Neutrino Telescopy in the Mediterranean Sea – Towards the km³-Scale Detector KM3NeT

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- Introduction
- Current Deep-Sea Projects
- Aiming at a km³ Detector in the Mediterranean Sea
- The KM3NeT Design Study
- Conclusions and Outlook
Why Neutrino Telescopes?

- Neutrinos traverse space without deflection or attenuation
  - they point back to their sources;
  - they allow for a view into dense environments;
  - they allow us to investigate the universe over cosmological distances.

- Neutrinos are produced in high-energy hadronic processes → distinction between electron and proton acceleration.

- Neutrinos could be produced in Dark Matter annihilation.

- Neutrino detection requires huge target masses → use naturally abundant materials (water, ice).
The Principle of Neutrino Telescopes

**Role of the Earth:**
- Screening against all particles except neutrinos.
- Atmosphere = target for production of secondary neutrinos.

**Čerenkov light:**
- In water: $\theta_C \approx 43^\circ$
- Spectral range used: ~ 350-500nm.

**Neutrino reactions (key reaction is $\nu_\mu N \rightarrow \mu X$):**
- Cross sections and reaction mechanisms known from accelerator experiments (in particular HERA).
- Extrapolation to highest energies (> 100 TeV) uncertain.
Neutrino Interaction Signatures

- Neutrinos mainly from $\pi$-µ-e decays, roughly $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$;
- Arrival at Earth after oscillations: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$;
- Key signature: muon tracks from $\nu_\mu$ charged current reactions (few 100m to several km long);
- Electromagnetic/hadronic showers: “point sources” of Čerenkov light.
Muons: The Background from Above

Muons can penetrate several km of water if $E_\mu > 1\,\text{TeV}$;

Identification of cosmic $\nu$‘s from above: needs showers or very high energies.
Particle and Astrophysics with $\nu$ Telescopes

Neutrino Oscillations:
Direction, Energy, Flavor

**Low-energy limit:**
- short muon range;
- only few photo sensors give signal;
- in sea water: $^{40}\text{K}$ background prohibitive.

Intrinsic limit, can only be overcome with specialized, very densely instrumented detector.

**High-energy limit:**
- fluxes decrease as $E^{-2} \ldots E^{-3}$;
- large detection volume needed.

Ultimate volume (at least) one cubic kilometer.

**Dark matter search (WIMPs):**
Direction, Energy

**Cosmic point sources:**
Direction, (Energy)

**Diffuse cosmic neutrino flux:**
(Direction), Energy

$\text{GeV}$ $\text{TeV}$ $\text{PeV}$ $\text{EeV}$ $E_\nu$

... and also:
- GZK-neutrinos
- Z bursts
- magnetic monopoles
- topological defects
- top–down scenarios
- supernova detection
...
Diffuse $\nu$ Flux: Limits and Sensitivities

\[
\log_{10}[E\Phi(E)/(\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1})]
\]

- $\nu_\mu + \bar{\nu}_\mu$
- Amanda, Baikal
- RICE
- AGASA
- RICE
- GLUE
- Anita
- AUGER $\nu_\tau$
- Amanda, Antares, Baikal, Nestor
- Auger + new technologies
- 2002
- 2004
- 2007
- 2012
- km$^3$
Neutrinos from Astrophysical Point Sources

- Association of neutrinos to specific astrophysical objects.
- Energy spectrum, time structure, multi-messenger observations provide insight into physical processes inside source.
- Searches profit from very good angular resolution of water Čerenkov telescopes.
- km$^3$ detectors needed to exploit full potential of neutrino astronomy.

![Diagram showing neutrino flux limits and sources with icecube and km3net data points.]
Indirect Search for Dark Matter

- WIMPs can be gravitationally trapped in Earth, Sun or Galactic Center;
- Neutrino production by \( \chi \chi \rightarrow \nu + X \)
- Detection requires low energy threshold (O(100GeV) or less).
- Flux from Galactic Center may be enhanced if a Black Hole is present → exciting prospects [see e.g. P. Gondolo and J. Silk, PRL 83(1999)1719].
- But: model uncertainties are orders of magnitude!

Specific km³ analysis not yet available.
The Neutrino Telescope World Map
Lake Baikal: A Sweet-Water $\nu$ Telescope

- Pioneers in under-water technology for $\nu$ telescopes.
- Many excellent physics results.
- Further upgrades planned, but km$^3$ hardly reachable.

The BAIKAL NT-200 Neutrino Telescope

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String-based detector;
Underwater connections by deep-sea submersible;
Downward-looking PMs, axis at 45° to vertical;
2500 m deep.
ANTARES: Status and Way to Completion

- **2003**: Deployment and operation of two prototype lines.
- Several months of data taking.
- Technical problems (broken fiber, water leak) → no precise timing, no $\mu$ reconstruction.
- **Early 2005**: 2 upgraded prototype lines;
- **Mid-2005**: Line 1;
- **2007**: Detector completed.
ANTARES: First Deep-Sea Data

- Rate measurements: Strong fluctuation of bioluminescence background observed

![Graph showing PM Rate (kHz) vs time (s) with fluctuations and a constant baseline rate from 40K decays.]
NESTOR: Rigid Structures Forming Towers

- Tower based detector (titanium structures).
- Dry connections (recover–connect–redploy).
- Up- and downward looking PMs.
- 3800 m deep.
- First floor (reduced size) deployed & operated in 2003.

Plan: Tower(s) with 12 floors
→ 32 m diameter
→ 30 m between floors
→ 144 PMs per tower
NESTOR: Measurement of the Muon Flux

Atmospheric muon flux determination by reweighting MC simulation to observed raw zenith distribution using

\[
\frac{dN}{d\Omega \cdot dt \cdot ds} = l_0 \cdot \cos^\alpha \theta
\]

Results agree nicely with previous measurements and with simulations.
The NEMO Project

- Extensive site exploration (Capo Passero near Catania, depth 3340 m);
- R&D towards km$^3$: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.

**Example: Flexible tower**

- 16 arms per tower,
  20 m arm length,
  arms 40 m apart;
- 64 PMs per tower;
- Underwater connections;
- Up- and downward-looking PMs.
NEMO: Junction Box R&D

**Aim:** Decouple the problems of pressure and corrosion resistance.
NEMO: Phase-1 Test

- Test site at 2000 m depth identified.
- Test installation foreseen with all critical detector components.
- Funding ok.
- Completion expected by 2006.
Current Projects: Summary

- **ANTARES + NESTOR**: first installation steps successfully completed, prototype detector modules deployed and operated;
- **ANTARES** construction in preparation, detector expected to be complete by 2007;
- Discovery potential for cosmic neutrinos and Dark Matter;
- Feasibility proof for neutrino telescropy in sea water;
- **NEMO**: Ongoing R&D work for next-generation km$^3$-scale detector.
Aiming at a km³-Detector in the Mediterranean

HENAP Report to PaNAGIC, July 2002:

- “The observation of cosmic neutrinos above 100 GeV is of great scientific importance. ...“
- “... a km³-scale detector in the Northern hemisphere should be built to complement the IceCube detector being constructed at the South Pole.”
- “The detector should be of km³-scale, the construction of which is considered technically feasible.”
Sky Coverage of Neutrino Telescopes

Region of sky seen in galactic coordinates assuming efficiency for downward hemisphere.

→ We need $\nu$ telescopes in both hemispheres to see the whole sky

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How to Design a km³ Deep-Sea $\nu$ Telescope

Existing telescopes “times 100”?  
- Too expensive  
- Too complicated:  
  production, deployment takes forever, maintenance impossible  
- Not scalable  
  (readout bandwidth, power, ...)

R&D needed:  
- Cost-effective solutions  
  to reduce price/volume by factor 2-5  
- Stability  
  goal: maintenance-free detector  
- Fast installation  
  time for construction & deployment  
  less than detector life time  
- Improved components

Large volume with same number of PMs?  
- PM distance:  
  given by absorption length in water (~60 m) and PM properties  
- Efficiency loss for larger spacing
The KM3NeT Design Study (EU FP6)

Design Study for a Deep-Sea Facility in the Mediterranean for Neutrino Astronomy and Associated Sciences

- Intense discussions and coordination meetings from beginning of 2003 on.
- Inclusion of sea science/technology institutes (Jan 2004).
- Proposal submission 04.03.2004.
- Evaluation report received June 2004 (overall mark: 88%).
- Unofficial but reliable message (Sept. 2004): The KM3NeT Design Study will be funded!
- Currently waiting for EU budget allocation.
KM3NeT Design Study Participants

- **Cyprus**: Univ. Cyprus
- **France**: CEA/Saclay, CNRS/IN2P3 (CPP Marseille, IReS Strasbourg), IFREMER
- **Germany**: Univ. Erlangen, Univ. Kiel
- **Greece**: HCMR, Hellenic Open Univ., NCSR Democritos, NOA/Nestor, Univ. Athens
- **Italy**: CNR/ISMAR, INFN (Univs. Bari, Bologna, Catania, Genova, Messina, Pisa, Roma-1, LNS Catania, LNF Frascati), INGV, Tecnomare SpA
- **Netherlands**: NIKHEF/FOM + Groningen?
- **Spain**: IFIC/CSIC Valencia, Univ. Valencia, UP Valencia
- **UK**: Univ. Aberdeen, Univ. Leeds, Univ. Liverpool, John Moores Univ. Liverpool, Univ. Sheffield

**Particle/Astroparticle institutes** – **Sea science/technology institutes** – **Coordinator**

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Objectives and Scope of the Design Study

Establish path from current projects to KM3NeT:

- Critical review of current technical solutions;
- New developments, thorough tests;
- Comparative study of sites and recommendation on site choice (figure of merit: physics sensitivity / €);
- Assessment of quality control and assurance;
- Exploration of possible cooperation with industry;
- Investigation of funding and governance models.

Envisaged time scale of design, construction and operation poses stringent conditions.
Design Study Target Values

- Detection principle: water Čerenkov.
- Location in Europe: in the Mediterranean Sea.
- Detection view:
  maximal angular acceptance for all possible detectable neutrino signals including down-going neutrinos at VHE.
- Detection volume: 1 km$^3$, expandable.
- Angular resolution: close to the intrinsic resolution ($< 0.1^\circ$ for muons with $E_\mu > 10$ TeV).
- Lower energy threshold:
  a few 100 GeV for upward going neutrinos with the possibility to go lower for $\nu$ from known point sources.
- Energy reconstruction: within a factor of 2 for muon events.
- Reaction types: all neutrino flavors.
- Duty cycle: close to 100%.
- Operational lifetime: $\geq$ 10 years.
- Cost-effectiveness: < 200 M€ per km$^3$.

Most of these parameters need optimisation!
Some Key Questions

- Which architecture to use? (strings vs. towers vs. new design)
- How to get the data to shore? (optical vs. electric, electronics off-shore or on-shore)
- How to calibrate the detector? (separate calibration and detection units?)
- Design of photo-detection units? (large vs. several small PMs, directionality, ...)
- Deployment technology? (dry vs. wet by ROV/AUV vs. wet from surface)
- And finally: The site choice/recommendation!

All these questions are highly interconnected!
Detector Architecture

(D. Zaborov at VLV̂)
Sea Operations

- Rigid towers or flexible strings?
- Connection in air (no ROVs) or wet mateable connectors?
- Deployment from platform or boat?
Photo Detection: Requirements

Example of a device discussed:
Hamamatsu HY0010 HPD
Excellent p.e. resolution

- Glass pressure vessel ≤ 17 inch
- Requirements for ν telescopes:
  - High quantum efficiency
  - Large photocathode areas
  - Wide angular coverage
  - Good single-photon resolution
  - High dynamic range

Output Pulse Height [ADC ch]
Photo Detection: Options

- Large photocathode area with arrays of small PMs packed into pressure housings - low cost!
- Determination of photon direction, e.g. via multi-anodic PMs plus a matrix of Winston cones.
- But: phase space for developments from scratch is too tight.
Readout and Data Transfer

- **Data rate** from a km³ detector will be ~2.5-10 Gb/s

- **Questions to be addressed:**
  - Optimal data transfer to shore (many fibers + few colors, few fibers + many colors, etc.);
  - How much processing to be done at the optical module?
  - Analogue vs. digital OMs: differing approaches for front-end electronics
  - Data filtering
  - Distribution of (raw) data to data analysis centers

- One possible data distribution concept;
- Application of current PP-GRID technologies to some of these open questions?

![Diagram showing data transfer from source to destination with labeled nodes and arrows]
Exploitation Model

**Reminder:** KM3NeT is an *infrastructure*;  
**Goal:** facility exploited in multi-user and interdisciplinary environment.

- Reconstructed data will be made available to the whole community.
- Observation of specific objects with increased sensitivity will be offered (by dedicated adjustment of filter algorithms).
- Close relation to space-based observatories will be established (alerts for GRBs, Supernovae etc.).
- “Plug-and-play” solutions for detectors of associated sciences.
Associated Sciences

- Great interest in long term deep-sea measurements in many different scientific communities:
  - Biology
  - Oceanography
  - Environmental sciences
  - Geology and geophysics
  - ... 

- Substantial cross-links to ESONET (The European Sea Floor Observatory Network).

- **Plan**: include the associated science communities in the design phase to understand and react to their needs and make use of their expertise (e.g. site exploration, bioluminescence).
KM3NeT Design Study: Resources

- Suggested overall budget of the Design Study: 24 M€
  (mainly personnel, but also equipment, consumables, travel etc.).

- Amount requested from EU: 10 M€;

- Estimated overall labor power: $\sim 3500$ FTEMs
  (FTEM = full-time equivalent person month)
  $\rightarrow$ 100 persons working full-time over 3 years!

Substantial resources (labor power) additional to those available in the current pilot projects will be required!
KM3NeT: Time Schedule

Experience from current first generation water neutrino telescopes is a solid basis for the design of the KM3NeT detector.

Interest fades away if KM3NeT comes much later than IceCube (ready by 2010).

Time schedule (optimistic):

- 01.01.2006: Start of Design Study
- Mid-2007: Conceptual Design Report
- End of 2008: Technical Design Report
- 2009-2013: Construction
- 2010-20XX: Operation
Conclusions and Outlook

- Compelling scientific arguments for complementing IceCube with a km$^3$-scale detector in the Northern Hemisphere.

- The Mediterranean-Sea neutrino telescope groups NESTOR, ANTARES and NEMO comprise the leading expertise in this field. They have united their efforts to prepare together the future, km$^3$-scale deep-sea detector.

- An EU-funded Design Study (KM3NeT) will provide substantial resources for an intense 3-year R&D phase; expected to start by beginning of 2006.
