# Precision Neutrino Oscillation Physics at the South Pole

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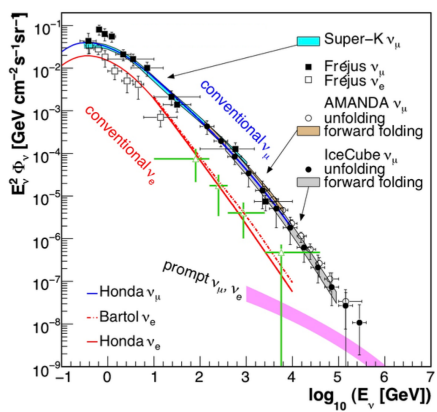
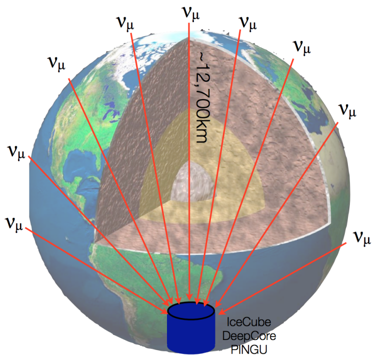
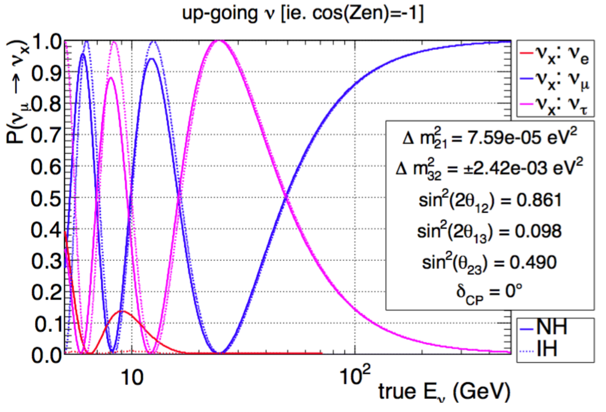
on behalf of the IceCube-DeepCore-PINGU Collaboration

- Produces $\nu_\mu$ and $\nu_e$ in $\sim$ 2:1 ratio over a wide range of energies.
- These come to the detector from all over the atmosphere, giving the neutrinos many baselines.



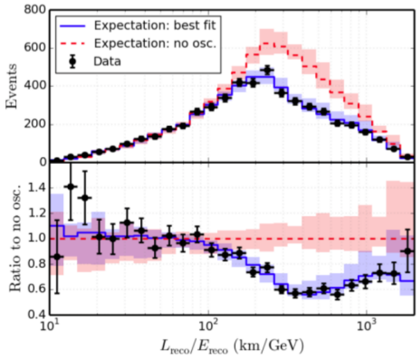



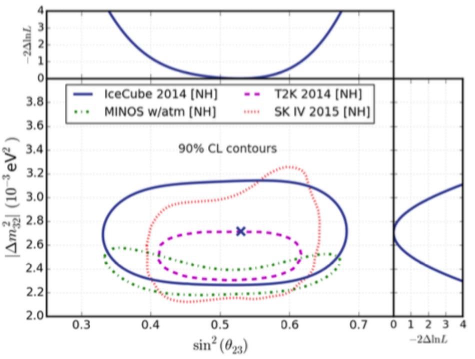
- Neutrinos detected by Cherenkov effect of secondary particles in the South Pole ice.
- Collects $\sim 10^3 - 10^4$ neutrinos per year at analysis level.



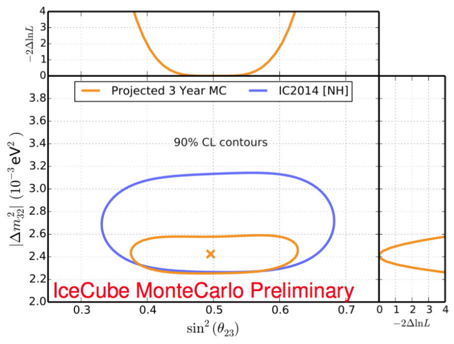

- Maximum $\nu_\mu$ disappearance happens $\sim$ 25 GeV.
- Can measure $\nu_\tau$ appearance through CC channel.
- Ordering-dependent matter effects at $\sim$ 12 GeV.

- Focus on $\nu_\mu$ CC events with clear, upgoing tracks - reduces contamination from cascades
- Reconstruction based on unscattered photons - reduces systematic effect of medium.
- Gives 10° and 25% resolutions in neutrino zenith and energy.
- 5174 events in 953 days.
- Data fit in 2D space, $(E, \theta)$. Gives $\chi^2/ndf = 54.9/56$.



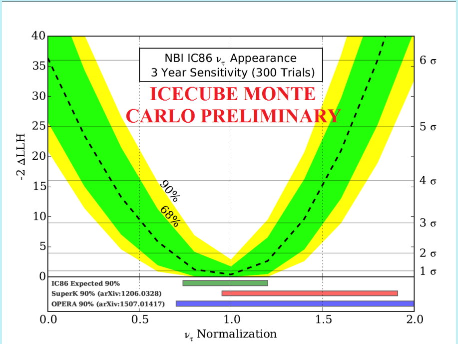



- Can get more out of data by relaxing event selection. Expect an order of magnitude increase in statistics.
- Cascade-like events have worse directional reconstruction. Separate track-like and cascade-like samples and fit separately.
- Requires better understanding of systematics and the ice properties.



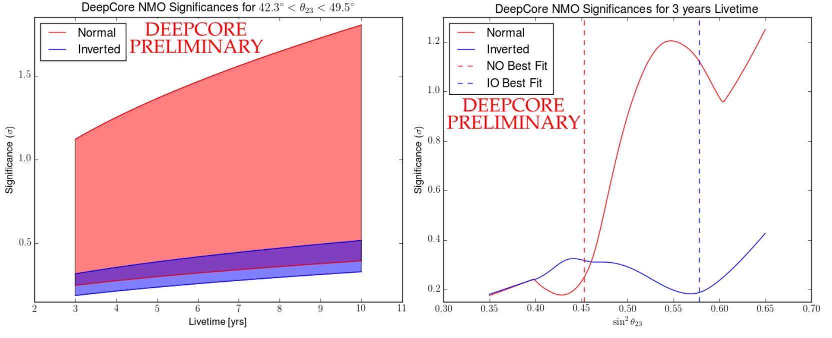

- Substantial improvement in measurement expected.
- Systematic and ice property models still being refined which may affect the expected contours.

- Higher statistics datasets should also allow for better measurements of $\nu_\tau$ appearance.
- Measurement critical in testing unitarity of neutrino oscillations.



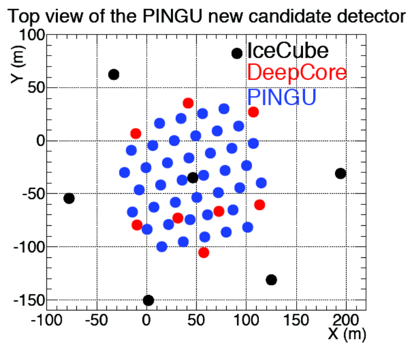

- Expected sensitivity will be world's best.
- Refinement of systematics also still ongoing, but shouldn't significantly deteriorate the result.

- Atmospheric neutrino datasets also sensitive to neutrino mass ordering (NMO) due to a combination of the MSW effect and parametric resonances.
- DeepCore can be used to begin to probe this effect.
- Significance low, but can be used to understand systematics and prove measurement is possible.

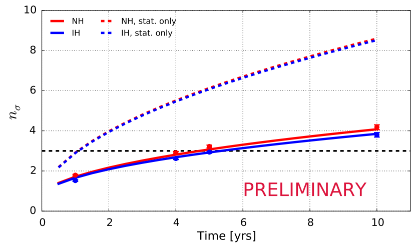


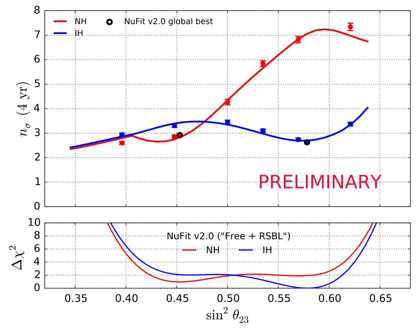
- The Precision IceCube Next Generation Upgrade.
- Lower the detection threshold to ∼ 1 GeV.
- Primary goal - determine the neutrino mass ordering.

- Other physics includes:
  - Precision neutrino physics.
  - Dark matter searches.
  - Earth tomography studies.
- 40 strings. Spacing ∼ 20m.
- DOMs per string not finalised - cost of extra DOMs is small. Will likely see ∼90 DOMs per string.
- Additional calibration devices will be included.



- Taking Nu-Fit 2014 as fiducial oscillations model, time to $3\sigma$ for either true ordering is $\sim 5$ years from deployment.
- Both a fast $\Delta\chi^2$-based analysis and a full LLR analysis have been performed and are in good agreement.
- Considering the full range of allowed values of $\theta_{23}$ shows us Nu-Fit is likely most pessimistic case.



- Even with only the current IceCube-DeepCore data, there is still much more neutrino physics to be probed:
  - Non-standard interactions - Looking for potential lepton non-universality due to hypothetical high mass bosons.
  - Sterile neutrinos - Both from effects at energies $\sim$ 20 GeV (like those already constrained by SuperK in ref [2]) and large matter resonances $\sim$ 1 TeV. A publication concerning the latter is imminent!
  - Large extra dimensions - The result of Kaluza-Klein models of sterile neutrinos.
  - Lorentz-Violating oscillations - As a result of, for example, the standard-model extension.
- IceCube is perfectly suited for such searches because it can probe higher energy neutrinos which have also experienced significant matter effects.

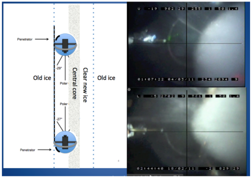
- DeepCore produced the first statistically significant measurement of neutrino oscillations for energies above 20 GeV.
- Since this the improvements in the measurements have been, and continue to be, quite substantial.
- There is a plethora of physics to probe with atmospheric neutrinos (and above!) including many exotic effects.
- With the planned PINGU extension to IceCube-DeepCore, the NMO could be determined on a short timescale.
- The future of neutrino oscillation physics at the South Pole should be very interesting!

1. A. Esmaili et al, *Probing Non-Standard Interaction of Neutrinos with IceCube and DeepCore*, arXiv:1304.1042 (2013).
2. K. Abe et al, *Limits on Sterile Neutrino Mixing using Atmospheric Neutrinos in Super-Kamiokande*, arXiv:1410.2008 (2014).
3. A. Esmaili et al, *Probing Large Extra Dimensions With IceCube*, arXiv:1409.3502 (2014).
4. R. Abbasi et al, *Search for a Lorentz-violating sidereal signal with atmospheric neutrinos in IceCube*, arXiv:1010.4096 (2010).
5. M. G. Aartsen et al, *Flavor Ratio of Astrophysical Neutrinos above 35 TeV in IceCube*, arXiv:1502.03376 (2015).

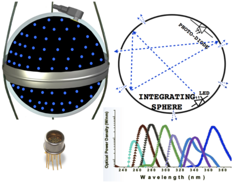
# BACKUP

- LED Flashers - Can be used to check ice scattering/absorption, DOM efficiency/directionality/timing and to calibrate geometry.
- Onboard cameras - Images of the surrounding ice help check models of anisotropic scattering.
- POCAM - Isotropic light source with well-defined intensity for DOM calibration.

IceCube DOM, LED flashers circled

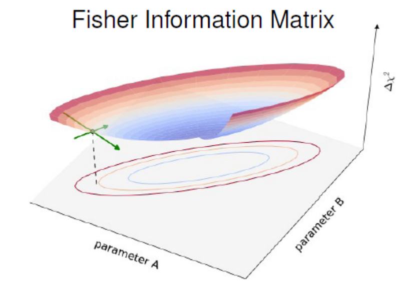


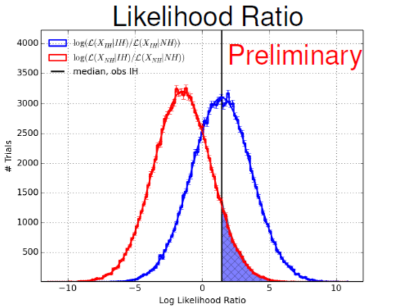

Picture of hole ice from IceCube “Swedish camera”




Precision Optical Calibration Module

- Fisher information matrix - Uses parameterised detector response based on full simulation. The gradients in likelihood space are used to calculate significances. This method is very quick.
- Likelihood ratio analysis uses full Monte Carlo. No assumptions need to be made here and so is the more robust method. For every included systematic this method gets slower.
- For a common set of systematics, these agree!

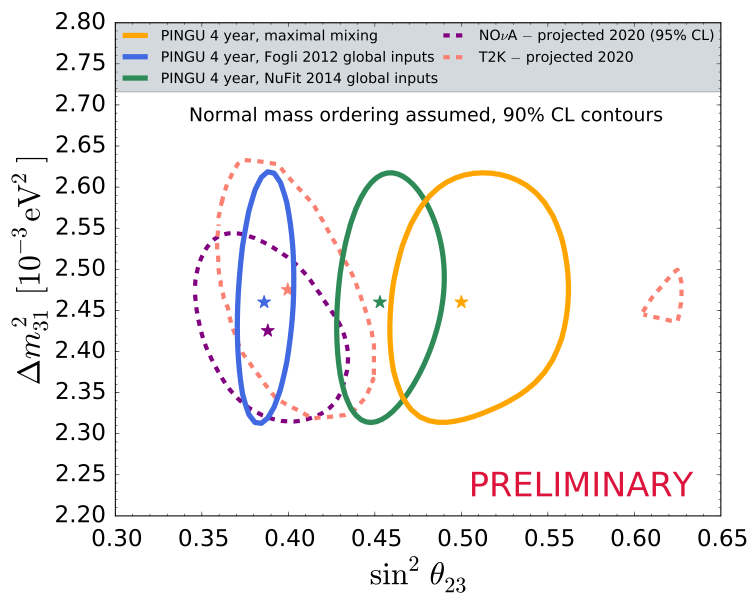


| livetime (years) | # Trials | $n_\sigma$ (NO/IO) | $\Delta n_\sigma / n_\sigma$ (NO/IO) (%) |
|---|---|---|---|
| 1 | 3200 | 1.8/1.5 | 1.9/2.0 |
| 4 | 3190 | 2.9/2.6 | 1.9/1.9 |
| 5 | 2680 | 3.2/2.9 | 2.1/2.0 |
| 10 | 1420 | 4.2/3.8 | 2.8/2.8 |

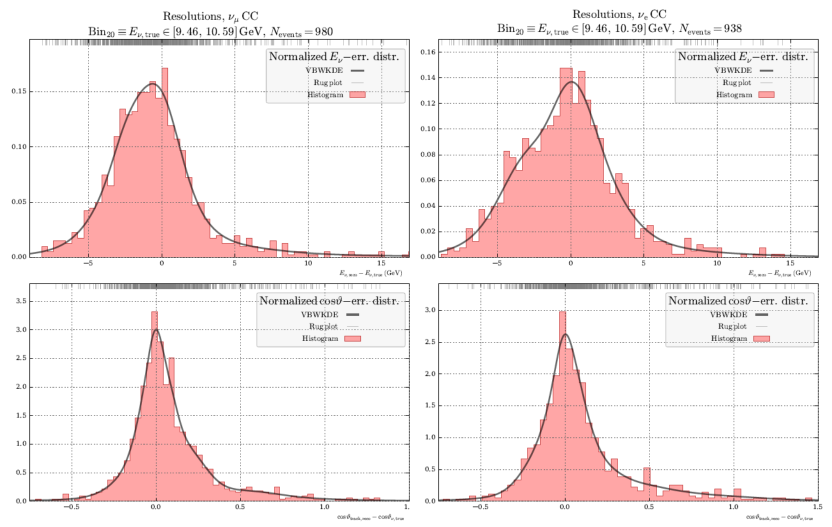
| $\theta_{23}$ (°) | # Trials | $n_\sigma$ (NO/IO) | $\Delta n_\sigma / n_\sigma$ (NO/IO) (%) |
|---|---|---|---|
| 39 | 2980 | 2.6/2.9 | 1.9/2.0 |
| 42 | 2870 | 2.9/3.3 | 1.9/2.0 |
| 42.3 | 3190 | 2.9 (NO) | 1.9 (NO) |
| 45 | 1750 | 4.3/3.4 | 2.5/2.6 |
| 47 | 2520 | 5.8/3.1 | 2.2/2.2 |
| 49 | 2760 | 6.8/2.7 | 2.1/2.0 |
| 49.5 | 3190 | 2.6 (IO) | 1.9 (IO) |
| 52 | 2540 | 7.3/3.4 | 2.2/2.1 |

# PINGU Atmospheric Oscillations



- Systematics removed in groups to test relative effects.
- Oscillations allows $\Delta m^2_{31}$, $\theta_{23}$ and $\theta_{13}$ to float.
- Flux allows $\nu_e/\nu_\mu$ ratio and atmospheric index to float.
- Detector allows the overall normalisation and the uncertainty on the overall energy scale calibration to float.
- All contains all of the above plus an additional uncertainty on the $\nu/\bar{\nu}$ ratio.

| | LLR | | $\overline{\Delta\chi 2}$ | |
|---|---|---|---|---|
| Systematic | 4 yr $n_\sigma$ (NH) | 4 yr $n_\sigma$ (IH) | 4 yr $n_\sigma$ (NH) | 4 yr $\sigma$ (IH) |
| None | 5.4 | 5.5 | 5.5 | 5.5 |
| Flux only | 5.1 | 5.2 | 5.2 | 5.1 |
| Detector only | 4.4 | 4.6 | 4.6 | 4.6 |
| Oscillation only | 3.6 | 3.2 | 3.5 | 3.2 |
| All | 2.9 | 2.6 | 2.8 | 2.7 |



Resolutions, $\nu_\mu$ CC
$\mathrm{Bin}_{20} \equiv E_{\nu,\mathrm{true}} \in [9.46, 10.59]$ GeV, $N_{\mathrm{events}} = 980$
Resolutions, $\nu_e$ CC
$\mathrm{Bin}_{20} \equiv E_{\nu,\mathrm{true}} \in [9.46, 10.59]$ GeV, $N_{\mathrm{events}} = 938$
Normalized $E_\nu$−err. distr.
Normalized cos$\vartheta$−err. distr.
VBWKDE
Rug plot
Histogram
$E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}$ (GeV)
$\cos\vartheta_{\mathrm{track,reco}} - \cos\vartheta_{\nu,\mathrm{true}}$