Snowmass2021 - Letter of Interest

Neutrino oscillations with IceCube-DeepCore and the IceCube Upgrade

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
□ (NF10) Neutrino detectors

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Neutrino oscillation physics at IceCube:

The IceCube neutrino observatory is sensitive to the oscillations of 5 - 100 GeV Earth-crossing atmospheric neutrinos, notably in the $\nu_\mu \rightarrow \nu_\tau$ channel, enabled by the densely instrumented DeepCore 10 Mton sub-array[1], as well as potential beyond Standard Model (BSM) flavor transitions up to TeV/PeV energies using the full IceCube array[2]. A broad range of both standard – ν_μ disappearance, ν_τ appearance, neutrino mass ordering (NMO) – and BSM oscillation measurements have been published using 1 and 3 year DeepCore data samples[3–7], and a new generation of 8 year measurements is underway.

Advantages of the IceCube-DeepCore oscillation program include:

High statistics: The vast size of the DeepCore detector coupled with the copious natural atmospheric neutrino flux affords very high neutrino detection rates, yielding >300,000 neutrinos in the current 8 year analyses (complimentary to a 300,000 ν_μ 0.5-10 TeV sample used for high-energy BSM oscillation studies[8]). This is orders of magnitude more statistical power than long baseline accelerator experiments, and $\sim 5\times$ larger than previous DeepCore results[4].

ν_τ **detection:** Charged current ν_τ interactions are inaccessible at most neutrino experiments due to the kinematic suppression resulting from the large τ lepton mass. DeepCore is uniquely able to detect large numbers of ν_τ in the $\nu_\mu \rightarrow \nu_\tau$ appearance channel at $\mathcal{O}$(10-20) GeV, with ~18,000 ν_τ events expected in the 8 year dataset (far exceeding the ~200 ν_τ detected to date by all other neutrino experiments com-

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bined[9;10]). $\sim$15% precision in the ν_τ appearance measurement is expected in the 8 year analysis, more than twice as precise that the existing DeepCore result (the current world best). The lack of precision in the ν_τ sector is the largest barrier globally to constraining the unitarity of the PMNS mixing matrix[11;12], with DeepCore data being invaluable in this crucial test of the 3ν paradigm.

Broad BSM reach: DeepCore detects neutrinos spanning more than an order of magnitude in energy and baseline, and traversing a range of matter profiles including the dense core of the Earth. This, in tandem with all-flavor detection capabilities, affords DeepCore unique and often world leading capabilities to search for neutrino flavor transitions resulting from BSM physics, including sterile neutrinos[6], non-standard interactions (NSI)[7], and neutrino decoherence[13–15].

Complimentarity: DeepCore probes comparable L/E oscillations to long baseline accelerator experiments, but at an order of magnitude higher energy (in the deep inelastic scattering regime) and with very different systematic uncertainties, and is thus highly complimentary to other global measurements.

Next-generation oscillation physics with the IceCube Upgrade:

In 2022-23, a sub-array of 7 strings featuring a total of $\sim$700 multi-PMT optical modules, spaced 3 m apart vertically, will be deployed within DeepCore, vastly improving the photocathode density in a 2 Mton fiducial volume. Known as the IceCube Upgrade[16], this new detector will:

- Improve neutrino energy and direction resolution by a factor 3 at the $\mathcal{O}$(10-20) GeV energies relevant for current DeepCore neutrino oscillation measurements.
- Lower the detector energy threshold to $\mathcal{O}(1)$ GeV and increase detection efficiency below 10 GeV by an order of magnitude.
- Vastly improve detector and ice property calibration using a plethora of new and densely deployed calibration devices (also allowing re-calibration of more than a decade of existing IceCube data) and improved deployment procedures.

This precision neutrino physics detector will facilitate the major reduction in systematic uncertainties required to fully exploit IceCube's huge statistical power. The IceCube Upgrade will achieve 10% precision in ν_τ appearance measurements with a single year of data (and significantly improve on this over time), match or surpass current long baseline accelerator atmospheric mass splitting and mixing angle measurement precision[17;18], and significantly extend BSM physics sensitivity[16]. The lowered energy threshold will also greatly enhance the IceCube Upgrade sensitivity to the NMO via matter effects, especially through combined fits with complimentary data from the JUNO reactor experiment which are anticipated to achieve 5σ sensitivity with 3-7 years of combined detector livetime[19].

Conclusions:

IceCube-DeepCore delivers a broad and exciting neutrino oscillation program, including world leading sensitivity to ν_τ physics and a powerful BSM reach. The IceCube Upgrade will deliver next-generation oscillation physics over this coming decade, highly complimentary to and well before the physics runs of many other next-generation neutrino experiments such as DUNE and Hyper-Kamiokande. Perhaps most excitingly, the broad and sensitive BSM physics reach of the IceCube Upgrade will be invaluable should any deviations from the standard 3ν paradigm be observed during the coming years of the global oscillation physics program.

References

[1] R. Abbasi et al. The Design and Performance of IceCube DeepCore. *Astropart.Phys.*, 35:615–624, 2012.

[2] M. G. Aartsen et al. The IceCube Neutrino Observatory: Instrumentation and Online Systems. *JINST*, 12(03):P03012, 2017.

[3] M. G. Aartsen et al. Measurement of atmospheric neutrino oscillations at 6–56 gev with icecube deepcore. *Phys. Rev. Lett.*, 120:071801, Feb 2018.

[4] M. G. Aartsen et al. Measurement of Atmospheric Tau Neutrino Appearance with IceCube DeepCore. *Phys. Rev.*, D99(3):032007, 2019.

[5] M. G. Aartsen et al. Development of an analysis to probe the neutrino mass ordering with atmospheric neutrinos using three years of icecube deepcore data. *The European Physical Journal C*, 80(1):9, 2020.

[6] M. G. Aartsen et al. Search for sterile neutrino mixing using three years of icecube deepcore data. *Phys. Rev. D*, 95:112002, Jun 2017.

[7] M. G. Aartsen et al. Search for nonstandard neutrino interactions with icecube deepcore. *Phys. Rev. D*, 97:072009, Apr 2018.

[8] M.G. Aartsen et al. Searching for eV-scale sterile neutrinos with eight years of atmospheric neutrinos at the IceCube neutrino telescope. 5 2020.

[9] N. Agafonova et al. Final Results of the OPERA Experiment on ν_τ Appearance in the CNGS Neutrino Beam. *Phys. Rev. Lett.*, 120(21):211801, 2018. [Erratum: Phys. Rev. Lett.121,no.13,139901(2018)].

[10] Z. Li et al. A Measurement of the Tau Neutrino Cross Section in Atmospheric Neutrino Oscillations with Super-Kamiokande. 2017.

[11] Stephen Parke and Mark Ross-Lonergan. Unitarity and the three flavor neutrino mixing matrix. *Phys. Rev.*, D93(11):113009, 2016.

[12] Sebastian Alfonso Richard Ellis, Kevin James Kelly, and Shirley Weishi Li. Current and Future Neutrino Oscillation Constraints on Leptonic Unitarity. 8 2020.

[13] P. Coloma, J. Lopez-Pavon, I. Martinez-Soler, and H. Nunokawa. Decoherence in neutrino propagation through matter, and bounds from icecube/deepcore. *The European Physical Journal C*, 78(8):614, 2018.

[14] T. Stuttard and M. Jensen. Neutrino decoherence from quantum gravitational stochastic perturbations, 2020.

[15] E. Lisi, A. Marrone, and D. Montanino. Probing possible decoherence effects in atmospheric neutrino oscillations. *Phys. Rev. Lett.*, 85:1166–1169, Aug 2000.

[16] Aya Ishihara et al. The icecube upgrade – design and science goals. *PoS (ICRC2019) 928*, 2019.

[17] Latest neutrino oscillation results from t2k (neutrino 2020). https://indico.fnal.gov/event/43209/contributions/187830/attachments/129636/159603/T2K_Neutrino2020.pdf.

[18] New oscillation results from the nova experiment (neutrino 2020). https://indico.fnal.gov/event/43209/contributions/187840/attachments/130740/159597/NOvA-Oscilations-NEUTRINO2020.pdf.

[19] M. G. Aartsen et al. Combined sensitivity to the neutrino mass ordering with JUNO, the IceCube Upgrade, and PINGU. *Phys. Rev. D*, 101(3):032006, 2020.