Fishing for neutrinos: Astroparticle and oscillations research with cosmics in the Abyss
Neutrino telescopes: science

Supernova
Solar flares

Atmos neutrinos
$\nu$ oscillations
$\nu$ mass ordering
Sterile, NSI, ...

Dark matter
Monopoles, Nuclearites,...

Cosmic neutrinos
Cosmic rays
Origin and production mechanism of HE CR

MeV to PeV energies

KM3NeT-ORCA  ANTARES  KM3NeT-ARCA
+ oceanography, biology, bioacoustics, seismology,...
Main question: what is the origin and the role of the cosmic rays in the Universe?

- Discover ~100 years ago but still unknown origin
- Spectrum over 32 orders of magnitude
- Mysteries at the ultra high energies $> 10^{20}$ eV, which acceleration mechanism?
  - Which sources?
  - Which cosmic evolution?
- Connection to the other messengers ($\nu$, $\gamma$, GW)
- At the heart of the non-thermal astronomy

Motivations for neutrino astronomy
Neutrinos: neutral, stable, weakly interacting
- not absorbed by background light/CMB → access to cosmological distances
- not absorbed by matter → access to dense environments
- not deviated by magnetic fields → astronomy over full energy range

‘Smoking gun’ signature for hadronic processes

Correlated in time/direction with electromagnetic and gravitational waves

New window of observation on the Universe
Multi-messenger connection (0\textsuperscript{th} order)

**Photo-hadronic interactions of CR**

\[ p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases} \]

**Neutrino emission**

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu, \]

\[ \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \]

**Photon emission**

\[ \pi^0 \rightarrow \gamma + \gamma \]

Most of the observed radiation is EM ☀

\[ E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma \]
A new window on the Universe

The Universe is opaque to EM radiation above 10-100 TeV, but not to neutrinos
Neutrinos fluxes from MeV to PeV

\[ \sigma(\nu p)/\sigma(\gamma p) = 10^{-7} \text{ at } 1 \text{ TeV} \]

Need very large detectors

IceCube
GVD
KM3NeT-ARCA
1 Gton

ANTARES
20 Mton

KM3NeT-ORCA
8 Mton

SuperK
50 kton
Very large volume neutrino telescopes

Mediterranean Sea
Saltwater: K40
Bioluminescence

Lake Baikal
Freshwater
Chemiluminescence

Antarctic
Ice
Dust, air bubbles
Current H20 (liquid+solid) neutrino telescopes

Antares
Med. Sea (-2.4km)
12 strings
885 PMTs (10“)
1/100 km3

Baikal-GVD
Lake Baikal (-1.3km)
1 cluster =8 strings
0.4 km3 (8 clusters)
2304 PMTs (10“)

KM3NeT
Med. Sea (-2.4km)
3BB (345 strings)
6000*31 PMTs (3“)
1.1 km3

IceCube
South Pole (-2.4km)
86 strings
5160 PMTs (10“)
1 km3

Mediterranean ~ 43° North

South Pole
Event Topologies

CC $\nu_\mu$ track like events
- good pointing

CC $\nu_e$+ all flavours NC shower like events
- good energy reconstruction
- neutrino or charged lepton

CC $\nu_\tau$
- “double bang”

BACKGROUND !!
- atmospheric muon

$\nu_\tau \rightarrow \tau + \text{shower}$
Resolutions

Angular resolution $10^\circ/1^\circ$ at 100 TeV for Ice/water

Energy resolution $\sim 5%$

Precision **multi-flavour** astronomy with water based telescopes
Diffuse flux observed by IceCube

$\nu_e$

IceCube Preliminary

$\nu_\mu$

IceCube 7-10 yrs

<table>
<thead>
<tr>
<th>Name</th>
<th>Approx. Neutrino Energy</th>
<th>Direction</th>
<th>Dominant Flavor</th>
<th>Unbroken Spectral Index</th>
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</thead>
<tbody>
<tr>
<td>HSE</td>
<td>50 TeV - 5 PeV</td>
<td>All-sky</td>
<td>$e, \mu, \tau$</td>
<td>2.89</td>
</tr>
<tr>
<td>Cascades</td>
<td>5 TeV - 5 Pev</td>
<td>All-sky</td>
<td>$e, \tau$</td>
<td>2.48</td>
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<tr>
<td>NuMu</td>
<td>50 TeV - 10 PeV</td>
<td>Northern sky</td>
<td>$\mu$</td>
<td>2.28</td>
</tr>
</tbody>
</table>
Site ANTARES/KM3NeT

Toulon

Institut M. Pacha

câble sous-marin de 40 km

Site ANTARES
42 50'N, 6 10'E
ANTARES Detector

- 12 lines (885 PMTs)
- 25 storeys / line
- 3 PMTs / storey
- 5-line setup in 2007
- Completed in 2008
- Dismantle 2022
Data: 50 events (27 tracks + 23 showers)

Background expectation (atm. flux, HONDA + Enberg, scaled $x \sim 1.25$) : $36.1 \pm 8.7$ (19.9 tracks and 16.2 showers) – stat. + syst.

Results not really constraining… but fully compatible with IceCube

Updated and improved analysis coming soon
Diffuse cosmic flux II

Combined tracks & showers likelihood fitting:

Cosmic flux:

\[ \Phi_{100 \ TeV} = (1.5 \pm 1.0) \times 10^{-18} \ \text{GeV}^{-1} \ \text{cm}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1} \]

\[ \Gamma = 2.3 \pm 0.4 \]
5σ in ~ 0.5 year for the full detector (230 DUs)
5σ ~ 1 year for one block detector (115 DUs)
Galactic plane

Guaranteed galactic neutrinos from CR interactions with matter

Analysis uses full model morphology & spectrum – tracks and cascades

ANTARES Limit is a factor 1.2 above the ‘KRAγ’ model.

ANTARES updated analysis soon

KM3NeT sensitivity very promising
Neutrino Sources?

- Supernova Remnants
- Kilonova
- Blazars
- Dark matter
- Supernova
- Gamma ray bursts
Point source searches

Updated: ANTARES 13 years (3845 days of live time): 10162 tracks and 225 showers

2\textsuperscript{nd} most significant cluster:
RA=343.8°  δ=+23.5°
pre trial: 4.2 σ
Close to blazar MG3 J225517+2409 (orange star)

The most significant cluster:
RA=39.6°  δ=+11.1°
pre trial: 4.3 σ (48% post)
Within 1 degree of J0242+1101 (orange star)
Candidate list

121 sources investigated

$\delta = \sin^{-1}(0.8 - 0.6 - 0.4 - 0.2 - 0)$

$E^2 d\Phi/dE, [\text{GeV cm}^{-2} \text{s}^{-1}]$

1st: J0242+1101

Pre (post) trial: 3.8$\sigma$ (2.4$\sigma$)

2nd: TXS 0506+056

Pre (post) trial: 3.1$\sigma$ (2.6$\sigma$)

4 muon events within 1°
J0242+1101: potential radio-γ-ν association
KM3NeT: sources

Point sources

Extended sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Decl, RA [°]</th>
<th>Ext [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXJ 713.7-3946</td>
<td>-39.77, 258.8</td>
<td>0.6 (disk)</td>
</tr>
<tr>
<td>HAWC J1825-134</td>
<td>-13.37, 276.4</td>
<td>0.53 (Gauss)</td>
</tr>
<tr>
<td>HAWC J2019+368</td>
<td>36.76, 304.92</td>
<td>0.356 (Gauss)</td>
</tr>
<tr>
<td>HAWC J1907+063</td>
<td>6.32, 286.91</td>
<td>0.67 (Gauss)</td>
</tr>
</tbody>
</table>
Multi-messenger network

**ANTARES/ KM3NeT**

- **Neutrinos**
  - *IceCube, GVD-Baikal*

- **Cosmic Rays**
  - *Pierre Auger, Telescope Array*

- **Grav Waves**
  - *LIGO, VIRGO*

- **Radio/Optical/X-ray**
  - *VLBI, MWA, TAROT, MASTER, Swift, INTEGRAL*

- **GeV/TeV γ rays**
  - *Fermi, H.E.S.S. HAWC*

**ANTARES real-time alerts**

- Time to send alert 5s, median resolution 0.5 deg
- A few 10 alerts per year sent
1st KM3NeT treatment of external alert: PKS 0735+17

- Dec ‘21: high energy IceCube neutrino alert. Flaring blazar just outside error Box
- Followed up with ARCA and ORCA

https://www.astronomerstelegram.org/?read=15290
Multi-site, deep-sea infrastructure
Selected for ESFRI roadmap
Single collaboration, Single technology
A NEW WAY TO STUDY THE ABYSS

KM3NeT is also a permanently cabled deep-sea observatory that enables the real-time acquisition of continuous, high-frequency, time series data for the study of the marine environment.

The synergetic science that can be addressed includes: climate change, ocean current circulation, biodiversity, bioluminescence, bioacoustics, cetacean population studies, monitoring of seismic and tsunami hazards, etc.
KM3NeT: ARCA and ORCA
KM3NeT building block

- 115 strings
- 18 DOMs / string
- 225m/1km
- 20m/90m
- 200m/800m
- 9m/36m
- Depth: 2440m/3400m

- 31 x 3” PMTs
- All data to shore: Gbit/s optical fibre
- White Rabbit time synchronisation
- LED flasher & acoustic piezo
- Tiltmeter/compass
- Low drag

Instrumented mass | 7 Mton | 500*2 Mton
Seafloor infrastructures

ORCA
2\textsuperscript{nd} junction box
Oct 2020

200 m

ORCA
2\textsuperscript{nd} Cable
Nov 2020

200 m

ARCA
junction box
+5 detection units
April 2021

ARCA
junction box
Oct 2020

ARCA
junction box
April 2021
Detector construction all around Europe

DOMs
- 8 integration sites
- 860 produced
- 105 currently on bench

Base Modules
- 9 integration sites
- 45 BM produced
- 5 currently on bench

Detection Units
- 6 integration sites
- 33 DUs produced
- 8 currently on bench
- 19 deployed

Despite pandemic big efforts are on going in the detector construction
Production ongoing around Europe

- Amsterdam
- Genova
- Nantes
- Erlangen
- Bologna
- Marseille
- Catania
- Athens
KM3NeT DU deployment
18 KM3NeT detection units operational
Effective areas: KM3NeT vs ANTARES

ARCA6+ORCA6 bit better than ANTARES

If completely funded:
Completion of ORCA115 array in 2026 and ARCA230 in 2027
Acoustic position calibration in KM3NeT

Animation of DU movement

Precision few cm

Use of dynamic positions, verified by muon calibration

Counts

preferred x-position from muon reconstructed track (m)

-0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8

static calibration
dynamic calibration
dynamic with gauss; σ = 0.05 m
ORCA6: Moon/Sun Shadow

Significance = 4.4 $\sigma$
Angular resolution = 0.54°±0.13°

Significance = 5.7 $\sigma$
Angular resolution = 0.59°±0.10°
ARCA6 data

3.  

KM3NeT-ARCA Preliminary

19 days
PMT efficiencies: $^{40}$K

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

$^{40}$K $\rightarrow$ $^4$He + e$^-$ ($\beta$ decay) → $^{40}$Ca
Supernova monitoring in KM3NeT

SN MeV neutrinos => collective excess of multi-fold coincidences on all DOMs


Discovery potential for 95% of Galactic CCSNe

ARCA6+ORCA6 already sensitive to 60% of Galactic CCSNe (<11 kpc)

Joint real time trigger operational for SNEWS since early 2019
Dark matter-indirect detection

- Sun
  - Dark matter particles
  - Scattering
  - Neutrinos produced from decays of annihilation products may be detected.

- Galactic Centre
  - Image of the Milky Way galaxy


\[\text{KM3NeT Preliminary} \]

\[\text{WIMP WIMP} \rightarrow \tau^+ \tau^-\]

\[\text{Log} M_{\text{WIMP}} \text{ [GeV / c}^2 \text{]} \]

\[\text{σ(v)}\text{ [cm}^3\text{s}^{-1}] \]

\[\sigma_{\text{WIMP}} \text{ [pb]}\]

\[M_{\text{WIMP}} \text{ [GeV]}\]


neutrino oscillations with atmospheric neutrinos

Normal ordering
- $m^2$
- $\Delta m^2_{atm}$
- $\Delta m^2_{sol}$

Inverted ordering
- $m^2$
- $\Delta m^2_{atm}$

$\theta_z = 130^\circ$
- $\nu_\mu$ NO
- $\nu_\mu$ IO
- $\nu_e$ NO
- $\nu_e$ IO
ORCA6 neutrino oscillations (tracks)
ORCA6: measurement of oscillation parameters

Contours: 90% CL

- Super-K
- IceCube
- T2K
- MINOS+
- NOvA
- KM3NeT
- NuFIT 5.0 (best fit)

KM3NeT preliminary
ORCA6 (355 days)

- $\sin^2 \theta_{23}$
- $\Delta m^2_{31} [10^{-3} \text{ eV}^2]$

$\sin^2 \theta_{23} = 0.50^{+0.097}_{-0.099}$ (stat+syst)

$\Delta m^2_{31} = 1.95^{+0.236}_{-0.212}$ (stat+syst) [10$^{-3}$ eV$^{-2}$]
ORCA115: neutrino oscillations sensitivity (3 years)

Contours: 90% CL

Super-K  
IceCube  
T2K  
MINOS+  
NOvA  
ORCA115  
KM3NeT  
NuFIT 5.0 (best fit)

KM3NeT preliminary ORCA6 (355 days)

NO
ORCA6: neutrino decay

ORCA6 353 kton-year sample:

\[ \frac{1}{\alpha_3} \equiv \frac{\tau_3}{m_3} > 2.4 \text{ ps/eV} \]

(comparable to LBL limits)
ORCA6: non-standard interactions

ORCA6 353 kton-year sample:

NSI parameter $|\epsilon_{\mu\tau}| < 0.009$ (comparable to world best limits)
Dependence on $\delta_{24}$

Factor of two better sensitivity on $U_{\tau 4}$ than current limits from SK and IC

Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude
The muon neutrinos mainly oscillate to tau neutrinos.

They appear as showers events.

Counting shower events is the sum of the tau and electron neutrinos

\[ \approx 3k \nu_\tau \text{ CC events/year with full ORCA} \]
ORCA115: neutrino mass ordering

3 years

6 yrs & combination with JUNO

2.5-5σ determination of Neutrino Mass Ordering possible in 3 years

Combination power relies on tension between best-fit of $\Delta m^2_{31}$ in “wrong ordering” between JUNO and ORCA
Draft SNOWMASS White paper, Denton et al., 2022

Figure 26: The estimated sensitivities to the three remaining oscillation unknowns based on the latest estimates of sensitivities and starting dates. Many caveats are required, see the text for details. [Note: DUNE has sensitivity to the octant; future versions will include this curve.]
Earth and sea sciences
Opération Nautile: Déploiement instrumentation

Biocaméras (IP2I)

Sismomètre (GeoAzur)

Spectromètre Gamma

BathyBot (MIO, DT-INSU)

https://www.mio.osupytheas.fr/fr/mers-et-oceans-changement-global/emso-lo-bathycruise
New idea: Tagged Protvino to ORCA

A. V. Akindinov et al.,
“Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA"
https://arxiv.org/abs/1902.06083

- Neutrino Beam from Protvino to ORCA
- Baseline 2590 km
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CPV
- Huge detector -> relax beam power
- New idea - ν tagging at source:

M. Perrin-Terrin
https://arxiv.org/abs/2112.12848
Summary

Water based nu telescopes:
- angular resolution, multi-flavour astronomy, galactic sources

Intriguing indications of cosmic neutrino sources from ICECUBE/ANTARES associated with radio loud and/or gamma blazar flares
- J0242+1101
- MG3 J225517+2409
- TXS 0506+056

KM3NeT taking data and growing rapidly
- First measurement of neutrino oscillation parameters by ORCA6
- First ATELs reacting to external alerts

New ideas in gestation
- Protvino to ORCA (P2O)
- Acoustic detection of UHE neutrinos

Come and join the adventure!
BACK UP
Old idea/New technology: Acoustic detection of UHE neutrino

Hadronic cascade:
~10m length
few cm radius

\[ E_{\text{casc}} = 10^{20} \text{ eV} @ 1 \text{ km} \]

\[ P(r = 200 \text{ m}) \approx 10 \times \frac{E_{\text{casc}}}{1 \text{ EeV}} \text{ mPa} \]