Neutrino Telescopes and the Neutrino Mass Hierarchy

Uli Katz
ECAP / Univ. Erlangen
The plan for the next 50 minutes:

• Introduction
• Present and future neutrino telescopes: ANTARES, IceCube, KM3NeT
• Studying low-energy neutrinos: Towards PINGU and ORCA
• A measurement of the neutrino mass hierarchy?
• Summary

Sincere thanks to all colleagues who allowed me to use their material and apologies to those who find out that I did so without asking
Introduction
How does a neutrino telescope work?

- Neutrino interacts in the vicinity of the telescope
- Charged secondaries cross the detector volume (water or ice) and stimulate Cherenkov emission recorded by a 3D-array of photo-sensors
- Most important channel: \( \nu_\mu + N \rightarrow \mu + X \)
- Energy range: \(10(0) \text{ GeV} \) – some PeV
- Angular resolution: \(<1^\circ(0.3^\circ)\) for \(E>1(10) \text{ TeV}\)
- \(\Delta[\log(E)] \sim 0.3\)
Backgrounds, or maybe not

- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow for oscillation studies

- Atmospheric muons from cosmic-ray interactions in atmosphere above NT
  - penetrate to NT
  - exceed neutrino event rate by several orders of magnitude

- Random light from K40 decays and bioluminescence
The neutrino telescope world map

ANTARES, NEMO, NESTOR joined efforts to prepare a km$^3$-size neutrino telescope in the Mediterranean Sea → KM3NeT
South Pole and Mediterranean fields of view

Galactic coordinates

$2\pi$ downward sensitivity assumed

In Mediterranean, visibility of given source can be limited to less than 24h per day
Neutrino oscillations and mass hierarchy (1)

• Neutrino flavour and mass eigenstates are not the same:

\[ [\text{mass}] \rightarrow \left| \nu_i \right\rangle = \sum_{\alpha=1}^{3} U_{i\alpha} \left| \nu_\alpha \right\rangle \rightarrow [\text{flavour}] \]

• Consequence: Neutrino oscillations
Unrealistic but didactically useful case: 2 flavours, vacuum

\[ P_{\alpha \rightarrow \beta} = \sin^2(2\theta) \sin^2 \left( 1.267 \frac{\Delta m^2/\text{eV}^2 \cdot L/\text{km}}{E_\nu/\text{GeV}} \right) \]

• No information on sign of \( \Delta m^2 \)
• In the above units:

\( L/E \ll 1/\Delta m^2 \) \rightarrow no effect

\( L/E \sim 1/\Delta m^2 \) \rightarrow observe oscillations

\( L/E \gg 1/\Delta m^2 \) \rightarrow observe averaged oscillations
Neutrino oscillations and mass hierarchy (2)

- Neutrino propagation in matter different for $\nu_e$ and $\nu_\mu,\tau$:
  $\nu_e e^- \rightarrow \nu_e e^-$ and $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$  
  W and Z exchange
  $\nu_\mu,\tau e^- \rightarrow \nu_\mu,\tau e^-$ and $\bar{\nu}_\mu,\tau e^- \rightarrow \bar{\nu}_\mu,\tau e^-$  
  Z exchange only
  Result: Modification of oscillation pattern

- Dominant cause of solar neutrino oscillations (MSW effect)

- For atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$:
  Matter effect depends on sign of $\Delta m_{13}^2$
  Same effect for $\Delta m_{13}^2 > 0$, $\nu_\mu$ and $\Delta m_{13}^2 < 0$, $\bar{\nu}_\mu$

- Atmospheric neutrinos offer just the right $L \lesssim 2R_E$ and $E = O$(a few GeV) to measure the effect.

- In neutrino telescope: $\nu_\mu$ and $\bar{\nu}_\mu$ cannot be distinguished, but net effect since $\sigma(\nu_\mu N) \approx 2\sigma(\bar{\nu}_\mu N)$
Present and future neutrino telescopes: IceCube, ANTARES, KM3NeT
IceCube: a km³ detector in the Antarctic ice
IceCube as of February 2013

- 86 strings altogether
  - 125 m horizontal spacing
  - 17 m vertical distance between Optical Modules
  - 1 km$^3$ instrumented volume, depth 2450m

- Deep Core
  - densely instrumented region in clearest ice
  - atmospheric muon veto by IceCube
  - first Deep Core results emerging

- PINGU/MICA: Plans for future low-energy extensions
ANTARES: The first NT in the deep sea

- Installed near Toulon at a depth of 2475m
- Instrumented volume $\sim 0.01\text{km}^3$
- Data taking in full configuration since 2008
- 12 strings with 25 storey each
- Almost 900 optical modules
- Acoustic sensor system
ANTARES achievements

- Proof of feasibility and long-term operation of a deep-sea neutrino telescope
- Position and orientation calibration of optical modules with required accuracy
  - acoustic positioning by triangulation
  - compasses and tilt-meters
- Time synchronisation at nanosecond level
- Use of optical technologies for readout
- All data to shore: Every PMT hit above threshold (typically 0.3 pe) is digitised and transmitted to shore
- Trigger/filter logic by computer farm on-shore
The KM3NeT project (1)

- Multi-km$^3$ NT in Mediterranean Sea, exceeding IceCube substantially in sensitivity
- Nodes for earth/sea science instrumentation
- EU-funded Design Study / Prep. Phase (2006-12)
- Central physics goals (by priority):
  - Galactic neutrino “point sources” (energy 1-100 TeV)
  - Extragalactic sources
  - High-energy diffuse neutrino flux
- Next steps
  - ~40 M€ available for first construction phase
  - final prototyping 2012/13
  - start of construction 2014
The KM3NeT project (2)

• Decisions taken:
  • Technology: Strings with multi-PMT optical modules
  • 5 building blocks of ~120 strings each
    (no sensitivity loss for Galactic sources, advantageous for earth & sea sciences)
  • Multi-site installation (France, Greece, Italy)

• Collaboration established

• … and the neutrino mass hierarchy?
  • Feasibility study ongoing: Oscillation Research with Cosmics in the Abyss (ORCA)
  • Idea: Densely instrumented detector using KM3NeT technology and funds.
Detection units: Strings

- Mooring line:
  - Buoy (empty glass spheres, net buoyancy 2250N)
  - 2 Dyneema ropes (4 mm diameter)
  - 18 storeys (one OM each), 30-36m distance, 100m anchor-first storey

- Electro-optical backbone:
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - Fibres and copper wires
  - At each storey: 1 fibre+2 wires
  - Break out box with fuses at each storey: One single pressure transition
OM with many small PMTs

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10” PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by compressible foam core
- 31 PMT bases (total ~140 mW) (D)
- Front-end electronics (B,C)
- Al cooling shield and stem (A)
- Single penetrator
- 2mm optical gel
- Advantages:
  - increased photocathode area
  - improved 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - directionality
Angular resolution

- Investigate distribution of angle between incoming neutrino and reconstructed muon
- Dominated by kinematics up to \( \sim 1\text{TeV} \)
Point source sensitivity (1 year)

**Expected exclusion limits / 5σ detection**
(for E⁻² source spectra, from Technical Design Report)

- Observed Galactic TeV-γ sources (SNR, unidentified, microquasars)

- KM3NeT (binned)
- IceCube


- Discovery at 5σ with 50%

- Observed Galactic TeV-γ sources (SNR, unidentified, microquasars)

U. Katz: Seminar Manchester, 27.02.2013
RX J1713: A prime candidate source

- Shell-type supernova remnant
- Compatible with proton acceleration in shock fronts (Fermi mechanism)
- Gamma spectrum measured by H.E.S.S.

H.E.S.S. Collaboration, ICRC 2007

H.E.S.S. data
- Fit
- Fit 2004

Energy (TeV)

H.E.S.S. Collaboration, ICRC 2007
RX J1713: A prime candidate source

- Figure of merit (FOM): time to make an observation at $5\sigma$ with $50\%$ probability
- KM3NeT analysis very conservative; $\sim20\%$ improvement by unbinned analysis
- Clear (but flat) optimum in horizontal distance between DUs
- Further candidate sources with similar or better discovery chances

Figure of merit (FOM):
- KM3NeT preliminary
  ($\gamma$ emission from R J1713 assumed 100\% hadronic)
From TeV to GeV: Can neutrino telescopes measure low-energy neutrinos?
Understanding detector and signals

ANTARES 2008

- data
- atm. neutrinos
- atm. muons

from above
ANTARES: Oscillations at 20 GeV

- Measure distribution of reconstructed $E / \cos \theta \propto E / L$
- Expected oscillation signal at lowest values
- Significant signal observed
- Demonstrates capability to reconstruct events down to 20 GeV with a detector optimised for the TeV range
- Results agree nicely with other experiments
Deep Core

• 8 extra strings + 12 standard strings in clearest ice (~5 times higher photocathode density)

• Photomultipliers with high quantum efficiency

• Rest of IceCube provides active veto against penetrating muons
Deep Core and the muon veto

- From Deep Core design study (2008).
- Simulation of $\nu_\mu$ interactions for 80+12 strings ($4\pi$, 5 GeV – 50 TeV, $E^{-2}$ spectrum).
- Use surrounding man detector as veto to select events with vertex in Deep Core volume.
Deep Core low-energy event sample

Deep Core extends IceCube energy range to \(~ 10 \text{ GeV}\)

(from $\nu_\mu$ oscillation analysis)
A first Deep Core result from 2012 …

- Identification of cascades, mainly from
  \[ \nu_e + N \rightarrow e + X \]
  \[ \nu_x + N \rightarrow \nu_x + X \]
- Main background:
  \[ \nu_\mu + N \rightarrow \mu + X \]
  with short \( \mu \) track
- Very difficult in IceCube
- Success in Deep Core! (see arXiv:1201.0801)
... and much more since then!

- Measurement of atmospheric $\nu_e$ flux (arXiv 1212.4760)
- Search for dark matter annihilation in Sun (arXiv 1212.4097)
- Atmospheric neutrino oscillations (arXiv 1301.4339)
What we learn

• Deep Core:
  • A close look at neutrino events above O(10 GeV); event identification and reconstruction possible.
  • The atmospheric muon veto works well.
  • Rich new physics results.

• ANTARES:
  • Event selection and reconstruction down to 20 GeV.
  • But not optimised for these energies!

Can we build on this success and go one step further?
PINGU & ORCA
PINGU and ORCA and their strategic context

- **PINGU**: Phased IceCube Next-Generation Upgrade
  - Extension of existing detector towards lower energies
  - Main focus: Mass hierarchy
  - … but also other physics topics such as dark matter
  - May be proposed/endorsed even if mass hierarchy measurement is not possible
- **ORCA**: Oscillation Research with Cosmics in the Abyss
  - Would imply a major change of paradigm in KM3NeT
  - Will not be pursued if mass hierarchy measurement is not possible
- Both currently concentrate on feasibility studies; detector configurations not yet determined
The major experimental questions

- What are the trigger/event selection efficiencies?
- How and how efficiently can we separate different event classes?
- How can we reconstruct these events, and what resolutions can we reach on $\theta$?
- How can we control the backgrounds?
- What are the dominant systematic effects and how can we control them?
- What precision of calibration is needed and how can it be achieved?

A proposal requires knowing the answers!

Questions under investigation, no firm conclusions yet
How PINGU might look like

- Add ~20 strings in Deep Core region, each with 60 OMs, 6m vertical distance
- Denser configurations also under investigation
- Instrumented volume ~5-6 Mton
- Expected energy threshold at ~1 GeV
- R&D opportunity for future developments
- IceCube plus further groups
PINGU: Estimate of effective volume

- Require 20 hits inside PINGU volume
- Constrain generation vertex
- Gives rough estimate of reconstructable events
- Quality cuts and reconstruction efficiency not included
PINGU: Hardware issues

- Mostly standard IceCube technology
- Upgrade/improve optical modules (electronics, flasher, power supply)
- DAQ under study
- Improve flasher calibration system (better time resolution, better control of intensity)
- Add degassing system to hot-water drill to avoid bubbles in refreezing water
- Also: Prototype tests of new components for possible future use
ORCA: A detector layout used for simulations

- 50 strings, 20 OMs each
- KM3NeT design: 31 3-inch PMTs / OM
- 20 m horizontal distance
- 6 m vertical distance
- Instrumented volume: 1.75 Mton water
ORCA reconstruction efficiency

- Up-going events generated inside detector volume
- 4 L1 required (large hit or local coincidence)
- No quality cuts, no background rejection

[Graph showing reconstruction efficiency vs. Neutrino Energy (GeV)]

PRELIMINARY
ORCA energy and zenith resolutions

- $E_\mu$ reconstructed from $\mu$ track length
- Shaded region: 16% and 84% quantiles as function of $E_\mu^{true}$

- Median of zenith angle difference $\nu - \text{rec. } \mu$

[Graph showing the relationship between $E_\mu$ and the shaded region, with quantiles and median of zenith angle difference.]
ORCA: Hardware and construction issues

• Use agreed KM3NeT technology; no major modifications required, but cable lengths etc. to be adapted
• String length restricted to avoid entanglement due to deep-sea currents
• Deployment requires care and studies (operation of deep-sea submersibles (ROVs) between deployed strings is impossible)
• New deployment scheme proposed (several strings in one sea operation)
• Very tight time constraints since most of the funding must be spent until March 2015
PINGU and ORCA systematics

PINGU (ice):
- inhomogeneity of ice
- light scattering in ice
- atmospheric muons (less deep than water)
- position/orientation calibration of optical modules

ORCA (water):
- optical background from K40 and bioluminescence
- missing veto detector
- temporal variations of data taking conditions

Systematics are complementary – it may be useful/necessary to make both experiments
Measuring the neutrino mass hierarchy
The full 3-flavour neutrino oscillation picture

- Parameterisation of mixing matrix (up to Majorana phases that are not discussed here):

\[
U_{\text{PNMS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \cdot \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \cdot \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

with \( s_{ij} = \sin \theta_{ij} \) and \( c_{ij} = \cos \theta_{ij} \)

- Neutrino oscillation parameters:

\[
\sin^2(2\theta_{23}) = 0.97; \quad |\Delta m_{23}^2| = 2.35 \times 10^{-3} \text{ eV}^2 \quad \text{atmos. + acc.}
\]
\[
\sin^2(2\theta_{12}) = 0.86; \quad \Delta m_{12}^2 = 7.58 \times 10^{-5} \text{ eV}^2 \quad \text{solar + reactor}
\]
\[
\sin^2(2\theta_{13}) = 0.096;
\]

- Unknown: sign of \( \Delta m_{23}^2 \)

CP-violating phase \( \delta \)
Neutrino mass hierarchy

- Depending on sign of $\Delta m^2_{23}$: “normal hierarchy” or “inverted hierarchy”
  (NH) (IH)

- A fundamental parameter of particle physics!
Mass hierarchy and atmospheric neutrinos

- Determining the sign of $\Delta m_{23}^2$ requires matter effect. Oscillation of $\nu_e$ and/or $\bar{\nu}_e$ must be involved.
- 3-flavour oscillations of $\nu_e \leftrightarrow \nu_\mu$ in matter:

  $$P_{e\rightarrow \mu} \approx P_{\mu\rightarrow e} \approx \sin^2 \theta_{23} \sin^2(2\theta_{13}^{\text{eff}}) \sin^2 \left(\frac{\Delta_{13}^{\text{eff}} L}{2}\right)$$

  $$\Delta_{13} = \frac{\Delta m_{13}^2}{2E_\nu} \quad \sin^2(2\theta_{13}^{\text{eff}}) = \frac{\Delta_{13}^2 \sin^2(2\theta_{13})}{\Delta_{13}^{\text{eff}} L}$$

  $$\Delta_{13}^{\text{eff}} = \sqrt{\left[\Delta_{13} \cos(2\theta_{13}) - A\right]^2 + \Delta_{13}^2 \sin^2(2\theta_{13})}$$

  $$A = \sqrt{2} G_F N_e \text{ for } \nu \text{ and } A = -\sqrt{2} G_F N_e \text{ for } \bar{\nu}$$

- “Matter resonance” for $A = \Delta_{13} \cos(2\theta_{23})$ (maximal mixing, minimal oscillation frequency). This is the case for $E_\nu \approx 30 \text{ GeV}/\rho[\text{g cm}^{-3}]$
Neutrino oscillations in Earth

- Earth density 4-13 g/cm³
- Relevant: $E_\nu \sim 3$–10 GeV
The Akhmedov/Razzaque/Smirnov paper (1)

Significance for perfect resolution:

\[ S_{\text{tot}} = \sqrt{\sum_{\text{bins}} \frac{(N_{i}^{\text{NH}} - N_{i}^{\text{IH}})^2}{\sigma_i}} \]

with \( \sigma_i = N_{i}^{\text{NH}} + f(N_{i}^{\text{NH}})^2 \)

Uncorrelated system. errors assumed \((f)\)

Result (5 years):

- \( f = 0.00 \): \( S_{\text{tot}} = 45.5\sigma \)
- \( f = 0.05 \): \( S_{\text{tot}} = 28.9\sigma \)
- \( f = 0.10 \): \( S_{\text{tot}} = 18.8\sigma \)
The Akhmedov/Razzaque/Smirnov paper (2)

- Taking into account experimental resolutions
  \[ \sigma_E = 0.2 E_\nu; \sigma_\theta = \sqrt{m_p/E_\nu} \]
  (just an example)
  deteriorates result
- Remaining significances in the range 3...15\sigma
- Not yet included:
  - Non-Gaussian tails
  - Inefficiencies
  - Backgrounds
  - …
Impact of oscillation uncertainties (1)
Impact of oscillation uncertainties (3)
A toy analysis (ORCA)

- Neutrino interactions generated in detector volume
- Require at least PMT 15 hits
- Use true muon direction for zenith
- Assume 20% Gaussian uncertainty on $E_{\nu}$
- No backgrounds, flavour misidentification etc.
- Assume hierarchy (NH or IH), pick oscillation parameters within experimental uncertainties, generate “toy experiment”
- Perform log-likelihood fit (free parameters: $\Delta m^2_{23}, \theta_{23}, \theta_{13}$), assuming both NH and IH
- Investigate log-likelihood ratio NH/IH
Results of toy analysis:

- Distribution of log-likelihood ratio NH/IH for toy experiments
- Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years
- Improved determination of $\Delta m^2_{23}, \theta_{23}$ seems possible
Summary and outlook
• Neutrino telescopes in deep ice and water provide increasing sensitivity to cosmic neutrinos (>1 TeV).
• They have demonstrated that low-energy measurements are possible (some 10 GeV).
• Even lower energies can be studied with densely instrumented configurations.
• A determination of the neutrino mass hierarchy with atmospheric neutrinos may be in reach but is experimentally difficult.
• If possible, this approach will be significantly faster and cheaper than any alternative.
• We will know more in a year – stay tuned.
• Help is more than welcome!