The KM3NeT
Neutrino Telescope
Status and outlook

Jutta Schnabel
IPA 2022
Vienna, 5 - 9th September 2022
Introducing KM3NeT

The detectors and collaboration

KM3NeT are Water Cherenkov detectors for high-energy neutrinos in the Mediterranean Sea, under construction

- **ORCA**
  - data taking with 10 lines
  - ~10 more lines ready for deployment
  - construction in progress (~50 lines)

- **ARCA**
  - data taking with 19 lines
  - funded for ~150 lines

Scientific motivation
Neutrino generation and sources
Cosmic, atmospheric or anything else

- in cosmic sources
  - classical $\pi^{+/0} \rightarrow e^{+/0} + \nu_e \nu_\mu \nu_\mu$
  - acceleration mechanisms for high energies
  - flavour composition 1:1:1 at detection

- in atmosphere
  - from cosmic ray interaction
  - background for cosmic search, signal for neutrino property study

- other interactions, e.g.
  - dark matter: WIMP annihilation
  - ...
Detection principle
Cherenkov radiation from neutrino interaction secondaries

- neutrino interaction producing high-energy charged leptons
  - Cherenkov radiation allows directional reconstruction
  - radiative processes allows energy reco
- Earth used for shielding of atmospheric muons
- resolution
  - track channel: better than 0.1° for E>100TeV
  - cascade channel: better than 2°
Oscillation Research with Cosmics in the Abyss

- **signal**: neutrinos produced by cosmic rays in atmosphere
- few-GeV energy range
- neutrino properties through oscillation studies
  - mass hierarchy
  - sterile neutrinos & other
- characteristic patterns of neutrino appearance/disappearance at different energies/pathlength
Astroparticle Research with Cosmics in the Abyss

- superior angular resolution
- decides origin, energy spectrum, flavour composition
- 87% of the sky mapped including the Galactic Center
- energies between $O(10 \text{ GeV}) - O(\text{PeV})$
Extra: Earth and sea science
Using the infrastructure for a wide science program

- access for Earth and Sea science community
  - dedicated instrumentation installable on Detection Units
  - or use of standard equipment of detectors

- standard equipment
  - water optical and oceanographic properties
  - behaviour of bioluminescent organisms
  - measurement of sea currents
  - identification of acoustic noise sources

- collaboration with the European Multidisciplinary Seafloor Observatory (EMSO)
Building the detectors
The sensors
High-precision photon detection

- Digital Optical Modules (DOMs) with 31 PMTs each
  - 3 inch diameter
  - PMT base for digitization of signal
- 1 Gb/s bandwidth per sensor module
  - typical bandwidth of ~20 Mb/s
  - mainly light emission of $K^{40}$ decay (5-8 kHz/PMT)
- similar approaches in different detectors of the Global Neutrino Network (GNN)

10.5281/zenodo.6781203

Deployment and installation

Same implementation, different detectors

- Detection Units (DUs) containing multiple DOMs
- anchored to the sea bed, uncoiled using a launcher vehicle to place DU within 1m accuracy on floor \[S. \text{Aiello et al. 2020 JINST 15 P11027}\]
- several DU deployments achievable during a sea operation
- connection to floor network using ROV
- readout of all data to shore

<table>
<thead>
<tr>
<th>Detector</th>
<th>String Spacing (m)</th>
<th>DOM Spacing (m)</th>
<th>Depth (m)</th>
<th>Instrumented mass (Mton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORCA</td>
<td>20-23</td>
<td>9</td>
<td>2470</td>
<td>5-8</td>
</tr>
<tr>
<td>ARCA</td>
<td>90</td>
<td>36</td>
<td>3400</td>
<td>500×2</td>
</tr>
</tbody>
</table>
Detector control and calibration
High precision in a varying environment

- timing calibration
  - LED pulser (nanobeacon) for inter-DOM calibration [arXiv:2111.00223 [astro-ph.IM]]
  - < 1 ns precision for relative timing between DOMs
  - individual control for each DOM, each DU base and slow control for the junction boxes at the seabed

- position calibration
  - Tilt and heading in each DOM
  - acoustic positioning system
  - precision down to around 10 cm

- results in < 0.1° precision for neutrino direction

The KM3NeT Neutrino Telescope, J. Schnabel, 05/09/2022
Data acquisition and computing
Big data: high volume, parallelized, distributed

- all digital data from the PMTs sent to shore
  - processing on computing cluster in real time
  - full MC simulation of data processing starting from neutrino generation
- physics events filtered through triggering software
  - different filters can be applied to the data
  - for full building block about 25 Gb/s reduced to 1/100
  - storage for further processing
- model based on the LHC computing model
  - hierarchical data processing system
  - distributed & parallel computing

KM3NeT-InfraDev-WP4-D4_1
All-sky neutrino flux and point sources
Cosmic neutrino searches from point-like to very extended sources

- all-sky neutrino flux (ARCA 101 days)
  - $\Phi_{90\% CL} = 17.3 \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
  - $\Phi_{\text{test}} = 1.44 \times 10^{-18} (E/100\text{TeV})^{-2.28} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
  - observation with 3$\sigma$ significance possible in about six years of operation for most intense sources

- extended source, e.g. galactic center
  - on/off-zone analysis 10.5281/zenodo.6767723

- neutrino flux from potential astrophysical neutrino sources
Neutrino oscillations

Determine basic neutrino properties

- after 3 years of data taking
  - sensitivity for neutrino mass ordering at 4.4σ (normal) and 2.3σ (inverted)
  - precision to measure $\Delta m_{32}^2$ and $\theta_{23} : 85 \cdot 10^{-6} \text{eV}^2$ (normal), $75 \cdot 10^{-6} \text{eV}^2$ (inverted) ordering
  - unitarity test of the leptonic mixing matrix: exclude $\nu_\tau$ event rate variations larger than 20% at 3σ level

$\rightarrow$ see talk be Lukas Maderer (Thursday)
Further neutrino research

ORCA research extended

- probing neutrino invisible decay (neutrino mass state $\nu_3$ decays into a sterile neutrino) (zenodo.org/record/6758959)
- sterile neutrino searches: active-sterile mixing with mass squared differences $\Delta m_{41}^2$ between $10^{-5}$ and 10 eV$^2$ (zenodo.org/record/6804567)
- non-standard interactions: sub-dominant effects in the oscillation patterns (zenodo.org/record/6785232)
- quantum decoherence from quantum gravity (zenodo.org/record/6781033)

Fig. 1: Muon neutrino survival probabilities in the presence of decay
WIMPs decaying
- with masses from 300 GeV/c$^2$ to 100 TeV/c$^2$,
- five annihilation channels: $\mu^+\mu^-, \tau^+\tau^-, \nu_\mu\bar{\nu}_\mu, b\bar{b}, W^+W^-$

sources with WIMP accumulation
- galactic center (zenodo.org/record/6785348)
- solar core (zenodo.org/record/6775092)

106 days of ARCA data available
- expecting competitive limits with increased data taking
Multimessenger alerts
Sending out alerts on neutrino events

- various alert types
  - supernova monitoring for prompt alerts, generation latency < 20 s
  - receive external EM/GW/ν alerts
  - send all flavor, all-sky ν alerts, multiplets & HE (GeV - PeV) neutrino alerts
- two pipelines
  - MeV supernova: alert
- planned alert types
  - neutrino triggers (~1/month): high energy and Multiplet neutrino alerts
  - physics triggers (~1-2/month): correlated neutrinos based on astrophysical properties (AGN/TDE/CCSN/GRB/Sun...)

zenodo.org/record/6805417
- high flux of low-energy neutrinos, generating positrons producing increase in photon rate
- CCSN detectable as excess of coincidences above the optical background KM3NeT
- building on both detectors for event identification
- injected to Supernova Early Warning System (SNEWS)
- 5σ discovery potential for Galactic and near-Galactic events

https://zenodo.org/record/6785410
Multimessenger analyses: Gravitational waves
Timing coincidences with GW alerts

- search for MeV-TeV neutrinos from compact binary mergers (LIGO and Virgo, 3rd observation period)
  - independent search focusing on the MeV and GeV-TeV ranges
  - stacking analysis for neutrino emission in different populations of mergers
- ORCA already surpassing ANTARES in GeV range

zenodo.org/record/6805229

<table>
<thead>
<tr>
<th>Limits on $\phi = E^2 \frac{d\nu}{dE}$</th>
<th>ORCA4</th>
<th>ORCA6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(all-flavour, $E^2$ spectrum)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limits [GeV/cm$^2$]</td>
<td>100-500</td>
<td>50-200</td>
</tr>
<tr>
<td>5-95% neutrino energy range</td>
<td>70 GeV - 5 TeV</td>
<td>40 GeV - 5 TeV</td>
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Multimessenger analyses: Gamma rays

Coincidences with other neutrino detections & gamma rays

- combine with gamma ray observations
  - joint binned likelihood analysis
  - for 4 different sources (VelaX et al)
  - pure leptonic / hadronic scenarios
  - gain from combined CTA/KM3NeT analysis

- follow-up IceCube neutrino alerts
  - looking for a signal excess around the best Active Galactic Nuclei (AGN) counterpart (4 alerts in 2021/22)
  - estimating background from off region
  - time window of ±1 day
  - extended search time window: 1 month

zenodo.org/record/6805372
zenodo.org/record/6785224
Open Science Program
open science policy

KM3NeT supports the aims of open data and open science and commits to implement the necessary steps wherever possible. This includes open data access, data supporting publications, open source software and open data in general including the information needed to appropriately use the data.

open data

- event data in full releases (after embargo)
- single neutrino events (alerts)
- services for background estimates/simulations
Open Science Environment

Only publishing data is not enough

data & servers

software & workflows

education & introductions

aggregators

openscience.km3net.de

The KM3NeT Neutrino Telescope, J. Schnabel, 05/09/2022
Developing with common initiatives
From institute initiatives to large-scale cooperation

Development happens in the community

● in ESCAPE/EOSC future
  ○ data lake infrastructure
  ○ common analysis platform
  ○ software sharing
  ○ common formats
● in various multi-messenger initiatives
Where are we going
Continuing building - and expanding the physics program

**Production ongoing**

Amsterdam

Nantes

Erlangen

Bologna

Athens

Genova

Catania
Thank you for your attention!