Ideas on multi-messenger approaches with AMANDA / IceCube and AMANDA results

Multi-messenger workshop
DESY Zeuthen
6 October 2005
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http://icecube.wisc.edu
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- The neutrino detection principles with AMANDA / IceCube
- Status of the AMANDA and the IceCube experiments
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Part 2: Towards Target of Opportunity measurements based on IceCube observations
- The multi-messenger approach including neutrinos
- A scheme for a neutrino-based alert trigger
- The AMANDA on-line event reconstruction and selection
- Guidelines for a feasibility study of Target of Opportunity programs including AMANDA / IceCube
Part 1: The AMANDA and IceCube neutrino telescopes: techniques and status
Muons:
Reconstructed from the arrival time of the Cherenkov photons emitted in ice
Optimized energy range: TeV to PeV
Angular resolution: 2° to 2.5°
Energy resolution: 0.4 in the log

Neutrino candidates:
are selected up-going muon tracks, with good angular resolution and reconstructed track quality

A few events/ year
~10⁹ events/ year
~10³ events/ year
Extraterrestrial neutrinos
Atmospheric neutrinos

E. Bernardini -- Multi-messenger Workshop -- DESY
**The IceCube experiment**

**Surface detector: IceTop**
- **80 stations** air shower array
- **2 tanks** per station (2 DOMs each)
- $E_{\text{threshold}} \sim 300\text{ TeV}$ for $\geq 4$ stations in coincidence
- Cosmic rays composition
- Cross-calibration, veto

**Deep ice detector: IceCube**
- **80 strings** / 60 DOM’s each
- **17 m spacing**

**The design:**
- 125 m strings spacing
- hexagonal pattern over $1\text{ km}^2 \times 1\text{ km}$
- Digital readout technology (DOMs)
- Construction started in January 2005 with the first string deployed
Status of the IceCube experiment

**AMANDA:**
Data available since 1997
Data taking will continue at least during the first years of IceCube deployment

**IceCube:**
Deployment of 70+ strings (expected 2010)
2006: 10 strings, for AMANDA equivalent sensitivity scale
AMANDA results in the search for point sources of neutrinos in the data collected between 2000 and 2003

- Search for **excesses of events** (from specific directions) compared to the background:
  - A diffuse flux of **atmospheric neutrinos**
  - A negligible (<5%) fraction of wrongly reconstructed muon tracks
- The background is **measured** from the events observed “off-source”
- The statistical tests are applied on a sample of events selected following a “**blind procedure**”:
  - Randomizing right ascension and/or time distributions of events
**Background estimation:**
From the event densities as a function of declination. At the South Pole each declination region has the same coverage.

**Searches in the Northern Sky:**
Angular cuts are applied to the reconstructed events to reject atmospheric (i.e. down-ward going) muons.

The data sample:
3329 up-going selected neutrinos detected between 2000 and 2003
The sample is optimized for the best sensitivity to point sources with energy spectrum proportional to both $dN/dE \sim E^{-2}$ and $E^{-3}$

Declination averaged sensitivity, integrated in energy ($E>10$ GeV), $dN/dE \sim E^{-2}$:

$\Phi_\nu^{\text{lim}} \approx 0.6 \cdot 10^{-8}$ cm$^2$ s$^{-1}$
Selected events between 2000 and 2003

3329 observed neutrinos in the Northern Sky
Contamination from fake-events (mis-reconstructed) < 5%
close to horizon

Point Sources search:
1. Search for excesses of events integrated in 4 years, coincident with:
   - A set of selected candidate sources (33 objects)
   - The full Northern Sky
2. Search for time variable signals
### Statistical test of 33 pre-selected objects

<table>
<thead>
<tr>
<th>Source</th>
<th>Nr. of ν events</th>
<th>Expected background</th>
<th>$\Phi_{90%}(E_\nu&gt;10$ GeV [10$^{-8}$cm$^{-2}$s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TeV Blazars</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Markarian 421</td>
<td>6</td>
<td>5.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Markarian 501</td>
<td>5</td>
<td>5.0</td>
<td>0.6</td>
</tr>
<tr>
<td>1ES 1426+428</td>
<td>4</td>
<td>4.3</td>
<td>0.5</td>
</tr>
<tr>
<td>1ES 2344+514</td>
<td>3</td>
<td>4.9</td>
<td>0.4</td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>5</td>
<td>3.7</td>
<td>1.0</td>
</tr>
<tr>
<td>QSO 0528+134</td>
<td>4</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
<td>QSO 0235+164</td>
<td>6</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>QSO 1611+343</td>
<td>5</td>
<td>5.2</td>
<td>0.6</td>
</tr>
<tr>
<td>QSO 1633+382</td>
<td>4</td>
<td>5.6</td>
<td>0.4</td>
</tr>
<tr>
<td>QSO 0219+428</td>
<td>4</td>
<td>4.3</td>
<td>0.5</td>
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<tr>
<td>QSO 0954+556</td>
<td>2</td>
<td>5.2</td>
<td>0.2</td>
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<tr>
<td>QSO 0716+714</td>
<td>1</td>
<td>3.3</td>
<td>0.3</td>
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<tr>
<td><strong>GeV Blazars</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS433</td>
<td>2</td>
<td>4.5</td>
<td>0.2</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>6</td>
<td>4.8</td>
<td>0.7</td>
</tr>
<tr>
<td>GRO J0422+32</td>
<td>5</td>
<td>5.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Cygnus X-1</td>
<td>4</td>
<td>5.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Cygnus X-3</td>
<td>6</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>XTE J1118+480</td>
<td>2</td>
<td>5.4</td>
<td>0.2</td>
</tr>
<tr>
<td>CI Cam</td>
<td>5</td>
<td>5.1</td>
<td>0.7</td>
</tr>
<tr>
<td>LSI +61 303</td>
<td>3</td>
<td>3.7</td>
<td>0.6</td>
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<tr>
<td><strong>MicroQuasars</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SGR 1900+14</td>
<td>3</td>
<td>4.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Crab Nebula</td>
<td>10</td>
<td>5.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Cassiopeia A</td>
<td>4</td>
<td>4.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Geminga</td>
<td>3</td>
<td>5.2</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>SNRs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The statistical significance is evaluated with MC experiments on events with randomized right ascension $= 2.25^\circ - 3.75^\circ$ $= 807$ days

The chance probability of such an excess (or higher) in any of the 33 objects is 64%.
Search for clusters in the Northern Sky

**The Significance map:**
From the search for clusters in direction, using a system of highly overlapping bins

Highest deviation **3.4 σ**
The probability of this excess (or higher) in any of the sky bins, due to a background fluctuation is **92%**
Search for time variable signals – Part 1: active periods

Search for coincidences with known periods of enhanced electromagnetic emission:

- **Periods** and **sources** selected based on the existing multi-wavelength information and the current theoretical understanding

- **Wavelengths**: indicators for possible correlated ν’s
  - X-ray for two Blazars and radio for one Microquasar

### Markarian 421: X-ray data

<table>
<thead>
<tr>
<th>Source</th>
<th>EM light curve source</th>
<th>Livetime in periods of high activity</th>
<th>Nr. of ν events in high state</th>
<th>Expected backgr. in high state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 421</td>
<td>ASM/RXTE</td>
<td>141 days</td>
<td>0</td>
<td>1.63</td>
</tr>
<tr>
<td>1ES1959+650</td>
<td>ASM/RXTE</td>
<td>283 days</td>
<td>2</td>
<td>1.59</td>
</tr>
<tr>
<td>Cygnus X-3</td>
<td>Ryle Telesc.</td>
<td>114 days</td>
<td>2</td>
<td>1.37</td>
</tr>
</tbody>
</table>
Search for time variable signals – Part 2: $\nu$ flares

Search for $\nu$ flares using time-sliding windows:

= 40/20 days for Extragalactic/Galactic Objects

= 2.25°-3.75°

<table>
<thead>
<tr>
<th>Source</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>40 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>1ES1959+650</td>
<td>40 days</td>
<td>1</td>
<td>0.34</td>
</tr>
<tr>
<td>3EG J1227+4302</td>
<td>40 days</td>
<td>1</td>
<td>0.43</td>
</tr>
<tr>
<td>3EG J0450+1105</td>
<td>40 days</td>
<td>1</td>
<td>0.47</td>
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<tr>
<td>QSO 0235+164</td>
<td>40 days</td>
<td>1</td>
<td>0.52</td>
</tr>
<tr>
<td>QSO 0528+134</td>
<td>40 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>Cygnus X-3</td>
<td>20 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>Cygnus X-1</td>
<td>20 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>20 days</td>
<td>1</td>
<td>0.32</td>
</tr>
<tr>
<td>GRO J0422+32</td>
<td>20 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>3EG J1828+1928</td>
<td>20 days</td>
<td>0</td>
<td>Close to 1</td>
</tr>
<tr>
<td>3EG J1928+1733</td>
<td>20 days</td>
<td>1</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Observations from the direction of 1ES 1959+650

An interesting coincidence with a gamma-ray flare:
5 events observed compared to 3.7 background expected from atmospheric neutrinos, between 2000 and 2003.
3 events are within 66 days in 2002, partly overlapping a period of major activity of the source.

AMANDA events within 2.25° from the direction of 1ES 1959+650

Whipple light curve [Holder et al 2003]
No statistically significant excess integrated in 4 years
No statistically significant excess in the search for time variable signals

All observed events are consistent with atmospheric neutrinos

Assessment of the systematic uncertainty (in the flux upper limit) and publication in progress
Analysis of data from 2004 and 2005 with new developments
Part 2: Towards possible Target of Opportunity measurements based on AMANDA / IceCube observations
The IceCube multi-messenger approach

Established off-line (blind) analyses:
- Use constraints from **existing data on the electromagnetic emission** of candidate sources to focus searches and limit the trial factors
- Proof of principle from the analysis of AMANDA data from 2000 to 2003, develop for analysis of 2004 and 2005 data

<table>
<thead>
<tr>
<th>Data Analysis</th>
<th>Data input</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Search for ( \nu )'s in coincidence with observed (known) active states</strong></td>
<td><strong>Combined light curves</strong> at different wavelengths</td>
</tr>
<tr>
<td>Based on data on the electromagnetic emission <strong>sources candidates</strong> and <strong>periods of interest</strong> are selected</td>
<td><strong>Sample of ( \nu )'s</strong> optimized for the duration of the periods of interest</td>
</tr>
<tr>
<td><strong>Search for ( \nu )'s flares</strong></td>
<td><strong>Combined light curves</strong> at different wavelengths (define the time-scale)</td>
</tr>
<tr>
<td>▪ Based on data on the electromagnetic emission <strong>sources candidates</strong> are selected</td>
<td>▪ <strong>Sample of ( \nu )'s</strong> optimized for the expected time-scale(s)</td>
</tr>
<tr>
<td>▪ Search for <strong>clusters in time</strong> of ( \nu )'s</td>
<td></td>
</tr>
</tbody>
</table>
Towards neutrino-based Target of Opportunity measurements:

- Promising with the advent of IceCube
- Can be explored with AMANDA to **collect information on the possible phenomenology** of the objects accessible

*Based on the current AMANDA on-line neutrino event reconstruction, an alarm could be issued to an *IceCube referent* and to one (or more) **coordinators of partner experiments***
Perform case studies to:

1. Select the most promising neutrino candidate sources
2. Identify the overlap in the scientific program of different observatories and IceCube
3. Based on the sustainable alert rate define the selected neutrino rate (cut strength)
Feasibility of a \( \nu \)-based Target of Opportunity?

- The majority of on-line filtered events will stem from atmospheric neutrinos
- A “potential” hadron trigger

**Possible implications for gamma-ray observatories:**
- Interference with other ToO programs and / or observation plans:
  - Define priorities
  - If the selected sources belong to the independent measurements program the \( \nu \)-based ToO would require no extra observation time

**Possible implications for AMANDA (IceCube):**
- Interference with the “blindness principle” for off-line analyses:
  - Events cuts and / or periods selection for off-line cross correlation searches should not be adapted based on the results of the target of opportunity alert
  - No issue for correlation with flares that would have not been detected otherwise
Possible sources of interest

First “trial”: TeV Blazars Markarian 421, Markarian 501, 1ES 1959+650

Neutrino event rates (800 days of effective exposure):

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta$ (°)</th>
<th>$n_{\text{obs}}$</th>
<th>$n_{\text{bck}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 421</td>
<td>38.2</td>
<td>6</td>
<td>5.6</td>
</tr>
<tr>
<td>Markarian 501</td>
<td>39.8</td>
<td>5</td>
<td>5.0</td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>65.1</td>
<td>5</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Expected alarm rate:
$\sim 10 / \text{year}$, to be matched with the operation time of the gamma-ray telescopes

To be considered in addition:
- GeV Blazars 3C 273 and 3C 279 currently non in the list of (33) selected neutrino candidate sources
- Variable Micro-quasars LSI +61 303 + ?
The current cut strength based on 4 yr of data corresponds to a fraction of the expected signal between approx. 65% and 75%.

To increase the alarm rate, a possible (stable) choice is to increase the search window bin size.

The rate of selected neutrino candidates can be “tuned”, based on a fixed class of events (quality of the reconstructed track).

The AMANDA-II Point Spread Function (highlighted the range of bin sizes used for analysis).
A scheme for the neutrino-based alert

- Raw data files
- 60 to 80 minutes
- ON-LINE DATA FILTERING AND RECONSTRUCTION
- MONITORING
- Events at final level (point source selection)
- DETECTOR STABILITY TESTS (Correlated noise rate, OMs stability …)
- IceCube alert trigger reference
- Modem
On-line filter event rates, a very first look

- By applying the event selection developed for the analysis of 4 yr of AMANDA data (same cuts), the event rates from the on-line analysis look stable:

**Intermediate level:** rejection of downward-going events

**Final level:**
- selected up-ward going neutrino-induced events

![Graph](image)

- No obvious anomalies
- Large pathologies found by the monitoring crew in charge
- More than 8000 events/day at previous level
Discrepancies ascribed to different treatment of noisy (X-talk) hits.

In the plot: more than 3300 events in 4yr, about 500 events from 2005 (no run selection applied!)
Prior to the trigger implementation it is necessary to define:

1. **Time window for the coincidence**
   - **Min.** Depends on the delay in delivering the alert and on the first time slot available for gamma-ray measurements
   - **Max.** Depends on the time evolution of the flares and on the time scale of the expected correlation between gamma-rays and neutrinos

2. **Topology of the gamma-ray flares**
   - **E.g.** Define the minimal gamma-ray flux that might be accompanied by a detectable \( \nu \) signal

3. **Probability of random coincidences**
   - Based on the measured \( \nu \) rates and expected gamma-ray flares rates
Feasibility study for a Target of Opportunity program

- Assessment of the performance of the AMANDA on-line event filtering procedures and automatic data-quality tagging (in progress)
- Create multi-messenger working groups
- Compile a proposal clarifying:
  1. Case studies (physics potential)
  2. Selected targeted sources
  3. Partner experiments
  4. Constraints on neutrino event rates and fake-alert probability
  5. Performance of the on-line AMANDA filtering
  6. Definition of the statistical tests and definition of coincidences
- Tests
  
  ...
Thank you!
### ON-LINE filtering (point source stream)

<table>
<thead>
<tr>
<th>Class 1 noise rejection</th>
<th>Reconstruction / filtering step</th>
<th>Event cut</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAD/dead OM selection (dynamical)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse shape cuts (OM-wise)</td>
<td></td>
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<tr>
<td></td>
<td>Correlated noise checks</td>
<td></td>
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<tr>
<td>Re-triggering (multiplicity 24)</td>
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<tr>
<td>Class 2 noise rej.</td>
<td>ADC cleaning (reject &lt;0.1 p.e.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Isolated hits and early/late hits rejection</td>
<td></td>
</tr>
<tr>
<td><strong>Fits</strong></td>
<td>Direct Walk (“first guess (*)”)</td>
<td>$\theta &gt; 70^\circ$</td>
</tr>
<tr>
<td></td>
<td>JAMS (“first guess”)</td>
<td>$\theta &gt; 80^\circ$</td>
</tr>
<tr>
<td></td>
<td>32-fold likelihood reconstruction (**)</td>
<td>$\theta &gt; 80^\circ$</td>
</tr>
<tr>
<td></td>
<td>16-fold bayesian reconstruction (**)</td>
<td>Smooth&lt;0.4</td>
</tr>
<tr>
<td></td>
<td>Track resolution (shape of the likelihood valley)</td>
<td></td>
</tr>
</tbody>
</table>

(*$\sim 10^{-3}$ s/events for 2.5 GHz)  
(**$\sim 1$ s/events)
Detection channels in AMANDA

**First $\nu_\mu$ signature:**
up-going $\mu$ track

**Second $\nu$ signature:**
Cascades $\nu_{e,\mu,\tau}$ NC and $\nu_{e,\tau}$ CC int.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Pointing Resolution</th>
<th>$\sigma[\log_{10}(E/\text{TeV})]$</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\uparrow \mu$-tracks</td>
<td>$1.5^\circ - 2.5^\circ$</td>
<td>$\sim 0.4$ ($&gt;1 \text{ TeV}$)</td>
<td>$2\pi$</td>
</tr>
<tr>
<td>Cascades</td>
<td>$30^\circ - 40^\circ$</td>
<td>$0.1 - 0.2$</td>
<td>$4\pi$</td>
</tr>
</tbody>
</table>