Neutrinos Out of the (Deep) Blue
-Status of Underwater Neutrino Telescopes

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TeV Particle Astrophysics II
28-31 August 2006, Madison
High Energy Messengers

- Neutrinos ($\nu_e; 2\nu_\mu$)
- Photons absorbed
- Charged particles bent by magnetic fields
- Neutrinos ($\nu_e; \nu_\mu; \nu_\tau$)

Log $E$ (GeV):
- TeV
- PeV
- EeV
- ZeV
Guaranteed: GZK neutrinos by CR interactions with CMB
Neutrinos due to CR interactions with galactic plane, sun

Expected: SNR, \( \mu \)quasars, AGNs, GRBs...

Possible: Dark Matter annihilation in sun, GC, IMBHs
Monopoles, top-down, ….

Supernovae Remnants
(e.g. RXJ1713.7-3946)

Microquasar
(e.g. GX339-4)

Active Galactic Nuclei
(e.g. M87)

Black hole with
\( 10^8 \times \) mass of sun

Potential Sources?
Time & position of hits allow the reconstruction of the $\mu$ (~ $\nu$) trajectory.

- $\cos \theta = 1/n\beta$
- Sea water $n \sim 1.44$
- 24hr-half hemisphere continuous monitoring
- Sensitive to $\nu$ flavour

Neutrino Detection

3D PMT array
Large Volume Neutrino Telescope Projects

ANTARES: La-Seyne-sur-Mer, France

BAIKAL: Lake Baikal, Siberia

DUMAND, Hawaii (cancelled 1995)

NEMO: Catania, Italy (evaluation of potential sites, R&D for KM3) Participates to ANTARES

NESTOR: Pylos, Greece

AMANDA/ICECUBE, Antarctica
1976: Dumand conceptually designed
1987: 7 module prototype to 4.5km depth
1989: funding secured for 0.1km² array
1993: funding lapses (along with SSC!)
The Baikal Detector
4 cables x 4km to shore
1100m depth
Deployment from ice sheet
The Baikal Detector NT200+

**NT200 running since 1998**
- 8 strings with 192 optical modules
- 72m height, R=20m, 1070m depth, $V_{\text{geo}}=0.1\text{Mton}$
- $\mu$ effective area: $>2000\text{ m}^2$ ($E_\mu>1\text{ TeV}$)
- Shower Eff Volume: $\sim1\text{ Mton}$ at 1 PeV

**NT200+ commissioned April 9, 2005**
- 3 new strings, 200 m height, 36 OMs
- 1 new bright Laser for time calibration
  imitation of 10 PeV-500 PeV cascades,
  $>10^{13}$ photons/pulse w/ diffusor, $\leftrightarrow$ SNO-Calib
- 2 new 4km cables to shore
- DAQ – New Underwater & Shore Station:
  Underwater Linux embedded PCs, Industrial Ethernet Systems

**NT200+ is tailored to UHE $\nu$-induced cascades**
- 5 Mton equipped volume
- $V_{\text{eff}} >10\text{ Mton}$ at 10 PeV
  $\rightarrow$ 4fold sensitivity gain with only 20% additional PMTS
For a $\gamma=2$ spectrum $\Phi_\nu \sim E^{-2}$ the measured Baikal limit is

$$E^2 \Phi_\nu < 8.1 \cdot 10^{-7} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

(20 TeV < $E$ < 50 PeV):

Most sensitive published cascade limit, APP 25 (2006) 140
Sparse instrumentation:

91 strings with $12/16 \text{ OM} = 1308 \text{ OMs}$

→ Cascade effective volume for 100 TeV: $\sim 0.5\text{ -}1.0 \text{ km}^3$

→ Muon threshold between 10 and 100 TeV

Baseline schedule:

- R&D +TDR 2006-08. Funded.
- Construction ≥2009.

A Gigaton (km3) Detector in Lake Baikal

Mini NT200+ (design not optimized)
- Rigid Towers in titanium
- Dry Connections
  (recover - connect - redeploy)
- Upwards and down-looking PMs
- Depth 3800m

**Tower**
- 32 m diameter
- 12 storeys
- 30 m between storeys
- 144 PMs
Electro-optical cable deployed June 2000, but damaged
- Cable recovered, repaired & redeployed (Jan 2002)
- 1 Floor deployed in 2003. downward cosmic ray muons reconstructed
  After few weeks-fault developed in the submarine cable, awaiting repair

Zenith angle distribution
G. Aggouras et al.
Astropart. Phys. 23 (2005) 377
- **Extensive site exploration**
  (Capo Passero near Catania, depth 3500 m)

- **R&D towards km³**: architecture, mechanical structures, readout, electronics, cables ...

- **Simulation studies for optimum geometry**

  **Example: Flexible tower**
  - 16 arms per tower,
    20 m arm length,
    arms 40 m apart;
  - 64 PMs per tower;
  - Underwater connections;
  - sideways and downward-looking PMs.
NEMO Phase-1: Test Site Catania

Underwater test site: 25km E of Catania, 2000m

Frame:
Deployed
January 2005

NEMO mini-tower
(4 floors, 16 OM)

Junction Box

Mini-Tower
unfurled

To be completed in 2006
OBJECTIVES
- Realization of an underwater infrastructure at 3500m on the CP site
- Test of the detector structure installation procedures at 3500 m
- Installation of a 16 storey tower
- Long term monitoring of the site

STATUS
- 100km electro-optical cable (40 kW) purchased, to be deployed
- A building (1000 m²) located inside the harbour area of Portopalo has been acquired. It will be renovated to host the shore station
- Project completion planned in 2007
21 Institutes from 6 European countries

**ANTARES**

Map showing locations of 21 Institutes, 40 km submarine cable, and Antares shore station at -2475m depth.
ANTARES Detector

- 12 flexible lines
- 900 PMs (3 per storey)
- ROV connection
- Acoustic positioning

Depth: 2475 m

40 km to shore

Junction box

450 m

Readout cables

P. Vernin from F. Montanet
ANTARES Construction Milestones

2001 – 2003:
- Main Electro-optical cable in 2001
- Junction Box in 2002
- Prototype Sector Line (PSL) & Mini Instrumentation Line (MIL) in 2003

2005 – Now:
- *Mini Instrumentation Line with OMs (MILOM)* operating since 12 April 2005
- *Line 1* operating since 2 March 2006, first complete detector line

2006 – 2007:
- Installation of remaining 11 lines

2007+: Physics with full detector
Line 1 ROV Connection

connected by Ifremer submersible on March 2nd
Singles Counting Rates

Burst-fraction:
fraction of time when rate > baseline + 20%

Baseline rates

seasonal variations
Coincidence rates from $^{40}$K decays

$\Delta T$ between hits in 2 OMs of the same storey

$^{40}$K coincidence rate from Gaussian fit:

- OM1-OM2: $13.0 \pm 0.5$ Hz
- OM1-OM3: $13.0 \pm 0.5$ Hz

Simulation: 12 Hz $\pm$ 4 Hz (sys)

Allows monitoring of:
- efficiencies
- time calibration within storeys
Line 1 time calibration with LED beacon

sigma = 0.7 ns

sigma = 2.6 ns

"diagonal"
 larger distance
 - less intensity
 - light scattering

"horizontal"

all timing measurements in good agreement with expectations

~150 m

~70 m

MILOM
Acoustic triangulation of Line 1 hydrophone

Acoustic distance measurement of hydrophones from fixed emitters on MILOM anchor + autonomous transponders

Trajectory of lowest hydrophone during 2 weeks

Horizontal displacement of lowest hydrophone

50cm

2 weeks

Line anchor axis
Reconstruction of atmospheric muon tracks

A nice, vertical track with hits in each storey of the line

Run 22753
Event 3880
Zenith $\theta = 180^\circ$

Hit altitude (relative to mid detector) [m]

Hit time [ns]

Antares preliminary

- Triggered hits
- Hits used in fit
- Snapshot hits
Atmospheric muon zenithal angular distribution

- Muon reconstruction is working well
- Hunting for neutrinos…

Number of events vs. zenith angle \( \theta \) [degrees]

- Time & amplitude information
- Time information

- Small
- Large
- Small
- Time

☑️ Muon reconstruction is working well
☑️ Hunting for neutrinos…
View of the Sky: Antares/Amanda

instantaneous common view: 0.5 \( \pi \) sr
average common view: 1.5 \( \pi \) sr

ANTARES (43° north)

- 3C 279
- Mkn 501
- RX J1713.7-39
- CRAB
- SS433
- GX339-4
- VELA

galactic centre: 2/3rd of the time

not observed

AMANDA (south pole)

- Mkn 421
- Mkn 501
- SS433

not observed

galactic centre: not seen

CR interaction in clouds

HESS SCAN OF GALACTIC PLANE
Effective Neutrino Area: AMANDA/ANTARES
Angular Resolution

At 100 TeV: Amanda ~2°
Antares ~ 0.2°
The next step in the Mediterranean Sea is an EU funded ‘Design Study’:

- Participation: all current projects + “newcomers” + marine institutes
- EU Contribution: 9 M€
- Starting date: feb 1, 2006
- Duration: 3 years (TDR: feb 2009)
- Target Cost: ~200 M€?
- Size: minimum 1km³ and extendable

KM3NET is included in the *Astroparticle Physics European Coordination (ApPEC)* ROADMAP

KM3NET is selected by the *European Strategy Forum for Research Infrastructures (ESFRI)* ‘List of Opportunities’
<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
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<tbody>
<tr>
<td>Cyprus</td>
<td>Univ. Cyprus</td>
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<tr>
<td>France</td>
<td>CEA/Saclay, CNRS/IN2P3 (CPP Marseille, IreS Strasbourg, APC Paris-7), Univ. Mulhouse/GRPHE, IFREMER</td>
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<tr>
<td>Germany</td>
<td>Univ. Erlangen, Univ. Kiel</td>
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<td>Greece</td>
<td>HCMR, Hellenic Open Univ., NCSR Demokritos, NOA/Nestor, Univ. Athens</td>
</tr>
<tr>
<td>Italy</td>
<td>CNR/ISMAR, INFN (Univs. Bari, Bologna, Catania, Genova, Napoli, Pisa, Roma-1, LNS Catania, LNF Frascati), INGV, Tecnomare SpA</td>
</tr>
<tr>
<td>Netherlands</td>
<td>NIKHEF/FOM (incl. Univ. Amsterdam, Univ. Utrecht, KVI Groningen)</td>
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<tr>
<td>Spain</td>
<td>IFIC/CSIC Valencia, Univ. Valencia, UP Valencia</td>
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<tr>
<td>UK</td>
<td>Univ. Aberdeen, Univ. Leeds, Univ. Liverpool, Univ. Sheffield</td>
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<tr>
<td>Ireland</td>
<td>Dublin (Aharonian)</td>
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**Particle/Astroparticle (30) – Marine (7) – Coordinator**
**KM3NeT: Technical Challenges**

- **Transmission, triggering of data**
  - High bandwidth data transmission

- **Electronics**
  - Low power microelectronics for underwater applications

- **Network of undersea cables**
  - High power load electro-optical cables for deep sea applications

- **Connections**
  - Underwater electro-optical connections

- **Deployment**
  - Deployment and connection of the structures with underwater vehicles

- **Deployment and connection of the structures with underwater vehicles**

- **Network of undersea cables**

- **Connections**

- **Deployment**

- **Mechanical structure**

- **Corrosion, Pressure**

- **Need at least factor 2 cost reduction C.F. ANTARES**
Many postdoc posts available – please apply!
Detector Architecture?

- Cube
- Ring 1
- Ring 2
- Multi-antares
  - Multi Small PM module understudy
KM3NET/ICECUBE

KM3NET (one example)

\[ A_{\text{eff}} / \text{km}^2 \]

\[ \cos \theta \]

\[ 1 - 10 \text{ TeV} \]
\[ 10 - 100 \text{ TeV} \]
\[ 100 \text{ TeV} - 1 \text{ PeV} \]

20 kHz bkgd

ICECUBE

\[ A_{\text{eff}} / \text{km}^2 \]

\[ \cos \theta \]

\[ 1 - 100 \text{ PeV} \]

5832 PMT
81 strings (18 floors)
String height 680m
KM3NET Diffuse Flux Limits

- Atmospheric $\nu$
- Galactic CR
- EGRET
- Baikal
- Amanda 05
- Antares
- Auger
- Anita
- Lofar
- Protons
- $p+CMB\rightarrow\gamma$
- Galactic $\nu$
- $p+CMB\rightarrow\nu$

Armengaud, Sigl APPEC ROADMAP
Flux Sensitivity of the KM3NeT \( \nu \) Telescope

- **requirement:** 10 hits/event
- **80\% duty cycle**
- **\( \nu_\mu \) flux**

KM3NeT sensitivity estimated for

Very preliminary!
The on-going projects (Antares, Baikal, Nemo, Nestor) have demonstrated the technical feasibility of operating underwater neutrino telescopes and in particular the Baikal upgrade (NT200+) and Antares are coming online.

Larger, km³-scale, northern-hemisphere neutrino telescopes are necessary to fully exploit the physics potential of high-energy neutrino detection.

A 3 year, EU funded, design study (KM3NET) for the technical design of a next generation detector in the Mediterranean Sea has recently started.

KM3NET will be a pan-European, interdisciplinary, infrastructure, open to the astrophysics and oceanographic communities.

KM3NET will be complementary to the southern hemisphere ICECUBE detector: **galactic centre, angular resolution**.