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Citizen science to enhance sub-GeV neutrino searches in IceCube

The IceCube Collaboration

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Machine learning has become a vital part of analysis in modern neutrino astronomy, and many recent discoveries would not be possible without it. This approach, however, is limited by the quality of available training data. Located at the South Pole, the IceCube Neutrino Observatory is a neutrino detector sensitive to astrophysical neutrinos from GeV to PeV energies, with ongoing efforts to push the sensitivity down to 100 MeV for neutrinos from transient events. IceCube is dominated by massive backgrounds, detecting more than 10 billion atmospheric muons for each astrophysical neutrino, and machine learning is a powerful tool to reduce this large background rate. However, undetected outliers in labelled training data negatively affect the final performance of machine learning algorithms. Citizen scientists can help to quantify and qualify outliers in IceCube data to improve the detection of such outliers. In this contribution, we present the ongoing efforts of utilising citizen science to improve a machine-learning-based event selection targeting sub-GeV astrophysical neutrinos.

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1. Introduction

We present in the following our current progress and plans for a citizen science project aimed at engaging the general public in neutrino astronomy. Citizen science provides a versatile tool to solve problems in ways that differ from many traditional ways of doing research, all while closing the gap between scientists and the broader community. The *TRAνEL* – Transient Astrophysical *ν*trinos at Extremely Low Energies – project aims to involve the public to help out with classifying low-energy neutrino signals in data from the IceCube Neutrino Observatory. It will provide motivated hobby-scientists with the opportunity to both learn more about the exciting field of neutrino astronomy, and contribute to the exciting research being performed by the IceCube Collaboration.

The IceCube Collaboration has a long history of outreach and public engagement projects, including the already successful citizen science project *Name that Neutrino* [1], in which volunteers were asked to classify high-energy neutrino events based on their topology. Its success shows that people generally are willing to help out with different classifications of IceCube events if they have a way of doing so. Our plans for the TRA*ν*EL project are to seize this opportunity to work with volunteers and have participants help classify lower-energy events, where detector noise is a larger issue.

In addition to helping out with event classification for scientific gain, the proposed project also aligns with broader European visions of connecting citizens to science through the *REINFORCE* project [2]. This international project aimed to engage and support citizens to work in collaboration with researchers and to actively contribute to the development of new knowledge needed for both modern science and society. Multiple successful citizen science programs have already been conducted within the *REINFORCE* project, and our proposed project will follow on these earlier successes, while bringing the exciting field of astroparticle physics into people's homes.

2. The IceCube Neutrino Observatory

The IceCube Neutrino Observatory is a particle detector located at the geographic South Pole. Designed with the main goal of detecting astrophysical neutrinos and identifying their sources [3–5], its scientific scope has grown to also include neutrino oscillation physics [6], beyond Standard Model physics [7], cosmic ray physics [8] and much more. IceCube has also provided complementary measurements to other specialised experiments by probing neutrinos with energies not accessible with reactor or accelerator experiments. IceCube consists of 86 strings, each instrumented with 60 digital optical modules (DOMs), buried in a hexagonal array between 1450 and 2450 metres below the surface, instrumenting a cubic kilometre of ice. Each of these DOMs is equipped with a photomultiplier tube (PMT), sensitive to the dim light produced by particle interactions in the ice.

Neutrinos pass through the gigaton of ice instrumented by IceCube all the time. Some of these neutrinos interact with atomic nuclei in the ice, resulting in high-energy secondary particles which produce Cherenkov radiation as they decelerate in the ice. Some of this light reaches the PMTs, and IceCube is able to reconstruct the direction and energy of the initial neutrino based on this light. The topological shape of this light depends on the characteristics of the initial neutrino [9]. Typically, high-energy events in IceCube are divided into two main categories: tracks and cascades. Track-like events are produced when an incoming muon neutrino has a charged-current

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(CC) interaction mediated by a $W^{\pm}$ boson. This results in an ultra-relativistic muon depositing light as a track going through the detector. Cascade-like events are produced when either electron or tau neutrinos have a CC interaction or when all three flavours have a neutral current (NC) interaction. The resulting particle showers lose energy almost immediately and the resulting light pattern looks much more spherical around the interaction vertex. For tracks, it is easier to reconstruct the arrival direction of the neutrino, but the energy of the particle is less known. For cascade-like events, it is usually the opposite.

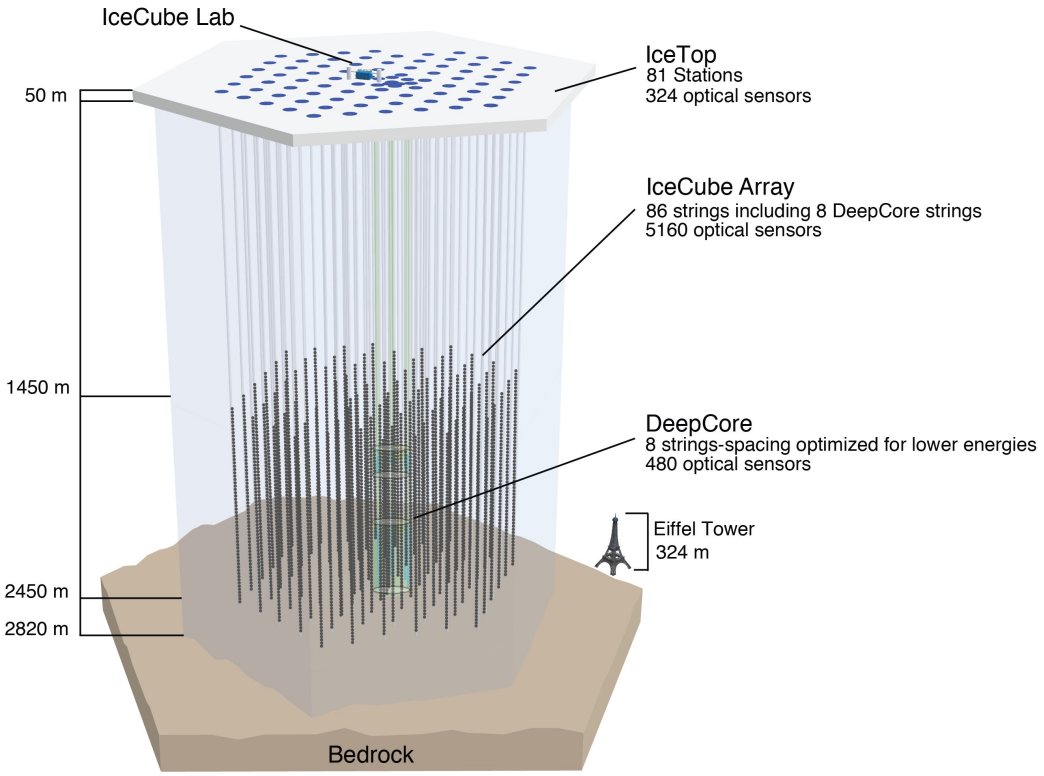


Figure 1: The IceCube Neutrino Observatory instruments a volume of roughly one cubic kilometre of clear Antarctic ice with 5,160 digital optical modules (DOMs) at depths between 1,450 and 2,450 metres. The observatory includes a densely instrumented sub-detector, DeepCore, and surface air shower array, IceTop.

2.1 Backgrounds in IceCube

Unfortunately for scientists studying astrophysics, neutrinos of astrophysical origin are not the only thing IceCube detects. At O(GeV) energies, the largest background in IceCube is dark noise consisting mainly of thermal noise from the electronics within the DOMs and from the decay of radioactive materials in the glass pressure-vessel surrounding the PMTs [10]. Noise caused by these radioactive decays shows up as correlated noise on an individual DOM level, as each decay can produce multiple photoelectrons. In addition, there is a temperature-dependent uncorrelated noise rate, noticeable as the ice has a temperature gradient decreasing the temperature as the depth increases. At higher energies, the main backgrounds come from correlated signals produced by atmospheric muons and neutrinos. Since IceCube is not a direct neutrino detector,

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but rather a detector for the light produced by charged particles, the large number of muons created by cosmic ray interaction in the atmosphere make up the vast majority of events seen by the detector. Every year, IceCube detects more than 10 billion atmospheric muons, which look similar to muons from astrophysical neutrinos going through the detector. In addition, there are also a large number of neutrinos produced in the atmosphere from air showers produced by primary cosmic rays. Our understanding of this atmospheric neutrino flux is being constantly improved [11], and knowing how it behaves, especially at higher energies, is crucial in a detector like IceCube to distinguish between atmospheric and astrophysical neutrinos. At O(GeV) energies, dark noise from the DOMs dominates over atmospheric muons. As a consequence of all these backgrounds, detecting astrophysical neutrinos in IceCube is like searching for a 'needle in a haystack'.

2.2 GeV neutrino detection

A neutrino with O(GeV) energies will only deposit light in a few DOMs in IceCube. Individual neutrinos are therefore almost impossible to distinguish from random background noise, especially at energies approaching 1 GeV. Therefore, in order to look for GeV neutrinos from astrophysical sources, time-window analyses are often used. By choosing a time-window around an electromagnetic or gravitational-wave signal detected by other telescopes, a comparison can be made between a time-window before and/or after the transient signal with the detector response during the transient event. If a significant difference is seen, a statistical argument can be made about possible neutrinos coming from the transient object. This is the general idea behind searches for GeV-scale neutrinos from transient, astrophysical objects in IceCube [12].

2.3 Unfiltered data – hitspool

Recent works summarised in [13] have made it possible to use sub-threshold data – data otherwise lost by the different filtering stages at the IceCube surface lab at the South Pole – in IceCube through a data stream called HitSpool. Multiple models for neutrino emission from astrophysical objects peak at around 1 GeV energy, resulting in the deposited signal in IceCube possibly being removed by the standard processing and filters applied. The new sub-threshold data now available presents a way to extract this otherwise lost signal. This sub-threshold data is completely dominated by noise from different backgrounds. To reduce the different dominating backgrounds, different algorithmic approaches, and manifold learning methods [14] are being developed. Building on this, we are currently working on implementing new machine learning algorithms, which we plan on improving through the use of citizen science.

3. Support from hobby scientists

Citizen science has been established as a powerful tool to complement scientific analyses. The prime example of this is the Galaxy Zoo project, which had over 10,000 volunteers classifying millions of images of galaxies captured by the Hubble Space Telescope, resulting in over 60 publications [15]. The success of this project has since grown into the web-based platform Zooniverse [16], which has hosted hundreds of different projects, where 'hobby scientists' team up with analysts to help solve problems in a wide field of science. As of writing this, Zooniverse has over 2.8 million registered users and is close to passing 1 billion classifications.

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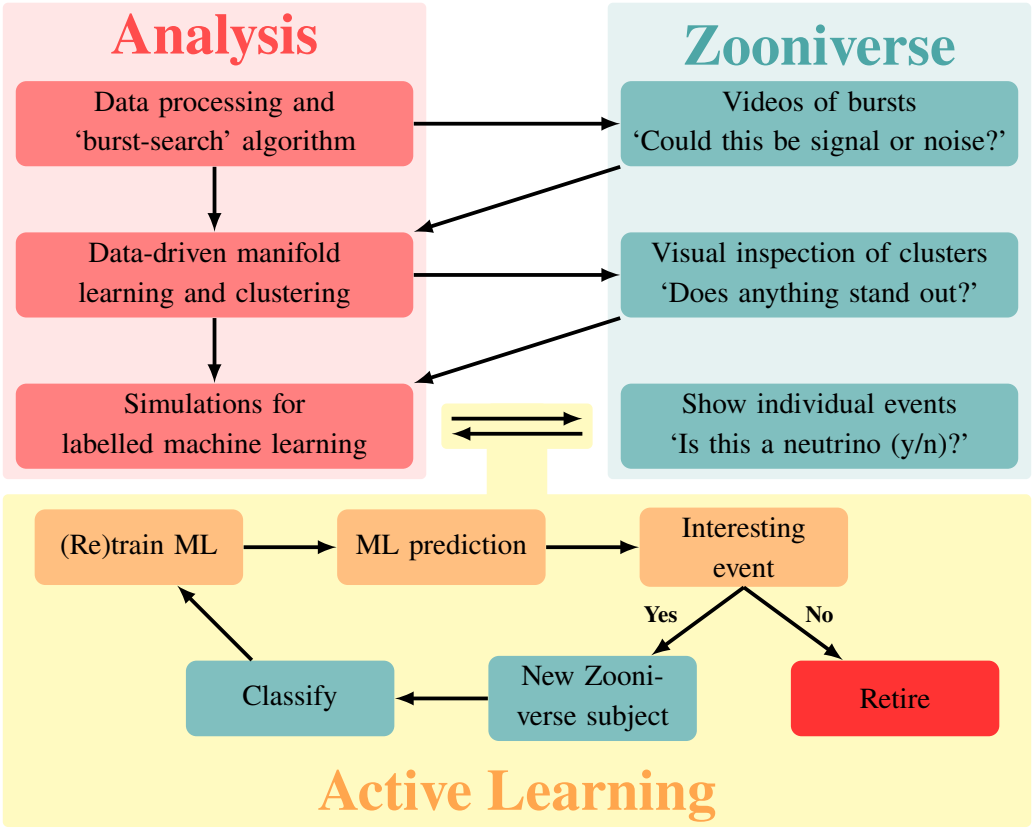


Figure 2: Planned workflow for the citizen science project presented in the main text. The steps under 'Analysis' are explained in [13]. The first (upper right) step of the 'Zooniverse' part is currently under review and will launch soon. The 'Active Learning' part will combine classifications from machine learning algorithms with that of volunteers to better classify outliers and improve the final event selection described in [13].

3.1 Zooniverse project

The TRAνEL Zooniverse project will be available in English, Spanish, German, French, Dutch, and Italian at launch. The videos prepared will consist of both simulated and real sub-threshold data from the IceCube observatory. The first time a new participant tries to investigate and classify events, a tutorial will be shown, walking the volunteer through what to look and listen for in the videos and how to classify the events accordingly. This tutorial, along with a more detailed field guide, will also be available afterwards in case the users are confused about what to do. They will be asked to identify collections of hits that are more likely caused by a single charged particle moving through the detector, as well as events with hits that are more spread out, characteristic of random detector noise. Additionally, a field guide containing all frequently asked questions and additional information will be available at all times to the volunteers. All videos are fixed to be 10 seconds long, and half of the video will show new hits appearing in the detector, whereas the latter half of the video will slowly zoom in on where the hits are to give a better view. Throughout the full duration of each video, the event will be rotating at a fixed angular velocity, showing the

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event from multiple angles. The playback speed can be adjusted, making it easier to identify when there are multiple hits close together. In addition to the visual, the events shown will be sonified, playing distinct piano notes for each new hit in the video. This has been designed specifically for volunteers with reduced vision capabilities, in such a way that participants are able to help classify events based purely on sound. It is designed in such a way that the first hit will always play a flat C tone, and increase by one half-tone if the subsequent hit is far enough away. This results in hits close together sounding identical, whereas hits farther away sound different. In addition to the event display, a progress arrow will be shown at the top of the videos with the hits of corresponding colour ordered in time. The total time elapsed, in ns, between the first and last hit in the event is indicated at the end of this arrow. This will provide additional information about the total duration of the event, as causally connected hits— hits that are closer together during some time than the distance light can travel in the same time— are more characteristic of a neutrino as opposed to background noise. The software that produces these videos was developed as part of this project and consists of generating videos of events, artificially matching and adding musical notes on top before combining and compressing the .mp4 videos to account for the Zooniverse limit of 1 MB per subject.

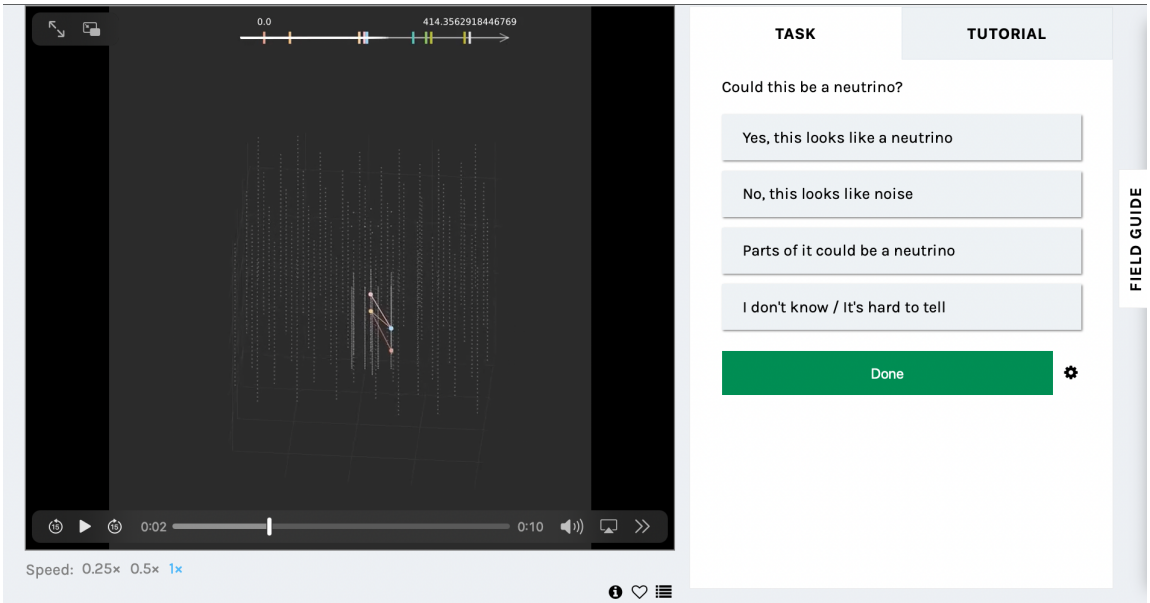


Figure 3: Screenshot of the 'classify' tab of the Zooniverse project. Volunteers will be shown short-duration videos of low-energy events and asked to classify them as either signal-like or noise-like based on how the event looks and its duration.

3.2 Machine learning complementarities

To detect neutrinos in sub-threshold IceCube data, we are developing machine learning algorithms to reduce the overwhelming amount of background noise. This Zooniverse project will be complementary to these machine learning methods [13]. By combining machine classifications with the results from volunteers through *active learning* [see e.g., 17], we hope the eventual final-level classification of (sub-)GeV neutrinos will improve. Moreover, we will be showing the Zooniverse

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volunteers special events that algorithms will struggle with, otherwise known as 'outliers'. Whereas machine-learning-based algorithms may work well on 95% of the events, we hope visual inspection of the last 5% by volunteers will help classify these outliers, boosting the final event selection further.

4. Conclusions and prospects

We have, herein, presented the motivation for and current plans for launching a new project on the Zooniverse platform to look for neutrinos in sub-threshold IceCube data. New code has been developed to display sub-threshold IceCube events, with added sonification, and uploaded to Zooniverse. The project is foreseen to enter internal review and beta-testing periods soon, and will be available worldwide in English, Spanish, French, German, Italian, and Dutch at launch. The main objective of volunteers will be to help detect outliers in sub-threshold data, which will improve the final classification by dedicated machine learning algorithms.

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