High Energy Neutrino Astronomy
a promising decade ahead

Christian Spiering,
DESY, September 17, 2002
Content

- Physics Goals
2. Detection Methods and Projects
3. Amanda and Baikal: Physics Results
4. The next decade
1. Physics Goals

A. High Energy Neutrino Astrophysics

B. Particle Physics
   WIMPs, Magnetic Monopoles, Oscillations, Neutrino Mass ...

C. Others
   Supernova Bursts, CR composition, Black Holes, ...
New Observational Window to Non-Thermal Universe
Cosmic Rays

$E_{\text{max}} \sim \beta \cdot B \cdot L$

$1\ \text{TeV}$
Supernova shocks expanding in interstellar medium

up to 1-10 PeV

Crab nebula
Gamma Observations: Crab is “Electron Accelerator”

- Synchrotron
- Inverse Compton
Active Galaxies: Jets

20 TeV gamma rays
Higher energies obscured by IR light

up to $10^{20}$ eV

VLA image of Cygnus A
Cosmic Rays with $E > 10^{20}$ eV ?

GZK effect:

$p + \gamma_{3K} \rightarrow p + ....$
Neutrino Astronomy
measuring $\nu_s$ by its $\mu$

- Stable particles: $\gamma$, $p$, $\nu$
- Astrophysical Sources
  - GRB, AGN, Super Novae
  - GZK ($p + \text{CMB } \gamma$)
  - Topological defects
- Backgrounds
  - Atmospheric $\mu$’s
  - Atmospheric $\nu$’s
$\log(E^2 \cdot \text{Flux})$

- **3** TeV, pp core AGN
- **6** PeV, $\gamma\gamma$ blazar jet
- **9** EeV, Top-Bottom

- Air showers
- Radio, Acoustic
- Underground
- Underwater

- WIMPs
- Oscillations
- Microquasars etc.

- GZK
Diffuse Fluxes: Predictions and Bounds

1 pp core AGN (Nellen)
2 pγ core AGN
   Stecker & Salomon)
3 pγ „maximum model“
   (Mannheim et al.)
4 pγ blazar jets (Mannh)
5 pγ AGN
   (Rachen & Biermann)
6 pp AGN (Mannheim)
7 GRB
   (Waxman & Bahcall)
8 TD (Sigl)
9 GZK
Time variations

- GRB
- SN MeV burst
- SN TeV bursts
- Blobs in Microquasars and blazars
- Binary eclipses etc.
- msec
- sec
- hour
- week
- month
- young SN
2. Detection Methods and Projects

A. Underwater/Ice Cherenkov Telescopes
B. Acoustic Detection
C. Radio Detection
D. Detection by Air Showers
Underwater/Ice Cherenkov Telescopes
muon cascade
AMANDA Event Signatures: Muons

CC muon neutrino interaction

$\nu_\mu + N \rightarrow \mu + X$

$\nu_\mu + N \rightarrow \mu + X$
AMANDA Event Signatures: Cascades

- CC electron and tau neutrino interaction:
  $$\nu_{(e, \tau)} + N \rightarrow (e, \tau) + X$$

- NC neutrino interaction:
  $$\nu_x + N \rightarrow \nu_x + X$$
Lake Baikal

First underwater telescope
First neutrinos underwater

4-string stage (1996)
Mediterranean Projects

- ANTARES: 2400m
- NEMO: 3400m
- NESTOR: 4100m
Site: Pylos (Greece), 3800m depth
towers of 12 titanium floors each supporting 12 PMTs
7 NESTOR towers? 75 000 m² at 1 TeV

EFFECTIVE AREA OF SEVEN NESTOR TOWERS

150 m

75.000 m²

accuracy

40°

(5°)

(1°)

1 TOWER (40°)
ANTARES Design

2500m × 2500m

300m × 300m

active × active

Electro-optic submarine cable ~40km

Junction box

Shore station

Electronics containers

Readout cables

~60m

10 strings

12 m between storeys

Anchor

300m active

~100m

Compass, tilt meter

hydrophone

Optical module

~100m

Acoustic beacon

10 strings

12 m between storeys
Very good angular accuracy below 3 TeV angular error is dominated by kinematics, above 3 TeV by reconstruction error (≈ 0.4°)

Effective area:
- ≈ 10,000 m² at 1 TeV
- ≈ 50,000 m² at 100 TeV
NEMO Neutrino Mediterranean Observatory

The Capo Passero Site

- Very good optical properties (light absorption length about 70 m)
- ~ 80 km from coast
- about 3400 m deep
- Very low sedimentation and biological activity

absorption length ~ 70 m at 400 nm
Coordinated by INFN, in collaboration with SACLANTcnen-NATO, CNR, OGS

**Cable construction and deployment**
NEXANS

**Detector:**
**design and construction**
ENI Consortium

**Detector:**
**deployment and recovery**
ENI Consortium

**ROV/AUV operations**
ENI Consortium

**Underwater connections**
Ocean Design

**abs. length ~70 m**
80 km from coast
3400 m deep

**Artist’s view**
### NESTOR

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991 - 2000</td>
<td>R &amp; D, Site Evaluation</td>
</tr>
<tr>
<td>Summer 2002</td>
<td>Deployment 2 floors</td>
</tr>
<tr>
<td>Winter 2003</td>
<td>Recovery &amp; re-deployment with 4 floors</td>
</tr>
<tr>
<td>Autumn 2003</td>
<td>Full Tower deployment</td>
</tr>
<tr>
<td>2004</td>
<td>Add 3 DUMAND strings around tower</td>
</tr>
<tr>
<td>2005 - ?</td>
<td>Deployment of 7 NESTOR towers</td>
</tr>
</tbody>
</table>

### ANTARES

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996 - 2000</td>
<td>R&amp;D, Site Evaluation</td>
</tr>
<tr>
<td>2000</td>
<td>Demonstrator line</td>
</tr>
<tr>
<td>2001</td>
<td>Start Construction</td>
</tr>
<tr>
<td>September 2002</td>
<td>Deploy prototype line</td>
</tr>
<tr>
<td>December 2004</td>
<td>10 (14?) line detector complete</td>
</tr>
<tr>
<td>2005 - ?</td>
<td>Construction of km³ Detector</td>
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</tbody>
</table>

### NEMO

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 - 2001</td>
<td>Site selection and R&amp;D</td>
</tr>
<tr>
<td>2002 - 2004</td>
<td>Prototyping at Catania Test Site</td>
</tr>
<tr>
<td>2005 - ?</td>
<td>Construction of km³ Detector</td>
</tr>
</tbody>
</table>
Amanda-II: 677 PMTs at 19 strings (1996-2000)
Unique:

- calibration of AMANDA angular resolution and pointing!

→ resolution Amanda-B10 ~ 3.5°

results in ~ 3° for upward moving muons

(Amanda-II: < 2°)
Atmospheric Neutrinos, 97 data

- vertically up
- horizontally

→ AMANDA sensitivity understood down to normalization factor of ~ 40%
  (modeling of ice ...)

~ 300 events
2002 real time analysis at Pole

On line reconstruction and filtering with 2 high end PCs at SP
→ 2 % minimum bias
→ upward tracks
→ cascades
→ high multiplicities
→ string trigger
→ Spase-Amanda

Friday, 14 June, 2002
2002 real time analysis

Daily transmission ~ 1 GB via satellite
Full data to tape (available next polar summer)
Monitoring shifts in home labs

From 02/03:
Iridium connection for supernova alarm

V event
June 14
IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km³
- Installation: 2004-2010

~ 80,000 atm.v per year
Effective area of IceCube

The graph shows the effective area $A_{\text{eff}}$ in km$^2$ as a function of $\cos \theta$ for different energy ranges:

- 1-100 PeV (stars)
- 100 TeV-1 PeV (squares)
- 1 TeV-10 TeV (triangles)
- 100 GeV-1 TeV (crosses)

The curves indicate the variation of effective area with respect to the angle $\theta$. The high-energy range shows a smoother decline compared to the lower energy ranges.
Angular resolution as a function of zenith angle

Waveform information not used. Will improve resolution for high energies!
Ice vs. Water

Ice:
- Proven technology
- Stable deployment surface
- Stable detector geometry
- Longer absorption length
- Sterile, low noise medium

Water:
- Longer deployment season
- More accessible locales
- Changeable detector geometry
- Longer scattering length
- More uniform medium
Acoustic Detection
Particle cascade $\rightarrow$ ionization $\rightarrow$ heat $\rightarrow$ pressure wave

Maximum of emission at $\sim 20$ kHz

Attenuation length of sea water at 15-30 kHz: a few km
(light: a few tens of meters)

? given a large initial signal, huge detection volumes can be achieved.

Threshold $> 10$ PeV
Renewed efforts along acoustic method for GZK neutrino detection

**Greece:** SADCO
Mediterranean, NESTOR site, 3 strings with hydrophones

**Russia:** AGAM antennas near Kamchatka:
existing sonar array for submarine detection

**Russia:** MG-10M antennas:
withdrawn sonar array for submarine detection

**AUTEC:** US Navy array in Atlantic:
existing sonar array for submarine detection

**Antares:** R&D for acoustic detection

**IceCube:** R&D for acoustic detection
AUTEC array in Atlantic

Atlantic Undersea Test and Evaluation Center

52 sensors on 2.5 km lattice (250 km²)
4.5 m above surface
1-50 kHz!
AGAM: Existing sonar array for submarine detection
Shore of Kamchatka, 2400 hydrophones, 102 m × 17.3 m × 4.5 m

\( f \) a few hundred Hz
→ small signals
→ large attenuation length
→ hundreds of km\(^3\) above \(10^{20}\) eV ?

First test measurements started!

MG-10M: cylindric modules, each with 132 hydrophones.

Bandwidth up to 25 kHz
→ better suited for e.m. shower detection!
Radio Detection
\[ \nu_e + n \rightarrow p + e^- \]
\[ e^- \rightarrow \ldots \text{ cascade} \]

- Relativistic pancake
  - ~1 cm thick, \( \varnothing \sim 10\text{cm} \)
- Each particle emits Cherenkov radiation
- C-signal is resultant of overlapping Cherenkov cones

\[ \Rightarrow \text{ for } \lambda \gg 10 \text{ cm (radio coherence)} \]
\[ \Rightarrow Q_{\text{net}} \sim 0.25 E_{\text{cascade}} \text{ (GeV)} \]

- Threshold \( > 10 \text{ PeV} \)
RICE Radio Ice Cherenkov Experiment

fирн слой (до 120 м глубины)

20 приемников + передатчики

$\mathcal{E}^2 \cdot \frac{dN}{dE} < 10^{-4} \text{ GeV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$

at 100 PeV
Natural Salt Domes: Potential PeV-EeV Neutrino Detectors

• Natural salt can be extremely low RF loss: ~ as clear as very cold ice, 2.4 times as dense

• Typical salt dome halite is comparable to ice at -40°C for RF clarity

SalSA
Salt Dome Shower Array
ANITA
Antarctic Impulsive Transient Array

Flight in 2006
Lunar Radio Emissions from Interactions of $\nu$ and CR with $> 10^{19}$ eV

Gorham et al. (1999), 30 hr NASA Goldstone 70 m antenna + DSS 34 m antenna

$\rightarrow E^2 \cdot dN/dE < 10^{-4}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

$\rightarrow 10^{20}$ eV

$\rightarrow 10^5$ km$^3$

Effective target volume
~ antenna beam (0.3°) $\times$ 10 m layer
• Radio is competitive with optical km3 arrays for E >10 PeV
• Required detection times are small, a benefit of the enormous volumes radio detectors can view
• But: background ??

AMANDA-II 3 years expected
km3, 3 years expected
Detection of neutrino induced air showers
AGASA 2001:
\[ < 10^{-5} \text{ GeV}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1} \]
for \( E > 10 \text{ EeV} \)

**Far inclined showers** (~ thousand per year)
- Flat and thin shower front
- Narrow signals
- Time alignment

**Deep inclined showers** (~ one per year?)
- Curved and thick shower front
- Broad signals

\( \nu_e \) hard muons from CR
el.-magn. cascade

\[ < 10^{-5} \text{ GeV}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1} \] for \( E > 10 \text{ EeV} \)
Predicted Auger Sensitivities

Comparable to 3-year optical km3 limit

Mass for $\nu_\mu$ and $\nu_e$
$\sim 15$ Gigatons

sensitivity $\approx 3 \cdot 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

Skimming $\nu_\tau$
high acceptance at $\sim$EeV!
Horizontal Air Showers seen by Satellite

- Horizontal air shower initiated deep in atmosphere
- $E > 10^{19}$ GeV
- Mass up to 10 Tera-tons
- Area up to $10^6$ km$^2$
- 1 - 20 GZK ev./y
- 5 - 50 TD ev./y
Extreme Universe Space Observatory

"standard" NEUTRINO SIGNAL: $\nu_e (\nu_\mu)$ DOWNWARD

EARTH

TARGET MASS OF ATMOSPHERE IN THE EUSO FIELD OF VIEW:

$1.5 \times 10^{18} \text{ g} \rightarrow 1500 \text{ km}^3 \text{ w.e.}$

Orbiting Wide-angle Light-collectors
# OWL Preliminary Electron Neutrino Event Rates

640 km Orbits, 10% Duty Cycle, 2.5 m Optical Aperture

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\gamma_{2.7K}$ (1)</td>
<td>16 Events/Year</td>
<td>5 Events/Year</td>
<td>1 Events/Year</td>
</tr>
<tr>
<td>Topological Defects (2)</td>
<td>46 Events/Year</td>
<td>17 Events/Year</td>
<td>13 Events/Year</td>
</tr>
<tr>
<td>$Z_{\text{Burst}}$ (3)</td>
<td>20 Events/Year</td>
<td>9 Events/Year</td>
<td>20 Events/Year</td>
</tr>
<tr>
<td>$E_{\text{Threshold}}$</td>
<td>$10^{19}$ eV</td>
<td>$2 \times 10^{19}$ eV</td>
<td>$10^{20}$ eV</td>
</tr>
<tr>
<td>No. of Satellites Viewing Event</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

2. Sigl, Lee, Bhattacharjee, & Yoshida, Phys Rev D 59 (1998), $m_{\chi} = 10^{16}$ GeV, $X \rightarrow q + q$, SuperSymmetric fragmentation
3. Yoshida, Sigl, & Lee, PRL 81 (1998), $m_\nu = 1$ eV, Primary $\Phi_\nu \sim E^{-1}$
3. Physics from AMANDA and BAIKAL
Expected sensitivity
AMANDA 97-02 data

4 years Super-Kamiokande

8 years MACRO

170 days AMANDA-B10

southern sky

northern sky

SS-433

Mk-421 ν/γ ~ 1

μ · cm⁻² s⁻¹

declination (degrees)
Preliminary limits (in units of $10^{-15}$ muons cm$^{-2}$ s$^{-1}$):

- Cas A: 0.6
- Mk421: 1.4
- Mk501: 0.8
- Crab: 6.8
- SS433: 10.5

Point Sources Amanda II (2000)

1328 events
Diffuse fluxes: theoretical bounds and experimental limits

- DUMAND test string
- FREJUS
- MACRO
- NT-200
- AMANDA-B10
- NT-200+
- AMANDA-II
- IceCube

Logarithmic scale for energy flux and energy.
Amanda 97: Upper limit on the diffuse flux of h.e. upward muon neutrinos

\[ E^2 \Phi < 0.9 \cdot 10^{-6} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

"AGN" with \( 10^{-5} \text{E}^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \)

full: experiment
dotted: atmos. \( \nu \)
EeV neutrinos underwater

Transmission of Earth for Neutrinos as a function of zenith angle and energy

→ Earth opaque above a few PeV

Downward-background at high energies is small.

PeV acceptance around horizon
EeV acceptance above horizon
AMANDA 97: EHE ($E \geq 10^{16}$ eV) Search

- Main background: muon “bundles”
- Comparable $N_{\text{PMT}}$ but smaller amplitudes

EHE events very bright; many PMTs detect multiple photons

Expect only events near horizon

Preliminary Limit

3 months B10

Diffuse up

Diffuse down

vertical

$R_{\mu} \geq 10$ km

$E^2 dN/dE_{\gamma}$ (GeV cm$^{-2}$ sr$^{-1}$)

$E_{\gamma} / \text{GeV}$

log10$(E_{\gamma} / \text{GeV})$
... and Baikal

\[ \Phi \cdot E^2 < 1.9 \cdot 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV} \]

Ve Cascades

1998

NT-200

NT-200+

Upgrade with only 22 PMTs
\( \rightarrow \) factor 4 in sensitivity
AMANDA: Correlations to GRB

Background cuts can be loosened considerably → high signal efficiency

78 BATSE bursts in 1997

88 BATSE searches
20 000 fake searches

GRB Neutrino Flux Upper Limit AMANDA B10 (1 yr of data)

GRB Neutrino Flux Prediction (Halzen et al., 2000)
EM & Hadronic Showers: “Cascades”

- Motivations for searching for cascades:
  - oscillations: $\nu_\mu \rightarrow \nu_e, \nu_\tau$
  - better $E_\nu$ measurement
  - less cosmic-ray background
  - contained events give sensitivity over $4\pi$
  - easier to calibrate
  - Glashow resonance
  - at $E > 100$ TeV, only $\nu_\tau$ can penetrate the Earth

- Drawbacks:
  - effective volume smaller than for $\nu_\mu$
  - angular resolution worse than for tracks

Analysis gets easier and more competitive with muons as detector grows in size.
Amanda-B $\rightarrow$ Amanda-II
20% Amanda II cascade limit (Y2K)

<table>
<thead>
<tr>
<th>Astrophysical $\nu$'s</th>
<th>Predicted events in 100% of 2000 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{\nu_e+\nu_e} = 10^{-6}$ E$^{-2}$ GeV cm$^{-2}$ s$^{-1}$</td>
<td>5.5</td>
</tr>
<tr>
<td>$\Phi_{\nu_{\tau}+\nu_{\tau}} = 10^{-6}$ E$^{-2}$ GeV cm$^{-2}$ s$^{-1}$</td>
<td>3.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atmospheric $\nu$'s</th>
<th>Predicted events in 100% of 2000 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ (CC), $\nu_{e} + \nu_{\mu}$ (NC)</td>
<td>0.15</td>
</tr>
<tr>
<td>Prompt charm (RQPM)</td>
<td>0.50</td>
</tr>
</tbody>
</table>
WIMP Search

(Area approximate)
Relativistic Magnetic Monopoles

\[ \beta = \frac{v}{c} \]

Upper limit (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))

- Soudan
- KGF
- MACRO
- Orito
- Amanda
- IceCube

\[ C - \text{light output} \propto n^2 \cdot (g/e)^2 \]

\[ n = 1.33 \]

\[ (g/e) = \frac{137}{2} \]

\[ \approx 8300 \]
Supernova Monitor

B10: 60% of Galaxy

A-II: 95% of Galaxy

IceCube: up to LMC
1 km

2 km

Bonus Physics: Cosmic ray composition

SPASE air shower arrays

preliminary
5.
The next decade
Point sources: detector South + detector North

Mediterranean

South Pole
Expected sensitivities to steady point sources.

- **GX 339-4**
- **SS-433**
- **Mk-501 \( v/\gamma \sim 1 \)**

“typical” predictions for AGN, SNR, ...

- 2001
- 2003
- 2007
- 2012

\( \mu \cdot \text{cm}^{-2} \text{s}^{-1} \)
We are close to some predictions!

Most promising: point sources

0.1 km² and 1 km² detectors underwater and ice

Huge step in GZK region

Exciting decade ahead