Maurizio Spurio
Department of Physics and INFN – Bologna
among the **most intriguing science questions:**
- origin of cosmic rays $\rightarrow 10^{20} \text{ eV}$?
- astrophysical acceleration mechanism?
- origin of relativistic jets?
- dark matter?
- exotics

**Cosmic sources of neutrinos**
- **Extragalactic:** Active Galactic Nuclei, GRBs
- **Galactic:** micro quasars, supernova remnants...


**TeV $\gamma$ rays** $(p+X \rightarrow \pi^0 \rightarrow \gamma\gamma)$ at the centre of **our galaxy** from supernova remnant **RX J1713.7-39.**

Expect:

$p+X \rightarrow \pi^\pm$  
$\rightarrow \nu\bar{\nu}$

**neutrinos reach Earth undisturbed:** **need large detector and good angular resolution**
SKY VIEW (GALACTIC COORDINATES)

AMANDA / IceCube (South Pole)  ANTARES (43° N)

acceptance

visible sky

Mkn 421  Mkn 501  CRAB  SS433  Mkn 501  RX J1713.7-39  CRAB  VELA

Galactic Centre

1.5 \( \pi \) sr common view over a day
THE ANTARES COLLABORATION

7 COUNTRIES
28 INSTITUTES
≈ 150 SCIENTISTS AND ENGINEERS

IFIC, Valencia
UPV, Valencia
UPC, Barcelona
THE TELESCOPE SETUP

- 12 detection lines
- 25 storeys/line
- 3x10” PMT/storey
- 885 PMT s
Two kinds of background:

1. *(Particle) Physics Background*: cosmic rays (atmospheric $\mu$ and $\nu$).
2. *Optical Background*: bioluminescence and $^{40}$K decay (sea environment):
   - Continuous $^{40}$K (~30kHz) and bioluminescence (~40 kHz, long term average).
   - Bursts from bioluminescence (~MHz).
Fast tracking:

• almost online to discriminate atmospheric muons / neutrinos;
• No detailed calibration/ no real time detector positioning needed;
• Angular resolution: $\Delta \theta \sim 3^\circ$.
• Used in most analyses in this talk.

The precise tracking:

• detailed real-time positioning of the detector;
• detailed PMTs charge/time calibration;
• detailed systematic knowledge of the apparatus (OMs angular acceptance, etc.)
• Angular resolution: up to $\Delta \theta \sim 0.2^\circ$.
• Used in the diffuse analysis search

Ref: arXiv 0908.0816
reconstruction of muon trajectory from time, charge and position of PMT hits assuming relativistic muon emitting Cherenkov light

Fast tracking
Example of a **reconstructed up-going muon** (i.e. a neutrino candidate) detected in 6/12 detector lines:
SELECTED RESULTS

• atmospheric muon flux
• atmospheric neutrinos
  • point sources
• diffuse $\nu_\mu$ flux
Zenith angle distribution of reconstructed tracks from atmospheric $\mu$’s. 5 line detector.

Main sources of syst. uncertainties:
- environmental parameters (absorption and scattering)
- detector parameters (OM efficiency)
- (physics) hadronic interaction models
- (physics) models of cosmic ray composition

Dots: Data
— CORSIKA + QGSJET + NSU (model of the primary CR)
— CORSIKA + SIBYLL + NSU
— CORSIKA + QGSJET + “polygonato” model.

Shadowed band: systematic uncertainty w.r.t. black line.

Ref: arXiv:1007.1777, Accepted to APP
MUON DEPTH-INTENSITY RELATION

Fast tracking
Fast tracking

- 5-line data (May-Dec. 2007) + 9-12 line data (2008) = 341 days detector live time

Upgoing:
- 1062 neutrino candidates:
  - 3.1 $\nu$ candidates/day

Monte Carlo:
- Atmospheric neutrinos: 916 (30% syst. error)
- Wrong reco atmospheric $\mu$: 40 (50% syst. error)
Fast tracking
Fast tracking

list of 25 potential sources (stringent cuts to reduce background)
Analysis optimization based on simulations
no excess found after 5-line data unblinding
140 days of detector livetime


\[ \frac{dE_\mu}{dx} = \alpha(E_\mu) + \beta(E_\mu) \cdot E_\mu \]

\( \mu \) direct photons + 
\( \mu \) scattered photons + 
light from EM showers

Energy estimator=
Repetition (R) of integration gate on the same Optical Module
ENERGY ESTIMATOR ON ATMOSPHERIC MUONS

Precise tracking

Well reconstructed

Wrongly reconstructed
1. Rejection of downward going atmospheric muons (using measured zenith angle, track quality parameter, number of hits)

2. Separation of the atmospheric $\nu$ background from signal $E^2 \Phi_{\text{test}} = 1.0 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ using the energy estimator $R$

Model Rejection Factor [APP 19 (2003)393] to select the best cut value on $R (=1.31)$ predefined from MC only.
DIFFUSE $\nu_\mu$ FLUX – RESULTS

R< 1.31
Bartol (conventional $\nu$) 104.0
Max “prompt” model 2.1
Data 125

Precise tracking

$E^2 \Phi_{\text{test}} = 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

R$\geq$ 1.31
Atmospheric $\nu$ 10.7 ± 2
Data 9
$E^2 \Phi(E)_{90\%} = 4.7 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

20 TeV < $E$ < 2.5 PeV
**DIFFUSE $\nu_\mu$ FLUX – UPPER LIMITS – (other energy spectra)**

<table>
<thead>
<tr>
<th>Model</th>
<th>$R^*$</th>
<th>$N_{mod}$</th>
<th>$\Delta E_{90%}$ (PeV)</th>
<th>$\mu_{90%}/N_{mod}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPR[7]</td>
<td>1.43</td>
<td>3.0</td>
<td>0.1 $\div$ 10</td>
<td>0.4</td>
</tr>
<tr>
<td>P96$\gamma$[31]</td>
<td>1.43</td>
<td>6.0</td>
<td>0.2 $\div$ 10</td>
<td>0.2</td>
</tr>
<tr>
<td>S05[32]</td>
<td>1.45</td>
<td>1.3</td>
<td>0.3 $\div$ 5</td>
<td>1.2</td>
</tr>
<tr>
<td>SeSi[33]</td>
<td>1.48</td>
<td>2.7</td>
<td>0.3 $\div$ 20</td>
<td>0.6</td>
</tr>
<tr>
<td>Mpp + $p\gamma$[34]</td>
<td>1.48</td>
<td>0.24</td>
<td>0.8 $\div$ 50</td>
<td>6.8</td>
</tr>
</tbody>
</table>

<1 : model rejected

---

• Receive GRB alerts from Satellites (Fermi, Swift...) search for coincident neutrinos within time window (~100 s)
• Send neutrino cluster alert for optical follow-up
Trigger: multiple / HE single neutrino event; Reconstruction “on-line” (<10ms)
Alert message to Tarot Telescope in La Silla (Chile). Tarot takes 6 images of 3 minutes immediately and after 1, 3, 9 and 27 days sending alerts to the ROTSE system (4 telescopes)
• Correlation with AUGER source distribution investigate directional correlation of neutrinos and UHE particles
• Correlation with VIRGO-LIGO signals investigate correlation of neutrinos and gravitational waves
CONCLUSIONS

ANTARES

• continuously taking data
• complements the sky coverage of IceCube
• has a broad physics program
• determined most sensitive upper limit on diffuse flux
• paves the way for KM3NeT
angular resolution = difference between reconstructed and MC generated angles vs. neutrino energy

\[ \Theta_{\nu-\mu} \leq \frac{0.7^\circ}{E_\nu \text{ (TeV) }^{0.6}} \]

angular resolution

< 0.2° above \( \approx 10 \text{ TeV} \)

limited tracking accuracy due to time resolution:

- Light scattering \( \sigma \sim 1.0 \text{ ns} \)
- TTS in PMT \( \sigma \sim 1.3 \text{ ns} \)
- time calibration \( \sigma < 0.5 \text{ ns} \)
- OM position \( \sigma < 10 \text{ cm} \) (\( \leftrightarrow \sigma < 0.5 \text{ ns} \))
- Transceivers on the bottom of each line
- 5 hydrophones at specific heights on each line
- 4 autonomous transponders around the apparatus
- Sound velocimeters installed at various depths
- Tiltmeter and compass at each storey

Measurements performed every 2 minutes

Position of hydrophone relative to line base location

20 days
resolution better than 10 cm
### Time Calibration

Time difference between the LED OB and an OM

- **Electronics + calibration** $\Rightarrow \sigma \sim 0.5$ ns
- **TTS in photomultipliers** $\Rightarrow \sigma \sim 1.3$ ns
- **Light scattering + dispersion in sea water** $\Rightarrow \sigma \sim 1.5$ ns at 40 m

---

**Angular resolution** $\Rightarrow 0.3^\circ$ (for $E_\nu > 10$ TeV)

Including the acoustic position resolution and the $\nu$-\(\mu\) angle
The biggest challenge is to determine the separate contribution of absorption and scattering

\[ Q(R) = \frac{Q_0 \exp(-R/L)}{R^2} \]
OM ANGULAR ACCEPTANCE

Has to be known to compute reconstruction efficiencies and effective areas

Measurements were performed in a water tank
Photon scattering affects the measurements

angular acceptance determination is not reliable at large $\theta_{\text{PMT}}$

Dedicated measurements of the photocathode surface of OMs

Angular acceptance uncertainty at large $\theta$ affects $\mu$ flux significantly, but not $\nu$ flux
**IN SITU CALIBRATION WITH $^{40}\text{K}$**

- **$\gamma$** (Cherenkov)
- **$e^-$ (β decay)**
- **$^{40}\text{K}$**
- **$^{40}\text{Ca}$**

**Gaussian peak on coincidence plot**

**Integral under peak = rate of correlated coincidences**

**Peak offset**

- No dependence on bioluminescent activity has been observed
- Cross check of time calibration

---

Heide Costantini – INFN Genova

RICH2010, 3rd May 2010
• REAL TIME POSITIONING ➔ Acoustic positioning system + set of tiltmeters and compasses.
• Transceivers (RxTx) on the bottom of the lines, 4 autonomous transponders around the apparatus.
• 5 hydrophones (Rx) per line at specific heights.
• Tiltmeter and compass per storey, sound velocimeters (various depths).

RECONSTRUCTION OF THE LINE SHAPE ➔ GLOBAL $\chi^2$ FIT TO LINE SHAPE MODEL (BEHAVIOUR OF LINE: SEA CURRENT)

Hydrophone position relative to line base location (20 days)