Astronomia con neutrini di alta energia: verso un telescopio da 1 km3

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High energy astrophysics

The detection of high energy gammas and cosmic rays are milestones in modern astrophysics but there are still open questions:

- Identification of high energy CR sources
- Solution of the UHECR puzzle
- Particle acceleration mechanisms in astrophysical sources
- Dark matter content in the Universe
Motivations for neutrino astronomy

Cosmic rays

• protons dominate CR at $E > 10^{18}$eV
• 1-10 TeV $\gamma$ rays detected from nearby sources

Gamma rays
Mechanisms for HE cosmic ray production

**Top Down**
- $M_x \sim 10^{24}$ eV
- Decay or annihilation
- $CR \leq 10^{21}$ eV
- Flat spectrum
- Gammas and neutrinos

**Bottom Up**
- $CR \leq 10^{21}$ eV
- $E^{-2}$ spectrum
- Gammas and neutrinos
- Acceleration
- p,e at rest

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Motivations for neutrino astronomy

Cosmic accelerators

Fermi acceleration mechanism
- Accelerated protons $dN_p/dE \sim E^{-2}$

Neutrino production
- Interaction target:
  - $p \rightarrow p$ (SNR, X-Ray Binaries)
  - $p \rightarrow \gamma$ (AGN, GRB, $\mu$QSO)
Gamma rays from $\pi^0$ decay in SNR?

CANGAROO observations fit with TeV gamma ray production originated by $\pi^0$ decay

Enamoto et al., 2002, Aharonian, 2002

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Absorption of photons and protons

Photomeson interaction (GZK cutoff)
\[ N\gamma_{\text{CMBR}} \rightarrow N\pi \]

\[
D_p \left( E_p > 10^{19.5} \text{ eV} \right) \sim \left( \sigma^* \rho_{\text{CMBR}} \right)^{-1} \sim 50 \text{ Mpc}
\]

pair production
\[ \gamma\gamma_{\text{IR, MW}} \rightarrow e^+e^- \]

\[
D_\gamma \left( E_\gamma > 10^{13} \text{ eV} \right) \sim \left( \sigma_{\gamma\gamma} \cdot \rho_{\text{IR, MW}} \right)^{-1} \sim 10 \text{ Mpc}
\]

Only neutrinos can reach the Earth from cosmological sources
Candidate neutrino sources

The most luminous astrophysical sources could also produce high energy neutrinos.

Extragalactic sources:

AGN: e.m. models fairly explain observed gamma ray emission (Mkn 421) but also discussed... acceleration of protons in the jet (Biermann, Mannheim, Dermer)

GRB: the standard scenario foresees the acceleration of UHECR and the production of $E>\text{TeV}$ neutrinos (Waxman, Vietri)

Galactic sources:

µQSO: the presence of an hadronic component in the jet (SS433) may lead to neutrino fluxes detectable by underwater/ice neutrino detectors (Levinson, Distefano)

SNR: $p-p$ interaction may produce neutrinos and TeV gamma rays, recently observed by CANGAROO (Enamoto)
Particle propagation in the universe

1 parsec (pc) = 3.26 light years (ly)

- High energy particles > $10^{17}$ eV (0.01 - 1 Mpc): gamma rays
- Protons $E > 10^{19}$ eV (10 Mpc)
- Protons $E < 10^{19}$ eV
- Neutrinos

Photons are absorbed on dust and radiation
Protons are deviated by magnetic fields
Extremely high energy protons interact with background radiation
Only neutrinos are direct
Diffuse neutrino fluxes sensitivity
Principles of neutrino astronomy

Flux estimate → need km3 scale detectors

atmospheric muon

~5000 PMT

l = 600 m

Cherenkov light

Connection to the shore

neutrino

deepth 3500 m

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Neutrino detection principle

\[ \nu_\mu + N \rightarrow \mu + X \]

\[ c(t_j - t_0) = l_j + d_j \tan(\theta_c) \]

\[ \delta x = 20 \text{ cm} \]
\[ \delta t = 1 \text{ ns} \]
\[ \delta \theta = 0.2 \text{ deg.} \]
Underwater neutrino telescope projects

ANTARES (0.1 km², in construction)

BAIKAL (in operation)

NEMO (km³ R&D)

NESTOR (in construction)

AMANDA (0.1 km², in operation)

ICECUBE (km³, in construction)
AMANDA neutrino sky map

Livetime
2000: 197 days
2001: 194 days
2000+2001: 959 events
465 below horizon

Step 2:
Search for clustering in Northern sky:
Grid search in rectangular sky bins
- bin size depends on declination
- shift grid 4 times to cover boundaries

No evidence for point sources with an $E^{-2}$ energy spectrum based on first 2 years of AMANDA-II data

Consistent with atmospheric $\nu$
NESTOR

32 m diameter
30 m between floors
144 PMTs

Energy threshold as low as 4 GeV

20 000 m² Effective Area for E>10TeV

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The ANTARES neutrino telescope

- 12 lines
- 25 storeys / line
- 3 PMTs / storey
- 900 PMTs

Submarine links
- Junction Box
- 40 km to shore
- Anchor/line socket
- to be deployed by 2005-2007

~70 m

14.5 m

350 m

100 m
The ANTARES prototype line
ICECUBE

Deep ice array
- 80 strings / 60 OM's each
- 17 m OM spacing
- 125 m between strings
- hexagonal pattern over 1 km²

geometry optimized for detection of TeV - PeV (EeV) ν's based on measured absorption & scattering properties of Antarctic ice for UV-blue Cherenkov light

Surface array IceTop
- 2 frozen-water tanks (2 OM's each) on top of every string
ICECUBE physics performances

IceCube will be able to identify
* μ tracks from νμ for $E_\nu > 10^{11}$ eV
* cascades from νe for $E_\nu > 10^{13}$ eV
* ντ for $E_\nu > 10^{15}$ eV

![Graph showing IceCube performances with hits counts for different energies and event types.]
ICECUBE Aeff and angular resolution

- $E^{-2} \nu_\mu$ spectrum
- quality cuts and bkgr suppression (atm $\mu$ reduction by $\sim 10^6$)

Median angular reconstruction uncertainty $\sim 0.8^\circ$
Sky view

Mediterranean km3
37° North
2/3 of time: Galactic Centre

ICECUBE
South Pole

0.5 \pi \text{ sr} \hspace{0.5cm} \text{instantaneous common view}
1.5 \pi \text{ sr} \hspace{0.5cm} \text{common view per day}
Towards the km3 detector

  - *Site selection and characterization*
    Several sites close to the Italian coasts have been studied. A site close to Capo Passero (Sicily) at 3500 m with optimal water characteristics has been identified for the installation.
  - *R&D activities*
    Development of specific ASICS for the underwater front end electronics
    Large area hybrid photomultipliers
  - *Feasibility study of the km3 detector*
    A complete feasibility study has examined all the detector critical components and the deployment procedures
    A preliminary project for the km3 has been developed.

- **Phase 1: Advanced R&D and prototyping (2002 - 2006)**
  - *Realization of a detector subsystem including all critical components*
    The system under realization at the Underwater Test Site of the LNS at 2000 m

- **Km3 detector realization (2007 ? - ...)**
The NEMO Collaboration

**INFN**
Bari, Bologna, Cagliari, Catania, Genova, LNF, LNS, Messina, Roma

**CNR**
Istituto di Oceanografia Fisica, La Spezia
Istituto di Biologia del Mare, Venezia
Istituto Sperimentale Talassografico, Messina

**Istituto Nazionale di Geofisica e Vulcanologia**

**Istituto Nazionale di Oceanografia e Geofisica Sperimentale**

**Universities:**
Bari, Bologna, Cagliari, Catania, Genova, Messina, Roma "La Sapienza"
Site selection criteria

- **Depth**
  - Reduction of atmospheric muon flux

- **Water optical transparency**
  - Optimisation of detector performances (efficiency and angular resolution)

- **Weak and stable deep sea currents**
  - Reduce stresses on mechanical structures
  - Reduce stimulation of bioluminescent organisms

- **Low biological activity**
  - Low optical background (bioluminescence) ⇒ detector performances
  - Low biofouling and sedimentation on OM

- **Distance from the shelf break and from canyons**
  - Installation safety

- **Proximity to the coast and to existing infrastructures**
  - Easy access for sea operations
  - Reduction of costs for installation and maintenance
Site exploration activities

• Since 1998 continuous monitoring of a site close (≈80 km) to the coast of Sicily (Capo Passero)

• More than 20 sea campaigns on the site to measure
  - water optical properties
  - optical background
  - deep sea currents
  - nature and quantity of sedimenting material
Water optical properties

Measure of profiles of water optical properties

The setup used (AC9+CTD) measures oceanographical (temperature, salinity, pressure) and optical (absorption and attenuation coefficients at 9 wavelengths) parameters along the whole water column.
Water optical properties

Seasonal dependence of optical parameters in Capo Passero

Seasonal dependence of oceanographical (Temperature and Salinity) and optical (absorption and attenuation) properties has been studied.

Variations are only observed in shallow water layers.

Data taken in:
- Aug 03 (2)
- Aug 02 (3)
- Mar 02 (4)
- May 02 (2)
- Dec 99 (2)

Average values 2850±3250 m
Water optical properties

Comparison of NEMO and Antares data

Optical water properties have been measured in the summer 2002 in Capo Passero and Toulon in two joint NEMO-ANTARES campaigns.

Absorption lengths measured in Capo Passero are compatible with optically pure sea water data.

Large differences between Toulon and Capo Passero are observed in the blue region.

Values measured with the Antares Test 3’ setup are in good agreement with the AC9 data.
Optical background

Sources of optical background

Decay of radioactive elements (mainly $^{40}$K) → stable frequency noise ($\approx$30 kHz on a 8” PMT at 0.3 p.e. threshold)

Light produced by biological entities (bioluminescence) → random bursts with very high counting rate

No luminescent bacteria have been observed in Capo Passero below 2500 m

Data taken by Istituto Sperimentale Talassografico, CNR, Messina
Optical background

Example of background rates in Toulon with different bioluminescence contribution
Optical background

Long period measurements in Capo Passero

NEMO setup (8" PMT) data

Baseline rate 28÷31 kHz

Burst fraction 0.2 %

Data taken in spring 2003 (45 days) with the Antares setup

Noise on a 8" PMT 28.5 ± 2.5 kHz
The count monitoring showed large variations in the optical background rates.

- Sometimes bioluminescence bursts increase the baseline (mainly due to $^{40}$K decays).
- Correlation between bioluminescence and current velocity has been measured.

### Baserate:
Median of rate in 15 min for 65 days

### BurstFraction:
Fraction of time in 15 min in which rate >1.2xbaserate
Deep sea currents

Currents have been continuously monitored over more than four years. Average value measured is \( \approx 3 \text{ cm/s} \). Intensities never exceed 12 cm/s.
Seabed geology from core analysis

- All the collected cores show the same stratigraphy
- Some features, associated to well known geological events, allow for a dating of the cores
- Only one evidence of a turbidity event is present, but it can be dated at about 60 kyr BP
- The average sediment accumulation rate is estimated to be 3-4 cm/kyr
Two series of collected data span an interval of about 1 year.
The mass flux is low (average of 62 mg m\(^{-2}\) day\(^{-1}\)), as expected in an oligotrophic environment such as the Ionian Sea, with a strong seasonal behaviour (spring bloom peak).

Data are comparable to those measured in the Northern Ionian which show the same features.

Interannual variability can also occur.
The Capo Passero site

Site optical and oceanographical characteristics

- Absorption lengths (~70 m @440 nm) are compatible with optically pure sea water values
- Measured values are stable throughout the years (*important: variations on La and Lc will directly reflect in changes of the detector effective area*)
- Optical background is low (consistent with 40K background with only rare occurrences of bioluminescence bursts)
- The site location is optimal (close to the coast, flat seabed, far from the shelf break and from canyons, far from important rivers)
- Measured currents are low and regular (2-3 cm/s average; 12 cm/s peak)
- Sedimentation rate is low (about 60 mg m\(^{-2}\) day\(^{-1}\))
- No evidence of turbidity events (from core analysis)
Feasibility study for the km3 detector

Aim: demonstrate that an underwater Cherenkov detector with effective area of more than 1 km$^2$ is technically feasible and can be constructed with a “reasonable” budget

Aspects that have been analysed in detail

• Mechanical structures
• Power distribution
• Front end electronics
• Data transmission to shore
• Cable network (submarine cables and connectors)
• Deployment of the structures and cables

The study shows that a km3 detector is presently technologically feasible
Preliminary project for a km\(^3\) detector

**Schematic detector layout**

Reference layout used for the feasibility study

- **Detector architecture**
  - Reduce number of structures to reduce connections and allow underwater operations with a ROV ⇒ non homogeneous sensor distribution
  - Modularity

- 1 main Junction Box
- 8 secondary Junction Boxes
- 64 Towers
- 16 storeys with 4 OM (active height 600 m)
- 4096 OM

**Total instrumented volume ≈ 1 km\(^3\)**
Comparison of different km3 architectures

Tower architecture (5832 OM)
- 18 storey towers with 4 OM per storey
- 20 m storey length
- 40 m spacing between storeys
- 81 towers arranged in a 9x9 square lattice
- 140 m spacing between towers
- \( \approx 0.9 \text{ km3 instrumented volume} \)

Lattice architecture (5600 OM)
- Strings with 58 downlooking OM spaced by 16 m
- 100 strings arranged in a 10x10 lattice
- 125 m spacing between string
- \( \approx 1.2 \text{ km3 instrumented volume} \)

Simulations have been performed with the ANTARES simulation package
Angular resolution

\[ \theta \leq \frac{1.5\, \text{deg}}{\sqrt{E_\nu} \, [\text{TeV}]} \]
Sensitivity for point-like sources

\[ \text{sensitivity} = \frac{\text{signal}}{\sqrt{\text{signal} + bckg}} = \frac{\phi_s AT}{\sqrt{\phi_s AT + \phi_b AT \langle \theta \rangle^2}} \propto \frac{\sqrt{AT}}{\langle \theta \rangle} \]

- \( A \) effective area
- \( T \) exposition time
- \( \langle \theta \rangle \) angular resolution
Comparison of string and tower geometries

✓ Up-going muons with $E^{-1}$ spectrum
✓ 60 kHz background
✓ Reconstruction + Quality Cuts

Angular resolution vs $E_\mu$

$A_{\text{eff}}^\mu$ vs $E_\mu$

Angular resolution vs $\theta_\mu$

$10^3 - 10^4$ GeV

Nemo20m 140 (5832 OM)
Lattice 125 16 (5600 OM)
Comparison of different background rates

- Up-going muons with E$^{-1}$ spectrum
- Tower architecture (5832 OM)
- Reconstruction + Quality Cuts

Optical background rate

Angular resolution vs $E_\mu$

$A_{\text{eff}}^\mu$ vs $E_\mu$
Sensitivity to point like sources

- Simulation of the km3 response to high energy neutrino fluxes from microquasars
- Simulation of background
  - Atmospheric muon background
  - Atmospheric neutrino background
- Background rejection
- Detector angular resolution
Atmospheric muon background rejection

Rejection with quality cuts

The value of the logarithm of the likelihood function, at the fitted maximum, divided by the number of degrees of freedom:

\[ QC = \frac{\log(L)}{N_{DOF}} \]

is used as a goodness of fit criterion.

Selection cuts increase the angular resolution but decrease effective area.

<table>
<thead>
<tr>
<th>QC Threshold</th>
<th>Number of Muons (Nμ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QC &gt; -10</td>
<td>Nμ = 20761</td>
</tr>
<tr>
<td>QC &gt; -9</td>
<td>Nμ = 11011</td>
</tr>
<tr>
<td>QC &gt; -8</td>
<td>Nμ = 1374</td>
</tr>
</tbody>
</table>

1.8 \cdot 10^7 downgoing muons simulated (Okada parameterization)

1.1 \cdot 10^6 reconstructed (using Antares code)
Sensitivity to point-like sources

Source and atmospheric neutrino background

Equatorial coordinates

SS433

GX339-4

16204 atm. $\nu_\mu$ events reconstructed in 1 year

Simulated spectrum from Learned & Mannaheim, 2000

Simulated microquasars spectrum from Distefano et al., 2002

in the $3^\circ \times 3^\circ$ bin = 84$\pm$5
circular (r=1$^\circ$) bin = 79$\pm$1

in the $3^\circ \times 3^\circ$ bin = 106$\pm$6
circular (r=1$^\circ$) bin = 97$\pm$0
Sensitivity to point-like sources

The case of the SS433 microquasar

250 days time integration

counts 1° radius circular bin around the source

<table>
<thead>
<tr>
<th>source</th>
<th>bkg</th>
<th>source+bkg</th>
<th>cut level</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>354</td>
<td>412</td>
<td>NO QC</td>
</tr>
<tr>
<td>58</td>
<td>195</td>
<td>253</td>
<td>QC -10</td>
</tr>
<tr>
<td>57</td>
<td>115</td>
<td>172</td>
<td>QC -9</td>
</tr>
<tr>
<td>53</td>
<td>15</td>
<td>68</td>
<td>QC -8</td>
</tr>
</tbody>
</table>

At QC > -8:

\[
\frac{\text{source}}{\sqrt{\text{source} + \text{bkg}}} = \frac{53}{\sqrt{68}} = 6.4
\]

Background is the sum of atmospheric \( \mu \) and \( \nu \)
The NEMO Phase 1 project

A step towards the km3 detector

Realization of a detector subsystem including all critical components

EO CABLE

Length – 25 km
10 Optical Fibres ITU-T G-652
6 Electrical Conductors Φ 4 mm²

Project jointly funded by INFN and MIUR
Completion foreseen in 2006

SHORE LABORATORY

UNDERWATER LAB

NEMO TOWER

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The LNS Test Site

Deployment of the electro-optical cable

Cable deployed in september 2001

Deployment of the branching unit

Optical fibre connections

Electrical connections
The NEMO tower

"Tower" structure

**Semi rigid structure**

*Tensioning and electro-optical cables are kept separated*

*The structure can be packed for transportation and deployment*

16 storeys spaced by 40 m

4 OM per storey

64 OM per tower

600 m active length
The NEMO tower

Deployment of the tower

Tested in shallow waters with a 1:5 scale model of the tower
Deployment and submarine operations

*Deployment will be performed by double positioning surface vessels*

*Unfurling of the tower and connections will be performed by means of submarine Remoted Operated Vehicles (ROV)*
The NEMO tower
Junction Boxes

Alternative design to the Titanium container (Antares-like)

**Aim**

*Decouple the two problems of pressure and corrosion resistance*

- Splitting box
- Switching box
- Pressure vessel for electronics devices
- Transformers
- Fibreglass external container
- Oil filled tubes
- ROV mateable connectors

1 m
Optical module electronics

Data Acquisition:
- 200Msample/s
- 8bit (logarithmic compression)
- User programmable digital threshold level

On-board sensors:
- Temperature
- Humidity

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New low power electronics for the OM

- Sample frequency: 200 MHz
- Trigger level remotely controlled
- Max power dissipation less than 200 mW
- Input dynamic range 10 bit
- Dead time < 0.1%
- Time resolution < 1 ns

New full custom VLSI ASIC
Presently under final laboratory testing
Will be tested in some optical modules in Phase 1
Floor electronics

**MAIN INTERFACES**
- 8x Optical Module (LVDS)
- 4x Slow Control Module (SPI bus)
- 1x DWDM Optical Transceiver
- 1x PCI Bus

- **Sea side**
  - DWDM Transc.
  - FCM

- **To/From TJB**

- **From/To MOB**

- **Land side**
  - PCI BUS

- **NEMO**

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70 mm
Data transmission system

Aux exp 1

2.5 Gb/s

Aux exp 2

2.5 Gb/s

SJB

MJB

2 x 2.5 Gb/s

Shore system

Tower 1

Tower 2

Aux 1

Aux 2

sea - shore

NEMO
INFRASTRUTTURA PROPOSTA
- Stazione di terra a Portopalo di Capo Passero per l'alimentazione degli apparati sottomarini, acquisizione dati e montaggio degli apparati
- Cavo elettro-ottico di circa 100 km
- Struttura sottomarina composta da una Junction Box, dal sistema di connessione tra cavo elettro-ottico principale e JB e da una docking station per AUV/ROV
Capo Passero
Connessione cavo EO - Junction Box
Test di sistemi ibridi AUV/ROV
Conclusions

- A km3 detector is needed to open the neutrino astronomy field
- The NEMO collaboration has carried out an advanced R&D activity towards the realization of the km3
- Studies of the Capo Passero site have shown that it is an excellent location for the km3
- A feasibility study has analysed in detail all the km3 components
- A Phase 1 project, aiming at the realization of a subset of the detector including all the critical components, is currently in realization; completion is foreseen for 2006
- Future plans:
  - Completion of R&D activities
  - Design study for the km3 (KM3NeT)
  - NEMO Phase 2
  - Construction of the km3 within a large international collaboration