Neutrino astronomy and oscillation research in the Mediterranean:

ANTARES and KM3NeT
• **PART 1:** Introduction to physics motivations for Cherenkov Neutrino Telescopes
• **PART 2:** ANTARES: the precursor of under-sea neutrino telescope
• **PART 3:** KM3NeT: the next generation of neutrino telescope in the Mediterranean Sea
Motivations for Astrophysics Neutrino Measurement

- Low energy particles
- Protons (50 Mpc)
- HE $\gamma$ (10 Mpc)
- Neutrons (unstables)
- Low energy particles
- Galactic Dark Matter
- Extra Galactic Dark Matter

Exotics:
- Magnetic Monopoles
- Nuclearites
- Micro-Qausars
- Fermi-Bubbles
- SNR

- TeV-PeV
- GeV-TeV

- AGN
- GRB
- PeV-EeV
- >EeV
**Very small neutrino cross-sections** with matter $\sigma_{\nu N} \sim 7.8 \times 10^{-36} \left(\frac{E_{\nu}}{\text{GeV}}\right)^{0.36} \text{ cm}^2$ for $E_\nu > 1 \text{ TeV}$

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**Multi-km$^3$ volume size detector**

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**Glashow Resonance**
Enhancement of cross-section in the anti-$\nu_e - e^-$ interaction @ $\sim 10^6 \text{ GeV}$
Good for energy calibration
• Astronomy:
  \( \downarrow \mu_{\text{atm}} \Rightarrow \) looking for upgoing (\( \uparrow \))

• Energy spectrum deformation
  \( \uparrow \nu_{\text{atm}} \Rightarrow \) energy cuts (\( E > 10-100 \text{ TeV} \))

Quantity of detected light is a good energy proxy. In case of cascades the telescope can act as a calorimeter. Need of very large instrumented volumes.

Exploiting the background:

\( \mu_{\text{atm}} \Rightarrow \) study of sytematics
\( \nu_{\text{atm}} \Rightarrow \) neutrino oscillations
ANTARES and KM3NeT: neutrino telescopes in the Mediterranean Sea.

34 European Institutes
8 Extra-European Institutes

* ANTARES
● KM3NeT

Sydney
Perth (observer)*

8 Extra-European Institutes

34 European Institutes

* ANTARES
● KM3NeT

Sydney
Perth (observer)*

Antares
KM3NeT

Deployment sites

ANTARES ORCA

ANTARES ORCA

Deployment sites

34 European Institutes
8 Extra-European Institutes
The ANTARES undersea neutrino telescope:

- Running since 2007
- 885 10” PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey
- 0.05 km³ instr. vol.

450 m
40 km to shore

Junction Box
Interlink cables
One possibility to measure the pointing accuracy is to measure the shadow of the Moon, i.e. the deficit in the atmospheric muon flux in the direction of the Moon induced by absorption of cosmic rays.

Data from 2007-2016 -

Moon shadow observed at 3.5 $\sigma$ significance level;

Angular resolution for downgoing tracks $\sigma_{\text{res}} = 0.73^\circ \pm 0.14^\circ$

$\frac{dn}{d\delta^2} = k(1 - \frac{R_{\text{Moon}}^2}{2\sigma_{\text{res}}^2} e^{-\frac{\delta^2}{2\sigma_{\text{res}}^2}})$

The position of the Moon shadow is consistent with not shifted pointing.

$\begin{align*}
68.27\% \text{ C.L.} \\
95.45\% \text{ C.L.} \\
99.73\% \text{ C.L.}
\end{align*}$
Data taking period: 2007-2015

Reconstructed events after quality cuts:

<table>
<thead>
<tr>
<th></th>
<th>Bkg expectation</th>
<th>Signal expectation</th>
<th>N events measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracks</td>
<td>13.5+/-4</td>
<td>3-3.5</td>
<td>19</td>
</tr>
<tr>
<td>Showers</td>
<td>10.5+/-4</td>
<td>3-3.5</td>
<td>14</td>
</tr>
</tbody>
</table>

- 1.6 \( \sigma \) excess
- Results compatible with IceCube diffuse flux
“KRA Gamma model” has been introduced recently to explain the high-energy gamma ray diffuse Galactic emission. This model reproduces Fermi & Milagro data. 

Combined U.L at 90% CL (blue line) on the 3-flavor neutrino flux of the KRA\(\gamma\) model (5-50 PeV cutoff). 

Results

Total flux contribution of diffuse Galactic neutrino emission <8.5% of the total diffuse IC astrophysical signal (E_{\nu} > 30 TeV) [ApJ 809:98(2015)].

Combined U.L. (ANTARES+IceCube) excludes the diffuse Galactic neutrino emission as the major cause of the “spectral anomaly” between the two hemispheres measured by IceCube.
Full-sky search (2007 – 2015; livetime 2424 days)
1°x1° squares over ANTARES visible sky
7622 track-like, 180 shower-like neutrino candidates

Most significant cluster of the full-sky search (1.9\(\sigma\) post-trial significance)
\(\alpha = 343.8^\circ\; \delta = 23.5^\circ\)

Candidate list searches:
106 known astrophysical objects (Pulsars, SNRs, …), 13 IceCube HESE tracks

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

Most sensitive limits for a large fraction of the southern sky, especially at neutrino energies below 100 TeV

Phys. Rev. D 96, 082001
Gamma-ray Coordinates Network (GCN)

https://gcn.gsfc.nasa.gov/
Online searches for $\nu$’s associated to IceCube-170922A EHE

- Direction in ANTARES: 14.2° below horizon
- Use of a fast online algorithm that selects only upgoing candidates
- No upgoing $\nu$ candidate recorded within 3° of IceCube event and within ±1 h time-window centred on the event time
- No events within ±1 day

Time-integrated search for neutrinos from TXS 0506+056

- Maximum likelihood ratio approach used in PS searches (Phys. Rev. D 96, 082001)
- Expected background from the source in 2424 days livetime:
  - 0.18/deg$^2$ for track-like
  - 0.004/deg$^2$ for shower-like events
- # of signal events, $\mu_{\text{sig}}$, fitting the likelihood signal function for the source: $\mu_{\text{sig}} = 1.03$
- Pre-trial p-value of 2.6% to be compatible with background only
- In the list of 107 pre-selected sources, only two have smaller p-value

Time-dependent search for neutrinos from TXS 0506+056

- Two time window shapes: Gaussian (500 days) and rectangular (158 days)
- Selection cuts which optimise the MRF with flux $\sim E^{-\gamma}$ ($\gamma = 2.0, 2.1, 2.2$)
- No signal found after data unblinding.
4 bright GRBs have been selected: 
GRB080916C, GRB110918A, GRB130427A and GRB130505A

**Upper limits**
Two models investigated:
- internal shock (IS)
- photospheric (PH)

**Constraints** on baryonic component $f_p$ and Lorentz factor $\Gamma$

- 90% C.L. (solid line)
- 50% C.L. (dashed line)

The red dot shows the benchmark values $f_p = 10$ and $\Gamma = 316$.

(a) IS constraints on GRB130505A.
(b) PH constraints on GRB130427A.
Recent spotlight on the GW events detected by the Ligo-Virgo Collaboration:

- GW150914 (BBH merger)
- GW151226 (BBH merger)
- LVT151012 (candidate)
- GW170104 (BBH merger)
- GW170817 (NS merger)

So far no coincidences with neutrino from the region of interest at 90% C.L.:

The jet of the NS-NS event (GW170817) was not aligned to our Line of Sight to provide a visible neutrino signal → upper limit on the neutrino fluence from each events over the whole spectrum.

ANTARES and a few KM3NeT lines operational for Virgo/LIGO run 03!
• **ANTARES** Alert VHE (Sept. 1, 2015) $\implies$ E~50 TeV; RA=246.3°; $\delta$=-27.4°

• Sent after 10 s to MASTER, Swift-XRT

![Graph showing X-ray emission over time](image)

- Unknown, relatively bright and variable X-ray source-(0.5-1.4)x10^{-13} erg cm^{-2} s^{-1} detected by Swift XRT 9h after the ATEL
- Great interest in the community (15ATels+6 GCN)
- Later, the X-ray source associated with a **young accreting G-K star**, or a binary system of active stars undergoing a **flaring episode** with X-ray emission.
- No relevant accelerator of CR, then no $\nu$ source, is connected to this object.

- IceCube: no event detected
- H.E.S.S.: No VHE transient source
  $\Phi(E > 320\text{GeV};99\%\text{C.L.}) < 2.7\times10^{-8}\text{m}^{-2}\text{s}^{-1}$

**Globular cluster M4**

Antares

X-ray source

$0.14^\circ$ separation

Neutrino

USNO-B1: 0626-0501169
Rmag = 12.6
Fast Radio Bursts (FRB):
- arXiv:1807.04045

Neutrino oscillations and NMH:
- ...Works on going

Indirect Dark Matter searches
- Physics of the Dark Universe 16 (2017) 41
- JCAP05(2016)016

Magnetic Monopoles:
- JHEP 07 (2017) 054

Sea and Earth Science
- Scientific Reports 7(2017): 45517
- Jou. Geophysical Research 122(2017) 2291
- Ocean Dynamics 64 (2014)507–517
- Deep-Sea Research I 58(2011)875

During operation on the ANTARES/ KM3NeT site, last summer
Deep-sea array of photo-sensors
31x3”-PMTs in one Digital Optical Module (DOM)
18 DOMs per Detection Unit, DU
115 DUs per building block
All data to shore

KM3NeT 2.0

KM3NeT - The next generation neutrino telescope.
The common element is the Detection Unit (DU): vertical structure hosting 18 Digital Optical Modules (DOMs), each one equipped with 31 3” PMTs and 1 piezo acoustic sensor for the positioning system.

**Astronomy Research with Cosmics in the Abyss (ARCA)**

Study of astrophysical neutrinos

2 building block in the Italian site
vertical spacing: ~35 m
horizontal spacing: ~90 m

**Oscillation Research with Cosmics in the Abyss (ORCA)**

Study of neutrino mass hierarchy

1 building block in the French site
vertical spacing: ~6 m
horizontal spacing: ~20 m
• 31x3” PMTs (Hamamatsu R12199-02) in 17” glass sphere
• Front-end electronics, digitisation, optical signal → glass fibre
• Single penetrator

Advantages:
• Increased photocathode area
• 1-vs-2 photo-electron separation → better detection of coincidences
• Directionality
• Cost / photocathode area
• Minimal number of penetrations → reduced risk

Each DOM implements a dedicated FPGA firmware for DAQ with an embedded software for slow-control. Communication is set via 1Gbps ethernet connection to shore. DOMs are the submarine nodes of the full DAQ LAN (>10 GbE on-shore). Time synchronisation (better than 1 ns) is achieved exploiting the White Rabbit (CERN) technology.
The DU is furled in the Launcher Vehicle (the LOM), which is deployed on the sea-bed.

Mechanical release by ROV

Unfurling

Several DUs per sea operation
ORCA

- Successful deployment & operation of first string (Sept 2017)
- Cable problem, replacement in summer 2018, resume operations thereafter

DOM and DU assembly proceeding Deployment after repairs, consistent with schedule

ARCA

- 3 strings deployed Dec 2015 & May 2016
- 2 out of 3 operated, string #3 with short in power system, recovered
- New sea-operations by Fall 2018, resume of operations thereafter.
- Full restoration of sea-bed network by mid-2019

Paper in preparation
Expected $5\sigma$ significance on diffuse IC flux in $< 1$ year:
Tracks per year:
• 6 signal
• 4 background
Cascades per years:
• 16 signal
• 9 background

KM3NeT and IceCube are complementary in their field of view, energy range and flavour coverage

**PRELIMINARY**

KM3NeT-ARCA significance for two of the most promising sources.
Significant discovery potential for extragalactic sources, complementing IceCube field of view.

Note: comparison between detector sensitivities (not discovery potential at a given time. IceCube will have additional ~10 years of data taking w.r.t. KM3NeT)
Signature of the neutrino mass hierarchy

→ energy-zenith $\zeta$ distribution of atmospheric neutrinos

Measurement requires

- best possible resolution in energy and zenith
- separation $\nu_e/\nu_\mu$
- detailed understanding of systematics

$$\nu_e + \bar{\nu}_e \ (\text{NH - IH}) / \text{NH}$$

$$\nu_\mu + \bar{\nu}_\mu \ (\text{NH - IH}) / \text{NH}$$

$E_{\text{res}} = 25\%$  $\zeta_{\text{res}} = (m_p/E)^{1/2}$
Neutrino mass hierarchy significance

Measurement of $\sin^2\theta_{23}$ and $\Delta m^2_{32}$
• ANTARES: more than 10 years of continuous data taking!  
  … and still stably ongoing!

• ANTARES: neutrino telescope in the Northern hemisphere looking for neutrinos in coincidence with GW events expected during the Ligo/Virgo O3, waiting for KM3NeT
  • Then, KM3NeT in the Mediterranean Sea.

• ANTARES: solid results from various searches of astrophysical neutrino emission.
  • (point-like, diffuse, extended regions, dark matter, …)

• Active multi-messenger program:
  • Neutrino alerts distribution, participation to GCN and AMON
  • External alerts reception, prompt analysis
  • Offline multi-messenger analysis.
  • Combined analyses with IceCube (point sources, galactic plane, time correlation…).

• Outlook and conclusions.
  • Best practice and multi-messenger searches ported to KM3NeT!
  • Neutrino astronomy is on its way to increased sensitivity and full sky coverage
  • Neutrinos are an indispensable ingredient of multi-messenger astronomy
  • Neutrino telescopes also offer opportunities for precision measurements in neutrino physics
  • KM3NeT ARCA: Confirmation of IceCube flux in less than one year
  • KM3NeT ORCA: Competitive with JUNO, determination of neutrino mass hierarchy in ~3 years
Thank You
16 FRB (Parkes, UTMOST, ASKAP) → 12 in the FoV during the data taking.
± 6h search period in 2°.
Event selection optimization – 1 seen neutrino = 3σ discovery.
No events found → limits set.

<table>
<thead>
<tr>
<th>FRB</th>
<th>$z_{DM}$</th>
<th>$T_0$ (UTC)</th>
<th>RA (°)</th>
<th>dec (°)</th>
<th>radio telescope</th>
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<td>101.04</td>
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<td>03:52:24</td>
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<td>-40.78</td>
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<td>20:05:45</td>
<td>170.79</td>
<td>-5.02</td>
<td>ASKAP</td>
</tr>
</tbody>
</table>

Fluence 90% C.L for $E^{-\gamma}$

- $\gamma = 1.0$
- $\gamma = 2.0$
- $\gamma = 2.5$

arXiv:1807.04045
Multi Messenger Searches: neutrino alerts from ANTARES.

ANTARES real time alerts:
- Doublet of neutrinos: ~0.04 events/yr
- Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events/yr
- Single HE neutrinos: ~5 TeV, 20 ev/yr
- Single VHE neutrinos: ~30 TeV, ~3-4 ev/yr

Sent neutrino alerts (2009-2018)

277 to robotic telescopes
+15 to Swift
+8 to INTEGRAL
+22 to MWA (radio)
+2 to HESS


2018 - 30/07/2018
Flux decreases with energy
Need larger and larger detectors
WIMPs accumulate in massive celestial objects (Sun, Galactic Centre, …)
- Neutrinos could be produced in WIMP-WIMP annihilation
- Clean signal and low expected background

**Ingredients** used in the analysis:
- Signal energy spectra for each considered WIMP mass and annihilation channel:
  \[ WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+ \tau^-, \mu^+ \mu^-, \nu\bar{\nu} \]
- Spatial distribution of dark matter in the source:
  - Point-like (Sun)
  - NFW, Burkert, McMillan halos (GC)

- **No excess** above background observed;
- Upper limits derived, as a function of the WIMP mass and annihilation channel on
  - spin-(in)dependent WIMP-nucleon scattering cross-section (Sun)
  - thermally averaged annihilation cross-section (Galactic center)
KM3NeT: ORCA neutrino candidate.

Evt: id=3860 run_id=2609 #hits=87 #mc_hits=0 #trks=0 #mc_trks=0

hit time(ns) vs z(mb)
SHOWERS:
\( \nu_e \) CC, \( \nu_{\text{all}} \) NC

Tracks:
\( \nu_{\mu} \) CC

Ang. Res. < 0.4 deg
@ \( E_\nu > 10 \text{ TeV} \)

Ang. Res. < 0.1 deg
@ \( E_\nu > 100 \text{ TeV} \)

\( \nu_{\mu} \) CC

Ang. Res. < 3 deg

\( \nu-\mu \) angle

E. IC

Ang. Res. < 2 deg

\( 90\% \, 1\sigma \)

ANTARES - KM3NeT ARCA: track/shower angular resolutions.
The neutrino telescope timeline

- **ANTARES**
- **KM3NeT/ARCA**
- **KM3NeT/ORCA**
- **KM3NeT/Neutrino astronomy**
- **KM3NeT/Neutrino oscillations**
- **IceCube Gen2**
- **IC Upgrade**
- **IceCube Gen2**
- **Baikal/GVD-1**
- **Baikal/GVD (next steps)**
- **Baikal GVD**

Timeline:

- **2015**
- **2020**
- **2025**
- **2030**

Operation
Construction
Distribution of ANTARES events in the $(\text{RA}, \delta)$ coordinates around the position of TXS 0506+056. The inner (outer) green line depicts the $1^\circ$ ($5^\circ$) distance from the source. The blue (red) points indicate track (shower)-like events. Different tones of red and blue correspond to the values assumed by the energy estimators.
Transit Time Spread = FWHM of main peak \( \sim 1.5 \text{ ns} \)

ToT peak: 26.8561 ns
Prepulses: 0.00292931%
Delayed: 0.0709103%
Afterpulses: 0.476641%

PMT working point: \( \sim 1200 \text{ V} + 0.5 \text{ p.e. threshold} \)

Dark rates \( \sim O(300 \text{ cps}) \)

JINST Vol 11, 2016
ANTARES, the largest underwater neutrino telescope in the Northern Hemisphere, has been continuously operating since 2007 in the Mediterranean Sea. The transparency of the water allows for a very good angular resolution in the reconstruction of signatures of interactions from neutrinos of all flavors. This results in unprecedented sensitivity for neutrino source searches in the Southern Sky at TeV energies, so that valuable constraints can be set on the origin of the cosmic neutrino flux discovered by the IceCube detector.

Building on the successful experience of ANTARES the next generation KM3NeT neutrino telescope is now under construction in the Mediterranean Sea to significantly boost the sensitivity. Two detectors with the same technology but different granularity are under construction at two sites and will focus on high energy cosmic neutrinos (ARCA with Gton instrumented volume, offshore Capo Passero, Italy) and on atmospheric neutrinos at low energies down to a GeV to address atmospheric neutrino oscillations (ORCA with Mtons instrumented volume, offshore Toulon, France). The basic KM3NeT detection element, the Digital Optical Module (DOM), houses 31 three-inch PMTs inside a 17 inch glass sphere. This multi-PMT concept yields significant allows for an accurate measurement of the light intensity (photon counting) and offers directional information with an almost isotropic field of view, at a reduced cost.

The presentation will provide an overview on the newest results from Antares and an outlook towards the construction plan and exciting science potential of KM3NeT.