The neutrino telescope

ANTARES

(antares.in2p3.fr)

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Thomas Eberl
for the ANTARES collaboration
Fermi and Jansky Meeting
St. Michaels, November 12th, 2011
Neutrino Astronomy

A new window to the Universe
Why high-energy neutrino astronomy?

- Neutrinos point back to the source
- Neutrinos travel cosmological distances
- Neutrinos escape from optically thick sources
- Neutrinos are a clear sign for hadron acceleration

→ Understand origin and acceleration of HE hadronic CRs
→ Neutrinos provide complementary information to gamma-rays and protons
Neutrinos are unique cosmic messengers!

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

Photons: absorbed on dust and radiation
Protons/nuclei: deflected by magnetic fields, reactions with radiation (CMB)
High-energy neutrino production in the Universe

- CR (hadron) accelerators
- Shock fronts (Fermi acceleration)
- Strong magnetic fields up to $10^{15}$ Gauss (pulsars, magnetars)

- Beam dump (secondary particle production)
  - Interaction with photon field, matter, interstellar medium
  - Protons: pion decay gives photon <-> neutrino connection

\[
p + p(\gamma) \rightarrow \pi^\pm + X \\
\xrightarrow{\mu + \nu_\mu} \\
\xrightarrow{e + \nu_\mu + \nu_e} \\
p + p(\gamma) \rightarrow \pi^0 + X \\
\xrightarrow{\gamma + \gamma \ (TeV)}
\]

→ Many diffuse and point source flux predictions available

see e.g. reviews Becker 2008 Phys. Rep., Chiarusi et al. 2010 EPJ C,
Neutrino fluxes: overview

Neutrino Energy

- underground
  - deep water
  - deep ice
- optical:
  - air showers
  - radio
  - acoustics

Flux (cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\))

- Cosmological \(\nu\)
- Solar \(\nu\)
- Supernova burst (1987A)
- Reactor anti-\(\nu\)
- Background from old supernova
- Terrestrial anti-\(\nu\)
- Atmospheric \(\nu\)
- \(\nu\) from AGN
- GZK \(\nu\)

\(\nu\) from AGN

Courtesy C. Spiering

Th. Eberl for the ANTARES collaboration, Fermi & Jansky, St. Michaels, Nov. 2011
Physics with neutrino telescopes

- **Galactic sources**
  (Supernova remnants, Binary systems, Pulsar Wind Nebulae . . .)

- **Extra-Galactic sources**
  (Gamma-ray Bursts, Active Galactic Nuclei . . .)

- **Dark Matter**
  (WIMPs)

- **Cosmogenic neutrinos**
  (GZK, Top-down, . . .)

- Supernovae (MeV neutrinos)
- Neutrino oscillations (atmospheric neutrinos 10 - 100 GeV)
- Cosmic-ray anisotropy (atm. muons)
- Exotic physics
  (Lorentz violation, monopoles, . . .)
A particle detector in the deep sea!
ANTARES

- 12 Lines (885 PMTs)
- since 05/2008
- Volume: ~0.03 km$^3$
A Storey: The Basic Detector Element

- Local Control Module (titanium cylinder)
- LED Optical Beacon timing calibration (4 per line)
- Hydrophone RX (5 per line)
- Optical Module: 17” glass sphere 10” PMT Ham. R7081-20
The ANTARES Collaboration

27 institutes in 7 European countries
ANTARES deployment
ANTARES in the Mediterranean Sea

La Seyne-sur-Mer, near Toulon, France

42°47.935′N, 6°09.942′E
ANTARES in the Mediterranean Sea

La Seyne-sur-Mer, near Toulon, France
High-energy Neutrino Telescopes 2011

IceCube
V ~ 1 km³ since 12/2010

ANTARES
NESTOR
NEMO
BAIKAL
The Telescope: principle and performance
Neutrino nucleon interactions

"golden" channel for astronomy

J. Tiffenberg, NUSKY11
Principle of (muon) neutrino detection

ANTARES:
Angular resolution
0.3 ° for $E_\nu > 10$ TeV

$\nu_\mu$ trajectory
Time & position of detected Cherenkov light
PMT amplitudes
$\mu (~ \nu)$ trajectory
Energy

$43^\circ$
Particle background: atm. muons and neutrinos

- Flux from above dominated by atmospheric muons
- Neutrino telescopes optimised to be sensitive to neutrinos from below
Muon background suppression

Good Data – MC agreement!
Angular resolution (from MC)

ANTARES 2007-2010 $E^2$ neutrino MC

- Median angular resolution $0.46 \text{ deg}$ (2007-2010 data)
- Absolute pointing $\sim 0.1 \text{ deg}$

Cumulative distribution

PSF
Sky coverage

ANTARES
- > 75%
- 25% – 75%
- < 25%

TeV γ-Sources
- galactic
- extra-galactic

IceCube
- 100%
- 0%

0.5 \( \pi \) sr instantaneous common view
1.5 \( \pi \) sr common view per day
First Results
Atmospheric muon flux: depth-intensity relation with 5 Lines

Upper limit on diffuse flux of cosmic HE $\nu$

$E^2 \Phi(E)_{90\%CL} = 5.3^{+2}_{-1} \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

0.83 * $2\pi$ sr

monitored for
334 days

with reduced detector setup
during construction phase
First neutrino sky map, 2007-2008 data


objects for candidate list search
Updated sky map, 2007-2010 data, prelim.

3058 neutrino events

Candidate list search
(51 candidate sources, best HESS J1023-575, $p=41\%$)

All-sky search
$p$-value: 2.6%
not significant
Method: unbinned search with likelihood ratio

\[
\log L_{s+b} = \sum_i \log[\mu_{\text{sig}} \times F(\beta_i, \delta_s, \alpha_s)] \times \mathcal{N}(N_{hit}^{i, \text{sig}}) \\
+ B_i \times \mathcal{N}(N_{hit}^{i, \text{bkg}})] + \mu_{\text{tot}},
\]

test statistic: \( Q = L_{s+b}^{\text{max}} - L_b \)

---

Table 1: Results of the candidate source search. The source coordinates and the p-values (p) are shown as well as the limits on the flux intensity \( \sigma_{\text{90%CL}} \); the latter has units \( 10^{-8} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \).

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<th>Source</th>
<th>( \alpha_s (\degree) )</th>
<th>( \delta_s (\degree) )</th>
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</table>

Th. Eberl for the ANTARES collaboration, Fermi & Jansky, St. Michaels, Nov. 2011
Sensitivity: best limits for the southern sky!
Auto-correlation: 2007-2008

search for deviations from isotropy in neutrino sky
• cumulative number of neutrino pairs in increasing ang. bins
  compared to mean randomized sky
→ no significant excess found
First time dependent analysis

• use “high-state” time information from other experiments: e.g. Fermi, H.E.S.S., Swift etc.

• Idea: space and time coincidences reduce background

• improve discovery potential over time-integrated searches

• Method in the following:
  - unbinned search using likelihood ratio
  - optimization: min. flux for 5 sigma discovery

• Search for flaring Fermi-LAT blazars in Sept. – Dec. 2008
Potential of time dependent analysis

Average number of events per source required for 5 sigma discovery (50% probability) as function of the flare period width.

factor 2 – 3 improvement compared to time-integrated analysis
Blazar coincidence searches

- identify flare period for 10 gamma sources, search for neutrino coincidence
- 1st year Fermi cat + LBAS → 6 FSRQs+4 BL Lacs, only 4 seen by IACTS
- 1 coincidence found for 3C279, 0 for the other 9 objects

<table>
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<th>Source</th>
<th>visibility</th>
<th>timePDF (MJD+54000)</th>
<th>Live time (day)</th>
<th>N(5σ)</th>
<th>Nobs</th>
<th>Fluence U.L. GeV/cm²</th>
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<td>749-51, 787-809, 812-5, 817-21, 824-6</td>
<td>13.8</td>
<td>5.0</td>
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<td>8.2</td>
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</table>

3C279, Fermi and ANTARES data
Neutrino search result for 3C279

- 61 days live-time of ANTARES data from Sept. – Dec. 2008 used
- 1 neutrino compatible with time range of flare and with coordinates of 3C279 (ang. distance 0.56 degrees)
- post-trial probability of 10%
  → compatible with atmospheric background fluctuation

- energy of event not yet used
Outlook on time dependent analysis

- Several thousand neutrino candidates recorded since start of 2008, data analysis in progress
Outlook on ANTARES & TANAMI

Idea: develop a dynamical blazar $\nu$-candidate list, based on the variable GeV Fermi sky and the jet-production activity as revealed by TANAMI.

→ work in progress:
C. Müller, M. Kadler, U. Fritsch, K. Fehn, TE, … (ECAP and U. Würzburg).
Recent ANTARES publications
... much more to come

- First search for point sources of high energy cosmic neutrinos with the ANTARES neutrino telescope
  J.A. Aguilar et al.

- Acoustic and optical variations during rapid downward motion episodes in the deep north-western Mediterranean Sea
  H. van Maren et al.
  Deep-Sea Research I 58 (2011) 875–884

- ANTARES: the first underwater neutrino telescope
  J.A. Aguilar et al.

- A Fast Algorithm for Muon Track Reconstruction and its Application to the ANTARES Neutrino Telescope
  J.A. Aguilar et al.
  To be published in Astroparticle Physics

- Time Calibration of the ANTARES neutrino Telescope
  J.A. Aguilar et al.

- Search for a diffuse flux of high energy $\eta_\nu$ with the ANTARES neutrino telescope
  J.A. Aguilar et al.

- AMADEUS - The Acoustic Neutrino Detection Test System of the ANTARES Deep-Sea Neutrino Telescope
  J.A. Aguilar et al.

- Zenith distribution and flux of atmospheric muons measured with the 5-line ANTARES detector
  J.A. Aguilar et al.

- Performance of the front-end electronics of the ANTARES Neutrino Telescope
  J.A. Aguilar et al.

- Measurement of the atmospheric muon flux with a 4 GeV threshold in the ANTARES neutrino telescope
  J.A. Aguilar et al.

- Performance of the First ANTARES Detector Line
  M. Agaron et al.
No time to talk about …

- TATOO: Fast optical follow up program
- GRB analyses
- Dark matter searches
- Neutrino oscillations
- Joint analyses with VIRGO/LIGO and Pierre Auger
- Exotics: limits on nuclearites and monopoles
- CR composition studies
- AMADEUS: Acoustic neutrino detection feasibility study
- … but some words about the future: KM3NeT
The Future: KM3NeT

artist’s impression, 1/3

www.km3net.org
KM3NeT: What & why?

- Large deep-sea infrastructure in the Mediterranean Sea
  - next generation neutrino telescope: \textit{multi - km}^3 \textit{size}
  - cabled observatories for Earth & Sea sciences

- Science
  - discovery of sources of (high-energy) cosmic neutrinos
  - continuous and long-term measurements in the areas of oceanography, geophysics and marine biological sciences
KM3NeT: Scientific focus

- Geographical location
  Field of view includes Galactic centre

- Optical properties of deep-sea water
  Excellent angular resolution

- Envisaged budget 220–250 M€
  Large effective neutrino area

Observe Supernova Remnants in our Galaxy
Fermi & Jansky .... & Pauli?

Sensitivity of KM3NeT (TDR) to neutrino point sources

Figure 6-10: Sensitivity of the full KM3NeT detector to neutrino point sources with an $E^2$ spectrum for one year of observation, as a function of the source declination. The red lines indicate the flux sensitivity (90% CL; full line) and the discovery flux (5σ, 50% probability; dashed line). Both are estimated with the binned analysis method. The black line is the IceCube flux sensitivity for one year, estimated with the unbinned method [2] (full line). IceCube’s discovery flux (5σ, 50% probability) is also indicated (shaded band, spanning a factor 2.5 to 3.5 above the flux sensitivity). The red ticks at the bottom of the horizontal axis show the positions of Galactic gamma ray sources [3]; the position of the Galactic Centre is indicated by a blue star.
KM3NeT: Timeline from TDR

Summary and Conclusions

ANTARES …

• is a pilot project in the MedSea and takes data for 4.5 years now
• proves feasibility of deep sea concept for KM3NeT
• FOV and excellent angular resolution allow to complement IceCube
• has a broad (particle and astro-) physics program
• determines sensitive upper limits on HE diffuse $\nu$ flux and on fluxes from Galactic and Extra-Galactic point sources
• makes use of multi-messenger information to increase sensitivity
Backup slides
### Fermi sources for time dependent analysis

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ANTARES vs IceCube: $5\sigma$ discovery flux

- Combined data analysis of ANTARES with IceCube in progress

ANTARES vs IceCube: $5\sigma$ discovery flux

- ANTARES adds sensitivity at $\delta < 0$ at $E \sim 10\text{TeV}$: Galactic sources!
- Very different energy ranges!!!

**Graph:**
- $\delta = -8^\circ$
- $\delta = -30^\circ$
- $\delta = -60^\circ$

**Notes:**

Th. Eberl for the ANTARES collaboration, Fermi & Jansky, St. Michaels, Nov. 2011
Optical Background: the deep sea is not dark !!!

Optical background due to $^{40}$K-decay and bioluminescence

- Typical rates per PMT 60-120 kHz
- Additional short bursts and periods with higher rates
Bioluminescent Sources

- Bacteria: steady baseline source of light (30kHz in 10” PMT)
- Macro-organisms: short flashes (up to MHz)

  e.g. large colonial organisms such as pyrosomes (megaplankton)

  size range: 0.2 - 2000 mm
Angular resolution

Angular resolution $< 0.3^\circ$ for $E_\nu > 10$ TeV

Tracking accuracy limited by timing 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)
Angular resolution compared to IceCube

advantage of water over ice:

less light scattering
-> better angular resolution

ANTARES: 80% in 1 deg
IceCube : 60% in 1 deg

expectation for KM3NeT:
50% better than 0.1 deg
(longer lever arm!)
Detector positioning

- Acoustic system
  - 1 emitter (+ receiver)
  - at each line socket
  - 5 receivers along each line
- Compass and Accelerometer
  - 1 Compass at each storey
  - 1 Acc. at each storey
- Measure every 2 min
  - Acoustics: distance sockets - receivers
  - Compass: heading
  - Accelerometer: tilt

Line shape
Detector positioning

typical line shape

\[ r = (az - b \ln[1-cz]) v^2 \]

Example for Sea current
\[ v = 25 \text{ cm/s} \]
\[ r_{\text{max}} = 22 \text{m} \]

mostly coherent movement of lines
Neutrino Detector / Energy Spectrum

Accelerator-based

Energy ↔ Volume

Atmospheric/Astrophysical

T. deYoung, MANTS2011
Neutrino – nucleon cross sections

PhD thesis O. Schulz
Neutrino mean free path in water

\[ \log_{10}(L_{\text{cm}}) \]

- \( L_{\nu} \)
- \( L_{\bar{\nu}} \)
- Earth diameter

\[ \log_{10}(E[\text{GeV}]) \]

PhD thesis O. Schulz
Why we need a km3 array?

Putting things together: the 1km³ estimate

Waxman-Bahcall flux limit
\[ E^2 \Phi = 2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \]
Should produce several neutrinos per year
Use muon flux:
\[ \Phi_\mu = \Phi_\nu \times \sigma_\text{muon range} \times \text{muon range} \]
Then
\[ \text{Integral}(\Phi_\mu \, dE) \times 1 \text{yr} \times A = O(1-10) \]
This results in \( A \sim 1 \text{ km}^2 \)

Then same area for all directions \( \sim 1\text{km}^3 \)
Estimated neutrino fluxes (SNR)

- Photon ↔ neutrino connection:
  \[ p + p \rightarrow \pi^0 + X \quad \rightarrow \quad \gamma + \gamma \]
  \[ p + p \rightarrow \pi^\pm + X \quad \rightarrow \quad \mu + \nu_\mu + \nu_e + \nu_e \]

- Observed from RX J1713.7–3946:
  - \( \gamma \)-rays up to several 10 TeV
  - \( \rightarrow \) particle acceleration up to 100 TeV and above

- Calculated neutrino fluxes:
  For strong sources:
  \[ 10^{-12} - 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ @ 1 TeV} \]

Halzen et al., PRD (2008)
pp interactions, E spectra, decay products

Kelner et al, PhysRev D74, 2006
Atmospheric neutrino sources

Atmospheric neutrino sources

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \]

\[ \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \bar{\nu}_\mu (\nu_\mu) \]

If all particles decay then:

\[ \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2, \quad \frac{\nu_\mu}{\bar{\nu}_\mu} \sim 1 \quad \text{and} \quad \frac{\nu_e}{\bar{\nu}_e} \sim \mu^+ / \mu^- . \]

Muons with energy of several GeV and above reach the ground before decaying.
Neutrino interaction signatures
CR air shower
HE neutrino production

Example: Active galaxy
(Halzen, Venice 2009)
Hadronic jets as possible HE neutrino sources