Aktuelle Ergebnisse und Zukunft der Neutrinoastronomie

Uli Katz
ECAP / Univ. Erlangen
The plan for this presentation:

• Introduction
• Present neutrino telescopes: ANTARES, IceCube and their recent results
• KM3NeT
• Studying low-energy neutrinos: The PINGU and ORCA options
• Summary

Sincere thanks to all colleagues who provided advice and material for preparing this presentation
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:
  \(10^0\ \text{GeV} - \text{some PeV}\)
- Angular resolution:
  \(<1^\circ\ \text{for } E>1\ \text{TeV}\)
- \(\Delta[\log(E)] \sim 0.3\)
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
- Sea water: light from K40 decays and bioluminescence
The neutrino telescope world map

KM3NeT: A distributed multi-km³ neutrino telescope in the Mediterranean Sea
Example targets of neutrino astronomy

- Galactic neutrino sources
- Extragalactic sources
- Transient sources
- Diffuse neutrino flux
- Neutrinos from Dark Matter annihilations
- Particle physics with atmospheric neutrinos
- Search for exotics (monopoles, nuclearites, ...)

> Example: Supernova remnant RX J1713

Gamma observation by H.E.S.S.

Active Galactic Nuclei (AGN):
- Super-massive black hole in centre of galaxy with accretion disk and jet emission
- Extremely bright gamma ray flash (sec-min)

Isotropic high-energy neutrino flux above atmospheric neutrino background from unresolved astrophysical sources or of cosmogenic origin (GZK)
South Pole and Mediterranean fields of view

Galactic coordinates

$2\pi$ downward sensitivity assumed

IceCube @ South Pole: Sees Northern hemisphere
ANTARES, IceCube and (a restricted selection of) their recent results

IceCube:
Aachen, Bonn, Bochum, DESY, Dortmund, Mainz, TU München, Wuppertal
See:
T9.4, Do 15:15, Sebastian Böser, T20, T21, T55, T74, T86-T90, T92, T93, T104, T109, T111

ANTARES:
Erlangen
See:
T78, T86, T88-T90, T104, T110, T111
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 storeys each
- Almost 900 optical modules
- Acoustic sensor system
ANTARES: Point source search

- 4 years of data, 3058 neutrino candidate events
- Search for neutrinos from selected source candidates (no significant signal)

\[ \text{DEC} = -65.0^\circ; \text{RA} = -46.5^\circ \]

\[ N_{\text{src}} = 5/9 \text{ in } 1/3 \text{ degrees} \]

\[ p\text{-value: post-trial } = 2.6\% \]

\[ (2.2 \sigma) \]
ANTARES: Neutrino oscillations

- 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
ANTARES proves the feasibility and sensitivity of a deep-sea neutrino telescope!
IceCube: A km$^3$ detector in the Antarctic ice
IceCube: Completed in December 2010

- 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
- Plan for future low-energy extension (PINGU)
IceCube: Event skymap (IC40+59+79)

- **atm. muons**
  - **PeV**
  - Southern hemisphere

- **atm. neutrinos**
  - TeV – PeV
  - Northern hemisphere
  - 108,317 events

**Preliminary**
IceCube: Significance map (IC40+59+79)

DEC = -38.8° ; RA = 219.3°

$N_{src} = 20.8$

p-values: pre-trial = $9 \times 10^{-5}$
post-trial = 98%

DEC = 2.8° ; RA = 34.3°

$N_{src} = 23.1$

p-values: pre-trial = $2 \times 10^{-5}$
post-trial = 57%

U. Katz: Neutrino Astronomy, 04.03.2013
IceCube: Sensitivities & limits (IC40+59+79)

90% CL sensitivity / upper limits for $E^{-2}$ spectrum

- ANTARES and IceCube see different energy ranges!
- Discovery region

Galactic γ-ray sources

- Expected improvements: Statistics, reconstruction quality
- Attention: IceCube for Southern hemisphere ($\sin(\delta)<0$) not sensitive to neutrino fluxes with cutoff at 10...100TeV (typical Galactic sources)
- Full access to Galactic sources only from Northern detector

Predictions
Halzen, Kappes, O’Murchadha (2008)
Kistler, Beacom (2006)
IceCube: Neutrinos from GRBs (IC40+59)

- Search for neutrinos from observed GRBs
- Increased sensitivity due to reduced time window
- 117+98 GRBs in Northern sky for IC40 and IC59 (plus 85 Southern GRBs)
- 0 neutrinos observed
- Severely constrains models

Nature 484 (2012) 351

GRB models

IceCube allowed

low $\Gamma$ \hspace{1cm} $E_\nu$ [GeV] \hspace{1cm} high $\Gamma$
IceCube: Diffuse neutrino flux

- Prompt component still unmeasured
- Is there a diffuse flux from unresolved cosmic sources?
- Disentangling cosmic and prompt fluxes challenging

Waxman&Bahcall upper bound

astrophysical neutrinos

\[ E^2 \phi_\nu \text{ [GeV cm}^{-2} \text{s}^{-1} \text{ sr}^{-1}] \]

\[ \log_{10} (E_\nu \text{ [GeV]}) \]
Atmospheric muon neutrinos (IC59)

- Search for excess in high-energy tail
- Observed spectrum slightly harder than predicted
  → Limit > sensitivity
Searching for a high-energy $\nu_e$ excess

$\nu_e N \rightarrow eX$:
- all energy inside detector
- low atmospheric background
- cascade channel good for excess search

IC40 cascade analysis:
- 3 events found $>100$ TeV
- Estimated background: (0.4+prompt) events
- Significance 2.4$\sigma$
Cosmogenic neutrinos (IC79+86-l, 670 days)

- Optimized cuts for UHE neutrinos:
  - Expected background = 0.05/0.08 (without/with prompt)
  - Observed = 2 events (3.0/2.7σ)

![Graph showing data and expected backgrounds](image)
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
- Extends accessible energy range down to 10 GeV
• 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!

- Search for dark matter annihilation in Sun (arXiv:1212.4097)
- Atmospheric neutrino oscillations (arXiv:1301.4339)

→ no-oscillation hypothesis ruled out by 5.8σ
IceCube: Further results

• Search for high-energy Galactic neutrinos (Astrophys.J.763(2013)33)
• Neutrinos from Crab nebula (Astrophys.J.745(2012)45))
• Search for UHE tau neutrinos (Phys.Rev.D86(2012)022005)
• Search for Galactic PeV gamma rays (arXiv:1210.7992)
• Lateral distribution of μ’s in cosmic ray events (Phys.Rev.D87(2013)012005)
• Search for relativistic magnetic monopoles (Phys.Rev.D87(2013)022001)
• …
KM3NeT

KM3NeT: Erlangen, Tübingen, Würzburg
See: T78, T104, T109, T110
The KM3NeT project

- Multi-km$^3$ NT in Mediterranean Sea, exceeding IceCube substantially in sensitivity
- Nodes for earth/sea science instrumentation
- Central physics goals (by priority):
  - Galactic neutrino “point” sources (energy 1-100 TeV)
  - Extragalactic sources
  - High-energy diffuse neutrino flux
- Decisions taken:
  - Technology: Strings with multi-PMT optical modules
  - Multi-site installation (France, Greece, Italy)
  - 5 building blocks of ~120 strings each
- Collaboration established
- Next steps
  - prototyping and construction (~40 M€ available for first phase)
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
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - directionality
RX J1713: A prime candidate source

- Figure of merit (F.o.M.): time to make an observation at 5σ with 50% probability
- KM3NeT analysis very conservative; ~20% improvement by unbinned analysis
- Clear (but flat) optimum in horizontal distance between DUs
- Further candidate sources with similar or better discovery chances

KM3NeT preliminary
(γ emission from RX J1713 assumed 100% hadronic)
The Fermi bubbles

- Two extended regions above/below centre of Galactic plane
- Fermi detected hard $\gamma$ emission ($E^{-2}$) up to 100 GeV
- Origin and acceleration mechanisms under debate – if hadronic, hot neutrino source candidate
- Could be first source detected by KM3NeT

\[
E^2 \Phi (\text{GeV cm}^{-2} \text{s}^{-1})
\]

- $E^{-2}$, 30 TeV cut-off
- $E^{-2}$, 100 TeV cut-off
- $E^{-2}$, no cut-off

3$\sigma$ @ 50%

5$\sigma$ @ 50%

Astropart.Phys.42(2013)7
Towards exploring the low-energy regime: PINGU and ORCA

PINGU:
Aachen, Bonn, Bochum, DESY, Dortmund, Erlangen, Mainz, TU München, Wuppertal
See:
T89, T104, T109,

ORCA:
Erlangen, Tübingen, Würzburg
See:
T104
Why low energies?

- Increased sensitivity for indirect dark matter searches
- Investigate oscillations and neutrino flavour composition of atmospheric neutrinos

And in particular:

- **Measure the neutrino mass hierarchy (sign of $\Delta m^2_{23}$)**
  - Matter effect for neutrino propagation through Earth “just right” for energies $E_{\nu} \sim 3 \ldots 15$ GeV
  - Discussion initiated by paper by Akhmedov, Razzaque and Smirnov (JHEP 02 (2013) 082)
PINGU: Dense instrumentation in IceCube

- 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
ORCA: A case study for KM3NeT

- Investigated: 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

Note; This is not a proposal but just a (scalable) example configuration
Effective volume ad efficiencies

- Require 20 hits inside PINGU volume
- Constrain generation vertex
- Gives rough estimate of reconstructable events
- Quality cuts and reconstruction efficiency not included
- Similar efficiency for ORCA
ORCA energy and zenith resolutions

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

- Median of zenith angle difference $\nu - \text{rec. } \mu$
Neutrino oscillations in Earth

- Earth density $4-13 \text{ g/cm}^3$
- Relevant: $E_\nu \sim 3-10 \text{ GeV}$
The Akhmedov/Razzaque/Smirnov paper (1)

\[(N^{\mu\text{IH}}_\mu - N^{\mu\text{NH}}_\mu)/(N^{\mu\text{NH}}_\mu)^{1/2} \text{ [PINGU 1 yr]}\]

- **Significance for perfect resolution:**
  \[S_{\text{tot}} = \sqrt{\sum_{\text{bins}} \frac{(N^{\text{NH}}_i - N^{\text{IH}}_i)^2}{\sigma_i}}\]
  with \(\sigma_i = N^{\text{NH}}_i + f(N^{\text{NH}}_i)^2\)

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

- **Result (5 years):**
  \[f = 0.00 : S_{\text{tot}} = 45.5\sigma\]
  \[f = 0.05 : S_{\text{tot}} = 28.9\sigma\]
  \[f = 0.10 : S_{\text{tot}} = 18.8\sigma\]

*JHEP 1302 (2013) 082; arXiv 1205.7071*
The Akhmedov/Razzaque/Smirnov paper (2)

- Taking into account experimental resolutions
  \[ \sigma_E = 0.2E_\nu; \sigma_\theta = \sqrt{m_p/E_\nu} \]
  (just an example)
  deteriorates result

- Remaining significances as low as 3\(\sigma\)

- Not yet included:
  - Non-Gaussian tails
  - Inefficiencies
  - Flavour separation
  - Backgrounds
  - …
Impact of oscillation uncertainties

\[ \Delta m^2_{12} \]

\[ \Delta m^2_{23} \]

\[ \theta_{23} \]

\[ \theta_{13} \]

\[ \theta_{12} \]
Results of toy analysis (ORCA):

- Neutrino vertex in detector volume, true $\mu$ direction, $\sigma(E_\nu) = 0.2 E_\nu$
- Distribution of log-likelihood ratio NH/IH for toy experiments
- Experimental determination of mass hierarchy at 4-5$\sigma$ level requires $\sim 20$ Mton-years
- Improved determination of $\Delta m^2_{23}$ and $\theta_{23}$ seems possible
PINGU and ORCA systematics

PINGU (ice):
• inhomogeneity of ice
• light scattering in ice
• missing segmentation of photocathode

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

Systematics are complementary – it may be advantageous to make both experiments
Summary and Outlook
• Neutrino telescopes in deep ice and water provide increasing sensitivity to cosmic neutrinos (>1TeV).
• Their results are significant and intriguing.
• The construction of the KM3NeT neutrino telescope in the Mediterranean Sea will start 2013/14.
• ANTERES and IceCube have demonstrated that studying neutrinos with energies down to 10 GeV is possible.
• Even lower energies can be studied with densely instrumented configurations, which may allow for a determination of the neutrino mass hierarchy with atmospheric neutrinos.
• If possible, this approach is expected to be significantly faster and cheaper than any alternative.
• These are exciting times for neutrino astronomers – stay tuned!