PROCEEDINGS OF SCIENCE

Searching for Askaryan Emission from Neutrinos with the Payload for Ultrahigh Energy Observations (PUEO)

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The Payload for Ultrahigh Energy Observations (PUEO) is a long-duration balloon payload under construction scheduled to fly over Antarctica in late 2025. PUEO will deploy a broadband interferometric radio telescope pointing down at the ice sheet with a primary science goal of detecting the impulsive Askaryan radio emission expected to accompany interactions of ultrahigh-energy (UHE) neutrinos (> 1 EeV) in the glacial ice. PUEO's design represents an order-of-magnitude improvement to neutrino sensitivity compared to the predecessor ANITA program. This contribution will give an overview of PUEO's science case and detection concept, as well as present the expected diffuse and transient sensitivity of PUEO to UHE neutrinos.

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1. Introduction

Neutrinos are produced at ultrahigh energies (UHE, $\gtrsim$ 1 EeV) under many theoretical models[1–6] but so far have evaded detection despite many attempts (e.g. [7–10]). The Payload for Ultrahigh Energy Observations (PUEO) [11] is a long-duration balloon experiment aiming for world-leading sensitivity for UHE neutrinos. Like PUEO's direct predecessor the Antarctic Impulse Transient Antenna (ANITA) [12], PUEO uses the radio-detection technique [13] with the instantaneous exposure afforded by a high-altitude platform. Compared to ANITA, PUEO will have a significantly lower signal detection threshold which translates to an order of magnitude improvement in sensitivity over the most interesting energy range.

PUEO is expected to launch in late 2025, incurring a one-year delay due to the substantial CoVID19-induced backlog of long-duration balloon (LDB) missions in Antarctica. A typical LDB mission lasts for around 30 days, but durations up to nearly 60 days are possible under favorable circumstances.

This contribution covers the PUEO science case, detection technique and the current estimate of sensitivity to neutrinos via the Askaryan technique. Additional details on PUEO hardware are available in [14]. PUEO is also sensitive to extensive air showers in the atmosphere, which allows for detection of ultrahigh-energy cosmic rays and provides another channel for tau neutrinos. PUEO's sensitivity to air showers, including the low-frequency dropdown array, is further detailed in [15]. Additional details on simulation of PUEO are in [16].

2. Science Case

PUEO targets neutrinos above 1 EeV, which are the highest energy neutrinos expected to be produced in the universe. Fig. 1 shows fluxes predicted by several cosmogenic and astrophysical neutrino models, along with existing limits. Unlike other energetic particles, UHE neutrinos travel unimpeded through the universe, therefore providing a unique window to the high-energy universe.

2.1 Cosmogenic Neutrinos

Cosmogenic neutrinos are produced in the interactions of charged cosmic rays with the CMB. For protons, this is the GZK process ($p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \pi's \rightarrow \nu's$) [1, 2], while heavier nuclei can interact via photodisintegration [17]. Given a charged cosmic ray source flux, composition, and distribution of sources with redshift , the implied neutrino and charged cosmic ray flux at Earth can be jointly calculated, for instance, with CRPropa[18]. Measurements of charged cosmic ray flux and composition, such as those by Pierre Auger Observatory (PAO) [19] or the Telescope Array(TA) [20], can therefore be used to inform the neutrino flux. Such modeling, assuming a single population of cosmic ray sources along with the current best-fit cosmic ray composition currently favored by PAO, suggests very low cosmogenic neutrino fluxes above 1 EeV, out of reach of PUEO and other planned observatories [21].

Howver, limitations of such modeling ensures that detectable fluxes of UHE cosmogenic neutrinos remain viable. While PAO favors a heavy composition at the highest energies, it cannot rule out a subdominant light component that could produce many more neutrinos [22]. TA favors a

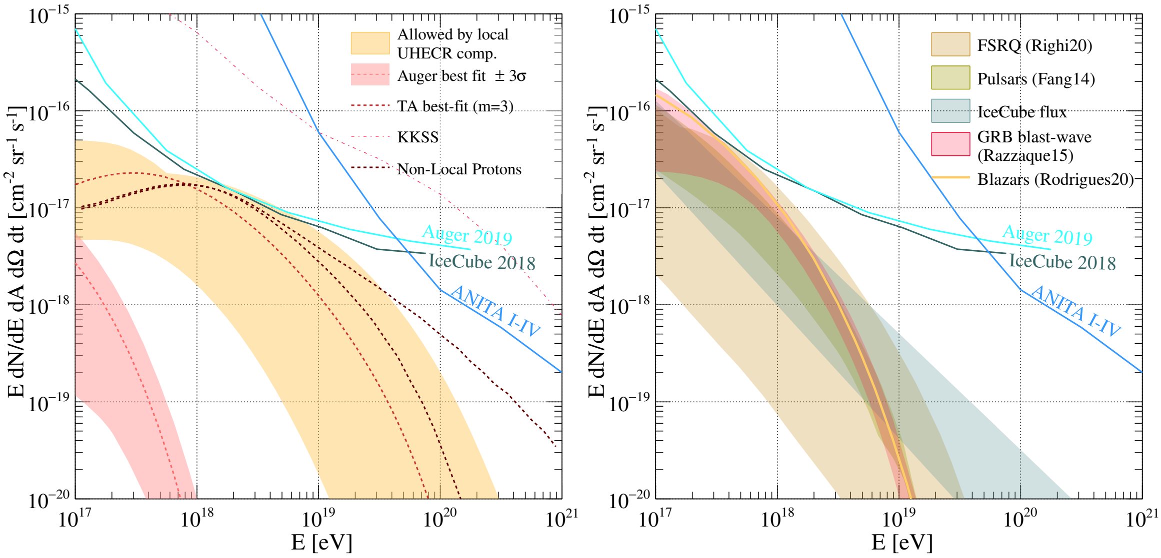

Figure 1: Some cosmogenic and astrophysical neutrino models targeted by PUEO, including some already ruled out. Also shown in solid lines are current limits. See text for additional details.

somewhat lighter composition, which could produce even more cosmogenic neutrinos in PUEO's energy range [23, 24].

Furthermore, cosmic ray measurements such as PAO and TA only probe the local universe. Higher-energy proton sources could exist only at redshifts beyond the GZK horizon. This is not a far-fetched scenario given positive source evolution and a finite number of proton accelerators as illustrated in Fig. 2.

To study what neutrino fluxes such non-local proton sources could produce, PUEO has performed proton-only CRPropa simulations with sources limited to $z > 0.1$. As expected, this suppresses proton fluxes while producing copious neutrinos, depicted in Fig. 1 as "non-local protons."

2.2 Astrophysical Neutrinos

UHE neutrinos can also be produced inside or near astrophysical sources, rather than during propagation. Astrophysical neutrinos have famously been measured by IceCube up to 10 PeV or so [25], though the specific mechanism has not yet been identified, despite two putative source associations. It is possible that either the IceCube-detected astrophysical flux, or another astrophysical flux that is more abundant at higher energies, could extend to the PUEO energy range.

Some models that can produce astrophysical neutrinos at EeV energies include gamma-ray bursts, pulsars, and FSRQs [3–6, 26]. As these models may not produce significant gamma-ray fluxes, a detector like PUEO is necessary to probe them. Fig. 1 (right) shows some of the astrophysical models. If astrophysical neutrinos are produced in combination with some sort of astrophysical transient in another band, identification of the source may be possible.

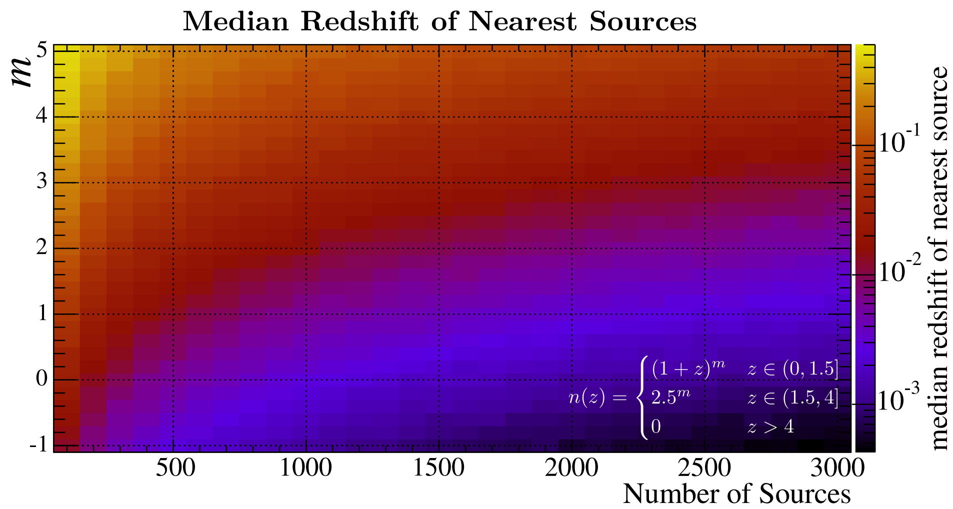

Figure 2: The result of a numerical simulation showing median distance to the nearest prototype given a source evolution parameter *m* and the number of prototypes in the universe.

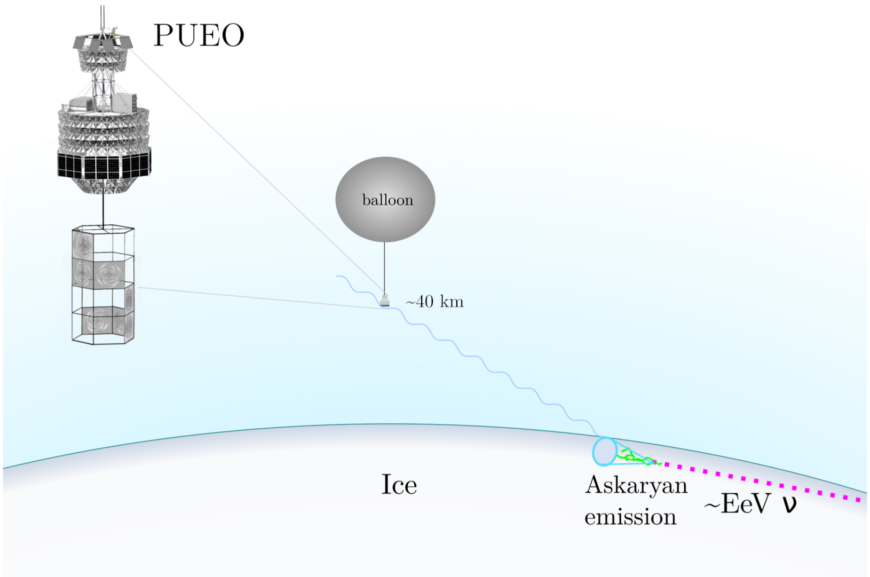

Figure 3: A sketch of the PUEO detection method for UHE neutrinos. UHE neutrinos interacting in the ice will produce radio emission via the Askaryan mechanism, which can then be detected by PUEO.

2.3 Fundamental physics

If PUEO were to detect UHE neutrinos, these would likely be the most energetic neutrinos ever detected. As such, they provide a unique probe of fundamental physics. By measuring the elevation distribution of energetic neutrinos, bounds can be set on the neutrino-nucleon cross-section [27]. PUEO could also be able to constrain violation of Lorentz invariance and some dark matter models.

3. Detection Mechanism

Exploring the low predicted fluxes in Fig.1 requires a tremendous detection volume. Like its predecessor ANITA, PUEO takes advantage of the serendipitous coincidence that the long-duration balloon program happens to be located on Antarctica, which has an ice sheet up to 4km deep.

3.1 Balloon-borne detection of Askaryan emission

Should an UHE neutrino interact in the ice, it will produce a particle shower that will eventually contain a negative charge excess, due to the presence of atomic electrons in the ice. As suggested by Askaryan [28] and confirmed in beam test experiments [29], this negative charge excess within a confined volume produces coherent radio emission at frequencies up to a GHz or so. Unlike most other dense materials readily available on earth, ice is radio transparent [30] so this radio emission can escape the ice and be detected from a balloon, as depicted in Fig. 3.

Compared to the alternative of embedding antennas in the ice like ARA, ARIANNA or RNO-G [8, 9, 31], the balloon platform can instantaneously view orders of magnitude more ice (at 40 km altitude, the horizon is 700 km away) and is (perhaps paradoxically) easier logistically to deploy, but at the same time is significantly farther away from the interaction and only operates during a relatively short balloon flight. As such, the shower energy detection threshold is generally somewhat higher, and while the instantaneous exposure of a balloon flight is much greater, ground-based experiments can integrate for longer.

3.2 Improvements over ANITA

In order to compete with future ground-based experiments, the PUEO design prioritizes reduction of the detection threshold compared to the previous ANITA experiment. The final ANITA flight (ANITA-IV) had 48-dual polarization horn antennas with a band of 180 MHz-1200 MHz and an analog trigger using temporal coincidence in nearby channels between threshold crossings of tunnel diode square law detectors. Because the size of the payload is constrained by the launch vehicle, the size of PUEO at launch must remain approximately the same.

PUEO achieves significantly improved performance in the Askaryan channel using several techniques. Most important is replacing the analog coincidence trigger with an all-digital beamforming trigger. Signals from nearby antennas are coherently added according to different plane wave hypotheses, and these “beams" are compared to thresholds for the trigger. The antenna band is modified to 300-1200 MHz, which reduces the size of the antennas so that 96 antennas can fit in the same footprint, allowing for further improvements from phasing. Improvements in the signal chain reduce the noise figure, further improving signal to noise. A higher rate of data to disk (100 Hz), allows yet more threshold reduction, and adaptive digital filtering allows for reduction in contamination from radio-frequency interference (RFI).

Combined, these result in a threshold reduction in triggered electric field strength of around five compared to ANITA. Details of the implementation of these improvements can be found in the accompanying proceeding. PUEO also contains two drop-down arrays, a nadir-pointing array and a low-frequency array that are primarily intended to improve the response to air showers, but also contributing to improved reconstruction for Askaryan neutrinos. Improved navigation systems also help with reconstruction and background rejection.

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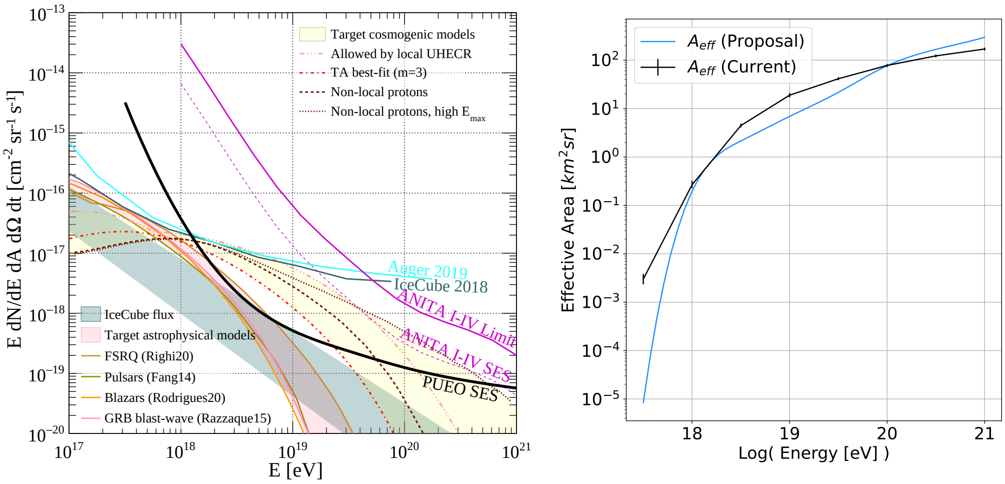

Figure 4: The left panel expected sensitivity for a 30-day flight of PUEO compared to some target astrophysical and cosmogenic models. The right panel shows the latest diffuse all-flavor effective area computed by a realistic simulation for PUEO, compared to an earlier estimate using scaling relations.

4. PUEO Sensitivity

Initial studies of PUEO sensitivity were performed by applying threshold scaling to simulations for ANITA [11]. Since then, we have adapted the ANITA simulation [32] to properly include the PUEO instrument response in order to provide a more realistic estimate of PUEO's sensitivity. As we cannot predict the flight path and duration of PUEO, we assume a similar flight trajectory to ANITA-IV and a 30-day duration.

Simulation of PUEO sensitivity is an involved process requiring a detailed model of the Antarctic ice sheet, covered in more detail in [16]. First a position is sampled from a balloon trajectory, then an interaction location is chosen within view of the payload, adding weights for the relative amount of ice within view at each position. For computational reasons, the neutrino trajectory is chosen such that there is a chance that the emission pattern reaches the payload, with an appropriate weight assigned for the direction and the survival probability. The resulting electric field at the payload is then computed, including propagation through the ice and the ice-air interface, applying the instrument response and a realistic trigger model. The diffuse effective area can then be calculated from the fraction of the weighted neutrinos that trigger and the total visible ice volume. Simulation of non-diffuse neutrinos requires a separate, less-computationally efficient strategy.

The resulting single-event sensitivity at the trigger level is shown in the left panel of Fig 4. The right panel shows a comparison of effective area between the previously published results using threshold scaling and the current simulation using a realistic model of the instrument. We find that our scaling assumptions produced a reasonably close answer, but in fact slightly underestimated the PUEO sensitivity. Further work is currently underway to improve the modeling of propagation in ice and update the Askaryan emission model to more state-of-the-art parameterizations.

The trigger-level sensitivity can be used to predict the number of neutrinos that PUEO may trigger on, but analysis efficiency and background estimates must be folded in order to predict the final sensitivity of the instrument. ANITA has achieved analysis efficiencies above 80% [7]

for diffuse Askaryan neutrino analyses with a background estimate of order one. The primary background is from impulsive anthropogenic radio emission, which is typically rejected by requiring that neutrino candidates be spatially isolated on the continent. While the lower threshold in PUEO may make this rejection more challenging, the improved payload attitude and larger baselines afforded by the improved navigation systems and the nadir antennas, respectively, should aid in this rejection. For searches looking at specific types of sources, the analysis efficiency and background estimates can further be improved in non-diffuse searches by applying time or spatial restrictions in accordance to the search target.

5. Conclusion

The PUEO instrument is expected to be the most powerful probe of neutrinos above 1 EeV, which remains an interesting phase space for neutrino models. Further validation of the PUEO design has only improved sensitivity from preliminary estimates.

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