The next generation neutrino telescope in the Mediterranean

In this talk:
• motivation for high-energy astronomy in the deep-sea (very briefly!)
• technical solutions for KM3NeT: Digital Optical Modules and Detection Units
• status & plans:
  o qualification
  o “Phase-1”
  o next phases (including “ARCA” and “ORCA”, aimed respectively at: high-energy neutrino astronomy and measurement of neutrino mass hierarchy)
Neutrino telescopes for high-energy astrophysics

The concept: use neutrinos to unambiguously identify sites of hadronic acceleration in the Cosmos

The approach: to build a very large Cherenkov detector in a deep transparent medium (water or ice)

Evidence of cosmic neutrinos reported from IceCube at Antarctica opened the era of neutrino astronomy

Remark: the Mediterranean Sea is an ideal location to look at the Galactic Plane, including the Galactic Center (with very good angular resolution)
The KM3NeT research infrastructure

The Collaboration comprises ~300 researchers from more than 40 institutes in 11 countries (Cyprus, England, France, Germany, Greece, Ireland, Italy, Morocco, the Netherlands, Romania, Spain)

Multi-site installation:
Fr: 40 km offshore Toulon (2500 m depth)
It: 80 km offshore Capo Passero (3500 m depth)
Gr: 20 km offshore Pylos (> 4000 m depth)

Nodes for astrophysics and marine science at each site

Infrastructures at KM3NeT-Fr and -It

**KM3NeT-Fr**
- Main electro-optical cable installed (Dec. 2014)
- Submarine node deployed (April 2015)
- Onshore station up and running

i.e.: infrastructure completed!

**KM3NeT-It**
- Main electro-optical cable installed years ago
- Prototype string in operation
- New cable termination frame and submarine junction boxes ready for deployment
- Onshore station ready
- Construction of 8 ‘tower’ structures ongoing

i.e.: infrastructure up and running, about to be completed!
DOMs and DUs

- 31 DUs (Detection Units) in Phase 1:
  - 24 DUs ("ARCA layout") in KM3NeT-It (~0.1 km³, ~3 x ANTARES)
  - DU-1 plus 6 more DUs ("ORCA layout") in KM3NeT-Fr

- 18 DOMs (Digital Optical Modules) on each DU, spaced by 36 m (in "ARCA layout")
More on Digital Optical Modules

• 31 PMTs of 3” photocathode in a 17” glass sphere

• Optical gel coupling between PMTs and glass

• Reflection rings around the PMTs to increase detection surface

• Electronics, optics for long-range communications and calibration devices (including: ‘nanobeacon’ LED pulser, compass/tiltmeter, and piezo-sensor for acoustic measurements) installed inside the sphere – each DOM acting as an individual, autonomous detection node

• Connection to the rest of the apparatus requires two conductors (+12 V power) and one optical fibre through a single penetrator
The multi-PMT Optical Module: rationale

- Segmentation of the photocathode allows photon-counting with high background rejection
- Maximum photocathode area in a sphere
- Extend sensitivity to a large fraction of solid angle
- Directionality!
- Local triggers can be exploited

- Cost-effective solution! Comparing $31 \times 3$" PMTs to a single 10" PMT:
  
  $31 \times \pi \times 1.5^2 / (\pi \times 5^2) = 2.8$ \textbf{(ratio of photocathode areas)}

  => need a factor of 2.8 fewer spheres, mechanics, electronics, network

  (it also turns out that the price per unit photocathode area is cheaper for the 3" PMTs)
DOM design (major components)

- penetrator (custom design)
- cooling structure
- signal collection boards
- power-board
  - Central Logic Board (CLB)
    - FPGA-based (Xilinx Kintex 7), (modified) white rabbit timing,
    - DWDM optical communication (50 GHz spacing)
- 3d-printed support structure
- "collar" (for fixing to ropes in string)
- 3” PMT + custom low-power base
- light collection cone
- acoustic piezo-sensor
- sphere
3" PMTs and readout

- timing \( \leq 4.5 \text{ ns (FWHM)} \)
- Q.E. \( \sim 30\% \)
- collection efficiency \( \geq 90\% \)
- Various serious suppliers

Custom-design, low-power base allows to:
- Set HV on PMT (controlled from shore)
- Discriminate hits above threshold (controlled from shore)
- Send output signal to Central Logic Board (where Time-over-Threshold is digitized and time-stamped with 1 ns resolution)

\[ \rightarrow \text{All PMT hits sent to shore (no offshore filter)} \]

**ETEL D792**  
**Hamamatsu R12199**  
**HZC XP53B20**
Detection units (DU)

- Mechanical structure of the string based on two dyneema ropes, anchored on sea floor and kept taught by a (commercial) top buoy (plus DOM buoyancy)
  - Robust and stiff arrangement
  - DOMs keep the correct attitude
  - String dynamics under control

- the VEOC (Vertical Electrical-Optical Cable) connects all DOMs to the DU base – the VEOC is an oil-filled pressure-balanced hose equipped with 18 optical fibres (one for each DOM)

- DOM collars keep the DOMs in their positions

- A Break-out-box (BOB) is the interface between a DOM and the VEOC
  - Very simple structure hosting fibre splices and a DC/DC converter
  - A short cable (BEOC – BOB Electrical-Optical Cable) connects the BOB to the DOM penetrator
Detection unit installation

• The detection unit is packed on a launcher vehicle (LOM) and installed on the anchor

• After deployment on sea bed, unfurling is done by operating an acoustic release

• LOM and acoustic release are recovered after operation

Arrangement on LOM (detail)
Deployment time
ROV inspection of an unfurled structure
Qualification plan

Staged process:

• 1<sup>st</sup> prototype Optical Module (installed April 2013)
• 1<sup>st</sup> prototype string (installed May 2014)
• Installation tests (various sea campaigns done in past years + tests in the lab)
• Onshore qualification
• First Detection Unit

being finalized
1st prototype Optical Module

Installed in April 2013
(2500 m depth)
1st prototype Optical Module

• all 31 channels working from the start
• worked fine and stably for more than 18 months
Results from PPM-DOM (I)

Deployed at ANTARES in April 2013

Coincidence rate on 2 adjacent PMTs
(33° angular separation)

K\text{\textsuperscript{40}} coincidence rate → PMT efficiencies
Peak position → time offsets

Concentration of K\text{\textsuperscript{40}} is stable (coincidence rate ~5 Hz on adjacent PMTs)

Results from PPM-DOM (II)


Number of coincident hits in a DOM

Zenith angle of hit PMTs in events with more than 6 coincident hits

>5 coincidences within 20ns ⇒ reduced K40 contribution, dominated by atmospheric muons

More upper PMTs in multi-hit events ⇒ directional information from single optical module
1st prototype string (3 Digital Optical Modules)

Integration of the 3 DOMs

Line ready for deployment

Deployment time!

ROV views of the operation: left – the ROV turns the structure in the best orientation for connection during deployment; right – connection done on the deep-sea infrastructure
1st prototype string (3 Digital Optical Modules)

- Installed at the KM3NeT-It site (3500 m depth) in May 2014
- Installation went quite smoothly
- All 3 DOMs ok
- Smooth, stable operation in water
- Still taking data, with nice results! (Paper in preparation)

Deployment time!

ROV views of the operation: left – the ROV turns the structure in the best orientation for connection during deployment; right – connection done on the deep-sea infrastructure
Results from prototype string

**Hit coincidences inside DOMs**

- Good understanding of optical module performance
- Stability of DOMs studied, plus: inter-optical module time calibration and search for muons

**Time offsets from $^{40}\text{K}$ coincidences**

- 7° FWHM resolution achieved – quite encouraging!
  (reminder: we aim at 0.1° resolution with full detector)

**Inter-DOM time differences**

- Reconstruct muon trajectory from hits on 3 DOMs
- Ambiguities can be reduced by cuts on time differences

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Coming up next: first Detection Unit

- Integrated end 2014
- Extensive tests ongoing
- Plan: ready to deployment by mid-June

Integration of first Detection Unit

Calibration in dark room

Mock-up of anchor used in test of submarine connection with ROV
Next step after Phase-1: KM3NeT 2.0

ARCA and ORCA

**ARCA =**
Astroparticle Research with Cosmics in the Abyss
(2 blocks of 115 detection units each, ∼1-2 km³)

**ORCA =**
Oscillation Research with Cosmics in the Abyss
(1 block of 115 detection units)

Vertical OM distance = 36 m

Vertical OM distance = 6 – 12 m
Next step after Phase-1: KM3NeT 2.0

- All-flavour neutrino astronomy
- Precision measurements in neutrino physics
- Nodes for earth and sea science research
Concluding remarks

• R&D
  • developed cost-effective technology
  • feedback from prototypes confirm key specifications
  • qualification plan close to fulfilment

• Ongoing: Phase-1 (funded)
  • going ahead as planned, preparing to install first detection unit
  • infrastructures at KM3NeT-Fr and KM3NeT-It ready to accept connections...

• Next step: KM3NeT 2.0 (proposal)
  • ARCA
    • measurement of IceCube flux with different methodology, complementary field of view and improved resolution
    • all flavour neutrino astronomy
  • ORCA
    • measurement of neutrino mass hierarchy

• Final goal (Phase-3)
  • neutrino astronomy with multi-km³ detector