KM3NeT – towards a km$^3$-Scale Neutrino Telescope in the Mediterranean Sea

Uli Katz
ECAP / Univ. Erlangen
• Scientific rationale
• Neutrino telescopes
• KM3NeT: Towards design and construction
• Summary
The Mysterious Cosmic Rays

- Particles impinging on Earth from outer space carry energies up to $10^{21}$ eV (the kinetic energy of a tennis ball at ~200km/h.)
- The acceleration mechanisms are unknown.
- Cosmic rays carry a significant fraction of the energy of the universe – cosmologically relevant!
- Neutrinos play a key role in studying the origin of cosmic rays.
Neutrino Production Mechanism

- Neutrinos are produced in the interaction of high energy nucleons with matter or radiation:
  \[ N + X \rightarrow \pi^\pm (K^\pm \ldots) + Y \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) + Y \]
  \[ e^\pm + \bar{\nu}_e (\nu_e) + \bar{\nu}_\mu (\nu_\mu) \]

- Simultaneously, gamma production takes place:
  \[ N + X \rightarrow \pi^0 + Y \rightarrow \gamma \gamma + Y \]

- Cosmic ray acceleration yields neutrinos and gammas!
- ... but gammas also from purely leptonic processes

Cosmic rays
Particle Propagation in the Universe

- Photons: absorbed on dust and radiation;
- Protons/nuclei: deviated by magnetic fields, reactions with radiation (CMB)

1 parsec (pc) = 3.26 light years (ly)

Protons $E > 10^{19}$ eV (few 10 Mpc)

Protons $E < 10^{19}$ eV

Gammas (0.01 - 10 Mpc)

Cosmic accelerator

Neutrinos
Potential Galactic Sources

• The candidate accelerators of cosmic rays
  • Supernova remnants
  • Pulsar wind nebulae
  • Micro-quasars
  • ...

• Interaction of cosmic rays with interstellar matter
  • Possibly strong $\nu$ signal if CR spectrum harder in Galactic Centre than on Earth (supported by recent MILAGRO results)

• Unknown sources – what are the H.E.S.S. ”TeV gamma only” objects?
High-Energy \( \gamma \) Sources in the Galactic Disk

The H.E.S.S. galactic plane scan

Status 2007:

- 18 Pulsar wind nubulae
- 7 Shell-type supernova remnants
- 4 Binaries
- 2 Diffuse
- 21 Unknown (no identified counterpart)
Example: $\nu$’s from Supernova Remnants

- **SNR RX J1713.7-3946** (shell-type supernova remnant)
- **H.E.S.S.: $E_\gamma = 200$ GeV – 40 TeV**

- Acceleration beyond 100 TeV.
- Power-law energy spectrum, index $\sim 2.1–2.2$.
- Spectrum points to hadron acceleration $\rightarrow \nu$ flux $\sim \gamma$ flux
- Typical $\nu$ energies: few TeV

W. Hofmann, ICRC 2005
ν Flux Predictions from γ Measurements

Note: hadronic nature of Vela X is not clear!


expected neutrino flux – in reach for KM3NeT

1 σ error bands include systematic errors (20% norm., 10% index & cut-off)

A. Kappes et al., astro-ph 0607286

measured γ-ray flux (H.E.S.S.)
Another Case: SNR RXJ1713.7-3946

- Good candidate for hadronic acceleration.
- Expected signal well related to measured $\gamma$ flux, but depends on energy cut-off.
- Few events/year over similar background (1km$^3$).
- KM3NeT sensitivity in the right ballpark!
Potential Extragalactic Sources

• AGNs
  • Models are rather diverse and uncertain
  • The recent Auger results may provide an upper limit / a normalisation point at ultra-high energies
  • Note: Above some 100 TeV the neutrino telescope field of view is restricted downwards ($\nu$ absorption), but starts to be significant upwards.

• Gamma ray bursts
  • Unique signature: Coincidence with gamma observation in time and direction
  • Source stacking possible
Candidate Accelerators: Active Galactic Nuclei (AGNs)

AGNs are amongst the most energetic phenomena in the universe.
• Directional correlation between AGN positions and cosmic rays ($E > 10^{19.7}$ eV, 27 events).
• Interpretation requires care and patience.
Science Cases for Neutrino Telescopes

- Astroparticle physics with neutrinos
  - “Point sources”: Galactic and extragalactic sources of high-energy neutrinos
  - The diffuse neutrino flux
  - Neutrinos from Dark Matter annihilation
- Search for exotics
  - Magnetic monopoles
  - Nuclearites, strangelets, …
- Neutrino cross sections at high(est) energies
- Earth and marine sciences
  - Long-term, continuous measurements in deep-sea
  - Marine biology, oceanography, geology/geophysics, …
The Principle of Neutrino Telescopes

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

Cherenkov light:
• In water: $\theta_C \approx 43^\circ$
• Spectral range used: $\sim 350$-500nm.

Angular resolution in water:
• Better than $\sim 0.3^\circ$ for neutrino energy above $\sim 10$ TeV, $0.1^\circ$ at 100 TeV
• Dominated by angle($\nu, \mu$) below $\sim 10$ TeV ($\sim 0.6^\circ$ at 1 TeV)
Neutrino Interaction Signatures

- Neutrinos mainly from $\pi$-$\mu$-$e$ 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 Cherenkov light.
Muon Reconstruction

- The Cherenkov light is registered by the photomultipliers with nanosecond precision.
- From time and position of the hits the direction of the muon can be reconstructed to some 0.1°.
- Minimum requirement: 5 hits … in reality rather 10 hits.
- Position calibration to ~10cm required (acoustic methods).

1.2 TeV muon traversing the detector.
ANTARES, NEMO, NESTOR joined efforts to prepare a km$^3$-size neutrino telescope in the Mediterranean Sea → KM3NeT.
2\pi downward sensitivity assumed

In Mediterranean, visibility of given source can be limited to less than 24h per day
IceCube

- 4800 Digital Optical modules on 80 strings
- 160 Ice-Cherenkov tank surface array (IceTop)
- Instrumenting 1 km$^3$ of Antarctic Ice
- Surrounding existing AMANDA detector
IceCube 22: Point Source Search

- Hottest spot found at right ascension 153°, declination 11°; pre-trial probability: $7 \times 10^{-7}$ (4.8 sigma).
- Accounting for trial factor, p-value is 1.34% (2.2 sigma).
- At this significance level, consistent with fluctuation of background.
ANTARES: Detector Design

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking photomultipliers (PMs), axis at 45° to vertical;
- 2500 m deep;
- First deep-sea neutrino telescope in operation!
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 – April 2007:
- Mini Instrumentation Line with OMs (MILOM) operated ~4 months in 2005
- Lines 1-5 running (connected between March 2006 and Jan. 2007)
- Lines 6+7 deployed March/April 2007

2007 – now:
- Deployment / connection of remaining lines completed in May 2008
- Replacement of MILOM by full instrumentation line (IL)
- Physics with full detector!
• 174 days of data with 9-12 lines
• Reconstruction tuned for up-going tracks
• Rate of neutrino candidates: ~ 3.5 events/day
The NEMO Project

- Extensive site exploration (Capo Passero near Catania, depth 3500 m);
- R&D towards km$^3$: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.

Example: Flexible tower
- ~10 m bar length, bars 30-40 m apart;
- 3 pairs of PMs per bar;
- Unfurls after deployment as compact structure.
NESTOR

- Tower based detector (titanium structures).
- Dry connections (recover – connect – redeploy).
- Up- and downward looking PMs (15’’).
- 4000-5200 m deep.
- Test floor (reduced size) deployed & operated in 2003.
- Deployment of 4 floors planned in 2009
NESTOR: the Delta-Berenike Platform
KM3NeT: from the Idea to a Concept

11/2002
First consultations of ANTARES, NEMO and NESTOR

3/2004
Design Study proposal submitted

9/2005
KM3NeT on ESFRI List of Opportunities

2/2006
KM3NeT on ESFRI Roadmap

9/2006
Begin of Design Study

4/2008
The KM3NeT Conceptual Design Report
Major Achievements to Date

- **Science & technology**
  - Successful prototype deployments by NEMO and NESTOR
  - Installation and operation of ANTARES
    - A large deep-sea neutrino telescope is feasible!

- **Politics & funding**
  - Endorsement by ESFRI, ApPEC/ASPERA and ASTRONET
  - Funding through EU: Design Study, Preparatory Phase
  - Funding through national authorities: pilot projects, commitments for KM3NeT

- **Towards construction**
  - Strong collaboration
  - Design concepts in CDR
The ESFRI Process

- ESFRI = European Strategy Forum for Research Infrastructures
- EU-initiated forum of research ministries and funding agencies.
- Objective: Identify and support the priority research infrastructures in all fields of science.
- KM3NeT included in both editions.
The KM3NeT Conceptual Design Report

- Presented to public at VLVnT0 workshop in Toulon, April 2008
- Summarises (a.o.)
  - Physics case
  - Generic requirements
  - Pilot projects
  - Site studies
  - Technical implementation
  - Development plan
  - Project implementation

Available on www.km3net.org
Configuration Studies

- Various geometries and OM configurations have been studied.
- None is optimal for all energies and directions.
- Local coincidence requirement poses important constraints on OM pattern.
The Reference Detector

- Sensitivity studies with a common detector layout
- Geometry:
  - 15 x 15 vertical detection units on rectangular grid, horizontal distances 95 m
  - each carries 37 OMs, vertical distances 15.5 m
  - each OM with 21 3” PMTs

This is NOT the final KM3NeT design!
Point Source Sensitivity

- Based on muon detection
- Why factor ~3 more sensitive than IceCube?
  - larger photocathode area
  - better direction resolution
- Study still needs refinements
Diffuse Fluxes

- Assuming $E^{-2}$ neutrino energy spectrum
- Only muons studied
- Energy reconstruction not yet included
Dark Matter Sensitivity

- Scan mSUGRA parameter space and calculate neutrino flux for each point
- Focus on points compatible with WMAP data
- Detectability:
  - Blue: ANTARES
  - Green: KM3NeT
  - Red: None of them
KM3NeT Design Goals

- Sensitivity to exceed IceCube by “substantial factor”
- Core process: $\nu_\mu + N \rightarrow \mu + X$ at neutrino energies beyond 100 GeV
- Lifetime > 10 years without major maintenance, construction and deployment < 4 years
- Some technical specifications:
  - time resolution 2 ns
  - position of OMs to better than 40 cm accuracy
  - two-hit separation < 25 ns
  - false coincidences dominated by marine background
  - coincidence acceptance > 50%
  - PM dark rate < 20% of $^{40}$K rate
Technical implementation

- Photo-sensors and optical modules
- Data acquisition, information technology and electronics
- Mechanical structures
- Deep-sea infrastructure
- Deployment
- Calibration
- Associated science infrastructure
Optical Modules: Standard or Directional

- A segmented anode and a mirror system allow for directional resolution.
- First prototypes produced.
- A standard optical module, as used in ANTARES.
- Typically a 10'' PMT in a 17'' glass sphere.
... or Many Small Photomultipliers ...

- Basic idea: Use ca. 30 small (3” or 3.5”) PMTs in standard sphere
- Advantages:
  - increased photocathode area
  - improved 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - directionality
- Prototype arrangements under study
… or Hybrid Solutions

- Idea: Use high voltage (~20kV) and send photo electrons on scintillator; detect scintillator light with small standard PMT.
- Advantages:
  - Very good photo-electron counting, high quantum eff.
  - Large angular sensitivity possible
- Prototype development in CERN/Photonis/CPPM collaboration
Photocathode News

Hamamatsu

- New photocathode developments by two companies (Hamamatsu, Photonis)
- Factor 2 in quantum efficiency → factor 2 in effective photocathode area!
- Major gain in neutrino telescope sensitivity expected

Photonis
Data Acquisition and Information Technology

Optical Module:
- Conversion of PM signal for transmission
- “Standard” electronic components or passive electro-optical solutions
- Local thresholds/requirements

Vertical signal transmission:
- Fibres or copper?
- Critical: time calibration and synchronisation, reliability

Transmission to shore:
- All data to shore (GB/s)
- No alternative to fibres

On shore:
- Computer farm for online data filter
- High-bandwidth connection to mass storage and data analysis facilities
Deep-Sea Infrastructure

Major components:
- main cable & power transmission
- network of secondary cables with junction boxes
- connectors

Design considerations:
- cable selection likely to be driven by commercial availability
- junction boxes: may be custom-designed, work ongoing in NEMO
- connectors: expensive, reduce number and/or complexity
- risk considerations (single-point failures etc.)

NEMO junction box design:
Deployment: on the Surface …

- Deployment operations require ships or dedicated platforms.
- Ships: Buy, charter or use ships of opportunity.
- Platform: Delta-Berenike.
… and in the Deep Sea

- Deep-sea submersibles are likely needed for
  - laying out the deep-sea cable network
  - making connections to detection units
  - possibly maintenance and surveillance

- Remotely operated vehicles (ROVs) available for a wide range of activities at various depths

- Use of autonomous undersea vehicles (AUVs) under study

### Commercially available ROVs:

<table>
<thead>
<tr>
<th>Number of Models</th>
<th>Maximum Depth (m)</th>
<th>Maximum Load (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td>Mini</td>
<td>1500</td>
<td>20</td>
</tr>
<tr>
<td>General</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6000</td>
<td>500</td>
</tr>
<tr>
<td>1</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Work Class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5000</td>
<td>4500</td>
</tr>
<tr>
<td>1</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3500</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>Trenching ROV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3500</td>
<td>38000</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2500</td>
<td></td>
</tr>
</tbody>
</table>
Installations for Earth and Sea Sciences

- Earth and sea science devices will be installed at various distances around the neutrino telescope
- Issues:
  - interfaces
  - operation without mutual interference
  - stability of operation and data sharing
- Synergy effects
The Candidate Sites

• Locations of the three pilot projects:
  • ANTARES: Toulon
  • NEMO: Capo Passero
  • NESTOR: Pylos

• Long-term site characterisation measurements performed and ongoing

• Site decision requires scientific, technological and political input
Site Characterisation: an Example

Important parameter: water transparency (absorption and scattering)

Pylos (460 nm)

Capo Passero

Also: optical background, sea currents, sedimentation, biofouling, radioactivity, …
A Green Power Concept for KM3NeT

- Idea: Use wind and/or solar power at KM3NeT shore installations to produce the required electrical power.
- Requires investment of 4-5 M€.
- Can only work if coupled to a larger (public) power network.
The KM3NeT Preparatory Phase

• “Preparatory Phase”: A new EU/FP7 funding instrument restricted to ESFRI projects.

• KM3NeT proposal funded with 5 M€

• 3-year project, 3/2008 – 2/2011

• Major objectives:
  • Initiate political process towards convergence (includes funding and site selection/decision)
  • Set up legal structure and governance
  • Strategic issues: New partners, distributed sites, extendibility
  • Prepare operation organisation & user communities
  • Organise pre-procurement with commercial partners
  • Next-step prototyping
Timeline Towards Construction

Note: “Construction” includes the final prototyping stage
Summary

• Neutrinos would (and will) provide very valuable astrophysical information, complementary to photons and charged cosmic rays.

• Exploiting the potential of neutrino astronomy requires cubic-kilometre scale neutrino telescopes providing full sky coverage.

• The KM3NeT detector in the Mediterranean Sea will complement IceCube in its field of view and exceed its sensitivity by a substantial factor.

• We are working towards a start of construction by 2011.