High-energy neutrino detection with the ANTARES underwater Cherenkov telescope

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Outline

1. High energy astroparticle physics
2. HE neutrino detection in the context of multi-messenger approach
3. This work: survey of a region of the supergalactic plane with ANTARES 2007 data
4. Summary
Starting point: observation of Ultra High Energy Cosmic Rays (UHECRs)

Where do they come from?

- Top-down: decay of super-heavy particles → disfavored
- Bottom up: acceleration in astrophysical sources → candidates?
  - Galactic:
    - Super Nova Remnants (SNRs)
    - Micro-quasars
  - Extra-Galactic:
    - Active Galactic Nuclei (AGN)
    - Gamma Ray Bursts (GRBs), …
Recent UHECRs observations

Arrival direction of UHECRs ↔ position of nearby AGN: Correlation ??

Galactic coordinates

[Abraham et al., 2008]

However:

• Pierre Auger Observatory results not confirmed by other experiments
• UHCRs propagation affected by unknown magnetic fields
CRs astronomy feasible at energies higher than $10^{19}$ eV \(\Rightarrow\) extra-galactic origin (B not well known)

UHECRs horizon limited to 10 - 100 Mpc due to interaction with CMBR (GZK effect)

Multi-messenger astronomy is likely to open new insights on the physics of the most violent events, combining results from CRs, $\gamma$-rays and traditional astronomy, neutrinos and gravitational waves.
Gamma Ray Astronomy

Advantages:

- $\gamma$-rays are expected together with UHECRs, e.g.
  \[ p + \gamma \rightarrow p + \pi^0 \rightarrow \text{UHECRs} + \gamma - \text{rays} \]

- Neutral particles \( \rightarrow \) propagation not affected by \( B \rightarrow \) point-back to the source

- $\gamma$ -rays detection is successful!

- high energy photons strongly absorbed
  - In the source: \textit{optically thick sources}
  - During propagation: \textit{over extra-galactic distances the Universe is opaque to photons for E larger than hundreds of TeV}

- difficult to disentangle the origin
  - Hadronic: \( p + \gamma \rightarrow p + \pi^0 \rightarrow \text{UHECRs} + \gamma - \text{rays} \)
  - Leptonic: \textit{synchrotron radiation of e\textsuperscript{-}, inverse Compton scattering}
Neutrino Astronomy

Advantages:

- HE vs are expected together with UHECRs, e.g.
  \[ p + \gamma \rightarrow \pi^+ + n \rightarrow \text{UHECRs} + \nu'\text{s} \]
- Neutral particles propagation not affected by B point-back to the source
- Only weakly interacting particles:
  - observation over cosmological distances identify production sites
  - inner layers of astrophysical objects understand production mechanisms
- Always of hadronic origin
- Flavor mixing
even if at the source \((\nu_e: \nu_\mu: \nu_\tau) = (1:2:0)\) at Earth \((\nu_e: \nu_\mu: \nu_\tau) = (1:1:1)\)

Only weakly interacting particles + Low fluxes expected from the sources
\(\Rightarrow\) Large detection volume (~km\(^3\)) is required
Neutrino Astronomy ... how?

Neutrinos can be detected using the visible Cherenkov radiation produced as the high-energy charged lepton (final state of CC interactions) propagates through a transparent medium with superluminal velocity.

Due to low fluxes expected, cubic-kilometer scale detector are required to perform HE neutrino astronomy (E ~100GeV -10 PeV) prototype structures currently taking data.
The ANTARES detector

- 12 Lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Depth: 2475 m

Completed May 08

Currently the largest neutrino detector in the Northern hemisphere.

Search for astrophysical muon neutrinos looking for upgoing muon tracks (from below the horizon)
Observable sky for ANTARES

The region where the bulk of the Auger event lie is within the ANTARES field of view.

Not observable from the ANTARES site

100% visibility from the ANTARES site
Muon flux at the detector

The data sample is dominated by the flux of atmospheric muons propagating downward through the detector. Atmospheric neutrinos contribute providing a flux that is 4-5 orders of magnitude less abundant than that of atmospheric muons.
Outline of this analysis

Aim of the present work is the study of the distribution of the reconstructed neutrino events over several equally extended areas in the sky, searching for uniformity or excesses.

**Why?**

In view of the recent results by the Pierre Auger Observatory we have decided to study the distribution of neutrinos arrival directions in the sky region where the bulk of the UHECRs Auger events lie.
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How?

• Perform a dedicated simulation of signal and background events.
• Optimize the analysis strategy and selection criteria on simulated (signal + bkg) events.
• Apply optimised cuts to data.
• Study the distribution of neutrino events falling within the selected region (ON region in the following) searching for uniformity/excesses.
• Study the distribution of neutrino events in 11 regions (OFF regions) of equal exposure/declination, to characterize the background. The bkg is assumed to be the same in the OFF and in the ON regions.
• Compare the number of events found in the ON region with bkg expectations.
• In case no significant excess is found, an upper limit to the neutrino flux from the ON region will be set.
• Serendipitous search is performed in order to investigate the presence of a significant excess of signal in each of the 11 regions used to estimate the bkg.
Monte Carlo simulations

Atmospheric neutrinos flux (bkg)

\[ E^2 \frac{dN}{dE} [m^{-2} s^{-1} sr^{-1} GeV^{-2}] \]

\( v \) signal \( \rightarrow \) power law spectrum \( E^{-2} \)

Atm. muons (bkg): primary CRs flux

\[ E^{2.7} \frac{dN}{dE} [m^{-2} s^{-1} sr^{-1} GeV^{1.7}] \]

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Manuela Vecchi - Seminario di Dottorato - XXII ciclo
Monte Carlo simulations

Propagation of muons in water up to the detector level + Cherenkov light + PMT response is simulated.

Front end electronics + data acquisition system is simulated and environmental bkg (~60 KHz) is “added” to MC events. Trigger algorithms are applied.
Muon reconstruction

Arrival time and amplitude are stored for each hit on PMTs, together with their positions ($\Delta x \sim 10 \text{cm}$).

The arrival time of a photon on the OM is given by:

$$t^{th} = t_0 + \frac{1}{c} \left( l - \frac{k}{\tan \vartheta_C} \right) + \frac{1}{v_\gamma} \left( \frac{k}{\sin \vartheta_C} \right)$$

Time for the $\mu$ to reach the point of light emission ($v_\mu \sim c$)

Time for the $\gamma$ to propagate in water ($v_\gamma = c/n$).
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- Time for the $\mu$ to reach the point of light emission ($v_\mu \sim c$)
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Full likelihood algorithm

- Time residuals pdf
- Alignment used

**ANTARES 2007**
arXiv:0909.1262
ANTARES 2007 data

The analysis that will be presented has been performed on data taken in 2007, when the detector was only composed of 5 lines.

**2007 data** -

19 \(\cdot 10^6\) \(\mu\) triggers

Total: 245 days

Selected: 168 days

Detected events are mainly due to downgoing atmospheric muons.
ON region

We have checked that the detector exposure and the detection rate is uniform within the chosen declination band \((-60^\circ \leq \delta \leq -30^\circ)\). The background is estimated from eleven OFF regions that fall in the same declination band.

Centaurus A recently detected in VHE $\gamma$ rays.
Optimization of selection criteria

Likelihood $L$

$$L = P(\text{event|track}) = P(\text{hits|}\vec{p}, d) = \prod_{i=1}^{N_{\text{hits}}} P(r_i|a_i, b_i, A_i)$$

The reco quality cut $\Lambda$

$$\Lambda \sim \frac{\log L}{N_{\text{DOF}}}$$

has been chosen in order to maximize the sensitivity of the search.

Model rejection factor (mrf) is used to choose the optimal cuts to be used in this analysis

$$\text{mrf} = \frac{\mu_{90}}{n_s}$$

The average upper limit $\mu_{90}$ (90% C.L.) is calculated (Feldman, Cousins) from background events.

The number of expected signal events in the ON region, $n_s$, is obtained from a full MC simulation, assuming an $E^{-2}$ power law, for the astrophysical neutrino flux.
Data - MC comparison

Elevation: nlines_prefit > 1

Azimuth: nlines_prefit > 1

Elevation: nlines_prefit > 1, \Lambda > -4.9

Azimuth: nlines_prefit > 1, \Lambda > -4.9
Data - MC comparison (2)

ANTARES 2007 unblind data, nlines_prefit > 1, elevation < -10°, Λ > -4.9

Data
MC atm. μ + ν

Right Ascension [°]

Declination [°]
Discovery Potential ...

... and signal strength as a function of a max. Likelihood cut

**Discovery potential** $n_0$: the number of events (signal + background) that are necessary, for a given $<n_b>$, to lead to a discovery. There is evidence for a discovery when we find a $5\sigma$ excess of signal over the background.

$$5\sigma \Rightarrow \sum_{n_{obs} = n_0}^{\infty} P(n_{obs} | <n_b>) \leq 2.85 \cdot 10^{-7}$$

**Signal strength** $n_s$ such that with a 70%, 90 or 99% probability, we can observe a total number of events (signal + bkg) which is sufficient to claim a $5\sigma$ discovery.
Detection probability as a function of number of signal events for a 5 sigma discovery for the optimal lambda cut value ($\Lambda > -4.9$).
Events in the On-Off regions

Basic hypothesis $H_0$: data follow a Poisson distribution with mean value $<N_{off}>$

$N_{on}=2 \quad <N_{off}> = 4.4$

$p$-value = $P(N \geq N_{obs} \mid H_0, <N_{off}>) = 0.91 \Rightarrow$ the hypothesis is accepted
Events in the On-Off regions

No significant excess is found.

We compute $\mu_{90} \Rightarrow$ the Upper Limit (90% C.L. - Feldman, Cousins) to the number of signal events $\Rightarrow$ U.L. to the neutrino flux in the ON region, assuming an $E^{-2}$ spectrum. $E^2 \Phi_{90} < 2.1 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}$
Assuming a uniform distribution of sources in the ON region, as well as in the SGP, we obtain the following upper limit to the diffuse neutrino flux.

Data-MC comparison

The number of events observed in the several right ascension bins show fluctuations larger than the ones expected from MC simulation.
Serendipitous search

We iteratively consider as On region each of the eleven Off regions. We evaluate an average background level, that will be compared to the number of events found in each region. The background, $<N>\approx 4.2$, is the average number of events found in the 12 regions in which we have divided the declination band.

- $N_{on}=3$, $<N>\approx 4.2$
  - p-value = 0.790
  - $H_0$ accepted

- $N_{on}=1$, $<N>\approx 4.2$
  - p-value = 0.985
  - $H_0$ accepted

- $N_{on}=11$, $<N>\approx 4.2$
  - p-value = 0.004
  - Post-trial probability 5%

$H_0 =$ data follow a Poisson distribution with mean value $<N> \approx 4.2$
Summary

- This analysis has been performed on 2007 ANTARES data, searching for a neutrino signal excess coming from an extended sky region (ON region) around the supergalactic plane (SGP).
- No significant excess of signal has been found. Upper limit has been set to the total neutrino flux from the ON region. $E^2 \Phi_{90} < 2.1 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}$
- Under the assumption of uniform sources distribution in the ON region, as well as along the SGP, an upper limit to the diffuse neutrino flux has been set.
- Improvement expected from event classification in energy.
- Serendipitous search shows no significant post-trial excess of signal in any of the 11 OFF regions.
- The same analysis will be repeated on the full ANTARES data sample as soon as available.