IceCube DeepCore Results and PINGU

Thomas Ehrhardt for the IceCube-Gen2 Collaboration

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Outline

- IceCube DeepCore: recent results on neutrino oscillations
  
  arXiv:1707.07081

- Looking to the future with IceCube-Gen2 Phase 1 and PINGU
  
  as of this September: updated LoI at arXiv:1401.2046v2
IceCube Neutrino Observatory

- 1 Gt of ice instrumented
- optimised for TeV–PeV range

- at the core: DeepCore
  - ∼ 10 Mt of densely instrumented clear ice
  - lower energy threshold at few GeV
  - measurement of atmospheric neutrino oscillations (this talk), $\nu_\tau$ appearance (talk by P. Eller)
Atmospheric Neutrinos

- steady $\nu$ flux available over large range of neutrino energies $E_\nu$ and oscillation baselines $L$

- for vertically upgoing $\nu_\mu$, first survival probability minimum at $E_\nu \sim 25$ GeV

- Earth matter effects: characteristic modifications of oscillation probabilities below $\sim 15$ GeV, depending on neutrino mass ordering (NMO)
Recent Oscillation Analyses

IceCube 2014

- select “golden” $\nu_\mu$ CC events
  - pronounced track-like topology
  - multiple unscattered photons

- restrict analysis to up-going region
  - reduction of backgrounds

- order of magn. statistics increase
  - include cascade- + track-like events
  - constrain systematics via inclusion of down-going events

- full likelihood event reconstruction
  - median resolutions at 20 GeV:
    $10^\circ (16^\circ)$ and $24\% (29\%)$ for track-like (cascade-like) events

- fits account for statistical uncertainty of expectation

- data-driven estimate of residual atmospheric muon background

IceCube 2017
arXiv:1707.07081

- data-driven estimate of residual atmospheric muon background
Measurement Strategy

- atmospheric $\mu$ background vetoed using IceCube array

- further selection criteria and quality cuts: suppression of $\mu_{atm}$ by factor of $\sim 10^8$

- reconstruct $\nu$ energy $E$ and zenith
  $\Rightarrow$ oscillation baseline ($L$) uniquely determined by zenith

- measure oscillations by fitting $L \times E \times$ event type distribution
\(\sim 41 \text{k events from 2012–14 data sets} - \text{projected onto } L/E \text{ for illustration}\)

**main sample contributions**

- **cascade-like sample:**
  \(\sim 48\% \nu_\mu \text{ CC, } \sim 32\% \nu_e \text{ CC}\)

- **track-like sample:**
  \(\sim 68\% \nu_\mu \text{ CC, } \sim 16\% \nu_e \text{ CC}\)

best fit uncertainty from statistics and data-driven background shape

- **binned \(\chi^2\) analysis with \(8 \times 8 \times 2\) bins in \(E \times L \times \text{event type}\)**

  \(\chi^2 / \text{n.d.f.} = 117/119\)
## Nuisance Parameter Fits

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Priors</th>
<th>Best Fit NH</th>
<th>Best Fit IH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flux and cross section parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrino event rate [% of nominal]</td>
<td>no prior</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>$\Delta \gamma$ (spectral index)</td>
<td>0.00±0.10</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e$ relative normalization [%]</td>
<td>100±20</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>NC relative normalization [%]</td>
<td>100±20</td>
<td>106</td>
<td>106</td>
</tr>
<tr>
<td>$\Delta (\nu/\bar{\nu})[\sigma]$, energy dependent$t$</td>
<td>0.00±1.00</td>
<td>-0.56</td>
<td>-0.59</td>
</tr>
<tr>
<td>$\Delta (\nu/\bar{\nu})[\sigma]$, zenith dependent$t$</td>
<td>0.00±1.00</td>
<td>-0.55</td>
<td>-0.57</td>
</tr>
<tr>
<td>$M_A$ (resonance) [GeV]</td>
<td>1.12±0.22</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td><strong>Detector parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>overall DOM efficiency [%]</td>
<td>100±10</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>relative DOM efficiency, lateral $[\sigma]$</td>
<td>0.0±1.0</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>relative DOM efficiency, head-on [a.u.]</td>
<td>no prior</td>
<td>-0.72</td>
<td>-0.66</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atm. $\mu$ contamination [% of sample]</td>
<td>no prior</td>
<td>5.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

$t$: Following Barr, et al., Phys. Rev. D74, 094009

- **no impact and thus fixed:**

\[
\Delta m_{21}^2 = 7.53 \times 10^{-5} \text{ eV}^2, \theta_{12} = 33.46^\circ, \theta_{13} = 8.47^\circ, \delta_{CP} = 0^\circ
\]
best fit (normal ordering): $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3} \text{ eV}^2$,

$$\sin^2 \theta_{23} = 0.51^{+0.07}_{-0.09}$$

- contours from Feldman-Cousins approach
- consistent with other dedicated experiments
- measurement still statistics-limited

underway: follow-on analyses with this same + a higher-statistics data set
IceCube-Gen2 Phase 1

- 7 new strings instrumented with multi-PMT mDOMs in DeepCore region
- deploy set of novel calibration devices → take into account past and ongoing IceCube calibration efforts
- benefit high- and low-energy IceCube physics abilities
- dedicated detector + stepping stone towards PINGU

mDOM

24 × 3” PMTs
Phase 1 (Oscillation) Physics Goals

- **tau neutrino appearance**
  
  < 10% precision with 3 year sample
  
  probe unitarity of PMNS matrix
  
  see P. Eller: $\nu_\tau$ Appearance in IceCube

- **maximal 2-3 mixing?**

  consistent with IceCube & T2K, but disfavoured (2.6$\sigma$) by NO$\nu$A

- **precision measurement of atmospheric mass splitting and (2-3) mixing angle**
Phase 1 (Oscillation) Physics Goals

- maximal 2-3 mixing?
  consistent with IceCube & T2K,
  but disfavoured ($2.6\sigma$) by NO$\nu$A

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  atmospheric mass splitting and
  (2-3) mixing angle

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  probe unitarity of PMNS matrix

see P. Eller: $\nu_{\tau}$ Appearance in IceCube
In total 26 additional strings in DeepCore region.

Significantly updated Letter of Intent as of this September.

arXiv:1401.2046v2
early geometries:

- 40 strings w/ 60 DOMs each
- 20 m horizontal spacing
- 5 m DOM-DOM spacing

various conferences

- 40 strings w/ 96 DOMs each
- 22 m horizontal spacing
- 3 m DOM-DOM spacing

now (arXiv:1401.2046v2):

- 26 strings w/ 192 DOMs each
- 24 m horizontal spacing
- 1.5 m DOM-DOM spacing

- reduced no. of holes to drill
- higher photocathode density
- performance just as good!
Analysis Goals

- improve on Phase 1 sensitivities across the board
- around 70k upgoing atmospheric neutrinos per year
- neutrino mass ordering and $\theta_{23}$ octant sensitivity
- tau neutrino appearance
- + additional science (WIMP dark matter, Earth tomography, SNe)
NMO Measurement Principle

- up to few $10\%$ differences in oscillation probabilities, depending on which NMO realised

- effect to $1^{\text{st}}$ order symmetric w.r.t. flip of NMO & $\nu \leftrightarrow \bar{\nu}$

but:

- atmospheric flux $\Phi_\nu / \Phi_{\bar{\nu}} \sim 1.3$

- $x$-sections $\sigma_{\nu N} / \sigma_{\bar{\nu} N} \sim 2$

  $\Rightarrow$ few percent residuals even w/o $\nu$ vs. $\bar{\nu}$ discrimination

- massive $O(\text{Mton})$ detector required for sufficient event statistics
NMO Sensitivity

- good agreement between Asimov and pseudo-data ensemble studies

- sensitivity strongly dependent on true value of $\theta_{23}$
  
  synergy potential: profit from better knowledge of $\theta_{23}$

- projected median sensitivity $\sim 3\sigma$ in 4 years for recent global best fit values (close to sensitivity minima)
Atmospheric Oscillation Parameters

- 4-year octant sensitivity $\gtrsim 3\sigma$ if
  - IO: $\sin^2 \theta_{23} \lesssim 0.38$ or $\gtrsim 0.62$
  - NO: $\sin^2 \theta_{23} \lesssim 0.38$ or $\gtrsim 0.58$

- for true first octant and NO, profit greatly from knowing the NMO

- precision of $\sin^2 \theta_{23}$ and $\Delta m_{32}^2$ measurement for different true $\sin^2 \theta_{23}$ and NO

- compared to projected accelerator constraints

Preliminary PINGU 4-year sensitivity

\[ \Delta \chi^2 \]

\[ \Delta m_{32}^2 \left[ 10^{-3} \text{ eV}^2 \right] \]
with expected $\nu_\tau$ appearance from standard 3-flavour oscillations:

- expect to reach $5\sigma$ exclusion of no $\nu_\tau$ appearance with a month of data
- expect better than 10% precision after one year of measurement
Summary

- **IceCube DeepCore**
  - new data set: significantly enhanced measurement of atmospheric oscillation parameters $\Delta m^2_{32}$ & $\sin^2 \theta_{23}$, maximal mixing preferred
  - follow-on studies underway

- planning for **IceCube-Gen2** in progress
  - Phase 1 as stepping stone, with substantial improvements to both high energy neutrino astronomy and low energy neutrino physics

- **PINGU**
  - going beyond Phase 1: potential low energy extension within IceCube-Gen2
  - crucial in determination of NMO
  - multifaceted physics reach, e.g., atmospheric oscillations, WIMPs, SNe
  - updated Letter of Intent available at arXiv:1401.2046v2
THANK YOU!

The IceCube–Gen2 Collaboration

International Funding Agencies

- Fonds de la Recherche Scientifique (FRS-FNRS)
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- NSF–Physics Division
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- US National Science Foundation (NSF)
BACKUP
Data and Best Fit in Analysis Binning

Cascade-like

- no osc.
- best fit
- data

Track-like

- no osc.
- best fit
- data

Events per energy band

\[ E_\nu \in [3.6, 7.5] \text{ GeV} \]

\[ E_\nu \in [7.5, 10.0] \text{ GeV} \]

\[ E_\nu \in [10.0, 13.3] \text{ GeV} \]

\[ E_\nu \in [13.3, 17.8] \text{ GeV} \]

\[ E_\nu \in [17.8, 23.7] \text{ GeV} \]

\[ E_\nu \in [23.7, 31.6] \text{ GeV} \]

\[ E_\nu \in [31.6, 42.2] \text{ GeV} \]

\[ E_\nu \in [42.2, 90.2] \text{ GeV} \]

\[ \cos(\theta_{\text{reco}}) \]

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“Inverted Corridor Cut”
Phase 1: Impact on Neutrino Astronomy

- improved knowledge of ice and calibration will benefit reconstruction, flavour ID
- gain by re-analysing decade of IceCube data
PINGU: NMO Signature

- expect $\sim 33k \; \nu_\mu + \bar{\nu}_\mu \; \text{CC} + \sim 25k \; \nu_e + \bar{\nu}_e \; \text{CC}$ per year
- distinct spectral features depending on NMO
- intensity: projected statistical significance per bin for 1 year of data
- perfect flavour ID only for illustration