Neutrino Astroparticle Physics
Francis Halzen

- Physics with neutrino “telescopes” using the atmospheric neutrino beam, also sterile neutrinos.
- The cosmic neutrino beam and neutrino physics using the cosmic neutrino beam.
- BSM neutrino physics using atmospheric and cosmic neutrinos.
- Neutrino physics with a Galactic neutrino explosion.
access to tau neutrinos in the atmospheric and cosmic beam

The PMNS mixing matrix

KamLAND
Reactor LBL
$\bar{\nu}_e$ Disappearance

SNO
Solar CC/NC Ratio

Reactors SBL
$\bar{\nu}_e$ Disappearance

MINOS/T2K
$\nu_e$ Appearance
$\nu_\mu$ Disappearance

MINOS/T2K
$\nu_\tau$ Appearance

OPERA and SK

SNO
Solar NC fluxes

Mark Ross-Lonergan NUFAC 2016

neutrino “telescopes”
10,000 times too small to do TeV-PeV neutrino astronomy...
the IceCube neutrino observatory

5160 PMs in 1 km³

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m
date: June 11, 2014
most probable energy: 9 PeV
topology: track
muons detected per year:

- atmospheric* $\mu \sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu > 10^5$
- cosmic $\nu \rightarrow \mu \sim 120$

* 3000 per second  
** 1 every 5 minutes
Next Step: the IceCube Upgrade (2022)

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy

soon ORCA with 110 highly instrumented strings
Mediterranean Detectors

ANTARES Complete since 2008
- 25 storeys / line
- 3 PMTs / storey
- 900 PMTs

KM3NeT Under Construction
- 18 storeys / line
- 1 DOM / storey
- ~200,000 PMTs

~20m/90m
~200m/~650m

~10 Mton
12 lines
First Generation
First line since 10 years

~1 Gton
~6 Mton

230 ARCA + 115 ORCA lines New Generation

• DOM: 31 3” PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016
ORCA will consist of one dense KM3NeT Building Block:

115 detection lines
Total: 64k * 3” PMTs

<table>
<thead>
<tr>
<th></th>
<th>ORCA</th>
<th>ARCA</th>
</tr>
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<tbody>
<tr>
<td>String spacing</td>
<td>23 m</td>
<td>90 m</td>
</tr>
<tr>
<td>Vertical spacing</td>
<td>9 m</td>
<td>36 m</td>
</tr>
<tr>
<td>Depth</td>
<td>2470 m</td>
<td>3500 m</td>
</tr>
<tr>
<td>Instrumented mass</td>
<td>1x 8 Mton</td>
<td>2x 0.6 Gton</td>
</tr>
</tbody>
</table>

Height: ~160m ORCA (600m ARCA)
Radius: ~120m ORCA (500m ARCA)
old and new physics with atmospheric neutrinos...

- neutrino oscillations
- tau neutrinos!
- mass ordering

non-standard neutrino interactions

$\delta c/c < 10^{-27}$

velocity vs flavor states

earth matter resonance for eV sterile neutrino
one million atmospheric neutrinos...
• oscillations at 5-55 GeV energy
• same oscillation parameters measured in a new energy range (BSM neutrino physics?)
Low energy neutrinos in the Upgrade

25 GeV $\nu_\mu$

DeepCore  $\rightarrow$  Upgrade
Neutrino Oscillation

- 3 years of IceCube Deep Core data
- Measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

\[ \Delta m_{32}^2 = 2.31^{+0.11}_{-0.13} \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 \theta_{23} = 0.51^{+0.07}_{-0.09} \]
<table>
<thead>
<tr>
<th>Analysis A</th>
<th>Analysis B</th>
</tr>
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<tbody>
<tr>
<td>GRECO</td>
<td>DRAGON</td>
</tr>
<tr>
<td>&quot;High statistics sample&quot;</td>
<td>&quot;High purity sample&quot;</td>
</tr>
</tbody>
</table>

### Simulation

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Neutrino Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE</td>
<td>1. Neutrino interactions / lepton generation: GENIE</td>
</tr>
<tr>
<td>PROPOSAL &amp; GEANT4</td>
<td>2. Lepton propagation / photon generation: PROPOSAL &amp; GEANT4</td>
</tr>
<tr>
<td>CLSim (GPU-based software)</td>
<td>3. Photon propagation: CLSim (GPU-based software)</td>
</tr>
<tr>
<td>Noise addition</td>
<td>4. Noise addition</td>
</tr>
<tr>
<td>PMT response &amp; readout elections</td>
<td>5. PMT response &amp; readout elections</td>
</tr>
</tbody>
</table>

#### Muon Background Simulation

<table>
<thead>
<tr>
<th>CORSIKA + Data-Driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORSIKA + MuonGun</td>
</tr>
<tr>
<td>Uses H4a Cosmic Ray flux model to directly predict muon background. Run through standard simulation chain.</td>
</tr>
</tbody>
</table>

### Goal

| High signal acceptance |
| "High statistics sample" |

| High signal purity |
| "High purity sample" |

### Trigger

| At least 3 pairs of locally coincident DeepCore DOMs detect hits in a 2.5 microsecond time window |

### Level 2 “Filter”

| Veto events with hits in “veto region” consistent with a muon travelling from there to interaction vertex at \( v = c \) |

### Level 3

| Eliminates events with more than 7 hits in veto region, too many noise hits, too many hits in outer region of DeepCore (i.e. not fully contained). |

### Other low-level cuts

| Removes events with too many non-isolated hits in veto region and/or too few non-isolated hits in DeepCore fiducial volume |

### Level 4

| BDT to remove atmospheric muons (6 variables) |
| Charge measured by PMTs (3 vars.) |
| Simple vertex estimator |
| Event speed simulator |
| Calculation of event shape |

### Level 5

| Another BDT to remove atmospheric muons (6 variables) |
| Time to accumulate charge |
| Vertex estimator |
| Center-of-gravity information (2 var.) |
| Causal hit identifier |
| Zenith angle estimation |

### Level 6

| Straight cuts |
| Inconsistent with intrinsic PMT noise |
| Spatially compact |
| Require likelihood-based vertex estimator to be well contained in DeepCore fiducial volume |
| Reject events with hits along “corridors” in surrounding IceCube volume |

### Level 7

| Reconstruction (better & more accurate than fast reconstruction information above) & reconstructed energy must be 5.6-56 GeV |

| Reconstruction & no cuts on L7? |

### IceCube

- two independent analyses
- one emphasizing quality of events
- one maximizing statistics
- both blind
atmospheric oscillation parameters: IceCube upgrade

• Currently unclear whether $\sin^2 \theta_{23}$ is maximal
  • 3rd mass state made up of equal parts $\nu_\mu$, $\nu_\tau$
  • Evidence of new symmetry?

• T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at $2.6\sigma^*$

• Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)
and with ORCA/PINGU
FIG. 14. Distributions of the data with best-fit neutrino and muon backgrounds subtracted, overlaid with the best fit $\nu_\tau$ hypothesis projected onto the reconstructed energy axis (left), the cosine of the reconstructed zenith angle (middle) and PID categories (right), for Analysis $\mathcal{A}$. Error bars are statistical only.

Tau Appearance and PMNS Unitarity

- 3-yr DeepCore result competitive with 15-yr Super-K measurement
  - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve ±7% in 3 years
  - ~10% precision needed for real tests of unitarity of PMNS mixing matrix
neutrino mass ordering?

"Normal"

\[ m^2 \]

\[ \Delta m^2(\text{atm}) \]

\[ \Delta m^2(\text{sun}) \]

"Inverted"

\[ \{ \Delta m^2(\nu e, \nu \mu) \} \]

\[ \{ \Delta m^2(\nu e, \nu \mu) \} \]
\[ \sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \cos 2\theta_{13} \pm \frac{\sqrt{2G_F n_e}}{\Delta_{13}}} \]

(mostly) neutrino + antineutrino -

\[ \Delta m_{31}^2 = m_3^2 - m_1^2 \]

sign \( \Delta_{13} \): hierarchy!
Using atmospheric neutrinos to measure the NMH

Up to 20% differences in $\nu_\mu$ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy.
\[ P(\nu_\mu \to \nu_\mu) \]

- Map upward $\nu$ flux in bins of $(E, \cos \theta)$;
- $\cos \theta = -1 \ L \sim 12000 \ \text{Km}$;
difference between between “statistical combined” and “combined” results from the different tension in the determination of the mass-squared difference of JUNO and Upgrade if one wrongly defines the mass ordering: $\Delta m_{31}^2 = m_3^2 - m_1^2$
no synergy effect from combing JUNO+PINGU/ORCA data

fitting the wrong hierarchy → opposite pull on $\chi^2_{\text{min}}$
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neutrinos interacting inside the detector

muon neutrinos filtered by the Earth

total energy measurement all flavors, all sky

astronomy: angular resolution superior ($<0.4^\circ$)
electron and tau neutrinos

IceCube preliminary
high-energy starting events – 7.5 yr

oscillations of PeV neutrinos over cosmic distances to ~ 1:1:1
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion

OPERATION: oscillation (appearance from CNGS muon neutrino beam) and emulsion


tau decay length
$\gamma c \tau$
50m per PeV
a cosmic tau neutrino: livetime 17m

WORK IN PROGRESS
* Bright DOMs are excluded from this analysis
tau decay length: 50m per PeV
event found in 3 different analyses
new physics?

if not...

every model for the astrophysical source ends up in the triangle
- neutrino oscillation at PeV energy
- test of the 3-neutrino scenario
- neutrino physics BSM
Glashow resonance: \( \bar{\nu}_e \) + atomic electron \( \rightarrow \) real W

- partially-contained PeV search
- deposited energy: 5.9\( \pm \)0.18 PeV
- visible energy is 93%
- \( \rightarrow \) resonance: \( E_\nu = 6.3 \) PeV

work on-going
• energy measurement understood
• identification of anti-electron neutrinos
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old and new physics with atmospheric neutrinos...

neutrino oscillations
tau neutrons!
mass ordering

non-standard neutrino interactions
$\delta c/c < 10^{-27}$
velocity vs flavor states

earth matter resonance
for eV sterile neutrino
In the Earth for sterile neutrino $\Delta m^2 = O(1\text{eV}^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_FN} \sim O(\text{TeV})$$

$\Delta m_{41}^2 = 1.0\text{eV}^2$

$\sin(2\theta_{24})^2 = 0.01$

solid : $\bar{\nu}$

dashed : $\nu$
IceCube 86 first year
7 year analysis soon
NTs sensitive to disappearance effects in atmospheric neutrinos, i.e., mainly to $\Delta m^2_{41}$ and $\sin 2\theta_{24}$

High energy analysis: $E_\nu \gtrsim 300 \text{ GeV}$

Low energy analysis: $E_\nu \lesssim 60 \text{ GeV}$

So far, results consistent with the standard three-neutrino hypothesis
neutrino interferometry tests

Lorentz symmetry:

- e.g. ratio of the vertical vs horizontal oscillation probability
- result for dimension 6 $\mu-\tau$ operator shown here
beyond the SM with high energy neutrinos

tests
- equivalence principle
- Lorentz invariance

\[ \frac{\delta c}{c} \sim 10^{-26} \]

also
- dark matter annihilation, decay, interactions
- magnetic monopoles, …
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<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kt)</th>
<th>Location</th>
<th>Events</th>
<th>Live period</th>
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<td>Baksan</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
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<td>Caucasus</td>
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<td>1980-present</td>
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<td>Super-Kamiokande</td>
<td>H\textsubscript{2}O</td>
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<td>Japan</td>
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<td>Near future</td>
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<td>Pb</td>
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<td>Canada</td>
<td>30</td>
<td>Near future</td>
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<tr>
<td>SNO+</td>
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<td>MicroBooNE\textsuperscript{*}</td>
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<td>NO\textit{v}A\textsuperscript{*}</td>
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<tr>
<td>LBNE liquid argon</td>
<td>Ar</td>
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<td>LBNE water Cherenkov</td>
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<td>Ar</td>
<td>100</td>
<td>Europe</td>
<td>9,000</td>
<td>Future</td>
</tr>
</tbody>
</table>
supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$

- PMT noise low (280 Hz)
- detect correlated rate increase (DC current) on top of PMT noise when supernova neutrinos pass through the detector
IceCube DOM photoelectron counts vs time: $10^6$ for a supernova at 10 kpc.
Neutrino Astroparticle Physics

- atmospheric and cosmic beam
- capabilities demonstrated by ANTARES and IceCube
- complementary to accelerator beams: higher energy, nutau