KM3NeT – The next-generation neutrino telescope in the Mediterranean Sea

Uli Katz
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The plan for the next 30 minutes

- The KM3NeT project: Concept and design
- ARCA and ORCA
- Results from prototypes and the first string
- Neutrino astronomy: Selected sensitivity studies
- Summary
The KM3NeT project: Concept and design
ANTARES:
The first deep-sea $\nu$ telescope

- Installed near Toulon at a depth of 2475m
- 12 strings with 25 storeys each, instrumented volume $\sim 0.01 \text{km}^3$
- Data taking in full configuration since 2008
- Proof of principle of deep-sea $\nu$ telescope
- Lots of results – but too small for cosmic neutrinos
The KM3NeT concept

- Deep-sea array of photodetectors
- Multi-PMT modules (31 3”-PMTs in one sphere)
- 18 modules per string (detection unit)
- 115 strings per building block
- All data to shore
The KM3NeT Collaboration

km3net.org
@km3net
The KM3NeT DOM

- 31 3-inch PMTs in 17-inch glass sphere (cathode area ~ 3x10-inch 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
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations → reduced risk
## PMT specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode diameter</td>
<td>&gt; 72 mm</td>
</tr>
<tr>
<td>Nominal Voltage for Gain $3 \times 10^6$</td>
<td>900 – 1300 V</td>
</tr>
<tr>
<td>Gain slope = $\log_{10}(\text{gain})/\log_{10}(\text{HV})$</td>
<td>6.5 – 8.0</td>
</tr>
<tr>
<td>QE at 404 nm</td>
<td>&gt; 23 %</td>
</tr>
<tr>
<td>QE at 470 nm</td>
<td>&gt; 18 %</td>
</tr>
<tr>
<td>TTS (FWHM)</td>
<td>&lt; 5 ns</td>
</tr>
<tr>
<td>Dark count rate (0.3 p.e. threshold)</td>
<td>&lt; 2 kHz</td>
</tr>
<tr>
<td>Pre-pulses</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>Delayed pulses</td>
<td>&lt; 3.5 %</td>
</tr>
<tr>
<td>Early afterpulses</td>
<td>&lt; 2 %</td>
</tr>
<tr>
<td>Late afterpulses</td>
<td>&lt; 10 %</td>
</tr>
</tbody>
</table>
PMTs available

ETEL D792
Hamamatsu R12199
HZC XP53B20

Fulfil specifications; orders placed / expected

First prototype not yet compliant with specifications (gain, dark rate, afterpulses, …), further development under way

Note: In all cases price/photocathode area < 10-inch tubes (MELZ?)
KM3NeT readout

31 PMTs + bases
2 octopus boards

Power board

Central Logic Board (CLB)

HV for PMTs

Discrimination w.r.t. predefined threshold

Signal collection

FPGA for TDC (time & time over threshold), time stamping (1 ns precision);
Interface for time synchronisation:
Control of calibration devices;
Communication;

All data to shore (optical fibres)

Online filter on shore
KM3NeT detection units (DUs)

- Mooring line:
  - Buoy (syntactic foam or empty spheres)
  - 2 pre-stretched Dyneema® ropes (4 mm diameter)
  - 18 storeys (one DOM each)
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - Optical fibres and copper wires
  - At each storey: Break-out box for connection to 1 fibre + 2 wires (one single pressure transition)
  - Point-to-point connection DOM-shore for each DOM
Deployment

* Deploy to sea bed
* Acoustic release
* Unfurl
* Collect frame
ARCA and ORCA
– Astroparticle and Oscillation Research with Cosmics in the Abyss –
The building block concept

- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons

- Large block (neutrino astronomy)
  - Sensitivity per string for muons independent of block size above ~75 strings
  - One block ~ half IceCube

- Small block (neutrino oscillations)
  - Precision measurement of atmospheric neutrinos
  - One block ~ 6 Mtons

- Allows for staged, block-wise, multi-site installation

DU distance adjusted to scientific objective:
- 90-120 m for neutrino astronomy
- 20 m for oscillation research
## KM3NeT development

<table>
<thead>
<tr>
<th>Phase</th>
<th>Blocks/strings</th>
<th>Primary deliverables / site(s)</th>
<th>Funding Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2/31</td>
<td>Proof of feasibility and first science results; KM3NeT-Fr + KM3NeT-It sites</td>
<td>Fully funded 2015-17</td>
</tr>
<tr>
<td>2.0</td>
<td>2/230</td>
<td>Measurement of neutrino signal reported by IceCube; All-flavor neutrino astronomy; KM3NeT-It site</td>
<td>Applications pending 2017-2020</td>
</tr>
<tr>
<td>1/115</td>
<td>Neutrino mass hierarchy; KM3NeT-Fr site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6+1/805</td>
<td>Neutrino astronomy including Galactic sources; Multiple sites</td>
<td>t.b.d. ?</td>
</tr>
</tbody>
</table>
KM3NeT Phase-1 = 31 DUs

ARCA =
Astroparticle Research with Cosmics in the Abyss

Vertical OM distance = 36 m
3 times ANTARES

ORCA =
Oscillation Research with Cosmics in the Abyss

Vertical OM distance = 9 m
**KM3NeT 2.0 = ARCA and ORCA**

**ARCA =**  
Astroparticle Research with Cosmics in the Abyss

**ORCA =**  
Oscillation Research with Cosmics in the Abyss

Vertical OM distance = 36 m

Vertical OM distance = 9 m
Results from prototypes and first string
DOM prototype (PPM-DOM)

Deployed at ANTARES in April 2013

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

K⁴⁰ coincidence rate → PMT efficiencies

Peak position → time offsets


Concentration of ⁴⁰K is stable (coincidence rate ~5 Hz on adjacent PMTs)

Up to 150 Cherenkov photons per decay

$\gamma$ $\gamma$

$\text{e}^- (\beta \text{ decay})$

$^{40}\text{Ca}$ $^{40}\text{K}$
PPM-DOM: Atmospheric Muons

Number of coincident hits in a DOM

Zenith angle of hit PMTs in events with more than 7 coincident hits

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

More upper PMTs in multi-hit events ⇒ directional information from single storey

DU prototype (PPM-DU): 3 DOMs

Deployed at KM3NeT-It in May 2014
PPM-DU: Intra-DOM timing

K40 coincidence rate as a function of the angle between PMTs. Note: Different PMT types!

Relative timing calibration of 31 PMTs in DOM using coincidences. Note: Extremely stable over many runs.

VHEPA2016: KM3NeT (U. Katz)
PPM-DU: Inter-DOM timing

- Calibration with pulsed LED
- Time difference – light travel time = Signal travel time
- Result very stable over several months, RMS of jitter < 1 ns

**KM3NeT preliminary**

- Mean: -228.4 ns
- RMS: 0.8 ns
PPM-DU: Muon reconstruction

- Reconstruct muon trajectory from hits on 3 DOMs
- Ambiguities can be reduced by cuts on time differences
- 7° FWHM resolution achieved
First string deployed on 3 Dec 2015

- Smooth operation
- All 18 DOMs alive and functional
- First muons reconstructed within hours after switch-on
- Data taking in progress
- Breaking news: Very first neutrino candidate on 5 Jan 2016
Neutrino astronomy:
Selected sensitivity studies
Muon angular reconstruction

- Reconstruction using new PMT response simulation:
  Median of angle $\Delta \Omega$ between reconstructed $\mu$ and true $\nu$ direction

![Graph showing angular resolution vs. $E_\nu$ for $\nu_\mu$ CC, $\Lambda > -5.8$.](image)

- Expected $\mu$ reconstruction precision $0.1^\circ$
**Shower reconstruction: Method**

- **Vertex fit**: Suitable hit selection, fit uses timing; result used for containment requirement
- **Direction and energy**: Uses PDF depending on
  - Distance vertex – DOM
  - Angle between shower direction and DOM
  - Orientation of PMTs
- **Hit information used**: yes/no

![PDF for E = 10 TeV at r = 100 m](image1)

![PDF for E = 1 PeV at r = 100 m](image2)
Shower reconstruction: $\theta, E$

- For contained $\nu_e$ CC events
- Event sample after selection cuts
- $\sim 10\%$ in $E$, better than $2^\circ$ in direction
- Systematic effects very small
All analyses proceed through 4 consecutive steps:
1. Preselection (e.g. quality cuts or cuts on reconstructed zenith or \(N_{\text{hit}}\))
2. Further background rejection by Boosted Decision Tree
3. ‘Cut-and-count’ significance analysis
4. Maximum-likelihood analysis using likelihood ratio

\[
LR = \sum_{k=1}^{n} \log \left( \frac{n_{\text{sig}}}{n} \cdot P_{\text{sig}}(X_k) + \left(1 - \frac{n_{\text{sig}}}{n}\right) \cdot P_{\text{back}}(X_k) \right)
\]

Significance determined by generating pseudo-experiments

Note: All detector information is in the probability density functions \(P(X)\), where the event variables \(X\) depend on the type of analysis.

Main results:
- Event samples with high signal content from step (3)
- Optimised sensitivities from step (4)
Assumptions:
1. Flavour-symmetric
2. Isotropic
3. Energy spectrum consistent with IceCube findings

\[
\Phi(E_\nu) = 1.2 \times 10^{-8} \cdot \left( \frac{E_\nu}{\text{GeV}} \right)^{-2} \cdot \exp \left( -\frac{E_\nu}{3 \text{ PeV}} \right) \quad \text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
\]

\[
\Phi(E_\nu) = 4.11 \times 10^{-6} \cdot \left( \frac{E_\nu}{\text{GeV}} \right)^{-2.46} \cdot \exp \left( -\frac{E_\nu}{3 \text{ PeV}} \right) \quad \text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
\]
Signal/background separation

Cascade analysis

Muon analysis
Diffuse flux results (max. likelihood)

Other flux assumptions yield 10-30% improvement in discovery time.

Event numbers (cut&count):
- 16/9 cascades
- 7.5/5 track-like

(signal/background per ARCA year)

Note:
For each energy, direction and flavour, KM3NeT is complementary to IceCube.

Flux per flavour:
\[ 1.2 \times 10^{-8} \frac{(E/1\, \text{GeV})^2}{\text{GeV}^{-1} \, \text{sr}^{-1} \, \text{s}^{-1} \, \text{cm}^{-2}} \]
Diffuse flux from galactic plane

- New model by D. Gaggero at al. (spatially dependent diffusion coefficient in galactic centre/plane)

- Neutrino flux prediction for central part of Galaxy (longitude $|l| < 30^\circ$ and latitude $|b| > 4^\circ$):

$$\frac{d\phi}{dE_\nu} = 5 \times 10^{-6} \left( \frac{E_\nu}{1 \text{ GeV}} \right)^{-2.3} \cdot \exp \left( -\sqrt{\frac{E_\nu}{1 \text{ PeV}}} \right) \text{ GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

per flavour (small region but much higher flux than extragalactic)

- Region very well visible for KM3NeT for up-going events → First analysis in muon channel
Galactic plane: First results

- Discovery in 4-5 years
- Inclusion of cascade channel will improve this result
- Confirmation of this flux: major breakthrough in astrophysics
Point-source results

- Galactic sources in reach

- Significant discovery potential for extragalactic sources

VHEPA2016: KM3NeT (U. Katz)
Point-source search with cascades

- Results are “rather preliminary”
- Important: Provides cascade event sample for source candidates
- Closes visibility gap
… concluding
Summary and outlook

• The KM3NeT neutrino telescope has entered its first construction phase
• Results from prototypes and first string very encouraging
• ARCA & ORCA to follow in 2016-20, sensitivity complementary to IceCube
• Priority science goals:
  • All-flavour neutrino astronomy
  • Measurement of the neutrino mass hierarchy

Stay tuned!