Suche nach hochenergetischen Neutrinos im Baikalsee und im Südpoleis

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Themen

• Eigenschaften von Neutrino ▶ Vortrag M Lindner
• Hochenergetische Quellen von Neutrino ▶ Vortrag G Sigl

• Neutrino Teleskope – Prinzipien
• Die Detektoren Baikal, AMANDA und IceCube
• Eine Auswahl von Ergebnissen:
  • Messung der atmosphärischen Muon- und Neutrino-Flüsse
  • Suchen nach einem “diffusen” Überschuss von Neutrinos
  • Suche nach Punktquellen von Neutrinos
  • Suche nach Neutrinos von GRBs und AGNs
• Zusammenfassung
Neutrino astro-particle physics

- Cosmic rays with energies TeV (and above) observed
- Photon sources with TeV energies

⇒ Are there neutrino sources: blazars, quasars, Gamma Ray Bursts, supernovae ... is there a diffuse flux?

Neutrinos are elementary particles
- light
- neutral
- interact only by weak force

⇒ good astrophysical probes:
- not deflected
- ‘not’ absorbed over cosmological distances and dense environment

connect astrophysics and particle physics

can help to understand
- the origin of cosmic rays
- cosmic cataclysms
- own basic properties (xsec, \( m_\nu \), \( \nu_\tau \))
- dark matter (neutralino annihilation)
- new kinds of objects
- tests of relativitiy, search for big bang relics, effects of ED etc ...
Observation of Neutrinos

Interaction cross section is small

\[ \sigma(\nu_\mu N) \approx 6.7 \times 10^{-36} \text{ E [TeV] /cm}^2/\text{nucleon} \]

\[ \Rightarrow \text{interaction probability [H}_2\text{O, d=1km]}: \]

\[ = N_A \sigma d \rho \approx 4 \times 10^{-7} \text{ E [TeV]} \]

and sources are million to billion LYs away

Requirement of a large neutrino interaction target \[\Rightarrow\]

Markov and Zheleznykh proposed the use of natural targets

Deep sea water and polar ice:

- huge (and inexpensive) targets for neutrino interaction
- good optical characteristics as Cherenkov radiators
- shielding from cosmic background
Expected astrophysical $\nu$ Rates

**Diffuse sources**

- Guaranteed (GZK): few / year?
- Diffuse GRB: 20 / year
- Diffuse AGN (thin): few / year
  - (thick): >100 / year

**Point sources**

- GRB: 1÷10 / burst
- AGN: few / y
- Galactic SNR (Crab): few / year?
- Galactic microquasars: 1 ÷ 100 / y

Rate of expected events from diffuse fluxes or point sources is small and has big uncertainties.
**Principles of Neutrino Telescopes**

- Earth screens detectors against particles except neutrinos
- rare neutrino interactions ⇒ big natural volume
- atmosphere: cupios production of muons ⇒ go underground

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Energy thresholds
Event Types

Dominant backgrounds:
- mis-identified atmospheric muons (down/up ~ million)
- after clean-up: atmospheric neutrinos (flux uncertainty)

Proc. Dumand Summer Workshop 1976

$E_{\mu}$ vs. Range in water

Gaisser

1 TeV, 1 PeV

2 km, 20 km

$\nu_\mu \rightarrow \mu$
The challenge:
reconstruct energy and
direction of particle tracks using
- light intensity
- arrival time

Cherenkov photons emitted by the muon track are
correlated by the space-time causality relation:
\[ c(t_j - t_0) = l_j + d_j \cot(\theta_c) \]
of the PMT signals (hits)

Proc. Dumand Summer Workshop
1976
Optical Module

HV supply flasher board
photomultiplier housing: precursor for Amanda, Antares...
without Benthos spheres, similar for IMB, Kamioka and Super-K

IceCube DOM

Proc. Dumand Summer Workshop 1976
From DUMAND to the Future
The Case for more than one Telescope

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.
The Baikal Detector

NT-200: 192 PMTs on 8 strings, commissioned in 1998

First underwater array: µ reconstruction, first ν events, verify BG-suppression, check MC/Water/..
Upgrade to NT200+ in 2005

NT200:
- 192 optical modules
- pair-wise coincidence
- $\rightarrow$ 96 space points
- Height = 70m $\phi = 40m$

NT200+:
- adding three new strings with 36 PMTs $\rightarrow$ improve sensitivity by factor 4 to cascades with sparse additional instrumentation

NT200+ might be a step ("prototype") towards a Baikal-km$^3$:
- 91 strings with 1308 OMs
First Signs of Life in NT200+

New laser: imitation of 10...500 PeV cascades, $>10^{13}$ photons/pulse

Position reconstruction (arrival times): $\delta r < 1$ m

Amplitude reconstruction: $\delta I/I \sim 6\%$

Very preliminary
The Pole Detectors

The Amundsen-Scott South Pole station is located at 78.5° S, 163° W, geographically at the South Pole. It is equipped with the AMANDA (IceCube) experiment, which consists of 19 strings, each 1,900 feet (2,075 km) deep, and the IceCube experiment, which consists of 86 strings, each 2,000 feet (600 m) deep.
The Detectors

- IceCube
- IceTop
- Amanda II
- Optical Module
Understanding the Medium

- **South Pole ice at AMANDA depths:**
  - Very transparent with a depth and wavelength dependence – average values
    - Absorption length $\sim$ 110 m at 400 nm
    - Scattering length $\sim$ 20 m at 400 nm
  - Measured with in-situ light sources and with atmospheric muons

*Scatt. Length Baikal $\sim$ 30-50 m*
- Full NSF funding since February 2004 for 12 US groups
- Belgium (4 groups), Sweden (2), Japan (1), NewZealand (1), Netherlands (1), German universities (4) and DESY

Deployment of 4200+ Digital Optical Modules on 70+ strings and 140+ DOMs in 70+ IceTop stations until 2010
- Installed in January 2005: one string with the full chain from DOM to surface electronics, event builder, trigger, data handling, data verification, reconstruction, analysis
- This season →2006: ~10 strings
- AMANDA will be integrated
The first Events

AMANDA 1rst IceCube string
Cosmic Ray Composition

What is coming from the cosmos?

30m grid of 30 stations

Unique combination with SPASE-2

AMANDA (number of muons)

log10(E/PeV)

Spase (number of electrons)

Iron

Proton

Cosmic Ray Composition

30m grid of 30 stations

Unique combination with SPASE-2

AMANDA (number of muons)

log10(E/PeV)

Spase (number of electrons)

Iron

Proton
Cosmic Ray Composition

- resolution ~7% in $E_{\text{primary}}$
- mean $\ln(A)$ normalized to direct measurements (normalization bin not shown)

Cosmic ray spectrum becomes heavier around the knee

1998 data set
Unfold a clean data set of ten hours of 2000 data: $\delta \Theta = 2.4^\circ \ldots 1.5^\circ$

Data exceed theoretical calculation by 30...50% (theory and true simulated distributions agree)
Atmospheric Neutrinos

Test beam of neutrinos (and background)

Search for extra-terrestrial component

Search for neutrino oscillation

Full simulation of atmospheric neutrino flux (Lipari), muon propagation through earth and ice including oscillation

First spectrum above 3 TeV matches lower-energy Frejus data
Search for diffuse Neutrino Sources

Preliminary

1. $\nu$ from $p\gamma$ interactions in AGN cores
2. $\nu$ from $p\gamma$ interactions from blazars

Use the unfolded atmospheric neutrino spectrum

How much $E^{-2}$ cosmic $\nu$ signal allowed within uncertainty?

Set limit on diffuse $E^{-2} \nu_\mu$ flux (100-300 TeV):

$$E^2 \Phi_{\nu_\mu}(E) < 2.6 \cdot 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$
Search for Neutrinos of all Flavours

Electromagnetic and hadronic cascades

\[ \text{NC: } \nu_{e,\mu,\tau} \] hadronic cascade

background:

\[ \mu \] em cascade (brems, delta, pair)

\[ \tau \] neutrino regeneration (double structure) will be visible in IceCube

Sensitivity to all three flavours

\[ N_{\text{obs}} = 1 \text{ event} \]
\[ N_{\text{bg}} = 0.96 + 0.7 - 0.3 \]

\[ E^2 \Phi_{\text{all } \nu(E)} < 0.87 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]
(equal mix of all flavors)
Search for high Energy Cascades

• NT-200 is used to watch the volume below for cascades
  \[ A_{\text{scatt}} = 30 - 50 \text{ m} \]

Look for upward moving light fronts
Signal: isolated cascades from neutrino interactions

Background: brems-showers on down-ward muons → final bg rejection by energy cut \( N_{\text{hit}} \)

No events observed

The 90% C.L. “all flavour” limit (780 days)
for a \( \alpha = 2 \) spectrum \( \Phi \sim E^{-2} \) (10 < \( E < 10^4 \) TeV), ratio and assuming \( \nu \) ratio of 1:1:1 at Earth

\[
E^2 \Phi_\nu < 8.1 \cdot 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}
\]
Summary of diffuse all Flavour Limits

Several models of AGN neutrino emission are ruled out by current measurements → precise flux measurement needs km$^3$-scale detector
Search for Neutrino Point Sources

Select up-going events: maximize $\uparrow \nu$ and minimize $\downarrow \mu$

Optimize cuts in each declination band for $E^{-2\ldots-3}$ signal spectrum

Sensitivity ~independent of direction

Published analyses on:
- 1997 data
- 2000 data
  PRL 92(2004) 071102

Newer results with different strategies:
- 2000-01 and 2002 data

3329 $\nu$ events in 2000-03 data (807 days)
(sensitivity ~3 higher as 2000)

No clustering in skyplot observed,
i.e. the measurement looks compatible with atmospheric $\nu$'s
$\Rightarrow$ statistical analyses
Neutrinos from known Sources?

Significance map for 2000-2003

[Map showing significance levels with marked sources: Crab, Mak421, Mk501, Cyg, Cas A, M87, SS433]
Search for Neutrino Point Sources

Blind-Analysis:
- Analysis of local fluctuations from expectation of atmospheric neutrinos
  - un-binned statistical analysis
  - maximum of 3.4 $\sigma$ compatible with background fluctuation

Preliminary 2000-03
Search for Neutrino Flares

Search for excesses in time-sliding windows:

= 2.25°-3.75°

= 40/20 days for extra-galactic/galactic objects

<table>
<thead>
<tr>
<th>Source</th>
<th>Nr. of ν events</th>
<th>Expected backgr.</th>
<th>Period duration</th>
<th>Nr. of doublets</th>
<th>Probability for highest multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 421</td>
<td>6</td>
<td>5.58</td>
<td>40 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>1ES1959+650</td>
<td>5</td>
<td>3.71</td>
<td>40 days</td>
<td>1</td>
<td>0.34</td>
</tr>
<tr>
<td>3EG J1227+4302</td>
<td>6</td>
<td>4.37</td>
<td>40 days</td>
<td>1</td>
<td>0.43</td>
</tr>
<tr>
<td>QSO 0235+164</td>
<td>6</td>
<td>5.04</td>
<td>40 days</td>
<td>1</td>
<td>0.52</td>
</tr>
<tr>
<td>Cygnus X-3</td>
<td>6</td>
<td>5.04</td>
<td>20 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>6</td>
<td>4.76</td>
<td>20 days</td>
<td>1</td>
<td>0.32</td>
</tr>
<tr>
<td>GRO J0422+32</td>
<td>5</td>
<td>5.12</td>
<td>20 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
</tbody>
</table>

... out of 12 sources: No statistical significant effect observed
Neutrinos from 1ES1959+650?

"A posteriori" knowledge: 3 (of 5) ν events in 66 days within a period of a major outburst, measured in 2002 in a multi-wavelength campaign.

One (of the 5) event is within a few hours of the orphan flare: γ-ray flare from a blazar without accompanying X-ray counterpart. Some interpret this as hadronic activity in the blazar jet.

Not a statistically significant results ⇒ but interesting observation ⇒ will lead to a modified search strategy and a close collaboration with the γ-ray.
Association of Neutrinos with GRBs

Low background analysis due to space and time coincidence!

Time of GRB

<table>
<thead>
<tr>
<th>Year</th>
<th>#GRBs</th>
<th>obs/ bg</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon</td>
<td>97-00</td>
<td>312</td>
</tr>
<tr>
<td>muon</td>
<td>01-03</td>
<td>51</td>
</tr>
<tr>
<td>cascade</td>
<td>00</td>
<td>73</td>
</tr>
</tbody>
</table>

BATSE (non) triggered, IPN3 & GUSBAD GRB catalogs

No coincident events observed

Flux limit at Earth: $97-00 \mu E^2 \Phi < 4 \cdot 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, all $\mu$

$3 \cdot 10^{-8}$, cascade $9.5 \cdot 10^{-8}$

for bursts assuming WB broken power-law spectrum ($E_{\text{break}} = 100 \text{ TeV}$, $\Gamma_{\text{bulk}} = 300$)
Neutrinos from GRBs cont’d

cascades in concidence with BATSE GRBs
\( t_{\text{BATSE}} -100 \ s < t < t_{\text{BATSE}} +100 \ s \)
722 evts Apr 98 - Feb 00

<table>
<thead>
<tr>
<th>N</th>
<th>Triggered GRB obs / bg</th>
<th>All GRB obs / bg</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>91/ 94</td>
<td>172/ 167</td>
</tr>
<tr>
<td>25</td>
<td>1/ 2.8</td>
<td>5/ 5.2</td>
</tr>
<tr>
<td>35</td>
<td>0/ 0.3</td>
<td>1/ 0.5</td>
</tr>
</tbody>
</table>

Data consistent with expected \( \mu \) at BG 90\% C.L. → differential flux limits
Neutrinos from Active Galactic Nuclei

AGNs grouped in classes of potential high energy neutrino sources

assumption: $\nu$ flux is linearly correlated with $\gamma$ luminosity

Optimized a search strategy for classes in different energy bands
- using 2000 data
- using a source stacking method with optimized #sources (optimum 8-12) and bin sizes (typical 2.8°)

⇒ no excess events over background found

$\Rightarrow$ set limits
$f_{lim} = \text{integral flux for } E^{-2} \text{ above 10 GeV in units } 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$

<table>
<thead>
<tr>
<th>sample</th>
<th>$f_{lim}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR blazars</td>
<td>2.0</td>
</tr>
<tr>
<td>keV blazars (ROSAT)</td>
<td>1.6</td>
</tr>
<tr>
<td>keV blazars (HEAO-A)</td>
<td>2.8</td>
</tr>
<tr>
<td>GeV blazars</td>
<td>4.0</td>
</tr>
<tr>
<td>unid. GeV sources</td>
<td>5.6</td>
</tr>
<tr>
<td>TEV blazars</td>
<td>2.8</td>
</tr>
<tr>
<td>GPS and CSS</td>
<td>4.3</td>
</tr>
<tr>
<td>FR-I galaxies</td>
<td>1.3</td>
</tr>
<tr>
<td>FR-I without M87</td>
<td>2.7</td>
</tr>
<tr>
<td>FR-II galaxies</td>
<td>2.7</td>
</tr>
<tr>
<td>radio-weak quasars</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Go beyond km$^3$?

- EeV neutrinos, particularly GZK $\nu$, will be a valuable source for astro- and astro-particle physics.
- At best a few ten neutrino per year and km$^3$ - IceCube can detect ~one GZK neutrino per year.
- 10-100 GZK events would give a quantitative measurement that will allow tests of cosmic ray production models and new physics.
- Different projects (e.g. Rice2, ANITA, SalSA, Glue, Lofar, acoustics...) were and are actively seeking this goal.
- IceCube joined the effort: proceed from a South Pole Acoustic Test Setup to a hybrid detector (IceCube + Acoustic + Radio) EeV Neutrino Array (if acoustic ice properties are measured to be as good as predicted).

<table>
<thead>
<tr>
<th>Properties of Ice</th>
<th>Optical</th>
<th>Radio</th>
<th>Acoustic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption [km]</td>
<td>0.1</td>
<td>1</td>
<td>~10 ?</td>
</tr>
<tr>
<td>Energy Threshold [eV]</td>
<td>$\sim 10^9$</td>
<td>$\sim 10^{15}$</td>
<td>$\sim 10^{18}$</td>
</tr>
</tbody>
</table>
Diffuse Searches now and in the Future
Nichtbehandelte Ergebnisse

Suchen nach:

ultralino Annihilation ⇔ Vortrag D Elsässer

Schnellen und langsamen Monopolen
- Neutrinos von Supernovae

Prompt μ’s aus charm-Zerfällen
ν aus der Michstrassen-Scheibe

Siehe auch http://amanda.uci.edu,
http://baikall.jinr.ru
Zusammenfassung

AMANDA/ IceCube und Baikal sind komplementär
(Nördlicher/ Südlicher Himmel, Eis/ Wasser, verschiedene Analyse Techniken)

und haben ein reiches physikalisches Programm:

• Zusammensetzung der kosmischen Strahlung
• Verständnis der atmosphärischen μ’s als Kalibrations-“Strahl”
• Messung des atmosphärischen Neutrino-Spektrums
• Grenzen auf diffuse Flüsse von extraterrestrisch TeV-EeV ν’s
• Punktquellen Suche in den Daten von 1997 bis 2003
• Suche nach Neutrinos in Koinzidenz mit Gamma Ray Bursts und aktiven galaktischen Kernen

Kein extra-terrestrisches ν Signal bis jetzt beobachtet
From Limits to Discoveries
Sonnenauftang am Südpol