XXVI Workshop on Recent Developments in High Energy Physics and Cosmology

Ancient Olympia, April 2008

HIGH ENERGY NEUTRINO TELESCOPES

J.P. ERNENWEIN, Université de Haute Alsace, Mulhouse, FRANCE.
Why the neutrino?

- Weakly interacting → Source exploration on cosmological distances
- Access to the heart of sources
- Weakly interacting → large detection volume required

### Neutrino γ :
- Absorbed (interaction with C. B.)
- Magn. field + GZK effect

### Log E (GeV):
- TeV
- PeV
- EeV
- ZeV
Potential sources of neutrinos

GALACTIC SOURCES:
- Supernovae,
- Supernova remnants,
- Micro Quasars:

EXTRA GALACTIC SOURCES:
- Gamma Ray Bursts

Dark Matter: annihilation of neutralinos inside massive objects (Sun, Earth, Galactic Center)

SNR RX J1713.7-3946

Galactic Center

Crab Nebula

Pulsars

M 87, HST

Active Galactic Nuclei
\( e \rightarrow \gamma \) (Inverse Compton, Synchrotron)

\[ p/A + p/\gamma \rightarrow \pi^0 + \pi^\pm + \ldots \]

\[ \gamma \gamma \nu_\mu \mu \rightarrow V \]

Hadronic interactions

**Electromagnetic or hadronic?**

**Clearly hadronic!**

**Electron model**

\[ E^{-2} \text{ power law} \]

**X data**

**Synchrotron Radiation**

**IC Radiation**

**Bremsstrahlung**

**Radio data**

**Hadronic scenario**

\[ \pi^0 \text{ kinematics included} \]

**Systematic error band**

**supernova remnant RX J1713.7-3946**

Simplest electronic models do not work well (very low magnetic field)

**Neutrino detection principle**

**Charged current interaction (W)**

- **μ** track:
  - Good angular resolution \(O(\text{degree})\) @ \(E>10\) TeV,
  - Poor energy resolution (factor 2-3)

- **e**
  - Good energy resolution \(O(30\%)\),
  - Poor angular resolution \(O(10^\circ)\)

**3D PMT array**

- Measurements:
  - Time \(O(\text{ns})\), amplitude (30\%)
  - & position of hits \(O(10\ \text{cm})\)

- Needs to be sensitive to the single photo-electron

- Threshold \(\sim 1/3\) pe

- Variable dynamic range
  - 20 pe/40 ns, 35 pe/25 ns, 500 pe/3.3 ns over 420 ns

- 2500-5000 m depth

© François Montanet
Signal & Backgrounds

Down-going atmospheric background (direct muons & muons from neutrinos)

Up-going atmospheric background (muon neutrinos)

Log \( E_{\nu} \cdot \text{Flux}(E_{\nu}) \)

\( \log(E/\text{GeV}) \)

Atmospheric muons

\( 2400 \text{ m depth} \)

\( E_{\nu} > 1 \text{ TeV} \)

Astrophysical neutrinos

A Neutrino telescope looks downwards and uses Earth as target and muon filter:

Very intense atmospheric muon flux

\( \text{d} \Phi / \text{d} \Omega = 10^{-7} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \)

\( 10^{-9} \)

\( 10^{-11} \)

\( 10^{-13} \)

\( 10^{-15} \)

\( 10^{-17} \)
ANTARES
42°50'N, 6°10'E
2475m depth,
sea water
3 PMTs/floor
12 lines of 25 floors
(total 900 PMTs)
this Summer.
NEMO
36°20'N, 16°E
3500m depth
sea water
4 PMTs/floor.
Currently run of a
mini tower of 4
floors.
Final design:
Towers of 16
floors (64 PMTs)
NESTOR
36°36'N, 21°30'E
3800m depth
sea water
12 PMTs/floor
One floor
immersed in 2003.
Final design:
towers of 12 floors
(144 PMTs)

BAIKAL
54°50'N, 104°20'E
1367m depth
water of Baikal Lake
(first prototype NT36:
1993, first stationary
string: 1984)
2 PMTs/storey
8 strings of 12
storeys (total 192
PMTs) + 3 outer
strings of 6 storeys
(36 additonal OM's)
Currently operating.

AMANDA: South Pole, ICE, 900-2350m depth, 1 PMT/floor:
AMANDA-B4 (1996): 4 strings, 80 PMTs
AMANDA-B10 (1997): 10 strings, 302 PMTs
AMANDA-II (2000->now): 19 strings, 677 PMTs

ICECUBE (2450m depth):
80 strings of 60 storeys (4800 PMTs). 40 strings deployed
VISIBLE SKY

On maps:
- microquasars (green)
- TeV sources (blue)

Never visible

Always visible

Galactic coordinates

Effect of latitude (rotation of Earth)

BAIKAL

AMANDA
ICECUBE

ANTARES, NEMO
NESTOR
The sites ...
BAIKAL, 1367m depth
2 PMTs/floor
8 strings of 12 floors (total 192 PMTs: NT200, since 1998)
+ 3 outer strings of 6 floors (total 36 additional PMTs: NT200+, since 2005)

15” PMTs

4 km to shore
Winter ice enables deployment and maintenance

NT200

1 Mton at 1 PeV
BAIKAL, 1367m depth
2 PMTs/floor
8 strings of 12 floors (total 192 PMTs: NT200, since 1998)
+ 3 outer strings of 6 floors (total 36 additional PMTs: NT200+, since 2005)

NT200+
+20% PMTs
sensitivity improved by a factor 4.
Tailored for UHE cascades:
\[ V_{\text{eff}} \approx 10 \text{ Mton at 10 PeV} \]
BAIKAL, towards a km³ project:

Sparse instrumentation:
91 strings with 12/16 OM = 1308 OMs

Effective volume for 100 TeV cascades
~ 0.5 – 1.0 km³

µ threshold between 10 and 100 TeV
AMANDA-II: 19 strings, 677 PMTs

15m between OMs of a string

AMANDA is operating its 19 strings since 2000

G. Hill, Neutrino 2006
Point source search: AMANDA sky maps: no significant excess


Highest excess = 3.7σ
Statistical probability = 69%

No source
Limits

Search bin
Background estimation

Real sky
Randomized MC sky

Significance maps
Point source search: AMANDA sky maps: no significant excess
AMANDA diffuse flux search (astro-ph 0705.1315)
ICECUBE (-2450m):
80 strings of 60 storeys = 4800 PMTs.
17m between OMs, 125 m between strings

2004-2005:
1 String

2005-2006:
8 Strings

2006-2007:
13 Strings

2007-2008:
18 strings

2008:
40 strings connected

Amsterdam

M. Ribordy
Moriond 2008
ICECUBE expected performances (M Ribordy, Moriond 2008)

Muon effective area

Angular resolution
ICECUBE commissioning (M Ribordy, Moriond 2008, G Hill, v2006)

9 strings (IC9) vs 22 strings vs 40 strings: reconstructed azimuth of tracks.
NESTOR
3800m depth
12 PMTs/storey
12 storeys/tower

A TOWER
32 m diameter floor
30 m between floors
144 PMTs
(facing up & down)

Optical Module
Titanium Sphere
buoys
Titanium floor
calibration module
Electrooptical cable
Junction box
Sea floor

2003
Up going muon

One storey immersed

OM looking upwards

2003
A result from 2003 operation: Atmospheric muon flux.

\[
\frac{dN}{d\Omega \, dt \, dS} = I_0 \cos^\alpha (\theta)
\]

Fig. 18. Distribution of the Zenith angle (\(\theta\)) of reconstructed tracks for the data (triangles) and Monte Carlo (solid points) event samples. The insert plot shows the same distributions on a linear scale.

\[I_0 = 9.0 \times 10^{-9} \pm 0.7 \times 10^{-9} \text{(stat)} \pm 0.4 \times 10^{-9} \text{(syst)} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}\]

\[\alpha = 4.7 \pm 0.5 \text{(stat)} \pm 0.2 \text{(syst)}\]
Plans:

KM3NeT participation:

An example from: Recent Results from Nestor, LK Resvanis, Neutrino Oscillations in Venice, 2006, (p.461-474)

100m diameter, Optical Modules every 18.5 m

Deployment of these structures:
specialized surface vessel (Delta-Berenike platform) developed by the NESTOR collaboration

13 towers of 12 floors (5928 PMTs):
~ 1 km$^3$

NuBe-NESTOR (collaboration with US physicists):
(Neutrino Burst Experiment-NESTOR):
search for 100 TeV neutrinos in coincidence with GRB emission.

Effective area ~ 2 km$^2$
NEMO, 3500m depth, 4 PMTs/storey  
16 storeys/tower (64 PMTs)

Phase 1 (Dec. 2006): 1 mini-tower installed at a depth of 2000 m, 30 km offshore Catania (still in operation)

Optical Modules

Electronics container

Isabella Amore: NEMO Phase 1: construction, operation and first results, ISAPP 2007

Full project:
NEMO km$^3$ proposal: 10 junction boxes, 81 towers, 5832 PMTs

C Distefano,
THE MULTI-MESSENGER APPROACH TO UNIDENTIFIED GAMMA-RAY SOURCES
Barcelona July 4 – 7, 2006
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THE MULTI-MESSENGER APPROACH TO UNIDENTIFIED GAMMA-RAY SOURCES
Barcelona July 4 – 7, 2006
ANTARES, 2475m, 3 PMTS/floor
12 lines of 25 floors
900 PMTs this Summer

JUNCTION BOX

BASE of a LINE
MEDIUM PROPERTIES for Cherenkov light propagation

<table>
<thead>
<tr>
<th></th>
<th>( \lambda_{\text{abs}} )</th>
<th>( \lambda_{\text{eff \ sca}} )</th>
<th></th>
<th>( \lambda_{\text{att}} )</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BAIKAL</strong></td>
<td>( \sim 20 \text{ m} ) &amp; ( \lambda_{\text{eff \ sca}} \sim 300 \text{ m} @ 470 \text{ nm} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AMANDA</strong></td>
<td>( \lambda_{\text{abs}} \sim 70 \text{ m} ) &amp; ( \lambda_{\text{eff \ sca}} \sim 25 \text{ m} @ 470 \text{ nm} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NESTOR</strong></td>
<td>( \lambda_{\text{att}} \sim 55 \text{ m} )</td>
<td>( @ 460 \text{ nm} ): ( \lambda_{\text{att}} ) includes abs &amp; scat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NEMO</strong></td>
<td>( \lambda_{\text{abs}} \sim 70 \text{ m} )</td>
<td>( @ 440 \text{ nm} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ANTARES</strong></td>
<td>( \lambda_{\text{abs}} \sim 60 \text{ m} ) &amp; ( \lambda_{\text{eff \ sca}} \sim 300 \text{ m} @ 470 \text{ nm} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Absorption reduces photon statistic
scattering introduces time delay and dispersion

\[ \lambda_{\text{effective scattering}} = \frac{\lambda_{\text{scat}}}{(1 - \langle \cos \theta_{\text{scat}} \rangle)} \]

V. Aynutdinov
(2005)
**OPTICAL BACKGROUND** : additional light coming from medium

*Depends on OM configuration (photocathode size) and on trigger threshold : ~ 1/3 photoelectron*

<table>
<thead>
<tr>
<th>OM Type</th>
<th>Frequency Range</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAIKAL (15” PMT)</td>
<td>0.1-0.3 kHz/2 OMs</td>
<td>coincidence within 15ns, no $^{40}$K</td>
</tr>
<tr>
<td>AMANDA (8”)</td>
<td>1 kHz/OM</td>
<td>no radioactivity, no bioluminescence : only photocathode noise</td>
</tr>
<tr>
<td>NESTOR (15”)</td>
<td>50 kHz/OM</td>
<td>$^{40}$K + few bioluminescence (-3800 m)</td>
</tr>
<tr>
<td>NEMO (10”)</td>
<td>30 kHz/OM</td>
<td>$^{40}$K + few bioluminescence (-3500 m)</td>
</tr>
<tr>
<td>ANTARES (10”)</td>
<td>60-100 kHz/OM</td>
<td>$^{40}$K + bioluminescence (-2500 m)</td>
</tr>
</tbody>
</table>

$^{40}$K : beta emitter $e^-$ 1.12 MeV$\sim$40 $\gamma$
Burst

$^{40}$K beta radioactivity & bioluminescence:
60-100 kHz/Optical Module + bursts

Baseline: $^{40}$K (30 kHz) + bacteria

Environmental background noise

2007
**Muon EFFECTIVE AREAS**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Area</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAIKAL NT200</td>
<td>2000 m²</td>
<td>@ 1 TeV</td>
</tr>
<tr>
<td>AMANDA 19 strings</td>
<td>30 000 m²</td>
<td>(ICECUBE: 1 km²)</td>
</tr>
<tr>
<td>NESTOR 1 tower</td>
<td>20 000 m²</td>
<td>@ 10 TeV</td>
</tr>
<tr>
<td>NEMO 9x9 towers, 140m spaced</td>
<td>1 km²</td>
<td></td>
</tr>
<tr>
<td>ANTARES 12 lines</td>
<td>20 000 m²</td>
<td></td>
</tr>
</tbody>
</table>

**ANGULAR RESOLUTION**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAIKAL NT200</td>
<td>4°</td>
</tr>
<tr>
<td>AMANDA 19 strings</td>
<td>2° (ICECUBE: 0.7°)</td>
</tr>
<tr>
<td>NESTOR 6 towers</td>
<td>better than 1°</td>
</tr>
<tr>
<td>NEMO 9x9 towers</td>
<td>0.1°</td>
</tr>
<tr>
<td>ANTARES 12 lines</td>
<td>0.3°</td>
</tr>
</tbody>
</table>

Dominated by reconstruction
ANTARES expected sensitivities

90% c.l. limits and sensitivities on $\nu_\mu$, $E^2$ diffuse fluxes

Diffuse fluxes

MACRO (GRAN SASSO)
From the simulation ...

*MC TeV muon traversing the detector.*
Line 1 analysis, May-September 2006, low sea current: 10 days equivalent

Atmospheric muon flux estimate (Zenith angle <-> depth)

... to the data: 2006, the first line:

2006
... to the data: 2006, the first line:

Line 1 analysis, May-September 2006, low sea current: 10 days equivalent

Atmospheric muon flux estimate
(Zenith angle <-> depth)
2007: 5 lines: Up going neutrino candidate
Atmospheric muon bundles
“Online” reconstruction with 5 lines

- MC Atm muons
  (dashed: MC truth, plain: MC reconstructed track)

- MC Atm neutrinos
  (dashed: MC truth, plain: MC reconstructed track)

37 days 2007

No alignment

Preliminary
Atmospheric neutrinos

54 days livetime, 4.35 M$\mu$

No detector alignment

5 lines

2007

down going

up going

> 0.1

55 Neutrino candidates
Applied quality cut: likelihood method

![Graph showing the number of remaining events per day as a function of the value of cut on \( \Lambda \). The graph includes lines for different categories: all, upward reconstructed atmospheric \( \mu \), atmospheric \( \nu \), signal efficiency.]
Absorption of atmospheric muons in water

Rate of correlated adjacent coincidences $= f(\text{depth})$

5 lines

2007
Improvement of performances: calibration (position)

Sea current velocity from ADCP measurement
Sea current velocity from fit of zenith angles

Check of the Line model $f$ used in the shape fit

Autonomous transponder and basis of lines

Zenith angle

hydrophones + tiltmeters & compass → shape

$\text{shape} = f(\text{sea current})$
Calibration/monitoring with Potassium-40

\[ ^{40}\text{K} \rightarrow ^{40}\text{Ca} \quad \gamma \quad (\beta \text{ decay}) \]

Cherenkov

\[ ^{40}\text{K} \rightarrow ^{40}\text{Ca} \quad \gamma \]

High precision (~5%) monitoring of OM efficiencies

Gaussian peak on coincidence plot

Integral under peak = rate of correlated coincidences

D Zaborov (Moriond 2008)

MC prediction 13 +/- 4 Hz (angular acceptance to be confirmed)
Improvement of performances: calibration (time)

LED Beacons & K40 OM offsets

Lines 1-5

Projection on Y axis

Good agreement between the 2 methods
The first neutrino with 10 strings

Zenith: 51.9
Fit on 4 line(s)

Run 30538 Frame 82439
Set Dec 8 12:36:30 2007
Trigger bits: 000000020
Line 1 - 10 Physica Trigg

1 2 3 4 5 6 7 8 9 10

Preliminary
Calibration: a KM3NeT idea on test in ANTARES framework?

- Angular offset
- Absolute position

Atmospheric Muon

Triangulation $\rightarrow$ ShowerDirection

Disc of particles sweeps down through atmosphere

Spyros Eust. Tzamarias, Apostolos Tsirigotis et al (HOU)

GPS timestamp to match events

$180\ m$

$350\ m$

$100\ m$
CONCLUSION

BAIKAL (fresh water) & AMANDA (ice) are the first high energy neutrino telescopes; They have already proved the feasibility and interest of such devices. The first “underwater atmospheric neutrinos” were reported in 1995 by the BAIKAL collaboration. Reliable atmospheric neutrino results are now available. Preliminary astrophysics results are produced.

ANTARES 5 lines data are now extensively analyzed; The 10 line detector is running since December 2007. In Summer 2008 ANTARES 12 lines will be completed.

NEMO phase 1 is currently on-going.

The Mediterranean sea cubic kilometer detector design is in progress, gathering all the efforts within the KM3NeT project.