The KM3NeT Project

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The plan for the next 40 minutes:

• Neutrino telescopes
• What is KM3NeT?
• Physics prospects with KM3NeT
• Recent achievements
• Studying low-energy neutrinos: The ORCA option
• Summary

Sincere thanks to all colleagues who allowed me to use their material
Neutrino telescopes
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) GeV – some PeV
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

- IceCube (South Pole)
- Lake Baikal
- DUMAND
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, ...)

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: 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
IceCube: Completed in December 2010

- 86 strings altogether
  - 125 m horizontal spacing
  - 17 m vertical distance between Optical Modules
  - 1 km³ 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)

Southern hemisphere:
atm. muons

Northern hemisphere:
24h
+45°

24h

Northern hemisphere
108,317 events

Equatorial coordinates

Preliminary

atm. neutrinos

TeV – PeV
IceCube: Significance map (IC40+59+79)

DEC = 2.8° ; RA = 34.3°
N_{src} = 23.1
p-values: pre-trial = 2 \times 10^{-5}
post-trial = 57%

DEC = -38.8° ; RA = 219.3°
N_{src} = 20.8
p-values: pre-trial = 9 \times 10^{-5}
post-trial = 98%
What is KM3NeT?
The KM3NeT project

- Multi-km$^3$ NT in Mediterranean Sea, exceeding IceCube substantially in sensitivity
- Central physics goals (by priority):
  - Galactic neutrino “point” sources (energy 1-100 TeV)
  - Extragalactic sources
  - High-energy diffuse neutrino flux
- EU-funded Design Study and Preparatory Phase
- Decisions taken:
  - Technology: Strings with 18 multi-PMT optical modules
  - Multi-site installation (France, Greece, Italy)
  - 6 building blocks of ~115 strings each
- Collaboration established
KM3NeT implementation parameters

- Staged implementation:
  Phase-1 in progress, 40 M€ available.
- Science potential from very early stage of construction on.
- Overall investment ~220 M€.
- Operational costs of full detector 4-6 M€ per year (2-3% of capital investment), including electricity, maintenance, computing, data centre and management.
- Node for deep-sea research of earth and sea sciences.
Installation Sites

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

- Long-term site characterisation measurements performed

- Political and funding constraints

- Solution: networked, distributed implementation
The building block concept

- **Building block:**
  - 115 detection units
  - Segmentation enforced by technical reasons
  - Sensitivity for muons independent of block size above ~75 strings
  - One block ~ one IceCube

- **Geometry parameters optimised for galactic sources (E cut-off)**

- **Final optimisation in progress**

Example configuration: 120 DUs, 100m distance on average
Detection units: Strings

- **Mooring line:**
  - Buoy (probably syntactic foam)
  - 2 Dyneema® ropes (4 mm diameter)
  - 18 storeys (one OM each), 30-36m distance, 100m anchor-first storey

- **Electro-optical backbone (VEOC):**
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - Fibres and copper wires
  - At each storey: connection to 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 plastic structure
• 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
Readout: time-over-threshold

From the analogue signal to time stamped digital data:

- Implemented through FPGA on central logic board contained in optical module
- All data to shore via optical fibres driven by lasers on shore
- Time synchronisation and slow control
Deployment Strategy

- Compact package – deployment – self-unfurling
  - Eases logistics (in particular in case of several assembly lines)
  - Speeds up and eases deployment; several units can be deployed in one operation
  - Self-unfurling concepts is being thoroughly tested and verified
- Connection to seabed network by ROV
Compactifying Strings

String rolled up for self-unfurling:

Physics prospects with KM3NeT
Angular resolution

- Investigate distribution of angle between incoming neutrino and reconstructed muon
- Dominated by kinematics up to \(~1\text{TeV}\)
- Energy resolution \(~0.3\) in \(\log_{10}(E_\nu)\) if \(E_\mu > 1\ \text{TeV}\)

\(\text{Median (degree)}\)

\(\log_{10}E_\nu \ (\text{GeV})\)

\(< 0.1^\circ\)
RX J1713: A prime candidate source

**Image Description**

![Image showing RX J1713](image_url)

**Graph Details**

- **x-axis**: Energy (TeV)
- **y-axis**: $dN/dE$ (cm$^2$ s$^{-1}$ TeV$^{-1}$)

**Graph Annotations**

- **H.E.S.S. data**
- **Fit**
- **Fit 2004**

**Textual Notes**

- **H.E.S.S. Collaboration, ICRC 2007**
- **PSF**
- **17h15m**
- **17h10m**
RX J1713: A prime candidate source

- Figure of merit (FOM): time to make an observation at $5\sigma$ 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 (Vela X, Fermi Bubbles)
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
Recent achievements
The preproduction optical module (PPM-DOM)

- Fully equipped DOM (31 PMTs + acoustic positioning sensors + time calibration LED beacon)
- Mounted on the instrumentation line of ANTARES
- Instrumentation line installed and connected on 16 April 2013
- PPM-DOM fully operational and working correctly

Final integration tests in dedicated dark box
First PPM-DOM data from the deep sea

- Up to 150 Cherenkov photons per decay
- \( e^- (\beta \text{ decay}) \)
- \( ^{40}\text{Ca} \)
- \( ^{40}\text{K} \)
- Concentration of \( ^{40}\text{K} \) is stable (coincidence rate \( \sim 5 \text{ Hz on adjacent PMTs} \))

![Diagram showing coincidence rate on 2 adjacent PMTs and number of coincident hits in a DOM.](image)
String deployment tests, April 2013

- Deployment and unfurling successful
- Problems occurred during recovery operations (heavy currents)
- Detailed analysis ongoing
- Further test necessary
Tower deployment, Capo Passero, April 2013

Tower with 8 storeys, 4 OMs each
(one 10-inch PMT per DOM)
First data: PMT rates

![Graphs showing PMT rates for different PMTs with respective rates and time frames.](image-url)
Studying low-energy neutrinos: The ORCA option
Neutrino mass hierarchy

- Depending on sign of $\Delta m_{23}^2$: “normal hierarchy” (NH) or “inverted hierarchy” (IH)

- A fundamental parameter of particle physics!
Mass hierarchy and atmospheric neutrinos

- Determining the sign of $\Delta m^2_{23}$ requires matter effect. Oscillation of $\nu_e$ and/or $\bar{\nu}_e$ must be involved.
- 3-flavour oscillations of $\nu_e \leftrightarrow \nu_\mu$ in matter:

  $$P_{e \rightarrow \mu} \approx P_{\mu \rightarrow e} \approx \sin^2 \theta_{23} \sin^2(2\theta_{13}^{\text{eff}}) \sin^2 \left(\frac{\Delta_{13}^{\text{eff}} L}{2}\right)$$

  $$\Delta_{13} = \frac{\Delta m^2_{13}}{2E_\nu} \quad \sin^2(2\theta_{13}^{\text{eff}}) = \frac{\Delta_{13}^2 \sin^2(2\theta_{13})}{\Delta_{13}^{\text{eff}} L}$$

  $$\Delta_{13}^{\text{eff}} = \sqrt{[\Delta_{13} \cos(2\theta_{13}) - A]^2 + \Delta_{13}^2 \sin^2(2\theta_{13})}$$

  $$A = \sqrt{2} G_F N_e$$ for $\nu$ and $A = -\sqrt{2} G_F N_e$ for $\bar{\nu}$

- “Matter resonance” for $A = \Delta_{13} \cos(2\theta_{23})$ (maximal mixing, minimal oscillation frequency). This is the case for $E_\nu \approx 30$ GeV/$\rho[g$ cm$^{-3}]$
Neutrino oscillations in Earth

- Earth density $4-13 \text{ g/cm}^3$
- Relevant: $E_\nu \sim 3-10 \text{ GeV}$
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 just a (scalable) example configuration
ORCA: Hardware and construction issues

- Use agreed KM3NeT technology; no major modifications required, but cable lengths etc. to be adapted
- String length restricted to avoid entanglement due to deep-sea currents
- Deployment requires care and studies (operation of deep-sea submersibles (ROVs) between deployed strings is impossible)
- New deployment scheme proposed (several strings in one sea operation)
- Very tight time constraints due to funding situation
The major experimental questions

- What are the trigger/event selection efficiencies?
- How and how efficiently can we separate different event classes?
- How can we reconstruct these events and what resolutions can we reach on $E_\nu$ and $q$?
- How can we control the backgrounds?
- What are the dominant systematic effects and how can we control them?
- What precision of calibration is needed and how can it be achieved?

A proposal requires knowing the answers!
ORCA reconstruction efficiency

- Isotropic $\nu_{\mu}$ CC events generated
- Event must be reconstructed as up-going with vertex in instrumented volume
- Efficiencies determined for two levels of quality cuts
- No background rejection

Reconstructed vertex inside the instrumented volume

$p_{\text{eff}}(\text{Mtons})$

Events selected with a looser quality cut

Events selected with a stricter quality cut

$E_{\nu}(\text{GeV})$
ORCA energy and zenith resolutions

- $E_\mu$ reconstructed from $\mu$ track length
- Shaded region: 16% and 84% quantiles as function of $E_\mu^{\text{true}}$
- $\Delta E_\nu \approx 1 \text{ GeV}_\mu + 0.2 E_{\text{shower}}$

- Median of zenith angle difference $\nu - \text{rec. } \mu$

Reconstructed vertex inside the instrumented volume

Upgoing events

preliminary
Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years.

Improved determination of $\Delta m_{23}^2$ and $\theta_{23}$ seems possible.
Summary and outlook
• ANTARES has demonstrated the feasibility of a deep-sea neutrino telescope.
• KM3NeT will provide a multi-km$^3$ installation in the Mediterranean Sea sensitive enough to detect Galactic sources and more.
• The design process has concluded in an agreed technology (strings with multi-PMT digital OMs).
• KM3NeT will be a multi-site installation (France, Greece, Italy).
• It will provide nodes for earth/sea sciences.
• A first construction phase in underway.
• A low-energy option (ORCA) is under investigation.