Recent Results from the ANTARES Underwater Neutrino Telescope

Giulia De Bonis
giulia.debonis@roma1.infn.it

on behalf of the ANTARES Collaboration

http://antares.in2p3.fr/
Outline

• Neutrino-Astronomy and the Multi-Messenger Approach
  - Candidate Neutrino Sources
  - Scientific Goals
• Neutrino Detection: Cherenkov Telescopes
• ANTARES – Detector Setup
• ANTARES – Selected Results
  - point-like sources
  - diffuse flux
  - dark matter, exotic matter...
  - multi-messenger approach
• Conclusions & Perspectives
Neutrino Astronomy

The Multi-Messenger Approach

Electromagnetic radiation ($\gamma$-rays) is absorbed

Protons/nuclei are deflected (magnetic fields) and/or absorbed

Weakly interacting neutrinos retain directional information, allowing deep insight into compact celestial objects and at cosmological distances.

UHE$\nu_s$ Production

| Bottom-Up Models (Acceleration) | Galactic Sources (SNRs, PWNae, $\mu$Qs) |
| Top-Down Models (Annihilation/Decay) | Extra-Galactic Sources (AGNs, GRBs) |
| GZK $\nu_s$ (cosmogenic flux) | WIMPs, TDs |

... not only Astronomy:

Astrophysics

UHE$\nu_s$ as a diagnostic of astrophysical processes
- astrophysical sources, acceleration engines
- neutrino observations can discriminate between different acceleration mechanisms (hadronic vs leptonic)
- CRs propagation $\Rightarrow$ GZK cut-off [cosmogenic $\nu$ flux]

Particle Physics

- Neutrino Physics
- $\sigma_{\nu N}$ at $E>E_{LAB}$ accelerators
- NewPhysics beyond SM

Cosmology

- top-down models
- (TDs, WIMPs – indirect dark matter search)

References

Candidate Sources

The most fascinating objects in the Sky are possible neutrino emitters

- Supernova Remnants (SNR)
- Gamma-Ray Bursts (GRB)
- Pulsar Wind Nebulae (PWN)
- Active Galactic Nuclei (AGN)
- MicroQuasars (μQ)
- Galactic Sources (SNRs, PWNaes, μQs)
- Extra-Galactic Sources (AGNs, GRBs)

Candidate Sources

**Supernova Remnants (SNR)**

[IC 443 - Credit: Jean-Charles Cuillandre (CFHT)]

**Gamma-Ray Bursts (GRB)**

[artist’s view – NASA/Swift]

**Pulsar Wind Nebulae (PWN)**

[Crab Nebula - Image courtesy NASA/ESA]

**Active Galactic Nuclei (AGN)**

[Centaurus A - ESO]

**MicroQuasars (μQ)**

[Cignus X-1 – artist’s view NASA/ESA]
**Scientific Goals**

*neutrinos are exciting guys!*

**The Multi-Messenger Approach**

- Weakly Interacting Neutrinos retain directional information, allowing deep insight into compact celestial objects and at cosmological distances.

** ANTARES results address all the major fields of investigation**

- **multi-messenger astronomy** (gamma astronomy, optical astronomy, gravitational waves...)

- **Astrophysics**
  - UHEνs as a diagnostic of astrophysical processes
  - astrophysical sources of neutrinos
  - neutrino observations of acceleration mechanisms
  - CRs propagation

- **Cosmology**
  - top-down models
  - (TDs, WIMPs – indirect dark matter search)

- **Particle Physics**
  - Neutrino Physics
  - σνν at E>E_{LAB} accelerators
  - NewPhysics beyond SM

**References**


**... not only Astronomy:**

- point sources
- diffuse flux
- monopoles
- nuclearites
- dark matter
... the other side of the coin: Neutrino Detection

Weakening-interacting is hard-detecting
(and very low fluxes are expected from the sources)

large detection volume (~km³) is required

Cherenkov Telescopes

Detection Principle

Neutrinos (E>100 GeV) can be detected collecting the visible Cherenkov radiation produced as the high-energy charged leptons (final state of CC interactions) propagate through a transparent medium with superluminal velocity.

Detection Channel:

νμ CC-interaction giving a relativistic μ
reconstruction of μ trajectory (~ ν)
from timing and position of PMT hits

NATURAL TARGET
• sea water (ANTARES)
• Antarctic ice (IceCube)

required:
σ_time ~ 1 ns (PMT timing)
σ_pos ~ 10 cm (PMT position)
signal vs background

Neutrinos from cosmic sources induce 1-100 muon evts/yr in a km³ Neutrino Telescope

up-going µ from neutrinos generated in atm. showers
S/N \sim \nu_{\text{astro}} / \nu_{\text{atm}} \sim 10^{-4}

down-going µ from atm. showers
\mu_{\text{upgoing}} / \mu_{\text{atm}} \sim 10^{-4} \text{ at 3500m w.e. depth}
S/N \sim 10^{-8}

atmospheric neutrino flux (an irreducible bkg)

→ Energy Reconstruction
- Atmospheric neutrino flux \sim E_{\nu}^{-3.5}
- Neutrino flux from cosmic sources \sim E_{\nu}^{-2}

→ Event Clustering (Point Sources)

search for up-going events

the deeper, the better

screen the atmospheric muon flux
(the most abundant source of bkg)

Neutrinos from cosmic sources induce 1-100 muon evts/yr in a km³ Neutrino Telescope

Sky Coverage
Complementarity to IceCube

Visibility

[galactic (•) and extra-galactic (●) gamma sources]

http://icecube.wisc.edu/
... summing up

**Neutrino Fluxes and Neutrino Detectors**

![Diagram illustrating neutrino fluxes and detectors.](image)
ANTARES
Astronomy with a Neutrino Telescope and Abyss environmental RESearch

- 25 storeys
- 350 m
- 14.5 m
- ~70 m
- 100 m
- ~2500 m depth
- String-based detector
- Downward-looking PMTs
- Axis at 45º to vertical
- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- ~900 PMTs

The Largest Neutrino Detector in the Northern Hemisphere

ANTARES Event Display
a Neutrino Candidate

reco. $\mu$ energy: 5-10 TeV
degl.: -6°23'20.98"
RA: 12h57 23.18
ANTARES
Selected Results
Point-like Sources
Detector Performance & Data/MC Comparison

µ tracks reconstructed using a likelihood-based algorithm
2007-2008 data
Integrated Live Time: 304 days

µ tracks reconstructed using a likelihood-based algorithm
2007-2008 data
Integrated Live Time: 304 days

Λ distribution for the up-going selected events
Λ > -5.4 → selected 2040 events

MC studies: angle between the true ν direction and the reconstructed µ direction.
Point-like Sources

Results

No significant cosmic neutrino sources have been observed

Galactic Coordinates

- 2040 data events (selected tracks – all sky)
- 24 candidate sources

ANTARES Sky Map

Sensitivity

The BEST limit in the Southern Sky!

\[ 7.5 \times 10^{-8} \, (E/\text{GeV})^{-2} \, \text{GeV}^{-1} \, \text{s}^{-1} \, \text{cm}^{-2} \]

[\delta < 48^\circ \text{ (the part of the sky always visible)}]
The autocorrelation method is an analysis tool widely used in astroparticle physics experiments to search for structures in arrival directions of astrophysical messengers. The main advantages of this method are:

- The method relies only on the selected data events. Tuning of parameters, which usually requires dedicated MC simulations, is not needed.
- The method is sensitive to a large variety of source structures from point like sources to large extended source morphologies (no a priori knowledge on source morphologies is needed).

\[ \text{Search for clusters: number of pairs in a given angular bin} \]

\[ \text{same data sample of the point source analysis (2007-2008)} \]
Diffuse Cosmic $\nu$ Flux

**the method**

**idea:**
- Background atmospheric neutrinos have steeply falling energy spectrum: $N \propto E^{-3.5}$
- Many cosmic neutrino models predict much harder spectra, typically $N \propto E^{-2}$
  
  $\Rightarrow$ Look for High-energy diffuse flux component

**analysis:**
- Live time: 334 days
- Stringent selection: 134 high energy $\nu$ candidates, no atmospheric muons
- Energy estimator $R$: a measure of the number of delayed photons

**energy estimate:**
- The muon energy at the detector is correlated with the neutrino energy
- Muons above 1 TeV produce additional Cherenkov light via secondaries ($\propto E$)
- Energy estimate $R$ based on number of repeating hits

$$ R = \frac{\sum R_i}{N_{OM}} $$
Diffuse Cosmic $\nu$ Flux

Results

No excess of high energy events found over expectation from atmospheric $\nu$

Flux Upper Limit (90% CL)

$E^2 \Phi(E) < 5.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{ sr}^{-1}$

[for 20 TeV < $E$ < 2.5 PeV]

J. Aguilar et al., “Search for a diffuse flux of high energy $\nu_{\mu}$ with the ANTARES neutrino telescope”, Phys. Letter B 696, 16-22 (2011)
Magnetic Monopoles

Magnetic monopoles are hypothetical particles predicted to be created in the early Universe in the framework of Grand Unified Theories (GUTs) ($M_{\text{mon}}$ predicted in the range $10^4$-to-$10^{20}$ GeV).

Relativistic magnetic monopoles are expected to emit a large amount of (direct) Cherenkov light when travelling through the ANTARES telescope → extremely BRIGHT events (~8500 times brighter than muon tracks) → unambiguous signature.

Further analysis performed on non-relativistic magnetic monopoles: monopoles ionize atoms leading to indirect Cherenkov light emission from $\delta$-rays along the monopole path.

Cherenkov threshold $\beta = 0.74$

no signal found competitive upper limit

[selection optimized for the discovery]
Nuclearites

Massive nuclearites (strange quark matter), produced in the early Universe and present in the cosmic radiation, could reach the ANTARES detector from above. They would produce a large amount of light in the detector, by emitting blackbody radiation at visible wavelengths while travelling through water with non-relativistic velocities.

**Signature:** long-lasting events, light pattern (hits) compatible with a slowly moving massive particle.

Main source of **background:** bioluminescent events.
WIMPs (Weakly Interacting Massive Particles) are gravitationally trapped via elastic collisions in the centre of massive object, as the Earth, the Sun or the Galactic Centre. 

**Indirect search for dark matter** in the ANTARES telescope is possible assuming *neutrinos* (in the GeV-TeV energy range) are produced in the WIMPs annihilation.

\[
\chi \chi \rightarrow \text{bb, WW, tt, } \tau \tau, \nu_\mu \nu_\mu, \nu_\tau \nu_\tau \rightarrow \nu_e, \nu_\mu, \nu_\tau
\]

**Feb-Dec 2007 data (5 Line Detector)**

68 active days

Upper limit on the total flux \(\Phi(\nu_\mu + \nu_\mu)\) from *neutralino* annihilations in the Sun as function of \(m_\chi\)

**NEXT**

- investigation of the Kaluza-Klein model
- data analysis of the FULL DETECTOR (soon ready!)
- upper limits from the Galactic Centre
Multi-Messenger Searches

Potential astrophysical sources are predicted to emit very faint neutrino signal. The Multi-Messenger Approach increases the **discovery potential**, by observing with different probes; the **significance**, by coincident detection; the **efficiency**, by relaxed cuts.

- **ANTARES** ↔ **VIRGO**
  - common working group (GWHEN)
  - 5 Line data analysis in progress paper in preparation

- **ANTARES** ↔ **LIGO**

- **ANTARES** ↔ **AUGER**

- **TAToO**
  - (Telescopes – ANTARES Target of Opportunity)
  - Optical follow-up of neutrino alerts for transient source search (GRBs, SNae).
  - Analysis in progress!

- **AGN Flares**
  - (ν emission from γ-flaring blazars)

- **ANTARES** ↔ **FERMI**

- **GCN**
  - (GRB Coordinat. Network)
Multi-Messenger Searches

GRBs

GCN = Gamma Ray Burst Coordination Network

Data taking triggered by a satellite

90% CL upper limit on \( \nu \) fluxes from 37 GRBs (Lines 1-5 data)

More than 1300 alerts from GCN recorded (Jan 2011)

GRB alerts received: the ones Antares triggered on
Most of GRB alerts by the Swift satellite
GRB alerts also from the Fermi satellite

Cumulative number of alerts

Flaring activity of SGR 1550-5418

GRB data taking triggered by a satellite

Lines 1-5 data: 148 alerts received (72 above the horizon, 23 rejected by run selection, 16 false trigger) \( \rightarrow \) 37 GRBs in the analysis (exposure 1882 s)
**Multi-Messenger Searches**

**AGN Flares**

**RESULTS**

- **1 neutrino candidate event** compatible with the time/space distribution ($\Delta \alpha = 0.56^\circ$) of 3C279 with probability (p-value) = 1% (but post trial probability = 10%) → very promising analysis → **extend the studied period** to 2009-2010 data set
- **Fluence Upper Limits** for the selected source

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**Source** 3C454.3

FERMI light curve

Period studied (~60 days live time) [Sep-Dec2008]

10 sources selected from the FERMI catalog, showing a large **variability** (flaring state) in the period studied for this analysis.

Performance of the **time-dependent analysis**
Multi-Messenger Searches

Correlation with UHECRs

- Search for correlation in the arrival directions of 2190 neutrino candidate events (detected by ANTARES in 2007-2008, effective live time: 304 days) and 69 UHECRs (detected by Pierre AUGER Observatory in 2004-2009, \( E > 10^{19.74} \) eV, all the events in the ANTARES telescope field of view).

- **Source Stacking Method.**

- UHECR magnetic deflection = 3° (light composition assumed)

- Statistical significance and optimal angular search bin is determined by \( 10^6 \) pseudo-experiments, each containing the 69 AUGER events at fixed coordinates and the 2190 neutrino events scrambled in right ascension.

no significant correlation observed

**Upper Limit on the Neutrino Flux**

\[ 4.99 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \]

(assuming a \( E^{-2} \) energy spectrum)

Skymap in Galactic Coordinates; neutrino events are represented with black dots and angular search bins of 4.9° centered on the observed UHECRs with black circles.
Conclusions

- **ANTARES** is **the largest neutrino telescope in the Northern Hemisphere** and the first undersea Cherenkov telescope
- Detector is completed (12 detection lines) since 2008
- **Multidisciplinary platform** for associated sea sciences
- Detector is working within design specifications - DAQ ongoing
- Data analysis ongoing → first results published
  → extended results forthcoming
- Milestone towards a km³ detector → KM3NeT

http://www.km3net.org/
back-up slides
UHE\(\nu\text{v}'s\) Production: Acceleration
(bottom-up model)

Fermi engine (AGNs, SNRs)

- protons, confined by magnetic fields, are accelerated through repeated scattering by plasma shock front;

- collisions of trapped protons with ambient plasma produce \(\gamma\)s and \(\nu\)s through pion photoproduction mechanism:
  \[
  p + N, \gamma \rightarrow X \quad \pi^\pm \rightarrow \text{neutrinos} \quad \pi^0 \rightarrow \gamma - \text{rays}
  \]

\[
E_\nu \sim 0.05 E_p
\]

\[
\frac{dn}{dE} \propto E^{-2}
\]

[A. Ringwald]
The UHE CR horizon is limited by interactions with low energy background radiation → Pion Photoproduction

\[ \lambda_{\text{att}} = \frac{1}{\sigma_{p\gamma} n_{\text{CMBR}}} < 50 \text{ Mpc} \]

GZK NEUTRINOS (cosmogenic neutrino flux)

Neutrinos at $10^{17-19}$ eV predicted by standard-model physics through the GZK process observing them is crucial to resolve the GZK puzzle
Multi-Messenger Searches

Correlation with UHECRs

Probability Density Functions (PDFs) of the number of neutrino events in 1-10° bins centered on 69 UHECRs observed by AUGER. The counts were obtained from the background only MC simulations, each with 2190 neutrino events blinded by scrambling the observed events in right ascension.

Discovery Potential of 3 sigma (dashed line) and 5 sigma (solid line) as a function of the number of neutrino events within 69 bins of 4.9° centered on UHECRs observed by AUGER.