particles in nature.

Background

The IceCube neutrino detector is

- near the geographic South Pole, buried at depths 1.5-2.5 km in the Antarctic ice
- composed of 5,160 optical detectors, spread over 86 vertical strings arranged in a hexagonal shape
- has a total instrumented volume of approximately one cubic kilometer

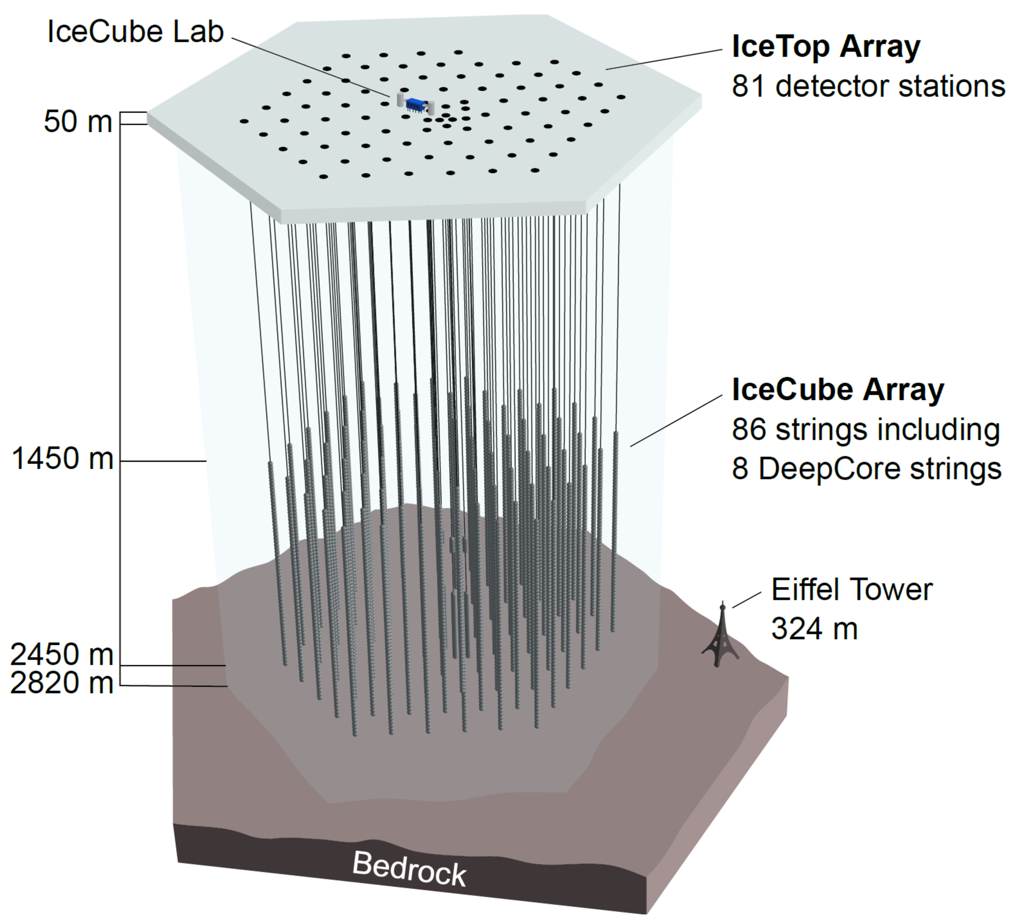
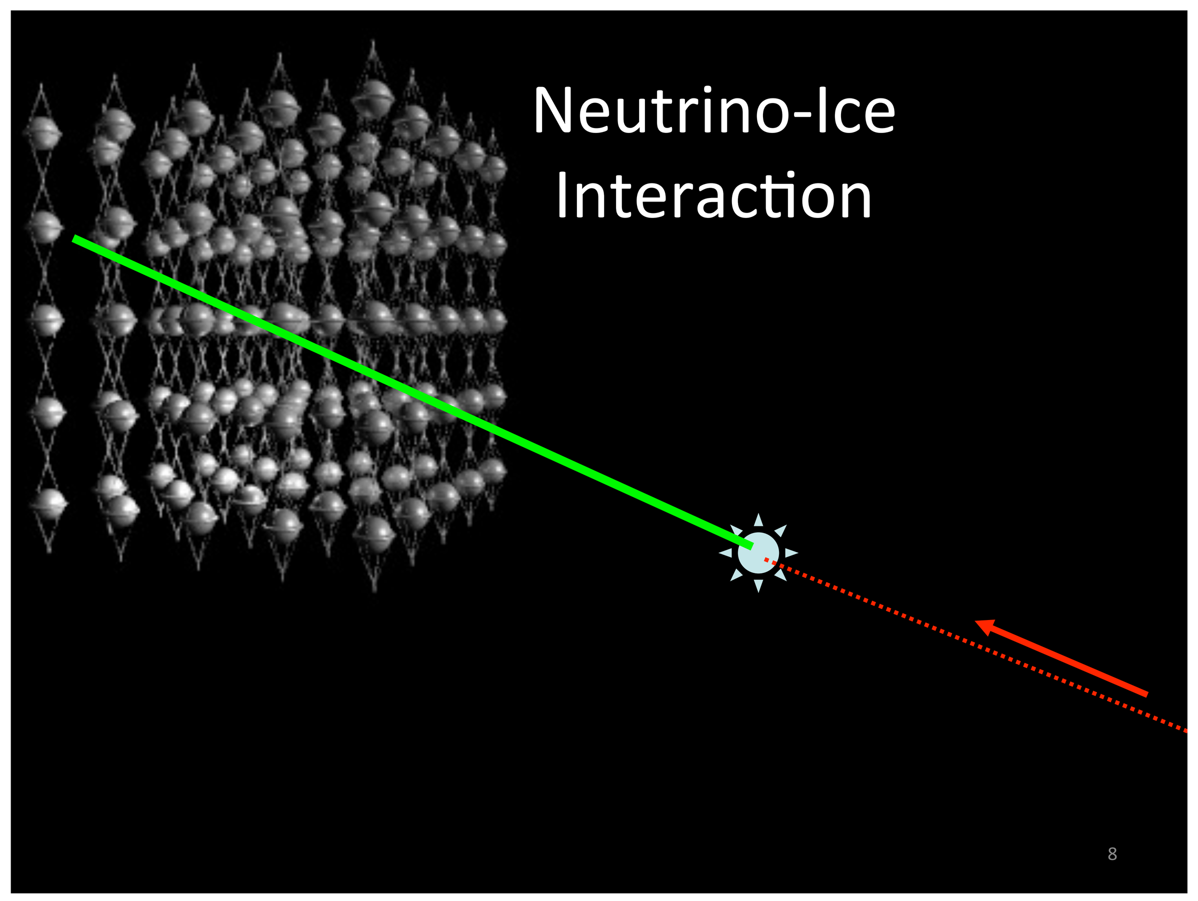


Diagram of the IceCube Detector

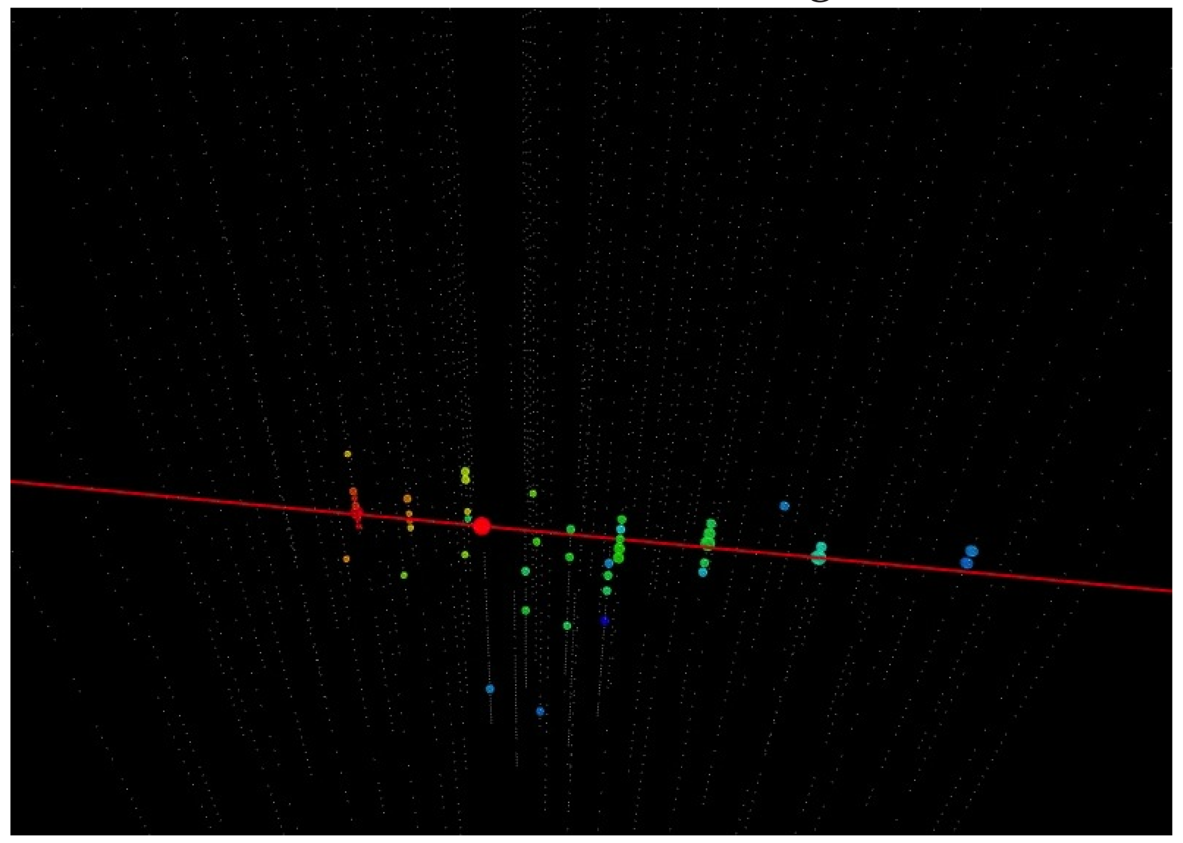
Neutrinos are detected by the charged particles, often a muon, produced in neutrino interactions with the rock or ice near the detector. This particles release light, which is observed by the detector.



A neutrino ice interaction generating a muon.

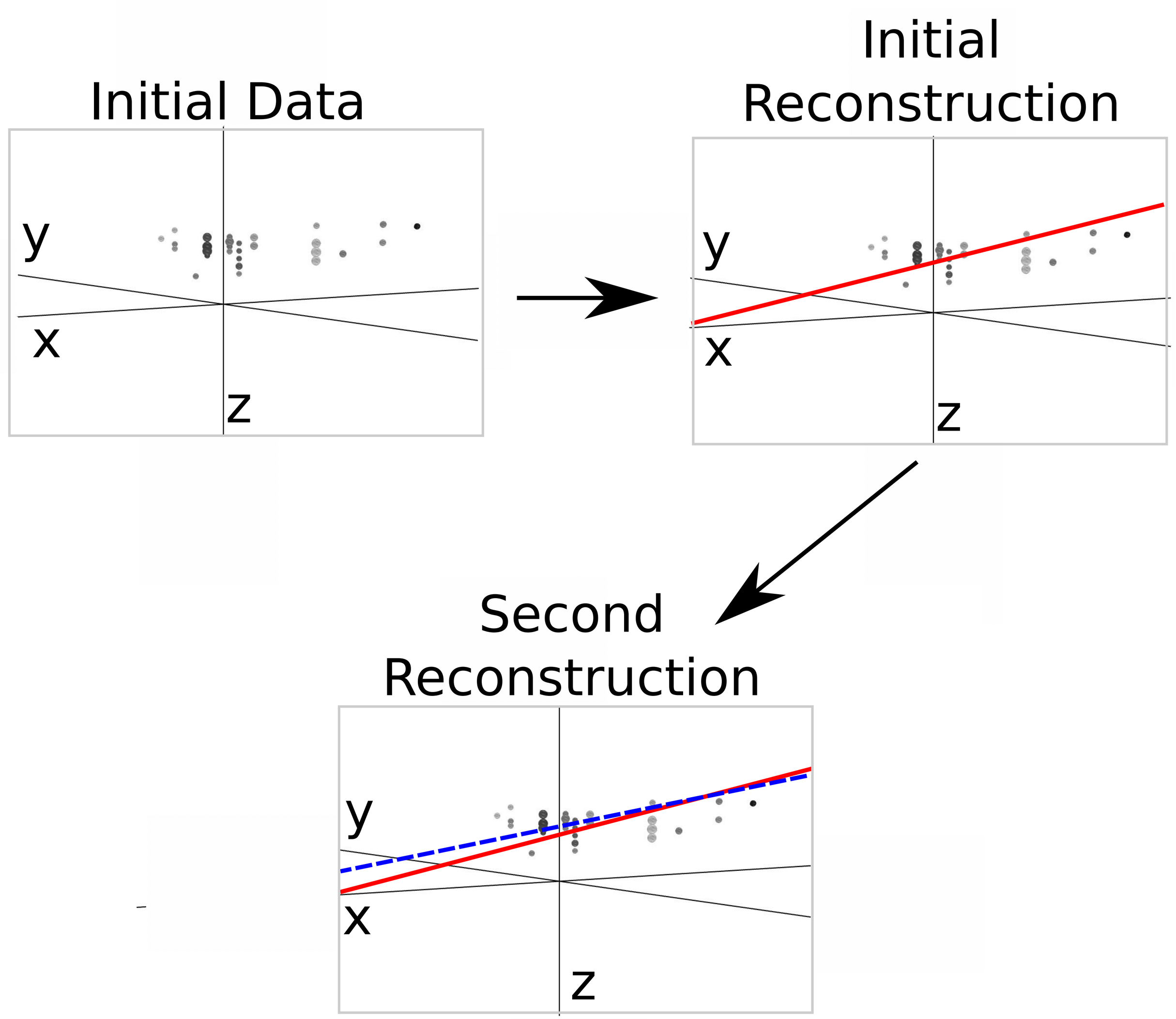
Problem

In the IceCube Neutrino Detector, muon tracks are reconstructed from the muon's light emission. Shown below is a reconstruction of the muon track. The colored dots indicate the PMTs that recorded light detection, and the white dots indicate PMTs that observed no light.



A reconstruction of the muon path.

The reconstruction algorithm uses a simple first-pass algorithm to generate an initial guess, which is then refined by a more sophisticated algorithm, illustrated below



The reconstruction pipeline

Thus, an improvement in the initial guess will improve the final reconstruction accuracy.

Contribution

We improve the reconstruction's accuracy by improving the initial reconstruction, thus giving the second reconstruction a better starting point. Reconstructing the muon track is a difficult problem due to two aspects.

Scattering The details of the ice's optical properties are nontrivial to model. The muon's light is scattered by dust impurities and air bubbles in the ice medium.

Noise The noise inherent in the data. The PMTs are so sensitive to light that they can record hits from the radioactive decay in the surrounding glass.

Computational Constraints The limited computational resources. Reconstruction algorithms need to be efficient enough to process about 3,000 muons per second.

We improve the initial reconstruction algorithm with robust statistical techniques, such as:

Scattering Adding a filter that detects and remove photons that have been excessively scattered.

Noise Replacing the fitting model one with one that identifies and ignores outliers in the data.

Computational Constraints Our algorithm improvements only add about 100 μs to the reconstruction time.

Results

Implementing our changes to the algorithm generates several improvements:

- 57.6% improvement in the median angular resolution of initial reconstruction.
- 13% improvement in the median angular resolution of the second reconstruction.
- 10% fewer atmospheric muons erroneously classified as neutrinos.
- 1% more muons correctly classified as neutrinos.

Our algorithm runs inside the detector, and is included in all IceCube analyses.