High Energy Neutrino Astronomy
with the ANTARES Deep-Sea Telescope

- research goals: deep kosmos
- the detector setup: deep sea
- status and performance
- some results: $\mu$, $\nu$
- expectations
- summary

Herbert Löhner, KVI, University Groningen, The Netherlands on behalf of the ANTARES collaboration http://antares.in2p3.fr
the sky in the light of $\gamma$ rays

HESS telescope in Namibia

VHE $\gamma$-ray Sky Map
($E_\gamma > 100 \text{ GeV}$)

VHE $\gamma$-ray sources
- Blazar (HBL)
- Blazar (LBL)
- Flat Spectrum Radio Quasar
- Radio Galaxy
- Starburst galaxy
- Pulsar Wind Nebula
- Supernova Remnant
- Binary System
- Wolf-Rayet Star
- Open Cluster
- Unidentified

2010-10-11 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/
neutrino astronomy

intriguing science questions:
• origin of cosmic rays \(\rightarrow 10^{20} \text{ eV} \) ?
• astrophysical acceleration mechanism?
• origin of relativistic jets?
• dark matter?

cosmic sources of neutrinos
• Active Galactic Nuclei: super-massive black hole in center of galaxies
• micro quasars: X-ray binaries (in our galaxy)
• supernova remnants and shock acceleration

TeV \(\gamma\) rays (\( p+X \rightarrow \pi^0 \rightarrow \gamma\gamma \)) in 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 sensitivity and angular resolution
Active Galactic Nuclei (AGN)

Hubble: galaxy M87 jet

Supermassive Black Hole ($>10^6 \, M_\odot$) → Accretion Disk → Frictional heating → Plasma → relativistic jet
sky view (galactic coordinates)

AMANDA / IceCube (South Pole)  

ANTARES (43° N)

acceptance density

acceptance range

Mkn 421  
Mkn 501  
SS433  
CRAB

Mkn 501  
RX J1713.7-39  
SS433  
GX339-4  
VELA  
Galactic Centre

1.5 π sr common view per day
indirect WIMP detection

Relic WIMPs (neutralino $\chi$ ?) from Big Bang scatter in e.g. the Sun and become gravitationally trapped

$\rightarrow$ increased WIMP density

$\rightarrow$ increased WIMP annihilation rate

$\rightarrow$ high-energy neutrino flux (limit) from the Sun
detection principle

Neutrinos can interact through charged current interaction in the vicinity of a neutrino telescope.

up-going neutrinos passing through the Earth are free from atmospheric muon background.

\( \nu_{\mu} \) track reconstructed from \( \mu \) Cherenkov cone passing 3D grid of PMTs.

10⁷ atm. \( \mu \) per year

10⁴ atm. \( \nu \)

1 - 100 cosm. \( \nu \)
the telescope setup

- 3 10” PMT/storey
- 25 storeys/line
- 12 detection lines:
  - ~900 PMT + acoustic detection

Dimensions:
- Buoy: 14.5 m
- Junction box: 100 m
- Electro-optical cable: 45 km
- Readout cables: ~60-75 m
The Antares Site

Villa Pacha

- 45 km submarine cable
- 2475 m

Astropart. Phys 13 (2000) (Background light)
Astropart. Phys 23 (2005) (Light transmission)
status of the experiment

Antares installation completed May 2008

Footprint of the 12-line detector in atmospheric muons

x, y coordinates of track fits at the time of the first triggered hit

~ 0.1 km² sensitive surface
Median rate of measured single photon counts: typ. 60 – 80 kHz caused by bioluminescence (~ 30 kHz) and $^{40}$K decay (~ 40 kHz) with occasional bursts of extreme high rates (~ MHz) caused by macro-organisms (depends on sea current):

multidisciplinary research, oceanographic studies
bursts from macro-organisms:  
~ few MHz,  
strongly affected by sea currents:

mechanically stimulated bioluminescence

interesting issues for ESONET – EMSO:  
European Multidisciplinary Sea Observatory  
to be published in Deep Sea Research I.
Local coincidences from $^{40}\text{K}$ decay

- Efficiency of Optical Modules ($\sim$8%)
- Accuracy of time calibration ($\sim$0.5 ns)

Peak integral

Gaussian distributed local coincidence time

- Efficiency of Optical Modules (~8%)
- Accuracy of time calibration (~0.5 ns)
track reconstruction

Cherenkov effect

Sea water $n \sim 1.35$

Position resolution: $\sim 10$ cm

Time resolution: $\sim 2$ ns

Optical Module $\text{OM}_i$

arrival time at $\text{OM}_i$

($v_g = \text{group velocity of light in water}$)

$$t_i = t_0 + \frac{1}{c} \left( \ell - \frac{k}{\tan \theta_C} \right) + \frac{1}{v_g} \left( \frac{k}{\sin \theta_C} \right)$$
expected performance: 12 lines

angular resolution = difference between reconstructed and MC generated angles vs. neutrino energy

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

angular resolution

\(< 0.2 \quad \text{above} \approx 10^5 \text{ GeV}\)

limited tracking accuracy due to time resolution:

- Light scattering $\sigma \sim 1.0$ ns
- TTS in PMT $\sigma \sim 1.3$ ns
- time calibration $\sigma < 0.5$ ns
- OM position $\sigma < 10$ cm
  ($\leftrightarrow \sigma < 0.5$ ns)
up-going muon: neutrino candidate

reconstruction of muon trajectory from **time, charge and position** of PMT hits assuming relativistic muons emitting **Cherenkov light: 34.8° up-going muon**
Muon Flux

$\Phi(h)$ depends on depth ($h$): dependence directly measured from adjacent storey coincidences:

$$\Phi(h) = \Phi_0 \cdot \exp\left(\frac{h-h_0}{\lambda}\right)$$

(slope $\lambda$ not affected by normalization uncertainty:

$$\lambda = 540 \pm 25 \text{ m}$$

in agreement with Monte Carlo:

$\lambda^{MUPAGE} = 560 \text{ m}$

$\lambda^{CORSIKA} = 570 \text{ m}$
Muon Depth-Intensity relation

\[ I(\vartheta, h_o) = \frac{N(\vartheta, h_o) \cdot \mu(\vartheta, h_o)}{A_{\text{eff}}(\vartheta) \cdot T \cdot \Delta \Omega(\vartheta)} \]

Parameterization from E. V. Bugaev et al., PRD 58 (1998) 05401

good agreement with Monte Carlo and various experiments
neutrino candidates from track zenith distribution

5-line data (May-Dec. 2007) +
9-12 line data (2008)

341 days detector live time,
reconstruction BBfit v3r2,
single- and multi-line fit:

1062 neutrino candidates:

3.1 \( \nu \) candidates/day

good agreement with Monte Carlo:

atmospheric neutrinos: 916 (30\% syst. error)
atmospheric muons: 40 (50\% syst. error)
Search for point-like neutrino sources

with the 2007 (5-line) data: effective live time 140 days
stringent selections: low background
high reconstruction quality (ang. resolution < 0.5°)

searches
on data with scrambled coordinates of 94 events (equatorial coordinates):

no correlation with 25 potential \( \nu \) sources;
no excess (± 1\( \sigma \)) in all-sky search;
sensitivity competitive with multi-year exposures of previous experiments
Improved sky map data

Scrambled data from 2007+2008 analysis: galactic coordinates

750 up-going neutrinos

actually, 2000 neutrino events available, analyzed: correlations published soon
Ice Cube sky map

1877 events, equatorial coordinates

“No significant deviation from the background hypothesis was found in the sky map.”
Antares event classes

Event Classes with a Track

\[ \nu_\mu, \bar{\nu}_\mu \quad CC \]

Event Classes without a Track

\[ \nu_\tau, \bar{\nu}_\tau \quad NC \]

\[ \nu_e, \bar{\nu}_e \quad CC \]

extend Antares sensitivity to all 3 neutrino flavours
$\nu$-induced shower in Antares
background suppression

Expected number of events/year after each criterion (logarithmic scale)

A: (down-going) atmospheric muons
B: False up-going events (2.5%)
C: Minimum deposited charge
   (0.5% false up-going)

A: All showers
B: All up-going events (70%)
C: Minimum deposited charge
   (28% left after the criteria)
apply selective cuts on shower observables

Using combined cut to maximize Purity & Efficiency

\[ \chi^2 \text{ cut} \]

\[ \text{residual cut} \]

combined cuts
high shower selectivity

Atmospheric muon suppression

Upgoing shower selection

Expected reconstruction of ~ 200 showers/year with good energy determination

(logarithmic scale)
Multi-Messenger astronomy

Strategy: higher **discovery potential** by observing different probes
higher **significance** by coincidence detection
higher **efficiency** by relaxed cuts

MoUs for joint research

**Ligo/Virgo**
Gravitational waves: trigger + dedicated analysis chain

**TAROT**
optical follow up: 10 s repositioning

**GCN**
GRB Coord. Network: γ satellites

Prague, February 16, 2011

H. Löhner, High Energy Neutrino Astronomy
Ice Cube at the Southpole

IceCube Lab

1 km$^3$ completed in 2010

IceCube Array
86 strings, 60 sensors each
5,160 optical sensors

DeepCore
6 strings optimized for low energies

Eiffel Tower
324 meters

Prague, February 16, 2011

H. Löhner, High Energy Neutrino Astronomy
future plans: KM3NeT concept

array of optical modules (OM) sensing Cherenkov light

instrumented volume several km$^3$

sensitive to all $\nu$ flavours

$E_\nu > 0.1$ GeV

angular resolution min $0.1^\circ$ for $E_\nu > 10$ TeV

acceptance: up-going tracks, up to $10^\circ$ above horizon
candidate deployment sites

criteria:
bioluminescence, $^{40}$K background, salinity, currents, water transparency: transmission length (recent data) \( \leq (46+3) \text{ m} \) at depth 2500 - 3000 m at \( \lambda = 450 - 470 \text{ nm} \)
optical module / string design

new multi-PMT Optical Module concept with 31 3” PMT

String Detection Unit

high 2-photon purity (sea background) and directional sensitivity
**KM3NeT Consortium**

42 institutes from:

Cyprus, France, Germany, Greece, Ireland, Italy, Netherlands, Romania, Spain, UK

pilot projects:

- **ANTARES**
- **NESTOR**
- **NEMO**
- +...

funded by EU FP6 for Design Study, by EU FP7 for Preparatory Phase, on the ASPERA roadmap

*Conceptual Design Report*
April 2008

*Technical Design Report*
July 2010

*start Construction Phase*
2012
The ANTARES Collaboration

- NIKHEF, Amsterdam
- KVI Groningen
- NIOZ Texel
- ECAP, Erlangen
- Bamberg
- CPPM, Marseille
- DSM/IRFU/CEA, Saclay
- APC Paris
- IPHC (IReS), Strasbourg
- Univ. de H.-A., Mulhouse
- Clermont-Ferrand
- IFREMER, Toulon/Brest
- C.O.M. Marseille
- LAM, Marseille
- GeoAzur Villefranche
- University/INFN of Bari
- University/INFN of Bologna
- University/INFN of Catania
- LNS – Catania
- University/INFN of Pisa
- University/INFN of Rome
- University/INFN of Genova

7 countries
30 institutes
140 scientists
Summary

- **ANTARES completed since May 2008**
- muon intensity-depth distributions determined
- angular resolution $<0.2$ degree for energies $>100$ TeV
- neutrino candidate events selected ($\sim3$ / day)
- point source distribution: no signal yet, work in progress
- multi-messenger observations on alert
- KM3NeT development for several km$^3$ observatory
track quality selection

reconstruction algorithm:
• linear prefit photon hit coordinates \(x, y, z, t\)
• minimization with hit-charge weights
• Maximum likelihood (L) fit using MC pdf of time residuals

quality cut variable:
\[
\Lambda = -\frac{\ln L}{N_{dof}} + 0.1 \cdot \left( N_{comp} - 1 \right)
\]

remaining 10 atmospheric \(\nu\) / day
1 atmospheric \(\mu\) / day
Event Display

Hits are plotted for each line: height (z) versus time (t)

⇒ Characteristic pattern depending on zenith angle and distance of closest approach

Several reconstruction strategies available and explored:
1D, 3D, $\chi^2$ minimization, Max. Likelihood optimization
Atmospheric muons

- **black points**: data 5-line detector (2007)
- **blue line**: MUPAGE Monte Carlo [Com. Phys. Comm. 179(2009)915]
- **red line**: CORSIKA + QGSJET + NSU param for

For details on:

Main sources of systematic uncertainties:
- environmental parameters (absorption and scattering length)
- detector parameters (OM efficiency)
- **Shadowed band**: systematic uncertainty w.r.t. the black line (40%).

- physics:
  - hadronic interaction models
  - models of cosmic ray composition

- within systematic uncertainties data are reproduced by MC
- good understanding of the detector and its environment
- work in progress to reduce uncertainties
Hillas criterion

Magnetic field confines charged particles in acceleration region:

\[ E_{\text{max}} \propto \beta c Z e B r_L \]

\[ \log (B) + \log (r_L) \propto E_{\text{max}} \]

candidate sites for 100 EeV, 1 ZeV protons

- Neutron star
- GRB
- Protons (100 EeV)
- Protons (1 ZeV)
- White dwarf
- Fe (100 EeV)
- nuclei, jets, hot-spots, lobes
- Active galaxies
- Colliding galaxies
- SNR
- Galactic disk, halo
- Clusters

log (magn. field B / Gauss)

log (size \( r_L \)/km)

1 au, 1 pc, 1 kpc, 1 Mpc
instrumentation line for environmental monitoring

Goals:
- monitor of environmental sea parameters
- apparatus calibration
- acoustic detection prototyping

- WetLabs CSTAR light transmissometer
- CT = Seabird Conductivity-Temperature probe
- SV = Sound Velocimeter
- ADCP = Acoustic Doppler Current Profiler
- GURALP seismometer
- 2 OMs
- 1 Laser + 2 Led Beacon
- Acoustic Positioning RxTx & Rx
- O₂-probe
- 2 cameras

Three floors equipped for acoustic detection R&D (part of the AMADEUS prototype system)
Storey coincidences

derive depth dependence of muon flux from coincidence-time distributions of (next-to) adjacent storeys, each with a local coincidence (± 20 ns):

low threshold of 4 GeV (minimum track length between adjacent storeys)

distribution of measured time differences agrees with MUPAGE MonteCarlo

mostly down-going muons: delay ~ + 20 ns)