Neutrino Telescopes
Status and Perspectives

Christian Spiering
DESY

TeV-III, Venice 2007
The unified spectrum of neutrinos

- deep water
- deep ice
- air showers
- radio
- acoustics
- Signal expectations
- The TeV domain
  Underwater/ice optical detectors, status and perspectives of experiments
- Some physics results
  from AMANDA/Baikal
- PeV and beyond:
  status and perspectives
- Summary
Neutrino Production

\[ p + p \rightarrow \pi + \ldots \]

\[ \rightarrow \mu + \nu_\mu \]

\[ \rightarrow e + \nu_e + \nu_\mu \]

\[ p + \gamma \rightarrow n + \pi^+ \quad \text{or} \quad \rightarrow p + \pi^0 \]

\[ \rightarrow \mu + \nu \quad \rightarrow \gamma + \gamma \]

\[ \nu_e : \nu_\mu : \nu_\tau \sim 1:2:0 \text{ turns to } 1:1:1 \text{ at Earth} \]
Diffuse Fluxes (1998)

\[
\log_{10}[E_{\gamma}/\text{GeV}] = \log_{10}\left[\frac{\phi(E_{\gamma})}{(\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1})}\right]
\]

- Atmospheric
- Galactic
- Cosmogenic
- AGN Core (SS)
- AGN Jet (MPR)
- GBB (WB)
- MPR bound
- \(\gamma\) bound
- \(p + \gamma_{\text{CMB}} \rightarrow p + \pi\)

\(\nu_{\text{Tel}}\)

Spiering TeV-III
Signal predictions: extragalactic sources

- WB bound corresponds to 100-500 neutrinos per km²·year
- AGN predictions are highly uncertain (many orders of magnitude!) but leave room for hopes
- Several older AGN models dramatically violate even soft upper bounds on diffuse fluxes, as derived from CR
- Fluxes from individual AGN: less constrained
- GRB: various models, benchmark model of Waxman-Bahcall can be easily tested with km3 detectors
Signal predictions: galactic sources

- Predictions on firmer ground than for AGN
  - Shell-type SNR
  - Pulsar Wind Nebula
  - Compact Binary Systems

- Many papers in the last 2 years:
  - Bednarek and Montaruli 2005
  - Vissani 2006
  - DiStefano 2006
  - Lipari 2006
  - Kappes, Hinton, Stegmann, Aharonian 2007
  - Gabici, Aharonian 2007
  - ...

- Unanimous conclusion: Cubic kilometer detectors will just scrape the detection region
Expected $\nu$ flux from galactic point sources, example: RXJ 1713-3946

Assume $\pi^0 \rightarrow \gamma$ and calculate related $\pi^\pm \rightarrow \nu$

mean atm. flux

measured $\gamma$-ray flux (H.E.S.S.)

expected neutrino flux

C. Stegmann
ICRC 2007
Neutrino Event Rates (II)

- **γ-ray sources with observed cut-off** (KM3NeT, 5 years)

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Dia. [°]</th>
<th>E &gt; 1TeV src</th>
<th>bck</th>
<th>E &gt; 5TeV src</th>
<th>bck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela X</td>
<td>PWN</td>
<td>0.8</td>
<td>9 – 23</td>
<td>23</td>
<td>5 – 15</td>
<td>4.6</td>
</tr>
<tr>
<td>RX J1713.7-3946</td>
<td>SNR</td>
<td>1.3</td>
<td>7 – 14</td>
<td>21</td>
<td>2.6 – 6.7</td>
<td>8.2</td>
</tr>
<tr>
<td>RX J0852.0-4622</td>
<td>SNR</td>
<td>2.0</td>
<td>7 – 15</td>
<td>104</td>
<td>1.9 – 6.5</td>
<td>21</td>
</tr>
<tr>
<td>HESS J1825–137</td>
<td>PWN</td>
<td>0.3</td>
<td>5 – 10</td>
<td>9.3</td>
<td>2.2 – 5.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Crab Nebula</td>
<td>PWN</td>
<td>&lt;0.1</td>
<td>4.0 – 7.6</td>
<td>5.2</td>
<td>1.1 – 2.7</td>
<td>1.1</td>
</tr>
<tr>
<td>HESS J1303–631</td>
<td>NCP</td>
<td>0.3</td>
<td>0.8 – 2.3</td>
<td>11</td>
<td>0.1 – 0.5</td>
<td>2.1</td>
</tr>
<tr>
<td>LS 5039* (INFC)</td>
<td>Binary</td>
<td>&lt;0.1</td>
<td>0.3 – 0.7</td>
<td>2.5</td>
<td>0.1 – 0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

NCP: no counterparts at other wavelength

* no γ-ray absorption

- **23 further γ-ray sources investigated:**
  - All γ-ray spectra show no cut-offs (but limited statistics)
  - Event numbers mostly below 1 – 2 in 5 years
PKS2105-304 (R. White, ICRC)

- PKS2105-304 as measured by H.E.S.S.
- Correcting for $\gamma$ absorption
- Kinematics for $\nu/\gamma$ in source
- KM3NeT with angular resolution $0.5^\circ$
- $S/Bg (> 1\text{TeV}) = 27/61$
- $S/Bg (> 5\text{TeV}) = 21/10 (\rightarrow 5\sigma)$

R.J. White, ICRC
Conclusions for galactic sources

- No strong need for PeV range
- No strong need for < 1 TeV and km³ det.
- Optimum threshold for typical analyses with a km3 detector more like 5 TeV
- Desirable area 5-10 km²
- But: don’t forget SN shells in first months after explosion!
- Always to the rescue: hidden sources
  (but they also eventually should be visible at low photon energies!)
Underwater/Ice: optical telescopes

Muon tracks

- $\sigma_{\text{angle}}$: water $<0.3^\circ$  
- $\sigma_{\text{angle}}$: ice $0.5-1^\circ$  
- $\sigma_{\text{energy}}$: 0.3 in log $E$

Cascades

- $\sigma_{\text{angle}}$: water $3-6^\circ$  
- $\sigma_{\text{angle}}$: ice $\sim25^\circ$  
- $\sigma_{\text{energy}}$: 30% in $E$

(at 10 TeV)
Effective $\nu$ area:

- $\sim 0.1$ m$^2$ @ 10 TeV Amanda/Antares
- $\sim 4$ m$^2$ @ 100 TeV Amanda/Antares
- $\sim 20$ m$^2$ @ 100 TeV IceCube now
- $\sim 100$ m$^2$ @ 100 TeV IceCube complete

Point source sensitivity:

- AMANDA, ANTARES: $\sim 3 \cdot 10^{-10}$ $\nu$ / (cm$^2$ s) above 1 TeV
- IceCube, KM3NeT $\sim 10^{-11}$ $\nu$ / (cm$^2$ s) above 1 TeV
  (for 5$\sigma$ discovery)
The Projects

- Antares
- Nestor, Nemo
- Baikal
- KM3NeT
- Amanda
- IceCube
North and South

South Pole

Mediterranean

BUT:

Galactic Center
At high energies: much less $\mu$ BG from above → look above horizon!

At low energies: contained events in large detectors → look above horizon!

(more below)
The Baikal Neutrino Telescope

- 1981 first site explorations
- 1998 NT200 finished

Ice as natural deployment platform

A textbook neutrino event (4-strings 1996)

see talk R. Wischnewski
From NT200 to NT200+

Detection of high energy cascades outside the instrumented volume

Since 2005: observation volume fenced with 36 PMTs

→ 4 times better sensitivity at high energies

Basic cell for future Gigaton detector
Mediterranean Experiments
- Project since 1991
- 1 floor deployed in 2004
- Took data for a few weeks, then cable defect
- Waiting for repair
- 4 floors ready for deployment

- Plans for 4 floors surrounded by autonomous stations
see talk A. Margiotta
- Project since 1996
- 12 lines in total
- 2001: cable
- 2002: junction box
- 2005: MILOM test line
- 2007: 7 lines deployed (525 PMTs)
- 5 lines connected and taking data
- Autumn/Jan/Feb: deploy & connect the rest
5-line detector: 
Muon angular distribution after cuts

CONGRATULATIONS!

very preliminary, from V. Flaminio, Budapest June 07
run 25922, frame 53569, $\Delta = -5.25$
- NEMO Phase-1 (2003-2007) @ LNS Underwater Test Site (2000 m)
  - Test prototypes of main km3 components
  - Validate installation and connection procedures

- NEMO Phase-2 (2005-2008) @ Capo Passero Site (3500 m)
  - Establish infrastructure suitable for a km3 detector
  - Test & validate advanced detector prototypes
  - Long term monitoring of site properties
Dec 2006: deployment of tower
NEMO downgoing muons (Jan. 2007)
NEMO-1 present status

- Floors are slowly sinking
- First and second floor now close to seabed
- Reason: deterioration of boy material
- Add buoyancy
- Learned a lot of important lessons
- Full tower, 16 floors
- Same electronics like Phase-1, 2 floors to test new concepts
- 100 km cable, deployment in summer 2007
- Completion of shore station early 2008
- Tower deployment mid 2008
- Impressing progress for both ANTARES and NEMO within the last 2 years
- Significant technological steps towards cubic kilometer detector

- Declaration of Greece minister: 50 M€ if cubic kilometer detector would be in Greece ....
A cubic kilometer detector in the Mediterranean

Design study: 2006-2009
- Technical Design Report

Preparatory phase: 2008-2011
(proposal submitted)
- Political convergence (site)
- Commitment for construction of funding agencies/ministries
- Governance and legal structure
- System prototype
- Tendering procedures

Construction phase: 2010-2013 (??)
- Build ≥1 km3 detector

Targeted budget: M€220-250 (ESFRI roadmap)
Final choice will depend on:

- Depth
- Bioluminescence rate
- Sedimentation, bio-fouling
- Distance from shore
- Sea currents, Earth quake profile
- ……

- Contributions from host country
- Strength of national community
- Global European considerations
- ……
One big or three smaller detectors?

Spherical detector

radius \( r \)

area \( A = 2\pi r^2 \)

distribute same \# of PMTs to 3 spheres

area = \( 2\pi \cdot 3^{1/3} \cdot r^2 = 1.44 \cdot A \)

\( \Rightarrow \) gain a factor of 44\% for muons?
One big or three smaller detectors?

- One site with area $A$
- Three sites with total area $1.44 \cdot A$
smaller lever arm
  → worse pointing
increase spacing
  – with same lever arm get higher threshold
worse energy sampling
worse background rejection
→ net effect for $\nu_\mu$ will be smaller than 44%
cascade events $(\nu_e, \nu_\tau)$:
  – VOLUME counts
  – with a fixed veto region for contained events, the net effect is negative
need 3 times the infrastructure and operation cost
For a complete sky coverage, in particular of the central parts of the Galaxy with many promising sources, we strongly recommend to work towards a cubic kilometre detector in the Northern Hemisphere which will complement the IceCube detector. **Resources for a Mediterranean detector should be pooled in a single, optimized large research infrastructure “KM3NeT”.** Start of the construction of KM3NeT is going to be preceded by the successful operation of small scale or prototype detector(s) in the Mediterranean. It’s design should also incorporate the improved knowledge on galactic sources as provided by H.E.S.S. and MAGIC gamma ray observations, as well as initial results from IceCube. Still, the time lag between IceCube and KM3NeT detector should be kept as small as possible.
Simulating configurations

Cuboidial, Ring, Hexagon, Clustered, IceCube-like
... Usually with Antares environmental parameters
**Configuration 1 (1 km$^3$):**
- 127 lines in hexagon
- 100m line spacing
- 25 storeys, 15 m apart
- 3 Antares (10") PMTs per storey

**Configuration 2 (1 km$^3$):**
- 225 lines in cuboid grid
- 95m line spacing
- 36 storeys, 16.5 m apart
- 21x3" PMTs per storey

**Antares site parameters**

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**ICRC0865, J. Carr et al**
R&D on Novel Optical Modules

Segmentation of photo cathode of 10” PMT

“Flykt” sphere

multi-PMTs in one glass sphere

Smart tube X-HPD (R&D)

Ref. ICRC0489, P. Kooijman
see talks of G.Hill, C.Rott, I.Taboada, M.Tluczykont (IceCube), T. Stanev (IceTop)
IceCube

IceTop
Air shower detector
80 pairs of ice
Cherenkov tanks
Threshold ~ 300 TeV

InIce
Goal of 80 strings of 60 optical modules each
17 m between modules
125 m string separation

2004-2005: 1 string
2005-2006: 8 strings
2006-2007: 13 strings deployed

2007/08: add 14 to 18 strings and tank stations
AMANDA-II
19 strings
677 modules
AMANDA now operating as part of IceCube
Completion by 2011.
IceTop
Air shower detector
80 pairs of ice
Cherenkov tanks
Threshold ~ 300 TeV

InIce
Goal of 80 strings of 60 optical modules each
17 m between modules
125 m string separation

IceCube

IceTop
- Angular calibration of IceCube
- chemical composition (with IceCube)
- veto for IceCube

see talk of T.Stanev yesterday and today A.Leisos for SEATOP
IceCube

IceTop
Air shower detector
80 pairs of ice
Cherenkov tanks
Threshold ~ 300 TeV

InIce
Goal of 80 strings of 60 optical modules each
17 m between modules
125 m string separation

Current configuration
- 22 strings
- 52 surface tanks
1450 m
2450 m
Neutrinos in IC9

- 9-string data (2006)
- Cosmic ray background seen with weak cuts
- Atmospheric neutrinos seen with strong cuts
- Agreement in event rate over 6 decades

Achterberg et al. astro-ph/0705.1781
IceCube Laboratory and Data Center

Commissioned for operation in January 2007
Growth of IceCube

Accumulated Exposure at 100 TeV

[Graph showing the growth of IceCube exposure from 2002 to 2014. Key milestones include AMANDA, +IC9, +IC22, +IC36-40, KM3NeT, and Full IceCube.]
AMANDA as low energy subdetector of IceCube

IceCube threshold 100 GeV

IceCube with Amanda 30 GeV

Amanda without IceCube 50 GeV
Effect on 22-string detector

Atmos. $\nu_\mu$ per 200 days (trigger level, IC22+AMANDA)

Preliminary

Gross, Tluczykont, Ha, Rott, DeYoung, Resconi, & Wikström, ICRC 2007

Atm. num per year [200 d lifetime]

8200 incl. AMANDA

30 GeV!

5400 IceCube only

30 GeV!
A new low energy subdetector for IceCube?

- 6 strings each with 40 PM, spaced by 10 m
- better veto from top
- located in best ice (below 2100 m exceptionally clear)
- uses IceCube technology
- considerably better performance at low energy
- see talk of Carsten Rott this afternoon

see talk of C.Rott
Some Physics Results

(see afternoon sessions)
Physics from Baikal & AMANDA

- Atmospheric neutrinos
- Point sources
- Diffuse fluxes
- Coincidences with GRB
- Supernova Bursts & SNEWS
- Cosmic ray search with IceTop/IceCube
- WIMP indirect detection
- Magnetic monopoles and other exotic particles
- Test of basic physics laws
- .....
Atmospheric neutrinos

K. Münich
RICAP 2007

spectrum measured up to 100 TeV
Search for steady point sources: AMANDA and Baikal
Search for steady point source

AMANDA-II: 2000-2004 (1001 live days) 4282 $\nu$ from Northern hemisphere

No significant excess found
Multi-Messenger Analyses

- Any source selection using information from optical, X-ray, gamma data
- Reducing trial factors
- Stacking analyses
- Transient sources
  - Searching around GRB signals from satellite data (see below)
  - Target of Opportunity programs (like AMANDA/MAGIC)
  - GRB candidate follow-up by optical telescopes

see talk M.Tluczikont

see talk M.Kowalski
Arrival time of neutrinos from the direction of the AGN ES1959+650

Flux of TeV photons (arb. units)

Spiering TeV-III

Tel

ES 1959+650

WHIPPLE

May

June

July

2000 2001 2002 2003

Year
Atmospheric neutrinos behave like $E^{-3.7}$

Typical extraterrestrial fluxes behave like $E^{-2}$

see talk of Gary Hill
Limit on diffuse extraterrestrial fluxes

- Atmospheric neutrinos behave like $E^{-3.7}$
- Typical extraterrestrial fluxes behave like $E^{-2}$
- From this method and one year data we exclude $E^{-2}$ fluxes with $\Phi \cdot E^2 > 2.7 \cdot 10^{-7}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$
From this method and one year data we exclude $E^2$ fluxes with $\Phi \cdot E^2 > 2.7 \cdot 10^{-7}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$

With 4 years and improved methods we are now at $\Phi \cdot E^2 > 8.8 \cdot 10^{-8}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$
Experimental limits & theoretical bounds

- MPR bound, no neutron escape (gamma bound)
- Factor 11 below MPR bound for sources opaque to neutrons
Experimental limits & theoretical bounds

- MPR bound, neutrons escape (CR bound)
- Factor 4 below MPR bound for sources transparent to neutrons
Experimental limits & theoretical bounds
Stecker model excluded
Experimental limits & theoretical bounds

AGN core (SS, new version)

„new“
Stecker model not excluded

(MRF = 1.9)
Experimental limits & theoretical bounds

still above
AGN jet (MPR)
(MRF ~ 2.3)
Limit on diffuse extraterrestrial fluxes

AMANDA HE analysis

Baikal

IceCube muons, 1 year

Icecube, muons & cascades 4 years

2003

2006

2009

2013
Coincidence with GRB

- close to WB within < factor 2
- with IceCube: test WB within a few months

Check for coincidences with BATSE, IPN, SWIFT

AMANDA limit from 408 bursts

Waxman-Bahcall GRB prediction

Off-Time
Precursor
Always Blind
On Time

1 hour 10 min 1 hour

110 s T90

time

10^{-7}

10^{-8}

10^{-9}

10^{-10}

10^{4} 10^{5} 10^{6} 10^{7} 10^{8}

neutrino energy $E_{\nu}$ (GeV)

1997-2003

see talk of I. Taboada
Supernova in IceCube

Detection by enhanced noise rates

5σ signal for SN of 1987A strength

Dark noise in IceCube Optical Modules is only ~ 320 Hz!
PeV and beyond
### Overview

- **Radio in ice:**
  - RICE, ANITA, AURA, ARIANNA-type (all Antarctica), SALSA (salt)

- **Radio in Moon:**
  - GLUE, NuMOON, ...

- **Radio in air:**
  - FORTE (from space), LOPES, ...

- **Horizontal air showers:**
  - AGASA, HiRES, Auger, EUSO, ...

- **Acoustic detection:**
  - SAUND (Caribbean), SPATS (South Pole), AMADEUS & others (Mediterranean), Baikal, SALSA (salt dome), Permafrost (Siberia), ...
Tel Spiering T e V - III

Muon Cascade: ~10m length

RF Cherenkov

RICE

Auger

Muons

ANITA

RF Cherenkov

air

electron and photons

Early region broad signals

Late region narrow signals

ANITA

GLUE 04

RICE'05 (e, \mu, \tau)

AMANDA (e, \mu, \tau)

Baikal (e, \mu, \tau)

AMANDA (\mu)

GZK, each flavor

neutrino

Cascade: ~10m length

Neutrino Energy [eV]
Present and projected limits and event numbers

- RICE limits, 3500 hours
- GLUE limits, 120 hours
- ANITA sensitivity, 45 days total: ~5 to 30 GZK neutrinos
- IceCube: high energy cascades ~1.5-3 GZK events in 3 years
- Auger: tau neutrino decay events ~1 GZK event per year?
Possible HE-Extensions to IceCube?

- radio/acoustic
- IceCube
- optical

surface radio stations? (smaller price per GZK event?)
### Event numbers

<table>
<thead>
<tr>
<th>Detection option</th>
<th>GZK events/year $^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Optical</strong> (IceCube + ring)</td>
<td>1.2</td>
</tr>
<tr>
<td>Radio</td>
<td>12.3</td>
</tr>
<tr>
<td>Acoustic</td>
<td>16.0</td>
</tr>
<tr>
<td>Optical + Radio</td>
<td>0.2</td>
</tr>
<tr>
<td>Optical + Acoustic</td>
<td>0.3</td>
</tr>
<tr>
<td>Radio + Acoustic</td>
<td>8.0 !!!</td>
</tr>
<tr>
<td>Opt.+Rad.+Acou.</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>21.1</strong></td>
</tr>
</tbody>
</table>

$^*$Numbers calculated, folding effective volumes with ESS GZK neutrino flux model
Installed in last season and under evaluation:

- 3 test strings acoustic SPATS
  - test:
    - noise
    - attenuation
    - length
    - refraction

3 test strings radio **AURA**
(Askaryan Underice Radio Array)

**South Pole Acoustic Test Setup**

see talks of F. Descamps and D. Williams
Summary
Sensitivity to HE diffuse neutrino fluxes

Flux \times E^2 \text{ (GeV/ cm}^2 \text{ sec sr)}

- Dumand
- Frejus Macro
- Baikal/Amanda
- Rice
- AGASA
- Rice GLUE
- Anita, Auger
- IceCube/KM3NeT

Waxman-Bahcall limit

10^{-4} \rightarrow 1 \text{ EeV}
10^{-10} \rightarrow 10^{-1} \text{ TeV}
10^{-11} \rightarrow 10^{-9} \text{ TeV}
10^{-12} \rightarrow 10^{-7} \text{ TeV}
10^{-13} \rightarrow 10^{-6} \text{ TeV}
10^{-14} \rightarrow 10^{-5} \text{ TeV}
10^{-15} \rightarrow 10^{-4} \text{ TeV}

tremendous technological progress over last decade
no positive detection yet, but already testing (optimistic) bounds
IceCube reaches $1 \text{ km}^3 \times \text{year}$ by early 2009
entering region with realistic discovery potential
IceCube (and HESS) will hopefully consolidate the physics case for KM3NeT
ready for the next Supernova
addressing also a wide range of particle physics questions
Vigorous activity at extreme energies (GZK)
Will the curtain go up before 100 years after Hess' discovery?