Recent results from Antares and prospects for KM3NeT/ORCA

Rencontres de Moriond
Electroweak session
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Ronald Bruijn
Universiteit van Amsterdam & Nikhef
for the Antares & KM3NeT Collaborations
Neutrino mass hierarchy

Neutrino Oscillations (incl. sterile)

KM3NeT/ORCA

Neutrino point sources
Unresolved sources/diffuse flux
Multi-messenger astronomy (‘photons’, gw)

Dark Matter
Monopoles/‘Exotics’

High Energy (TeV-PeV scale)

Low Energy (GeV scale)

KM3NeT/ARCA

Antares

Neutrino (other) Physics

Supernova neutrinos (MeV)

Neutrino Astronomy

Low Energy (GeV scale)

High Energy (TeV-PeV scale)
Neutrino mass hierarchy

Neutrino Oscillations (incl. sterile neutrinos)

Neutrino (+other) Physics

KM3NeT/ORCA

Low Energy (GeV scale)

High Energy (TeV-PeV scale)

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This talk

KM3NeT/ARCA

Neutrino Astronomy
Cherenkov light from the charged products of neutrino interactions in sea-water are detected by a sparse array of photo-multiplier tubes.

Two general event types:

Tracks
- Charged current (CC) $\nu_\mu$ interaction
- Charged current $\nu_\tau$ interaction

Showers
- Neutral current $\nu$ interaction
- $\nu_e$ CC electromagnetic shower
- Vertex of CC interaction
- $\tau$ decay shower

Sea-bed: ~2.5 km deep (KM3NeT/ORCA and Antares)
Antares

- Deep-Sea Cherenkov telescope:
  - Detect light from charged products of neutrino interactions
- 2.5 km deep, 40 km off-shore of Toulon, France
- 12 Vertical lines, each is 350 m high
- 25 storeys of 3 10” photomultiplier tubes per line
- 10 Mton instrumented volume
- First line deployed 2006, construction completed 2008
**All-flavour neutrino point source search**

Can we find sources of neutrinos in the sky?’

**Strategies:**
- Grid scan of sky-positions 1x1 degree
- GC region scan
- Sagittarius A* (Extended source: Gaussian profiles)
- Coordinates of interest
  - Candidate list of 106 (pulsars, SNRs)
  - IceCube events (13 HESE)

**Ingredients:**

**Dataset:**
- 2007 - 2015
- 2424 days lifetime
- All-flavour analysis:
  - 7622 tracks
  - 180 showers

**Background Simulation**
(Atmospheric Neutrinos and Muons)

**Likelihood ratio based test statistic**
Point Source Searches

Most significant cluster: 1.9 \sigma

Most sensitive upper limit in fraction of the sky, in particular at low energies (< 100 TeV)
Diffuse flux

‘Is there a neutrino flux resulting from unresolved sources? (on top of background)’

MC uncertainty bands include Honda +− 25 %
Enberg high/low
Detector systematics
Diffuse Flux: upper limits and best fit

Results:

33 events (19 tracks + 14 showers) in data
24 ± 7 (stat.+syst.) events from background MC

1.6σ excess, null cosmic rejected at 85% CL

Limits on 1-flavour flux normalization (100 TeV)

<table>
<thead>
<tr>
<th></th>
<th>Γ = 2.0</th>
<th>Γ = 2.5</th>
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<tbody>
<tr>
<td>$\Phi_0^{1f,90%\text{Sens.}} (100\text{ TeV})$</td>
<td>$1.2 \times 10^{-18}$</td>
<td>$2.0 \times 10^{-18}$</td>
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<tr>
<td>$\Phi_0^{1f,90%\text{U.L.}} (100\text{ TeV})$</td>
<td>$4.0 \times 10^{-18}$</td>
<td>$6.8 \times 10^{-18}$</td>
</tr>
<tr>
<td>$\Phi_0^{1f,68%\text{C.L.}} (100\text{ TeV})$</td>
<td>$(0.29–2.9) \times 10^{-18}$</td>
<td>$(0.5–5.0) \times 10^{-18}$</td>
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$\Phi_0^{1f}(100\text{ TeV}) \sim (1.7±1.0) \times 10^{-18} (\text{GeV cm}^2 \text{ s sr}^{-1})$  
Γ ~ $2.4^{+0.5}_{-0.4}$
Galactic plane

Neutrinos from interactions of cosmic rays with galactic matter

Cosmic Ray diffusion model: KRAγ
5 & 50 PeV CR cutoffs
(predicts photon+neutrino flux)

Evaluate Likelihood ratio
distribution using pseudo experiments for different
signal strengths

Get data Likelihood ratio
2007-2015
7300 tracks, 208 showers

(model dependent) upper limit
Multi-messenger program

**Bi-directional real-time:**
- Provide triggers (order 1/day over all programs)
  - Coincidence & High energy triggers
  - 5 s first response, 0.4 degree resolution
- Receive triggers, e.g.:
  - Supernovae
  - FRBs, AGNs
  - Flaring objects
  - Gravitational waves

**On- and offline Analyses, e.g.**
- Time and location coincidences
  - IceCube HESE events
  - Auger/TA cosmic ray events
  - AGN flares from HAWC

**Radio/Visible/X-rays**
MWA, TAROT, ZADKO, MASTER, SWIFT, SUPERB

**Gamma rays:**
Fermi, Hess, Magic

**Neutrinos**
IceCube

**UHE Cosmic Rays**
Auger, TA

**Gravitational Waves**
Ligo/Virgo
Gravitational Wave follow-up

Follow-up of several GW events
GW150914 (BBH merger)
GW151226 (BBH merger)
LVT151012 (candidate)
GW170104 (BBH merger)
GW170817 (BNS merger)

Features
• Optimized reconstruction
• +/-500 s search window
• Combined IceCube/Antares searches

No coincidences found

Search for coincidences of Antares/IceCube events with sub-threshold GW events ongoing
**KM3NeT/ORCA**
(Oscillations Research with Cosmics in the Abyss)

- 115 Detection Units
- 5 Mton
- 2.5 km deep, 40 km off-shore of Toulon

‘compact version of ARCA’

**Detection Units**:
- 18 optical modules per detection unit
- 9m between optical modules
- 153 m instrumented

**Digital Optical Modules**
- 31 3” PMTs in 17” sphere + electronics etc.
- Photon counting
- Directionality
- Cheap(er)

**KM3NeT Collaboration**
- 51 institutes in 15 countries (mainly European)
- 2 current deployment sites (Fr, It), one future (Gr)

**Infrastructure**:
- Sea-bed infrastructure (facility for long term high-bandwidth connection for sea-science, biology etc.)
- Optical data transmission
- *All-data-to-shore*
- Filtering/Trigger on-shore in computer farm
KM3NeT/ORCA Goal: Neutrino Mass Hierarchy

Neutrinos can change flavour during propagation as the mass eigenstates are not their flavour eigenstates.

Neutrino flavour oscillations are described by the PMNS matrix:

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{-i \delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i \delta} s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

and two mass squared differences:

Only the size (not the sign) of the large mass squared difference \( \Delta M^2 \) is known. This allows for two orderings of the neutrino mass eigenstates:

**Neutrino Mass Hierarchy (NMH)**

Also: CP violating phase \( \delta_{CP} \) unknown and octant of \( \theta_{23} \)
Determining the NMH with atmospheric $\nu$´s

In vacuum, neutrino oscillations are unaffected by the mass ordering. E.g:

$$P_{3\nu}(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_{\nu}} \right)$$

$$P_{3\nu}(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} (1 - \cos^2 \theta_{13} \sin^2 \theta_{23}) \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_{\nu}} \right)$$

In matter $\nu_e (\bar{\nu}_e)$acquires effective potential $A = \pm \sqrt{2} G_F N_e$ through charged current elastic interactions with electrons. And oscillations probabilities are modified. This affects phase and amplitude of oscillations and is strongest at resonance energy:

$$E_{res} = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2 \sqrt{2} G_F N_e} \approx 7 \text{GeV} \left( \frac{4.5 \text{ g/cm}^3}{\rho} \right) \left( \frac{\Delta m_{31}^2}{2.4 \times 10^{-3} \text{ eV}^2} \right) \cos 2\theta_{13}$$

Density profile of the path through the Earth depends on zenith angle

Measure atmospheric neutrino flux as function of energy and zenith angle!

Determining the NMH with atmospheric $\nu$'s

Relative difference in event numbers between normal and inverted hierarchy $(N_{\text{IH}}-N_{\text{NH}})/N_{\text{NH}}$

Zenith angle corresponds with different distance and density profile!
Sensitivity for Neutrino mass ordering

Sensitivity to distinguish between normal and inverted hierarchy:

**3 σ in 3 years** (median sensitivity)

Normal hierarchy + upper octant $\theta_{23}$ gives more sensitivity (5 σ in 3 years)

New (improved!) results underway!!
$\Delta m_{32}^2$ and $\sin^2 \theta_{23}$

Competitive measurements of $\Delta m_{32}^2$ (2-3%) and $\sin^2 \theta_{23}$ (4-10%)
Dark Matter

Spin-dependent scattering cross-section (Sun)

KM3NeT/ORCA sensitivity (3 years, tracks and showers)

KM3NeT preliminary

Thermally averaged annihilation cross-section (GC)

Antares limits
Competitive due to low energy threshold and good angular resolution
Other KM3NeT/ORCA Physics Topics

• Supernova detection
• Tau-neutrino appearance
• Non-Standard interactions and Sterile Neutrinos
• Neutrino Beam from Protvino to KM3NeT/ORCA
  • CP & NMH
• Low Energy Neutrino Astrophysics
• Earth Tomography and Composition
• Earth and Sea Sciences
KM3NeT/ORCA Status

First DU deployed September last year

DU behaved splendidly

Fault in commercial undersea cable (Will be repaired)

Construction of phase-1 DOMs and DUs ongoing

DUs to be deployed end of this year

Phase-2 partially funded, starting tenders for components
Summary

• Antares
  • 10 years operational and running
  • Large variety in physics results
  • Combined analyses
  • Multi-messenger astronomy

• KM3NeT/ORCA
  • Neutrino mass hierarchy
    • Strong potential to make the first measurement
    • ‘3 sigma in 3 years’
  • Broad physics program
  • Under construction
Backup
Oscillation parameters and sterile neutrinos

Evaluation of the sensitivity of Antares to oscillation parameters and sterile neutrinos work in progress
At relevant energies, neutrino/lepton scattering angle dominates.

Energy resolution < 20% for E > 4 GeV.
Supernova detection

~10 MeV supernova neutrinos can not be resolved individually

Detection of Galactic supernovae by enhanced collective coincidence rates between PMTs in DOMs

SN1987A - like supernova at 10 kpc, $3 \cdot 10^{53}$ erg, $\bar{\nu}_e$ component (1/6) with 25% in first 100 ms

At >= 6 coincidences per DOM, SN signal exceeds background.

KM3NeT/ORCA: 5 $\sigma$ discovery distance 16 (24) kpc at $\langle E_\nu \rangle = 12$ (16) MeV (KM3NeT/ARCA: up to 37 kpc)

(Note: neutrino fluxes from SN are influenced by mass-hierarchy)
τ appearance

Early physics result
3k tau events/year
Rate constrained to 10% in one year

KM3NeT Preliminary
**KM3NeT Design (ORCA)**

**Detection Units:**
- 18 optical modules per detection unit
- 9m between optical modules
- Lowest optical module 40m above seabed
- Two Dyneema® ropes
- Backbone: 2 copper conductors; 18 fibres (+spares)
- Break out of cable at each optical module
- Base module with DWDM at anchor
- Cable for connection to seafloor network

*Cost saving design*

**Infrastructure:**
- Building block of 115 strings
- Sea-bed infrastructure
- (facility for long term high-bandwidth connection for sea-science, biology etc.)
- Optical data transmission

*All-data-to-shore*
- Filtering/Trigger on-shore in computer farm
Sensitivity study

- Generate many pseudo-experiments
  - A set of ‘true’ values for oscillation parameters and systematics
  - Both normal and inverted hierarchy
  - Calculate oscillation probabilities
  - Apply resolutions, particle ID etc. (determined from simulations)
- Determine likelihood for both NH and IH cases
  - Maximize w.r.t. free parameters
- Calculate log-likelihood ratio $L_{IH}/L_{NH}$
- Calculate median sensitivity for hypothesis and time

A simpler approach based on Asimov-sets yields similar results