ANTARES and KM3NeT
Neutrino telescopes in the Mediterranean Sea

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INFN Bari

“Frontier Objects in Astrophysics and Particle Physics”
Vulcano, 20-26 May 2018
Mediterranean Neutrino Telescopes

- Physics motivation and Detection principle
  - High energy \( v \) astronomy and neutrino properties
  - Detection: large volume of transparent medium surveyed by photodetectors

- Location:
  - Northern terrestrial hemisphere:
  - Complementary to IceCube
  - Golden channel for southern sky sources. “Milky-Way optimized”

- Medium:
  - Deep Sea water
  - Very small light scattering (good angular resolution)
  - Natural backgrounds (\(^{40}\)K and biolum) can be handled.
Antares and KM3NeT Collaborations

ANTARES

KM3NeT

+ Since April 2017: CIRA Perth Australia as observer

+ Western Sydney University, Australia
ANTARES

12 lines (885 PMTs)
25 storeys / line
3 PMTs / storey
5-line setup in 2007
Completed in 2008

Mediterranean Sea (near Toulon) at 2500 m depth

AP 34 (2011) 539, NIM A656 (2011) 11
KM3NeT

- **ARCA (Astronomy)**
  - **Building Block:**
  - 115 strings
  - 18 DOMs / string
  - 31 PMTs / DOM
  - Total: 64k*3” PMTs

- **ORCA (NMH+ ν properties)**
  - Same technology, denser layout

<table>
<thead>
<tr>
<th></th>
<th>ORCA</th>
<th>ARCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>String spacing</td>
<td>23 m</td>
<td>90 m</td>
</tr>
<tr>
<td>OM spacing</td>
<td>9 m</td>
<td>36 m</td>
</tr>
<tr>
<td>Depth</td>
<td>2470 m</td>
<td>3500 m</td>
</tr>
<tr>
<td>Instrumented mass</td>
<td>5.7 Mton</td>
<td>0.6*2 Gton</td>
</tr>
</tbody>
</table>

- **Stages:**
  - **Phase 1:** 24 ARCA + 7 ORCA strings (already funded, being deployed)
  - **KM3NeT 2.0:** 2 ARCA + 1 ORCA blocks (~50% funded)
  - **Phase 3:** 6 ARCA + 1 ORCA blocks
**KM3NeT Technology**

**Digital Optical Module**
- DOM: 31 3” PMTs
- Digital photon counting
- Directional information
- Wide acceptance angle
- Cost reduction

- All data to shore
- Gbit/s on optical fibre
- Hybrid White Rabbit
- LED flasher & hydrophone
- Tiltmeter/compass

**String (Detector Unit)**

- High modulus polyethylene ropes
- Oil-filled backbone
- Low drag
- Low cost

- Unfurling started by ROV
- Reuseable

**Deployment Vehicle**
- Rapid deployment
- Multiple strings in one sea campaign

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First KM3NeT Detection Units

- Two full strings in ARCA site
  - Dec 2015 and May 2016
  - Muon reconstruction
  - Muons vs depth

- One full string in ORCA site
  - Sept 2017
  - Atmospheric neutrinos

- Some seafloor infrastructure teething problems, soon to be fixed
K40 Calibration

Up to 150 Cherenkov photons per decay; stable $^{40}$K concentration

precise PMT efficiencies vs time and location
Neutrino mass hierarchy with ORCA

- A “free beam” of known composition ($\nu_e, \nu_\mu$)
- Wide range of baselines (50 → 12800 km) and energies (GeV → PeV)

- Oscillation affected by matter (ordering-dependent):
  - maximum difference IO vs. NO at $\theta = 130^\circ$ (7645 km) and $E_\nu = 7$ GeV

- Opposite effects on neutrinos and anti-neutrinos: IO($\nu$) ≈ NO(anti-$\nu$)

But differences in flux and cross-section:
- $\Phi_{\text{atm}}(\nu) \approx 1.3 \times \Phi_{\text{atm}}($anti-$\nu$)
- $\sigma(\nu) \approx 2\sigma($anti-$\nu$) at low energies

- Approach: measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos, identify and count track and shower channel events
- Careful treatment of systematics mandatory!
**ORCA- neutrino properties**

KM3Net 2.0: Letter of Intent
http://dx.doi.org/10.1088/0954-3899/43/8/084001

**Time to measure octant**

![Graph showing time to measure octant](image)

**Mass hierarchy significance [σ]**

![Graph showing mass hierarchy significance](image)

**Median Significance [σ]**

![Graph showing median significance](image)

**KM3NeT**

3 yrs

**θ_{23}**

![Graph showing θ_{23}](image)

**θ_{23} [degrees]**

![Graph showing θ_{23} degrees](image)

**sin^2(θ_{23})**

![Graph showing sin^2(θ_{23})](image)

**KM3NeT**

**N̄H, δ_{CP} = 0°**

**IH, δ_{CP} = 0°**

**N̄H, δ_{CP} = 180°**

**IH, δ_{CP} = 180°**

**3 years**

**1σ, 2σ**

**dotted = true H not known**

**68% C.L.**

**T2K 2015**

**T2K 2020**

**NOvA 2020**

**KM3NeT (3 years)**

**MINOS**
Performance – Track events

CC $\nu_\mu$

- Golden channel
- High angular accuracy
- Enhanced volume (100’s m to a few km muon range)

Direction (ANTARES)

Direction (KM3NeT)

< 0.4° $E_\nu$ > 10 TeV

< 0.1° (E > 10 TeV)

Energy (KM3NeT)

0.3 Log E (E > 10 TeV)
Performance – Shower events

- Good energy reconstruction
- Fair angular resolution (low light scattering in water)

NC $\nu_{\text{all}}$
CC $\nu_e$

Energy (KM3NeT)

Direction (KM3NeT)

Direction (ANTARES)

$\sim 2^\circ$

1σ

90%

5%

$\nu + N \rightarrow \text{had} + \text{em}$

$\nu_e + N \rightarrow \text{had} + \text{em}$
**ANTARES – Diffuse Flux Search**

### Tracks

- All-sky / All-flavor neutrino search
- Look for excess above a given $E_{\text{th}}$
- 9 (7) yrs of data for tracks (cascades)

<table>
<thead>
<tr>
<th></th>
<th>Bkg expectation</th>
<th>Signal exception</th>
<th>Nb events measured</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Track</strong></td>
<td>13.5 +/- 4</td>
<td>3-3.5</td>
<td>19</td>
</tr>
<tr>
<td><strong>Shower</strong></td>
<td>10.5 +/- 4</td>
<td>3-3.5</td>
<td>14</td>
</tr>
</tbody>
</table>

$\Rightarrow 1.6\sigma$ excess, null cosmic rejected at 85% CL

### Showers

- $\Phi (100 \text{ TeV}) = (1.7 \pm 1.0) \times 10^{-18} \text{ (GeV cm}^2 \text{ s sr)}^{-1}$
- $\Gamma = 2.4 \pm 0.5$

[ApJL 853, L7 (2018)]
KM3NeT- Diffuse Flux

KM3NeT/ARCA is expected to observe the IC signal in less than 1 yr.

- Precise characterization (spectral shape, flavor composition, anisotropy)
- Excellent sensitivity in the galactic plane: identify gal/extra-gal components?
Galactic Plane

- ν’s from CR-gas interactions
- KRA_γ model of diffuse gammas
  - CR local features and gamma observations reproduced
- Search strategy:
  - Signal map according to KRA_γ modelling
  - Two ref models: 5 PeV and 50 PeV cutoffs
- Data 2007-2015
  - 7300 Tracks and 208 showers
- Results:
  - No excess of events
  - 90% flux limits for ref models:
    - < 1.1 Φ(5 PeV)  < 1.2 Φ(50 PeV)
  - Not the source of “spectral anomaly” (IC spectrum in hemispheres)
**Antares - Point Sources**

- **Sample:**
  - 2007-2015
  - 2424 days of live time
  - 7629 Tracks, 180 Showers (all flavour analysis)

- **Full-sky Search**

- **Candidate list Search**
  - 106 objects (pulsars, SNRs, etc.)
  - 13 IceCube HESE tracks

- **Galactic Centre Region**
  - Ellipse 15°x 20°
  - Test:
    - Spectral indices $\gamma = 2.1, 2.3, 2.5$
    - Extension $\sigma = 0.5^\circ, 1.0^\circ, 2.0^\circ$

- **Sagittarius A* location**
  - Extended source. Gaussian profile of various widths:
    $\sigma = 0^\circ, 0.5^\circ, 1.0^\circ, 2.0^\circ$

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*Phys. Rev. D 96, 082001 (2017)*
**Full sky**
Most significant cluster 
(\(\alpha, \delta\)) = (343.8°, 23.5°)
Post-trial significance: 
5.9% or 1.9\(\sigma\)
Upper limit on the neutrino flux: 
\(E^2 d\phi/dE = 3.8 \times 10^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\)

**13 HESE tracks**
Most significant cluster: 
(\(\alpha, \delta\)) = (130.1°, -29.8°)
at a distance of 1.5° from the 
HESE track with ID 3
Post-trial significance: 
20% or 1.3\(\sigma\)
Upper limit on the neutrino flux: 
\(E^2 d\phi/dE = 2.1 \times 10^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\)

**Galactic Centre**
Most significant cluster: 
(\(\alpha, \delta\)) = (273.0°, -42.2°)
E\(^{-2.5}\) spectrum
Point-like source
Post-trial significance: 
30% or 1.0\(\sigma\)

**Candidate List:**
Most significant cluster: 
HESSJ0632+057
(\(\alpha, \delta\)) = (98.24°, 5.81°)
Post-trial significance: 
13% or 1.5\(\sigma\)
Upper limit on the neutrino flux: 
\(E^2 d\phi/dE = 2.4 \times 10^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\)

**Sagittarius A**: 
(\(\alpha, \delta\)) = (266.42°, -29.01°)
Point-like source (\(\sigma = 0°\)) and
Extended source (\(\sigma = 0.5°, 1.0°, 2.0°\))
Largest excess as point-like
Pre-trial significance: 
22% or 1.2\(\sigma\)

ANTARES- Full sky and candidate list searches

Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches

ANTARES provides the best results for low declination or soft spectra or 100 TeV-ish cutoff
KM3NeT/ARCA Expectations (E^{-2} Spectrum)

KM3NeT/ARCA is expected to have more than one order of magnitude better sensitivity than IC in the Southern sky.

- Due to the good angular resolution for shower events, the shower point-source search is also very efficient.

- Expect better performances for the transient neutrino sources (GRB, AGN…)

Preliminary
KM3NeT/ARCA - point sources

Specific galactic sources

<table>
<thead>
<tr>
<th>Source</th>
<th>δ</th>
<th>extension</th>
<th>Φ₀</th>
<th>Γ</th>
<th>Eₘₐₓ</th>
<th>β</th>
<th>γ-ray data</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J1713.7-3946 (1)</td>
<td>-39.77°</td>
<td>0.6°</td>
<td>1.68</td>
<td>1.72</td>
<td>2.1</td>
<td>0.5</td>
<td>13</td>
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<tr>
<td>RX J1713.7-3946 (2)</td>
<td>-39.77°</td>
<td>0.6°</td>
<td>0.89</td>
<td>2.06</td>
<td>8.04</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Vela X</td>
<td>-45.6°</td>
<td>0.8°</td>
<td>0.72</td>
<td>1.36</td>
<td>7</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Vela Jr</td>
<td>-46.36°</td>
<td>1°</td>
<td>1.30</td>
<td>1.87</td>
<td>4.5</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>HESS J1614-518 (1)</td>
<td>-51.82°</td>
<td>0.42°</td>
<td>0.26</td>
<td>2.42</td>
<td>-</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td>HESS J1614-518 (2)</td>
<td>-51.82°</td>
<td>0.42°</td>
<td>0.51</td>
<td>2</td>
<td>3.71</td>
<td>0.5</td>
<td>17</td>
</tr>
<tr>
<td>Galactic Centre</td>
<td>-28.87°</td>
<td>0.45°</td>
<td>0.25</td>
<td>2.3</td>
<td>85.53</td>
<td>0.5</td>
<td>18</td>
</tr>
<tr>
<td>MGRO J1908+06 (1)</td>
<td>6.27°</td>
<td>0.34°</td>
<td>0.18</td>
<td>2</td>
<td>17.7</td>
<td>0.5</td>
<td>see text</td>
</tr>
<tr>
<td>MGRO J1908+06 (2)</td>
<td>6.27°</td>
<td>0.34°</td>
<td>0.16</td>
<td>2</td>
<td>177</td>
<td>0.5</td>
<td>see text</td>
</tr>
<tr>
<td>MGRO J1908+06 (3)</td>
<td>6.27°</td>
<td>0.34°</td>
<td>0.16</td>
<td>2</td>
<td>472</td>
<td>0.5</td>
<td>see text</td>
</tr>
</tbody>
</table>

γ→ν flux conversion:


Galactic sources in reach
Constrain hadronic component
Starting-event study in pipeline and also very promising
Multi-messenger Programme

- **Advantages:**
  - A-priori interesting sources or events
  - Reduced background:
    - Uncorrelated between techniques
    - Transient/short time events
    - Spatial location
  - Fully exploit the v telescopes features:
    - Continuous monitoring
    - Wide angle survey
    - High efficiency, low latency (all-data-to-shore, fast reconstruction)

- **Send and receive alerts:**
  - **Alerts from:**
    - Flaring AGNs, X-ray binaries
    - GRBs, FRBs
    - Gravitational waves
    - SN Ib,c
  - **Alerts sent out if:**
    - High energy neutrino
    - Multiplets
    - Preferred direction

- **GeV-TeV γ-rays**
  - *Fermi, HESS, HAWC*

- **Radio-Visible-X**
  - *MWA, SUPERB, TAROT, ZADKO, MASTER, Swift*

- **UHE Cosmic rays**
  - *Auger, TA*

- **Gravitational waves**
  - *LIGO-VIRGO-EGO*
Summary

ANTARES:
• 10 year experience. Thousand of neutrinos reconstructed (tracks and showers)
• Excellent resolution (down to 2° for showers!)
• Diffuse flux: a small excess at high energy compatible with a cosmic signal
• Point sources: best limits for southern sky Galactic sources (E<100 TeV)
• A lively and vibrant multi-messenger programme. We need a larger detector!

KM3NeT:
• KM3NeT 2.0:
  ESFRI Roadmap 2016, APPEC European Strategy 2017
  ARCA: high-resolution follow up of IceCube flux (5 sigma within 1 yr)
  ORCA: Measure neutrino mass hierarchy (3 sigma in 4 years)
• On the move!
  2 ARCA and 1 ORCA strings in water
• Mass production of DUs starting (about 400 DOMs mounted, and counting...)