KM3NeT: the next-generation neutrino telescope

A distributed research infrastructure with 2 main physics topics: ORCA & ARCA

>240 people
55 institutes / 41 cities
15 countries

- Single collaboration, same technology

Oscillation Research with Cosmics In the Abyss
Low-energy (~GeV) studies of atmospheric neutrinos

Astroparticle Research with Cosmics In the Abyss
High-energy (TeV-PeV) neutrino astrophysics

See poster G. Ferrara
The (new) ORCA detector

Digital Optical Module (DOM)

- Uniform angular coverage
- Directional information
- Digital photon counting
- All data to shore

~8 Mt instrumented volume
115 strings (detection units, DUs)
18 DOMs / DU (~50 kt ~ 2 × SK)
31 PMTs / DOM (~3 kt ~ MINOS)
Total: 64k x 3” PMTs

Depth = 2435 m
Light absorption length ~ 60 m
Cherenkov telescope: detection principle

- Detection of neutrino (ν) and electron (e)
- Measurement of time, position, and amplitude of hits
- Determination of energy and arrival direction

Diagram shows a Cherenkov telescope with a track and shower indicating the reconstruction of neutrino properties.
Simulations ongoing to study the detector performance with final layout:

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<tr>
<th>Geometry</th>
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<th>horizontal spacing (between strings)</th>
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<td>9 m on average with alternate 6 m and 12 m</td>
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All technical constraints (now) included in simulations

Instrumented volume: from 5.7 Mton (LoI) to ~8 Mton (with same number of DOMs)

New set of simulations launched with new geometry, improving in various areas:
  - Trigger + reconstruction + PID + background rejection
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- Trigger + reconstruction + PID + background rejection

Installed as of today: main electro-optical cable, juction box ...and first ORCA line!
Sept 22d: deployment + connection of first ORCA DU

Deployment of the line coiled in a spherical frame (position accuracy ~1m)
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Deployment of the line coiled in a spherical frame (position accuracy ~1m)

Inspection on the seabed with remotely operated submarine (ROV)
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Inspection of line by ROV
First ORCA data!

- First event with recorded track reconstructed by ORCA (down-going muon)
First ORCA data!

- A bright muon bundle

![Graph showing data points and time hit in the ORCA experiment.](image-url)
**ORCA: measuring the neutrino mass hierarchy**

- A "free beam" of known composition ($\nu_e, \nu_\mu$)
- Wide range of baselines ($\leftrightarrow$ zenith) and energies
- Oscillation pattern distorted by Earth matter effects
  - Maximum difference $\text{IH} \nRightarrow \text{NH}$ for resonance in Earth mantle: $\theta = 130^\circ$ (7645 km) and $E_\nu = 7$ GeV

**Approach:**
- Measure $\theta$, $E$ of upgoing atmospheric GeV-scale neutrinos, identify and count **track** and **shower** channel events
- Careful treatment of systematics mandatory

Credits: J. Coelho
Event topologies

Discrimination of tracks, showers and atmospheric muons (~%) via RDF
Event topologies

At 10 GeV:

~90% correct ID of $\nu_e^{CC}$

~70% correct ID of $\nu_\mu^{CC}$
Reconstruction performances (from LoI)

7°(5°) for 5(10) GeV for both channels
Dominated by kinematic smearing

Energy resolution below 30% in relevant energy range
### Statistical analysis

<table>
<thead>
<tr>
<th>parameter</th>
<th>true value distr.</th>
<th>initial value distr.</th>
<th>treatment</th>
<th>prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{23}$ $[^\circ]$</td>
<td>${40, 42, \ldots, 50}$</td>
<td>uniform over $[35, 55]$ †</td>
<td>fitted</td>
<td>no</td>
</tr>
<tr>
<td>$\theta_{13}$ $[^\circ]$</td>
<td>8.42</td>
<td>$\mu = 8.42, \sigma = 0.26$</td>
<td>fitted</td>
<td>yes</td>
</tr>
<tr>
<td>$\theta_{12}$ $[^\circ]$</td>
<td>34</td>
<td>$\mu = 34, \sigma = 1$</td>
<td>nuisance</td>
<td>N/A</td>
</tr>
<tr>
<td>$\Delta M^2$ $[10^{-3} \text{ eV}^2]$</td>
<td>$\mu = 2.4, \sigma = 0.05$</td>
<td>$\mu = 2.4, \sigma = 0.05$</td>
<td>fitted</td>
<td>no</td>
</tr>
<tr>
<td>$\Delta m^2$ $[10^{-5} \text{ eV}^2]$</td>
<td>7.6</td>
<td>$\mu = 7.6, \sigma = 0.2$</td>
<td>nuisance</td>
<td>N/A</td>
</tr>
<tr>
<td>$\delta_{CP}$ $[^\circ]$</td>
<td>0</td>
<td>uniform over $[0, 360]$</td>
<td>fitted</td>
<td>no</td>
</tr>
<tr>
<td>overall flux factor</td>
<td>1</td>
<td>$\mu = 1, \sigma = 0.1$</td>
<td>fitted</td>
<td>yes</td>
</tr>
<tr>
<td>NC scaling</td>
<td>1</td>
<td>$\mu = 1, \sigma = 0.05$</td>
<td>fitted</td>
<td>yes</td>
</tr>
<tr>
<td>$\nu/\bar{\nu}$ skew</td>
<td>0</td>
<td>$\mu = 0, \sigma = 0.03$</td>
<td>fitted</td>
<td>yes</td>
</tr>
<tr>
<td>$\mu/e$ skew</td>
<td>0</td>
<td>$\mu = 0, \sigma = 0.05$</td>
<td>fitted</td>
<td>yes</td>
</tr>
<tr>
<td>energy slope</td>
<td>0</td>
<td>$\mu = 0, \sigma = 0.05$</td>
<td>fitted</td>
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- **Profile over 4 oscillation & 5 systematic parameters**

- Generate pseudo-experiments and compute $\text{LLR} = \log \left( \mathcal{L}_{\text{NH}} / \mathcal{L}_{\text{IH}} \right)$

- **Median sensitivity** $\Leftrightarrow$ probability of observing median LLR of wrong hierarchy

$$S_{\text{NH}} = \frac{\mu_{\text{NH}} - \mu_{\text{IH}}}{\sigma_{\text{IH}}}$$
Sensitivity to NMH (from LoI)

- Worst case: $\sim 3\sigma$ sensitivity to NMH in 4 years
- The combination of NH and upper octant of $\theta_{23}$ gives significantly improved sensitivity ($>5\sigma$ in 3 years)
- For IH, sensitivity is essentially independent of $\theta_{23}$
- The value of $\delta_{cp}$ has moderate impact on sensitivity ($\sim 0.5\sigma$)
Other measurements

➢ Oscillation parameters
  • High statistics and excellent resolution
  • Achieve 2-3% precision in $\Delta m^2_{32}$ and 4-10% in $\sin^2\theta_{23}$ (depending on hierarchy)
  • Competitive with NOvA and T2K projected sensitivity in 2020

➢ Tau neutrino appearance
  • $\approx 3k n_\tau$ CC events/year with full ORCA $\rightarrow$ early physics result!
  • Rate constrained within $\approx 10\%$ in 1 year
Non-standard interactions

\[ H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{2\rightarrow 1}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{3\rightarrow 1}}{2E} \end{bmatrix} U^\dagger + V_e \left[ \begin{array}{cccc} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{array} \right] \]

- ORCA sensitive to NSI effects of the order of 10% of Fermi interaction
- for some of the parameters: x10 improvement on direct bounds
- competitive with global limits from oscillation (including solar neutrinos)
Sterile neutrinos

- Dominant effect of adding an eV-scale sterile neutrino: suppression of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation at $\sim 20\text{GeV}$
- ORCA sensitive to $|U_{\tau 4}|^2$ 2x smaller than current limits set by SuperK & IceCube
- ORCA is sensitive to the electron density $N_e$ while geophysics measure $\rho_m$

- 1σ stat.+ syst. uncertainty after 10 years (NH)
  - ~ 5% in the whole mantle (c)
  - ~ 6% in the whole outer core (b)

10 year sensitivity including systematics

\[
\frac{N_e}{\rho_m} \propto \sum_i w_i \frac{Z_i}{A_i}
\]

- PREM model basis for $\rho_m$
- uniform Z/A rescaling in layer
- Monte Carlo response & PID
- 4 osc. + 4 syst. param. fitted
ORCA(/ARCA) sensitivity to supernovae

SN1987A-like simulation: 10 kpc, 3x 10^{53} \text{ erg} \\
1/6 in $\bar{\nu}_e$ \\
25% in the first 100 ms

Spectra: $E_{\nu}^{\text{SN}} = \frac{1}{4\pi(10 \text{ kpc})^2} \left[ \frac{3 \times 10^{53} \text{ erg}}{6 E_{\nu}} \times \frac{0.25}{100 \text{ ms}} \right] \frac{E_{\nu}^{\text{SN}} \exp(-\alpha+1)E_{\nu}/E_{\nu}}{\text{Normalization}}$, $\alpha=3$

$E_{\bar{\nu}_e} = 12, 14 \& 16 \text{ MeV}$

Best sensitivity for PMT coincidence level between 6 and 10

$\tilde{E}_{\bar{\nu}_e}$

$\begin{array}{|c|c|c|c|}
\hline
\tilde{E}_{\bar{\nu}_e} & N_{\text{ev}} \text{ per block} & D_{5\sigma/3\sigma} \text{ (kpc)} \text{ ARCA} & D_{5\sigma/3\sigma} \text{ (kpc)} \text{ ORCA} \\
\hline
12 & 60 & 23/30 & 16/20 \\
14 & 100 & 29/37 & 19/25 \\
16 & 150 & 37/47 & 24/31 \\
\hline
\end{array}$

>80% of all Galactic SN with a single building block
Improved performances: trigger

- **New trigger**: requires only ONE local DOM coincidence (L1) + causally-connected hits (L0) on neighbouring DOMs (do not have to be coincidences)
  (before: cluster of 3-4 causally connected L1 coincidences)

- Keep bandwidth requirements: trigger rate from pure-noise (~20 kHz) smaller than irreducible trigger rate from atmospheric muons (~50 Hz)

Increase of effective volume at low energies despite sparser detector!
Improved performances: reconstruction

- Reconstruction strategies adjusted for new trigger: allow for fainter events

Efficiency significantly improved - angular resolution unchanged

Expect an increase in sensitivity to NMH and oscillation parameters

(full chain processing ongoing)
Outlook

- New realistic layout simulated accounting for all technical constraints
- Increased detector volume, improved trigger and event reconstruction wrt to LoI
  ...working hard to determine the corresponding increase in sensitivity
- ORCA $3\sigma$ median significance for NMH could be reached in less than 3 years (with full detector)
- First detection unit in data taking since last week!
- Plan for completing the construction by 2020
  - Process for securing the funds for construction
  - of full detector launched
  
  Sept 2017: 1 string
  End 2020: full ORCA (115 strings)
BACKUP
KM3NeT: calibration

40Ca

Up to 150 Cherenkov γ per decay; stable 40K concentration

40K (β decay)

Scattered photons
Direct photons
Nanobeacon

Cross-calibration with muons

Time offset
Efficiency
Time spread

2-fold coincidence rate [Hz]

Time difference [ns]

KM3NeT preliminary
DU-2 nanobeacon visibility (DOM1, run #2621)

Calibrated hit time [ns] modulo pulse period

#hits/pulse
• Optical background mostly from $^{40}$K decays in the water
• Look for coincidences in time and PMT direction to reduce trigger rate.
• Causality further restricts space and time correlations for extra power.
• Final trigger rate $\sim$59 Hz, with 70% of events containing a cosmic ray muon.
1) Start with a track or shower hypothesis
2) Use *causality* to perform a robust *hit selection*
3) Find *vertex* and *direction* that best match hit pattern
4) Estimate track range for computing *track energy* (0.24 GeV / m)
5) Estimate *Shower energy* and direction from hit distribution after initial fit to the vertex position and time
Oscillation parameters measurement

- Achieve 2-3% prec. in $\Delta m^2_{32}$ and 4-10% in $\sin^2\theta_{23}$ (3 years)
- Competitive with LBL experiments projected sensitivity in 2020
- Early determination of the octant of $\theta_{23}$ is feasible

- Analysis based on Asimov datasets
- $\theta_{12}$, $\theta_{13}$ and $\delta m^2$ fixed
- Other param. unconstrained
- Energy scale uncertainty added (has no impact on NMH sens.)
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- Energy scale uncertainty added (has no impact on NMH sens.)
  - MH known
  - MH unknown
Non-Standard Interactions (NSI)

\[
H_{\text{eff}} = U \begin{bmatrix}
0 & 0 & 0 \\
0 & \frac{\Delta m_{21}^2}{2E} & 0 \\
0 & 0 & \frac{\Delta m_{31}^2}{2E}
\end{bmatrix} U^\dagger + V_e \begin{bmatrix}
1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\
\epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\
\epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau}
\end{bmatrix}
\]

Sterile Neutrinos (3+N Flavours)

\[
H_{\text{eff}} = U_S \begin{bmatrix}
0 & 0 & 0 & 0 & \cdots \\
0 & \frac{\Delta m_{21}^2}{2E} & 0 & 0 & \cdots \\
0 & 0 & \frac{\Delta m_{31}^2}{2E} & 0 & \cdots \\
0 & 0 & 0 & \frac{\Delta m_{41}^2}{2E} & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{bmatrix} U_S^\dagger + \begin{bmatrix}
V_e & 0 & 0 & 0 & 0 & \cdots \\
0 & 0 & 0 & 0 & \cdots \\
0 & 0 & 0 & 0 & \cdots \\
0 & 0 & 0 & 0 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{bmatrix}
\]

\[
U_S = U_{N-1,N} \cdots U_{34} U_{24}^{(c)} U_{14}^{(c)} U_{23} U_{13}^{(c)} U_{12}
\]