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PINGU: a vision for neutrino and particle physics at the South Pole

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Abstract

The Precision IceCube Next Generation Upgrade (PINGU) is a proposed low-energy in-fill extension to the IceCube Neutrino Observatory. With detection technology modeled closely on the successful IceCube example, PINGU will provide a 6 Mton effective mass for neutrino detection with an energy threshold of a few GeV. With an unprecedented sample of over 60 000 atmospheric neutrinos per year in this energy range, PINGU will make highly competitive measurements of neutrino oscillation parameters in an energy range over an order of magnitude higher than long-baseline neutrino beam experiments. PINGU will measure the mixing parameters θ_{23} and Δm^2_{32}, including the octant of θ_{23} for a wide range of values, and determine the neutrino mass ordering at 3σ median significance within five years of operation. PINGU's high precision measurement of the rate of ν_τ appearance will provide essential tests of the unitarity of the 3×3 PMNS neutrino mixing matrix. PINGU will also improve the sensitivity of searches for low mass dark matter in the Sun, use neutrino tomography to directly probe the composition of the Earth's core, and improve IceCube's sensitivity to neutrinos from Galactic supernovae. Reoptimization of the PINGU design has permitted substantial reduction in both cost and logistical requirements while delivering performance nearly identical to configurations previously studied.

Keywords: neutrino oscillations, atmospheric neutrinos, IceCube Neutrino Observatory, PINGU

(Some figures may appear in colour only in the online journal)

Introduction

Following the discovery of neutrino oscillations which show that neutrinos have mass [1, 2], experiments using neutrinos produced in the atmosphere, in the sun, at accelerators, and at reactors have measured the mixing angles and mass-squared differences that characterize the oscillations between the three known flavors of neutrinos. Several important questions remain: whether the mixing angle θ_{23} is maximal and, if not, whether $\theta_{23} < 45°$ or $\theta_{23} > 45°$ (the 'octant' of θ_{23}), whether the ordering of the mass eigenstates is 'normal' or 'inverted', and whether charge-parity (CP) symmetry is violated with nonzero δ_{CP} in the lepton sector. More fundamentally, a better understanding of neutrino oscillations may shed light on the origins of neutrino mass, the possible relationship of neutrinos to the matter-antimatter asymmetry of the universe, and probe new physics beyond the Standard Model.

The Precision IceCube Next Generation Upgrade (PINGU) will provide unprecedented sensitivity to a broad range of neutrino oscillation parameters. Embedded in the existing IceCube/DeepCore subarray, with an energy threshold of less than 5 GeV, PINGU will make highly competitive measurements of atmospheric mixing parameters, the octant of θ_{23}, ν_τ appearance, and the neutrino mass ordering (NMO, also referred to as the neutrino mass hierarchy), through studies of a range of neutrino energies and path lengths which cannot be

Figure 1. The IceCube Laboratory building houses power, communications and data acquisition systems for IceCube and other experiments at the South Pole (photo by Sven Lidström, IceCube/NSF).

probed by long-baseline or reactor neutrino experiments. PINGU will also improve the sensitivity of IceCube to neutrino bursts from supernovae and to neutrinos produced by dark matter annihilations.

In the past few years, in addition to the discovery of high energy neutrinos of astrophysical origin [3], the IceCube Collaboration has made competitive measurements of neutrino oscillations [4, 5] and searches for dark matter [6]. The technologies for drilling holes, deploying instruments, and detecting neutrinos in the deep Antarctic ice are proven, and the costs and risks of constructing PINGU are moderate and well understood. As an extension of the IceCube detector, the incremental operational costs of PINGU would be correspondingly low.

The South Pole Station and the IceCube Neutrino Observatory

Over the past decade, the South Pole has emerged as a world-class site for astronomy, particle astrophysics and neutrino oscillation physics. At the Amundsen-Scott South Pole Station the glacial ice is more than 2.8 km thick, radiopure, and optically clear [7], enabling the construction of a neutrino telescope of unprecedented scale. The IceCube Neutrino Observatory, the world's largest neutrino detector, has been in full operation since 2011. IceCube uses 5160 optical sensors attached to 86 vertical 'strings' (cables) to transform one billion tons of Antarctic ice into a Cherenkov radiation detector. The sensor modules were deployed using a hot water drill to melt holes 2.5 km deep in the ice, with the modules deployed at depths of 1.5–2.5 km below the surface. The NSF's Amundsen–Scott Station provides comprehensive infrastructure for IceCube's scientific activities, including the IceCube Laboratory building that houses power, communications, and data acquisition systems, shown in figure 1.

The Antarctic ice cap permits very large volumes of material to be instrumented at relatively low cost. DeepCore, the low energy subarray of IceCube, is located at the bottom center of the array and observes some 20 000 neutrinos per year at energies below 50 GeV, incident from all directions. The temperature and radiopurity of the ice greatly reduce thermionic and radioactive noise in the photomultiplier tubes (PMTs), the fundamental building block of the IceCube detector, aiding in the observation of lower energy neutrinos. The outermost IceCube sensors detect and enable an active veto of incoming atmospheric muons, reducing muon background rates in the deep detector to levels comparable to those in deep mines.

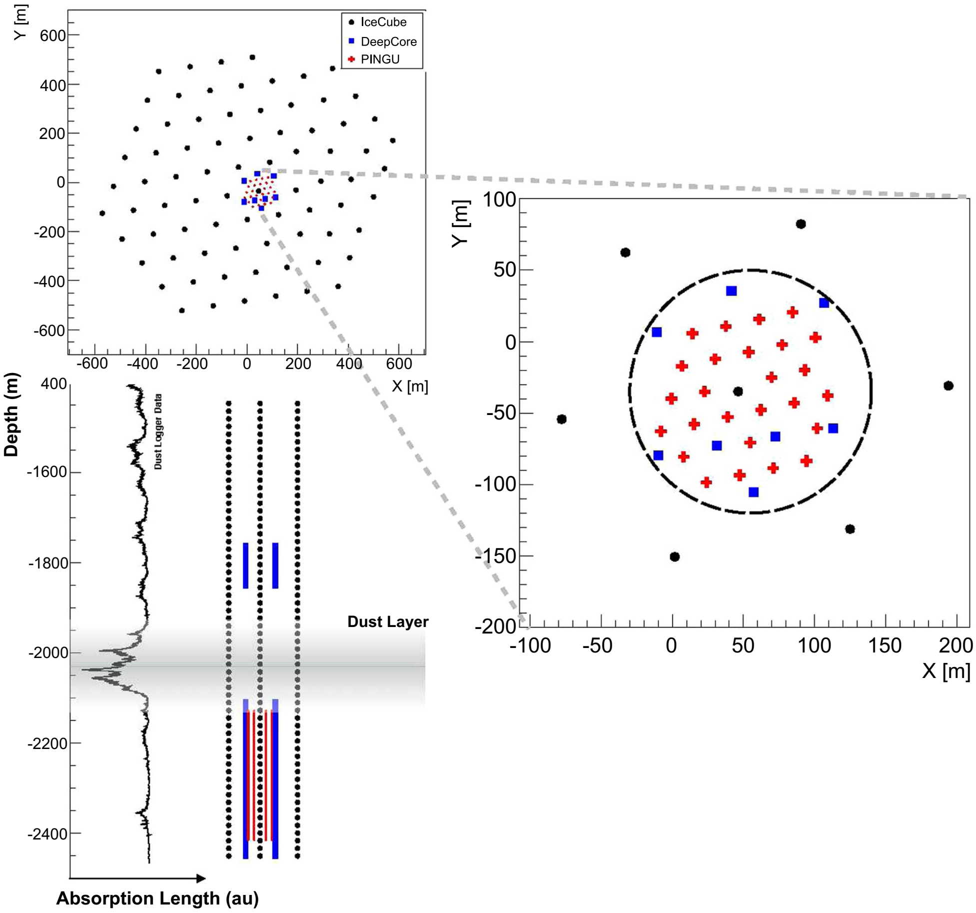


Figure 2. Schematic layout of PINGU within the IceCube DeepCore detector. In the top view inset at right, black circles mark standard IceCube strings, on a 125 m hexagonal grid. Blue squares indicate existing DeepCore strings, and red crosses show proposed PINGU string locations. PINGU modules would be deployed in the clearest ice at the bottom of the detector, as shown in the vertical profile at bottom, with vertical spacing several times denser than DeepCore.

PINGU design

PINGU will greatly enhance IceCube's capabilities below a neutrino energy of 50 GeV with the deployment of additional photodetector modules within DeepCore, over an instrumented volume of 6 Mton. With an energy threshold of a few GeV, PINGU will substantially improve precision for neutrino events below 20 GeV—the key energy range for measurements of the atmospheric neutrino oscillation patterns and detection of the imprint of the neutrino mass ordering on these patterns. PINGU has a number of attractive features:

- No state-of-the-art development required.
- $>$10 years experience of IceCube installation and operations.
- Performance and cost estimates based on existing detector and tools.
- Low marginal cost of operations, leveraging IceCube infrastructure.

- Near 100% duty factor.
- >60 000 neutrino events/year.
- >3000 ν_τ events/year.
- Broad sensitivity to new physics through observation of a wide range of neutrino energies and baselines.

PINGU leverages the experience gained from designing, deploying and operating IceCube, enabling a rapid construction time with minimal risk and at relatively modest expense. The recent development of the capability to deliver cargo and fuel to the station via overland traverse rather than aircraft, as well as planned improvements in drilling efficiency and sensor power requirements, make the logistical and operational footprint of PINGU significantly smaller than that of IceCube both during and after construction.

Initial studies of PINGU performance [8] showed that PINGU would deliver a world-class 6 Mton water Cherenkov detector for a cost below US$100M. Those projections were based on a configuration of 40 new strings, each mounting 96 optical modules. Our recent studies have shown that a geometry that concentrates a slightly larger amount of PMT photocathode area on fewer strings provides the same sensitivity while reducing both costs and logistical support requirements significantly. A schematic of this design is shown in figure 2. Based on our experience with IceCube, in which 18–20 strings were deployed per season once construction was underway, 26 strings of 192 optical modules each could be installed at the South Pole in two deployment seasons. This configuration would provide nearly identical performance to the original 40 string design. Even a reduced 20 string geometry, which could be deployed in two seasons with considerable schedule contingency, would still enable the essential scientific program, even though it would provide less precise event reconstruction and reduced performance compared to the projections presented here.

The studies presented in this document are based on the new, less expensive 26-string configuration. In this configuration, PINGU will be composed of sensors similar in shape and size to those already deployed in IceCube, enabling deployment with nearly identical techniques and equipment. For the purposes of this study, a sensor identical to the current IceCube DOM [9, 10] has been assumed. This would require only modest updates to the electronics to be used in PINGU. We are also evaluating the possibility of replacing the optical modules with multi-PMT mDOMs [11, 12]. A string consisting of 125 mDOMs would provide 40% more photocathode area, as well as directional information on the arriving photons, for the same cost as a string of 192 regular optical modules. This promises further potential improvements over current performance projections.

The existing IceCube DOMs that will surround PINGU will provide a highly effective active veto against downward-going cosmic ray muons, the chief background for all PINGU physics channels, a strategy successfully developed for DeepCore measurements [5]. The surrounding instrumentation will also provide containment of muons up to $E_\mu \sim 100$ GeV, improving energy resolution and utilizing the existing IceCube detector to substantially improve PINGU's performance relative to a stand-alone instrument. PINGU will be designed as an extension of IceCube, closely integrated with IceCube's online and offline systems, leading to a very low incremental cost of operation.

PINGU will provide an effective detector target mass of 6 Mton for ν_μ charged-current interactions, fully efficient above 8 GeV and 50% efficient at ~3 GeV, yielding data samples of approximately 65 000 upgoing neutrinos per year at energies below 80 GeV. On average, a 10 GeV ν_μ CC event will produce 90 Cherenkov photons detected by PINGU; existing IceCube reconstruction algorithms applied to simulated PINGU events yield an energy resolution $\Delta E/E$ of 20% and an angular resolution of around 15° for such events.

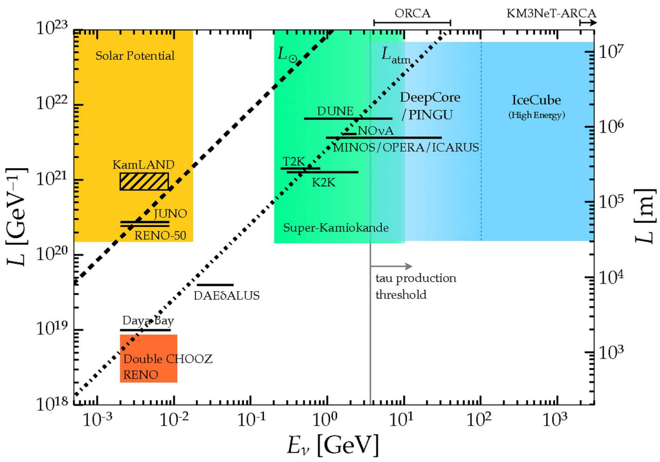


Figure 3. Energy ranges and baselines of operational and planned neutrino oscillation experiments. The diagonal lines indicate the characteristic oscillation scales $L_\odot$ set by the solar mass-squared splitting Δm_{21}^2 (dashed) and L_{atm} set by the atmospheric mass-squared splitting Δm_{32}^2 (dotted–dashed). The 3.5 GeV threshold for τ lepton production in ν_τ CC events is shown by a vertical line. The energy ranges covered by the KM3NeT ORCA and ARCA detectors are indicated by bars above the plot for clarity. For Super-Kamiokande, ORCA, and PINGU, the upper end of the energy range is that at which the ν_μ energy resolution degrades because muons are no longer contained within the detector. For IceCube and PINGU, this energy is marked by the vertical dashed line.

PINGU science

The primary scientific goal of PINGU is the observation of neutrino oscillations using the atmospheric neutrino flux. Several key parameters will be measured by PINGU, including the mixing angles and mass-squared splittings associated with both muon neutrino disappearance and tau neutrino appearance, the octant of the mixing angle θ_{23}, and the ordering of the neutrino mass eigenstates.

With neutrino path lengths through the Earth ranging up to 12 700 km, PINGU will observe the same oscillation phenomena at energies and baselines an order of magnitude larger than current and planned long-baseline neutrino beam experiments, as illustrated in figure 3. PINGU thus complements accelerator and reactor neutrino experiments, as the different set of systematic uncertainties confronting PINGU and the weak impact of δ_{CP} on PINGU measurements will lend robustness to global determination of neutrino oscillation parameters. Comparison of PINGU observations to those made by both currently running experiments such as T2K and NOνA and planned experiments such as DUNE, Hyper-Kamiokande, JUNO and KM3NeT/ORCA [13] will also provide broad and model-independent potential for discovery of new physics. Finally, PINGU will have unprecedented sensitivity to tau neutrino appearance. Compared to the 180 charged current tau neutrino interactions observed in 2806 days of Super-Kamiokande data [14], PINGU will be able to detect almost 3000 such interactions every year.

The performance projections presented here are a summary of detailed studies described in a more comprehensive document [15], which will be available shortly. They are based on full Monte Carlo simulations and detailed reconstructions, including the full detector model developed over 10 years of experience operating the IceCube detector. The full suite of

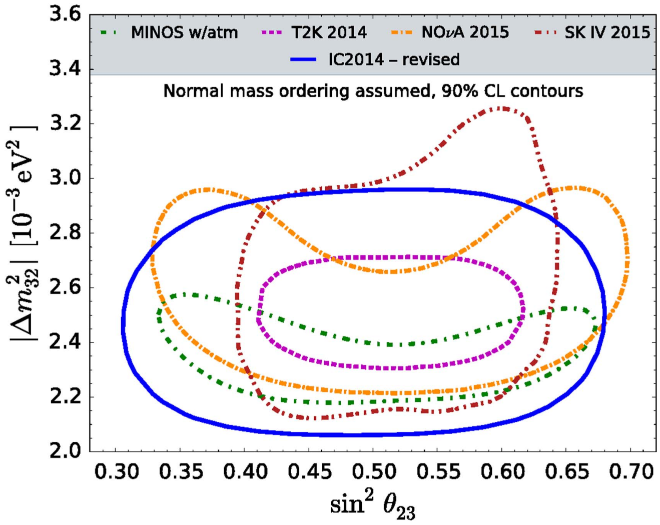


Figure 4. Current measurements of the atmospheric mixing between the second and third mass eigenstates from atmospheric and long-baseline neutrino experiments. Note that only the magnitude of the mass-squared splitting is known, not its sign.

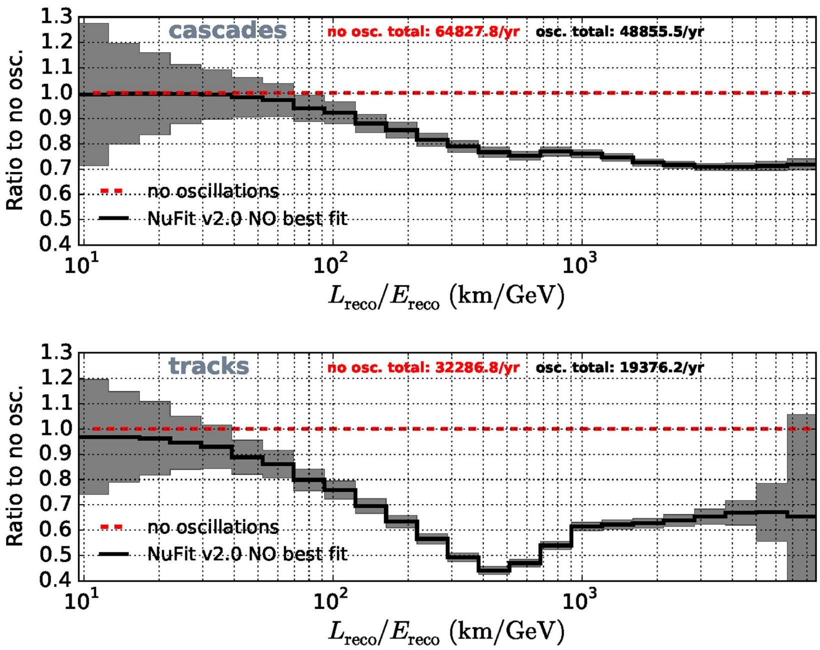


Figure 5. The disappearance, caused by standard neutrino oscillations, that will be observed by PINGU in the cascade (top) and track (bottom) samples, as a function of the ratio of the reconstructed neutrino travel distance to its reconstructed energy. The gray bands show the sizes of the statistical uncertainties.

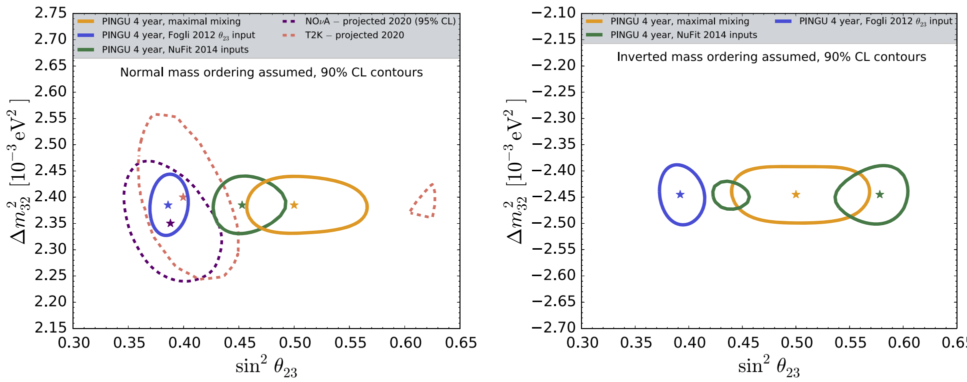


Figure 6. The atmospheric neutrino oscillation contours are shown under assumptions of both the (a) normal and (b) inverted orderings. Both orderings show the effect of different assumed true values: the Fogli 2012 [22] and NuFit 2014 [23] global fits, and maximal mixing. The normal ordering assumption includes projected sensitivities from NOνA (95% CL, first octant only) [24] and T2K [25] assuming $\delta_{\rm CP} = 0$. For NOνA, the second octant would be ruled out at 90% CL under this assumption.

systematic uncertainties used for IceCube data analysis have been taken into account in these studies.

Atmospheric oscillation measurements

The 'atmospheric' mixing between the second and third neutrino mass eigenstates, which produced the first strong evidence that neutrinos oscillate between flavors, is now the least well measured channel of neutrino oscillation. Current measurements of the atmospheric mixing parameters $\sin^2(\theta_{23})$andΔm^2_{32} by IceCube [5], MINOS [16], T2K [17], NOνA [18], and Super-Kamiokande [19] are shown in figure 4.

PINGU will measure the atmospheric parameters primarily through the disappearance of ν_μ from the atmospheric flux at energies above 5 GeV; figure 5 shows the disappearance that will be observed by PINGU in the cascade and track samples as a function of $L_{\rm reco}/E_{\rm reco}$, the reconstructed ratio of the neutrino travel distance to its energy. With increased photocathode density providing a lower energy threshold and significantly improved event reconstruction compared to current IceCube measurements [5], PINGU will determine these parameters with precision comparable to or better than that expected from current accelerator-based experiments (figure 6), but at much higher energies and over a range of very long baselines. This will provide world-class sensitivity to these parameters before the next-generation long-baseline beam experiments such as DUNE [20] and Hyper-Kamiokande [21] come online, as well as offering an important consistency check on the standard oscillation paradigm and the potential for discovery of new physics when higher precision measurements from next-generation long-baseline instruments become available.

Maximal mixing and the θ_{23} octant

Current measurements of the mixing angle θ_{23}, which specifies the relative amounts of the ν_μ and ν_τ flavors in the third neutrino mass eigenstate, suggest that the angle is close to 45° (corresponding to equal contributions from the two flavors). This possibility is known as 'maximal mixing' and could reflect a new fundamental symmetry. If θ_{23} is not exactly 45°,

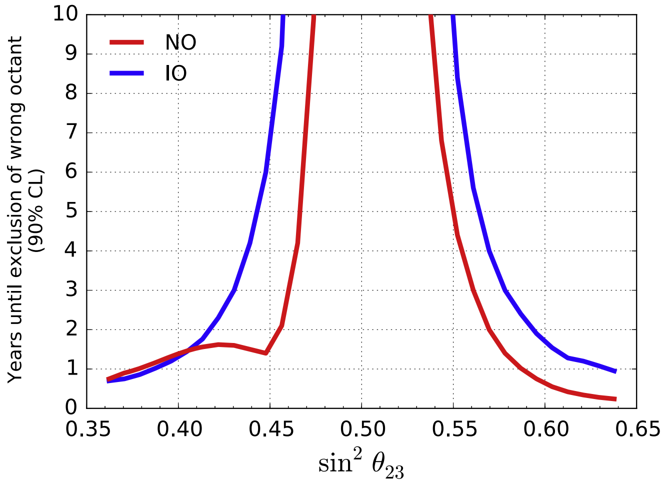


Figure 7. Amount of PINGU data required to determine the θ_{23} octant (i.e., to exclude the wrong octant at 90% C.L.), as a function of the true mass ordering and true value of $\sin^2(\theta_{23})$. Sensitivity is lower if the ordering is inverted as the matter resonance affects antineutrinos rather than neutrinos. The value of δ_{CP} has minimal impact and is assumed to be zero.

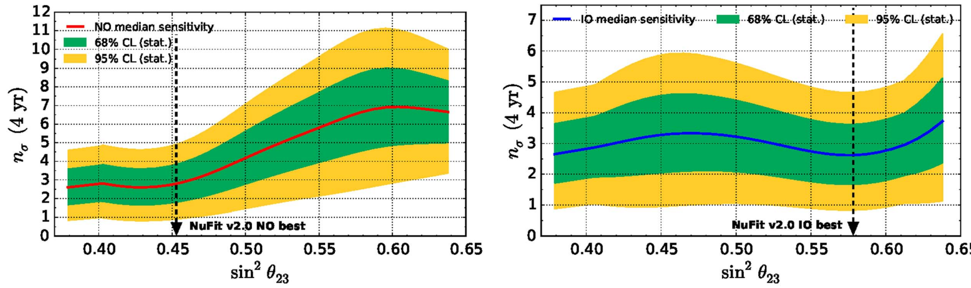
determining its value and whether it is slightly more or less than 45° (its 'octant') is of great interest for understanding the origin of neutrino masses and mixing [26]. In the simple two-flavor oscillation model, values of θ_{23} above and below 45° produce identical transition probabilities. However, this degeneracy is broken for three-flavor oscillations in the presence of matter due to the large value of θ_{13}.

Neutrino beam experiments such as NOνA and T2K can probe the θ_{23} octant by comparison of ν_e appearance rates for neutrinos and antineutrinos. However, as the matter effects at the energies and baselines of those experiments are relatively weak, the sensitivity to the octant depends considerably on the CP-violating parameter δ_{CP}. By contrast, PINGU will determine the octant by comparison of $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ transition probabilities for neutrinos and antineutrinos passing through the Earth's core and mantle [27–31]. The resonant matter effect on the conversion rates breaks the octant degeneracy, and the value of δ_{CP} has little impact on PINGU observations.

The sensitivity of PINGU to the θ_{23} octant is shown in figure 7. If the neutrino mass ordering, discussed in detail below, is normal, PINGU's sensitivity is slightly better than expected for the combined T2K and NOνA data sets [32]. If the mass ordering is inverted, PINGU is somewhat less sensitive than the long-baseline experiments as the matter resonance affects antineutrinos. In either case, PINGU can determine the octant for a wide range of θ_{23}, and for values close to maximal mixing PINGU data will be highly complementary to the long baseline information due to the different sources of degeneracy—δ_{CP} for the beam experiments versus the mass ordering for PINGU.

The neutrino mass ordering

The ordering of two of the three neutrino mass eigenstates, $m(\nu_2) > m(\nu_1)$, is known from solar neutrino measurements [33], but we do not yet know whether ν_3 is heavier or lighter than the other two eigenstates. This is known as the *neutrino mass ordering* (NMO) question.



(a) (b)

Figure 8. (a) Normal neutrino mass ordering assumed and (b) inverted neutrino mass ordering assumed. Expected significance with which the neutrino mass ordering will be determined using four years of data, as a function of the true value of $\sin^2(\theta_{23})$. Solid red (NO) and blue (IO) lines show median significances, while the green and yellow bands indicate the range of significances obtained in 68% and 95% of hypothetical experiments. The significance for determining the ordering when the true ordering is inverted is relatively insensitive to θ_{23}, while for the normal ordering large values of θ_{23} are advantageous. The range shown corresponds approximately to the current 3σ allowed region of θ_{23}; the global best-fit values from the NuFit group [23] for both orderings are indicated by black arrows.

The case in which ν_3 is heavier is called the 'normal' ordering (NO); if ν_3 is lighter, the ordering is 'inverted' (IO).

In addition to its intrinsic interest, the ordering has deep implications for the theoretical understanding of fundamental interactions. Its measurement would assist in discriminating between certain theoretical models at the GUT mass scale [34]. Experimentally, knowledge of the ordering would positively impact ongoing and future research of other crucial neutrino properties: the unknown NMO is a major ambiguity for running or approved accelerator neutrino oscillation experiments with sensitivity to leptonic CP violation [35–38]. PINGU data are not highly sensitive to δ_{CP}; if included as a completely free nuisance parameter in the analysis, δ_{CP} reduces the significance of the ordering determination by 10%–20% at most, depending on the true values of δ_{CP} and θ_{23}. In addition, atmospheric neutrino data from PINGU or other proposed experiments such as INO [39] or ORCA [40] in combination with existing neutrino beam experiments and proposed reactor experiments like JUNO [41] and RENO-50 [42] provide synergistic inputs that can improve the combined significance of the NMO determination beyond the purely statistical addition of results [43–45]. PINGU's determination of the NMO is thus highly complementary to other experimental efforts, resolving possible degeneracies between the mass ordering and CP violation and possibly increasing the precision with which CP violation can be measured by long-baseline experiments. In addition, the determination of the NMO will influence the planning and interpretation of non-oscillation experiments (neutrinoless double β decay and β decay) sensitive to the particle nature of the neutrino (Dirac versus Majorana) and/or its absolute mass [46], and help to test popular see-saw neutrino mass models and the related mechanism of leptogenesis in the early universe [47].

With a neutrino energy threshold below 5 GeV, PINGU will be able to determine the NMO using the altered flavor composition of atmospheric neutrinos that undergo Mikheyev–Smirnov–Wolfenstein (MSW) [48, 49] and parametric [50] oscillations as they pass through the Earth. At energies of approximately 5–20 GeV, the alteration of the oscillation patterns of both ν_μ and ν_e events is strong enough to enable PINGU to determine whether the NMOg is

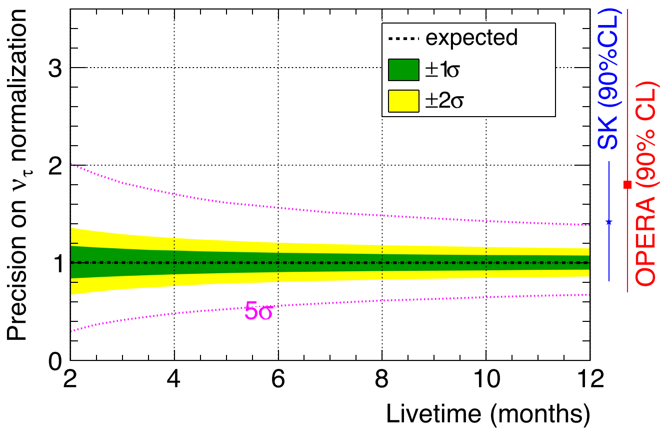


Figure 9. Precision with which the rate of ν_τ appearance can be measured, in terms of the PMNS expected rate, as a function of exposure (in months). The true value is assumed to be 1.0 (the standard expectation) for illustration. The expected $\pm1\sigma$ and $\pm2\sigma$ regions and $\pm5\sigma$ limits are shown, as well as current measurements by Super-K [14] and OPERA [52].

normal or inverted. Given the current global best fit values of the oscillation parameters, PINGU will determine the ordering with a median significance of 3σ in approximately five years. The significance derived from any actual measurement is subject to large statistical fluctuations, illustrated for PINGU in figure 8, so that multiple experimental efforts to measure the ordering are required to guarantee it is determined quickly. For PINGU, the expected significance also depends strongly on the actual value of θ_{23}, which is not well known. The expectation of year years to reach 3σ significance is conservative in the sense that PINGU's sensitivity to the NMO would be greater in almost any region of the allowed parameter space of θ_{23} other than the current global best fit, as shown in figure 8.

Unitarity of the neutrino mixing matrix

In the standard neutrino oscillation picture, atmospheric ν_μ disappearance arises primarily from $\nu_\mu \rightarrow \nu_\tau$ oscillations. However, in contrast to the CKM matrix in the quark sector, the unitarity of the mixing between the three known neutrino flavors has not been experimentally verified. Many theories of physics beyond the Standard Model include massive fermionic singlets which could mix with neutrinos, expanding the standard 3×3 PMNS neutrino mixing matrix into an extended $(3 + N) \times (3 + N)$ matrix and implying that the 3×3 PMNS submatrix is non-unitary. The unitarity of PMNS mixing has only been tested at the 20%–40% level, primarily due to the lack of direct measurements of ν_τ oscillations [51]. An extended mixing matrix could either decrease or moderately increase the rate of ν_τ appearance relative to the Standard Model expectation. Notably, both the current measurements of ν_τ appearance somewhat exceed the expected appearance rate, as shown in figure 9.

The relatively high mass of the τ lepton greatly reduces the interaction rate of ν_τ at low energies: current measurements of ν_τ appearance rates are based on data sets including 180 and 5 ν_τ events in Super-K [14] and OPERAs [52], respectively. Tau neutrino appearance on baselines comparable to the Earth's diameter gives rise to large numbers of ν_τ with energies around 20 GeV, well above PINGU's energy threshold. PINGU is expected to detect nearly 3000 ν_τ CC interactions per year. These ν_τ events can be distinguished from the background of ν_e and ν_μ CC and NC events by their characteristic angular distribution and energy spectrum, arising from their appearance via flavor oscillation at specific L_ν/E_ν (the ratio of the neutrino's path length through the Earth to its energy). This allows PINGU to measure the rate of ν_τ appearance with a precision of better than 10% with one year of data, as shown in figure 9, providing a significantly more precise probe of PMNS matrix elements in the ν_μ and ν_τ rows than previous experiments. The measurement could either strengthen the 3-flavor model and the underlying unitarity of its corresponding mixing, or point us in the direction of new physics due to sterile neutrinos, non-standard interactions, or other effects.

Additional PINGU science: dark matter, tomography and supernovae

By virtue of its GeV-scale neutrino energy threshold, PINGU will have sensitivity to annihilations of dark matter accreted by the Sun with mass as low as 5 GeV. In this neutrino energy regime, PINGU will also establish a new experimental technique for direct tomographic measurement of the Earth's composition through the faint imprint of the core's proton–neutron ratio on neutrino oscillations [53, 54]. Neutrino oscillation tomography relies on the MSW effect, which depends on the electron density. Seismic measurements by contrast are sensitive to the mass density and have resulted in a very precise determination of the Earth matter density profile, so the composition can be extracted from comparison of the two measurements. Although this technique is affected by unknown neutrino physics, especially the octant of θ_{23}, information regarding the Earth's composition can be extracted with uncertainties in the oscillation physics and density profile treated as nuisance parameters. As global understanding of the neutrino physics improves, more precise composition measurements will be possible.

The increased density of instrumentation in PINGU compared to IceCube and DeepCore will also enhance the observatory's sensitivity to bursts of low energy ($\sim$15 MeV) supernova neutrinos. These neutrinos are not detected individually, but rather observed as a detector-wide increase in count rates due to the collective effect of light deposited in the detector as the neutrino burst arrives [55]. Some information about the neutrino energy spectrum can be obtained by comparing the rate at which immediately neighboring DOMs detect light in close temporal coincidence, indicative of a brighter neutrino event, to the overall count rate [56, 57]. The PINGU instrumentation will provide an improvement in the sensitivity for detecting supernovae of a factor of two and, due to the closer DOM spacing, a factor of five in the precision of the measured average neutrino energy [15].

Cost, schedule, and logistics

The 26 string configuration of PINGU substantially reduces costs in several areas compared to the original 40 string configuration. First, personnel costs associated with deployment are reduced significantly by the elimination of the third drilling season. Second, although the number of optical modules increases slightly, other costs (cables, fuel for the hot water drill, and logistical support) scale with the number of holes and are cut by almost half. Finally, the reduced scope will allow us to refurbish the existing IceCube hot water drill for reuse, rather than building a full replacement.

Many components of the hot water drill used to install IceCube remain available at the South Pole Station or in McMurdo Station, and reusing them will greatly reduce the total project cost. The formation of bubbles in the re-frozen ice surrounding the optical modules is a leading source of systematic uncertainty in IceCube data analyses. The drill will be refurbished and a modified drill melting profile will be used that will significantly reduce the

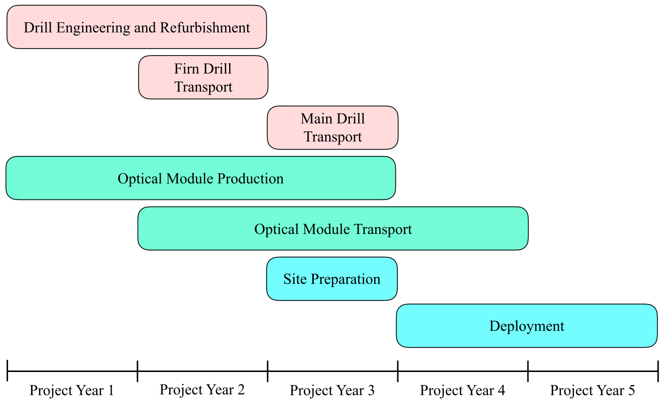


Figure 10. Summary schedule for construction of PINGU.

Table 1. Summary costs in USD, excluding fuel and contingency, for construction of PINGU. It is expected that non-US partners will provide the bulk of the instrumentation whose total cost is shown in the table. drill refurbishment and deployment include the labor of the scientists and engineers associated with the hot water drill and string installation effort. instrumentation costs include labor for module assembly, which contributes slightly over \$1M to the total. fuel requirements for the hot water drill are provided as volumes due to uncertainties in the price of oil and the impact of the overland traverse on transport costs; recent costs are approximately \$20/gal.

	Cost (20 strings)	Cost (26 strings)
Drill refurbishment	\$5M	\$5M
Deployment (labor)	\$5M	\$5M
Instrumentation	\$25M	\$33M
Management and other costs	\$5M	\$5M
Total	\$39M	\$47M
Fuel	146 000 gal	190 000 gal

quantity of dissolved gases introduced into the detector region. A water filtration and degassing stage will be added to the drill to assist in removing any remaining residual gases, thus limiting bubble formation. The total cost of drill refurbishment and deployment operations is approximately US\$10M. The instrumentation for each string costs approximately US \$1.2M; it is anticipated that the bulk of the instrumentation would be provided by non-US participants. Project management and other associated costs are expected to come to an additional US\$5M. A summary of costs is shown in table 1.

We anticipate that two years will be required for refurbishment and improvement of the hot water drill. Optical module assembly and transportation to the South Pole would occur in parallel. Once the drill and optical modules are available at the South Pole, the full PINGU array can be deployed in two seasons of activity. Some preparatory activity (snow compacting, firn drilling) would be required in the preceding South Pole season to enable a prompt start to deployment once the drill arrives. A summary of the schedule is shown in figure 10.

In contrast to the construction of the IceCube Observatory, for which all cargo and fuel had to be airlifted to the South Pole Station, nearly all materials required for PINGU construction would be transported to the Pole via overland traverse. In addition, improvements in electronics design permit a substantial reduction in power consumption by PINGU optical modules compared to IceCube DOMs. Both of these advances will greatly reduce the impact on Antarctic Program logistics, as well as reducing costs.

Conclusion

PINGU will be a world-class instrument for neutrino oscillation physics exploring an energy and baseline range that cannot be probed by long-baseline neutrino beam experiments. PINGU will make a leading measurement of the atmospheric neutrino oscillation parameters, test the maximal mixing hypothesis, provide significantly improved constraints on the unitarity of the Standard Model neutrino mixing matrix, and determine the mass ordering with an expected significance of 3σ within five years. PINGU observations of high energy atmospheric neutrinos will be highly complementary to existing and planned long-baseline and reactor neutrino experiments, providing a robust validation with very different systematic uncertainties as well as sensitivity to potential new physics. PINGU will also extend IceCube's reach in searches for dark matter annihilation to low mass particles, increase our sensitivity to neutrino bursts from supernovae, and provide a first-ever tomographic probe of the Earth's core.

Building on prior experience with IceCube and DeepCore, the risks associated with instrumentation design, drilling, and deployment are well understood and proven to be manageable. Likewise, the estimated cost is well grounded in knowledge gained in the design and construction of IceCube. The performance projections shown here are based on full detector simulation and reconstruction algorithms informed by a decade of experience operating IceCube. Moreover, there is potential for further improvements in the future using a detector based on multi-PMT DOMs.

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