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

Multi-messenger workshop

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6 **October 2005**

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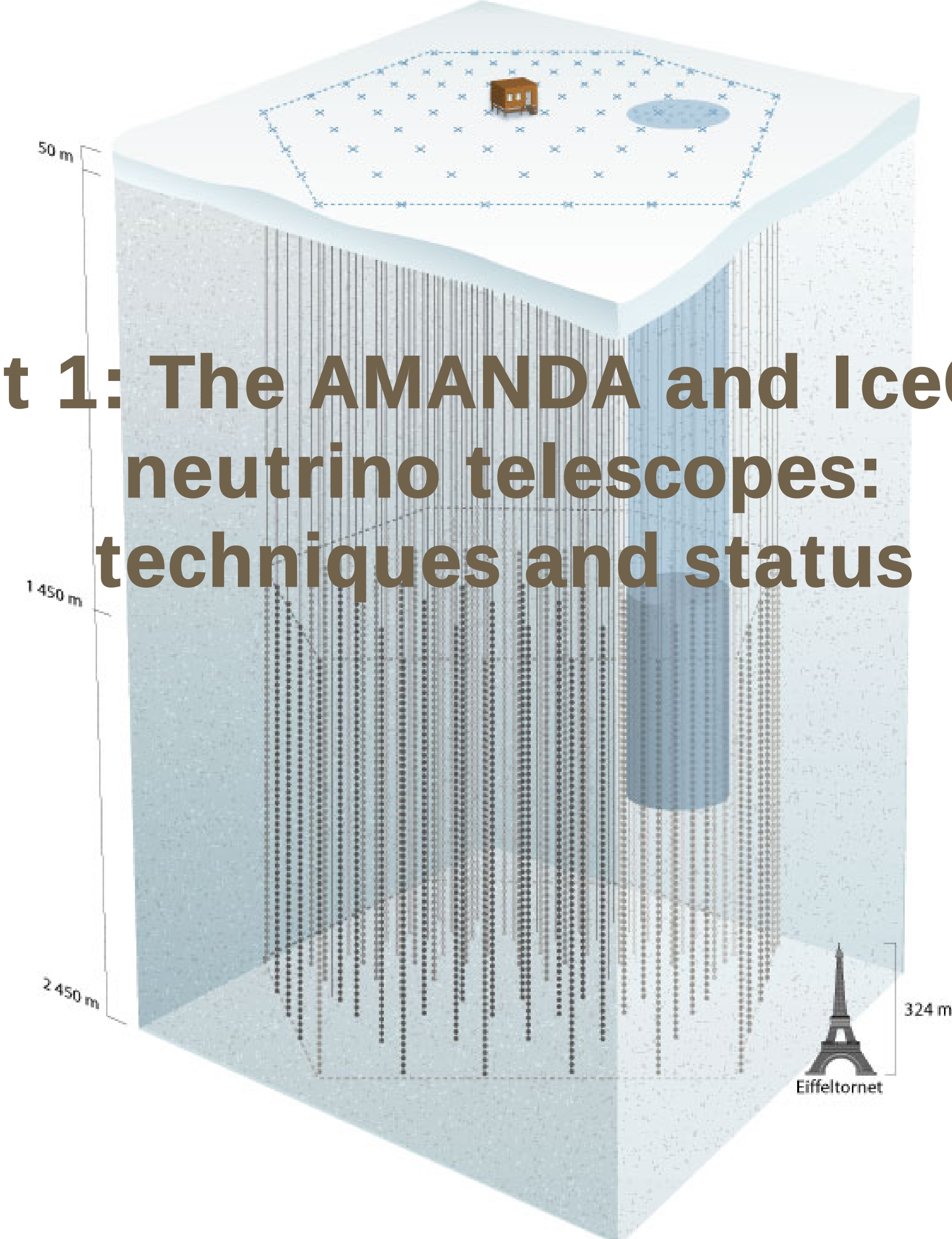
IceCube

http://icecube.wisc.edu

Contents

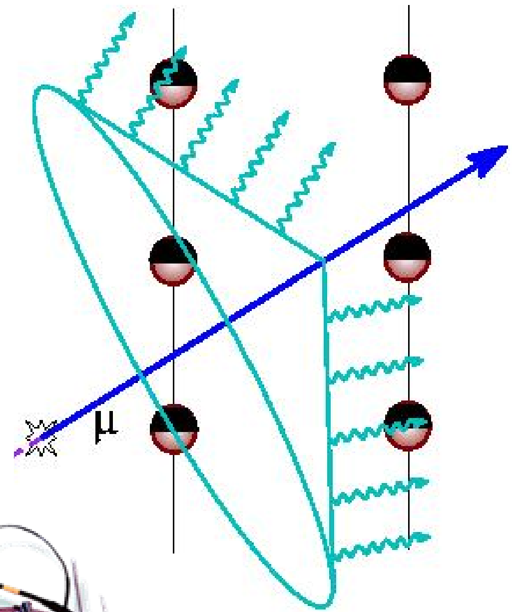
Part 1: The AMANDA and IceCube neutrino telescopes: techniques and status

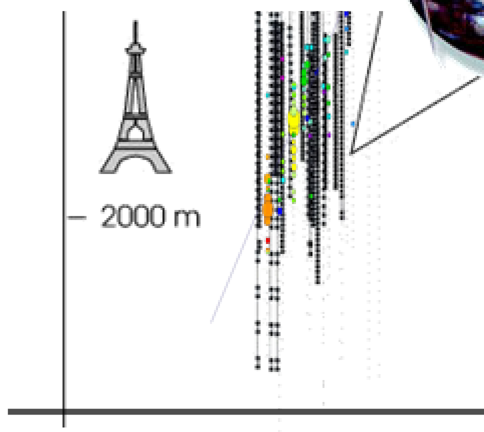


The neutrino detection principles with AMANDA

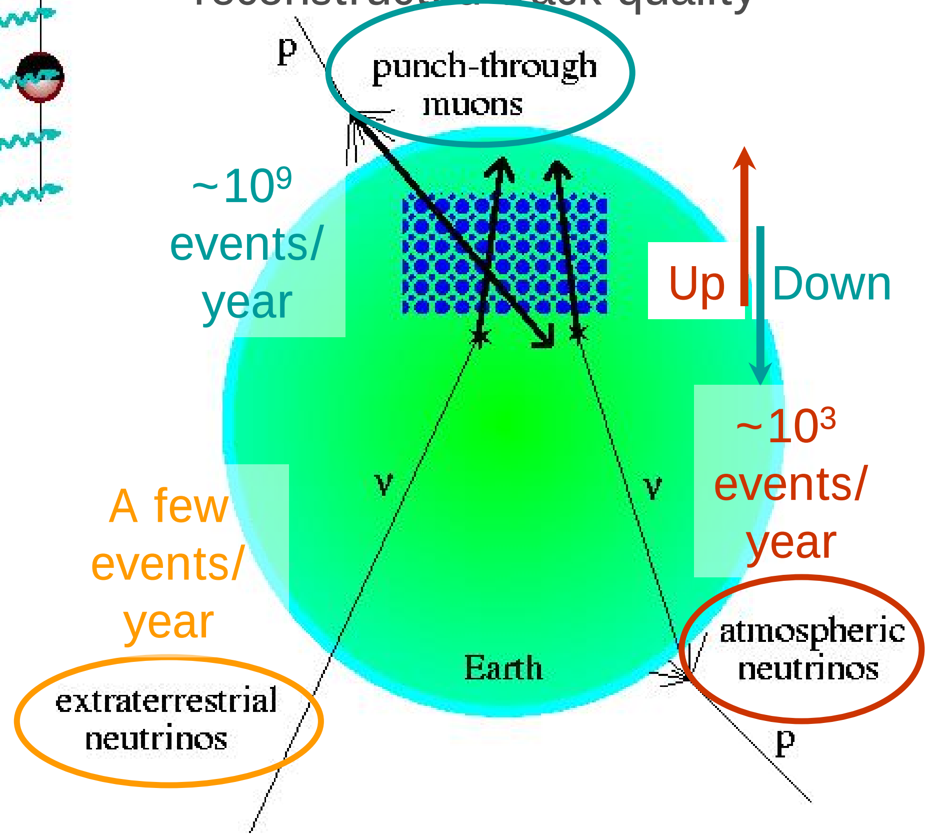
Depth

Muons:
Reconstructed from the arrival time of the Cherenkov photons emitted in ice
Optimized energy range: TeV to PeV
Angular resolution: 2^o to 2.5^o
Energy resolution 0.4 in the log





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



The IceCube experiment

Surface detector: **IceTop**

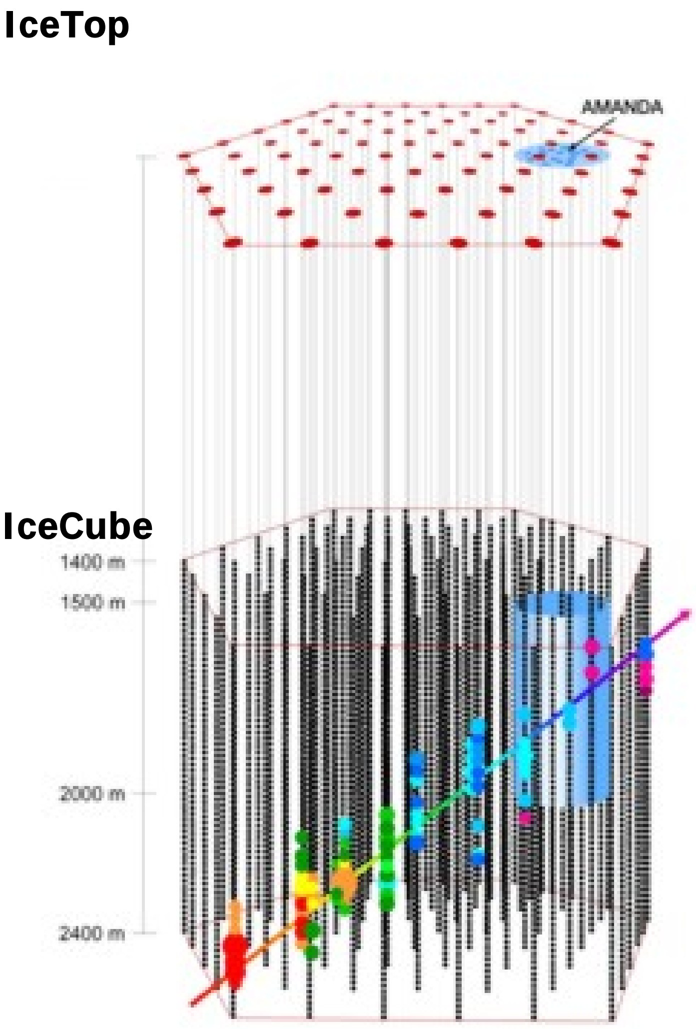
- **80 stations** air shower array
- **2 tanks** per station (2 DOMs each)
- $E_{threshold}$ ~ 300 TeV for $\geq$ 4 stations in coincidence
- Cosmic rays composition
- Cross-calibration, veto

Deep ice detector: **IceCube**

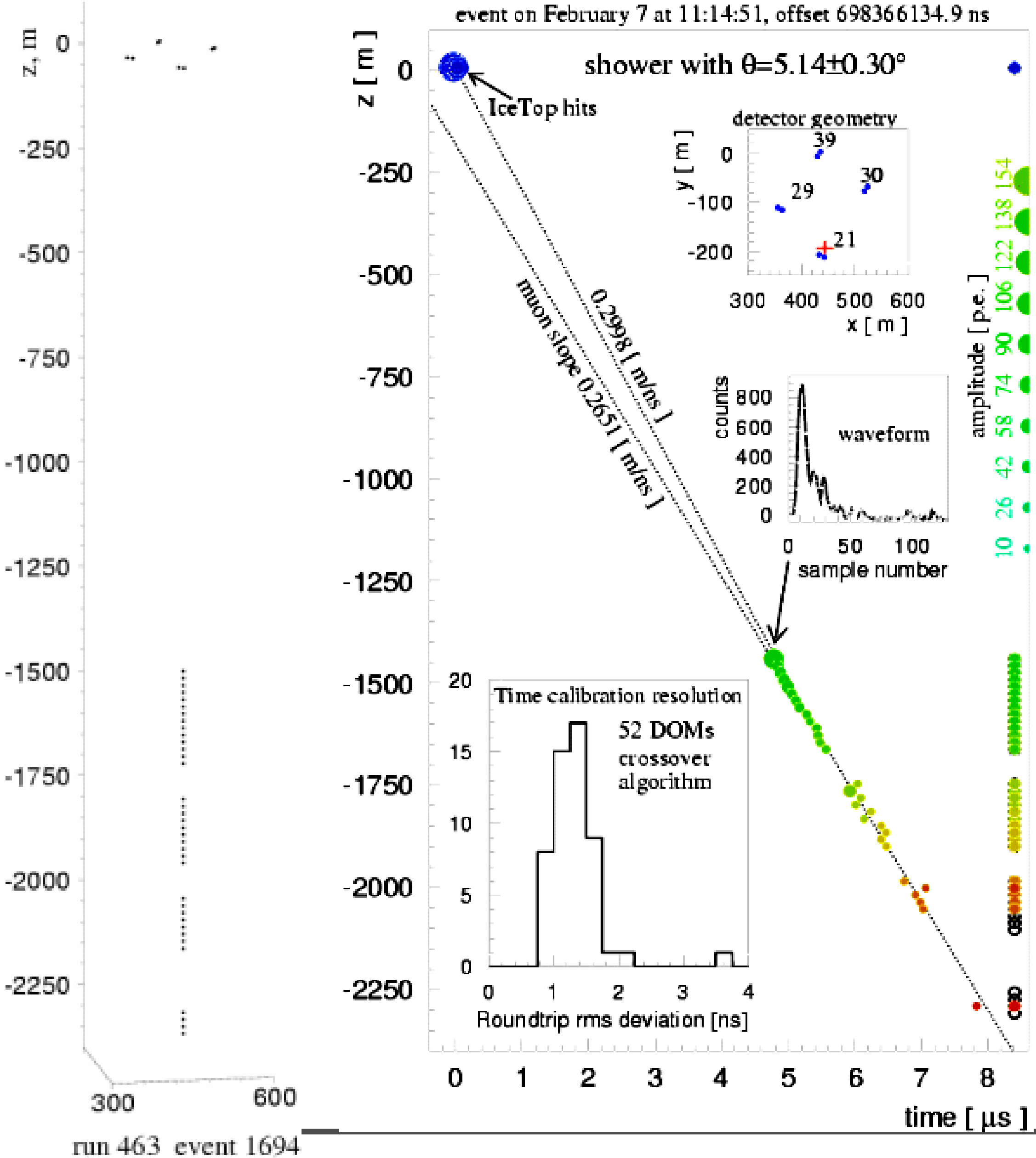
- **80 strings** / 60 DOM's each
- 17 m spacing

The design:

- 125 m strings spacing
- hexagonal pattern over 1 km^2x1 km
- Digital readout technology (DOMs)
- Construction started in January 2005 with the first string deployed



Status of the IceCube experiment



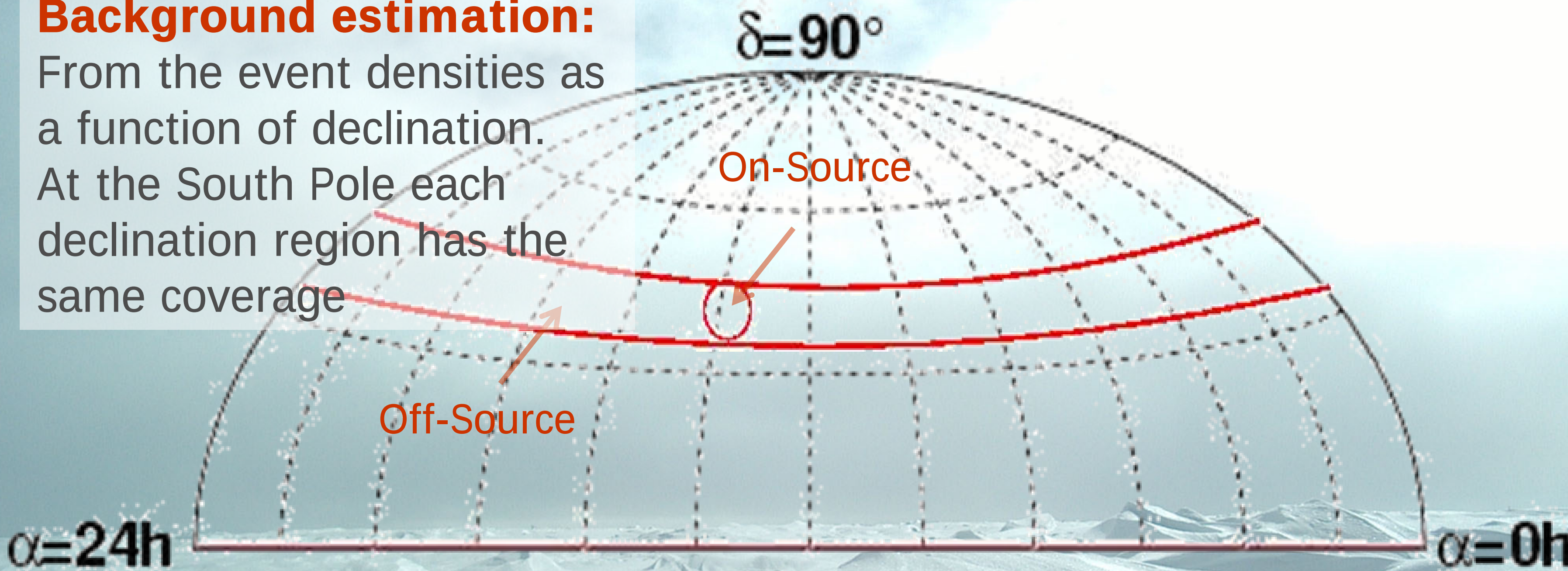
AMANDA:
Data available since 1997
Data taking will continue at least during the first years of IceCube deployment

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



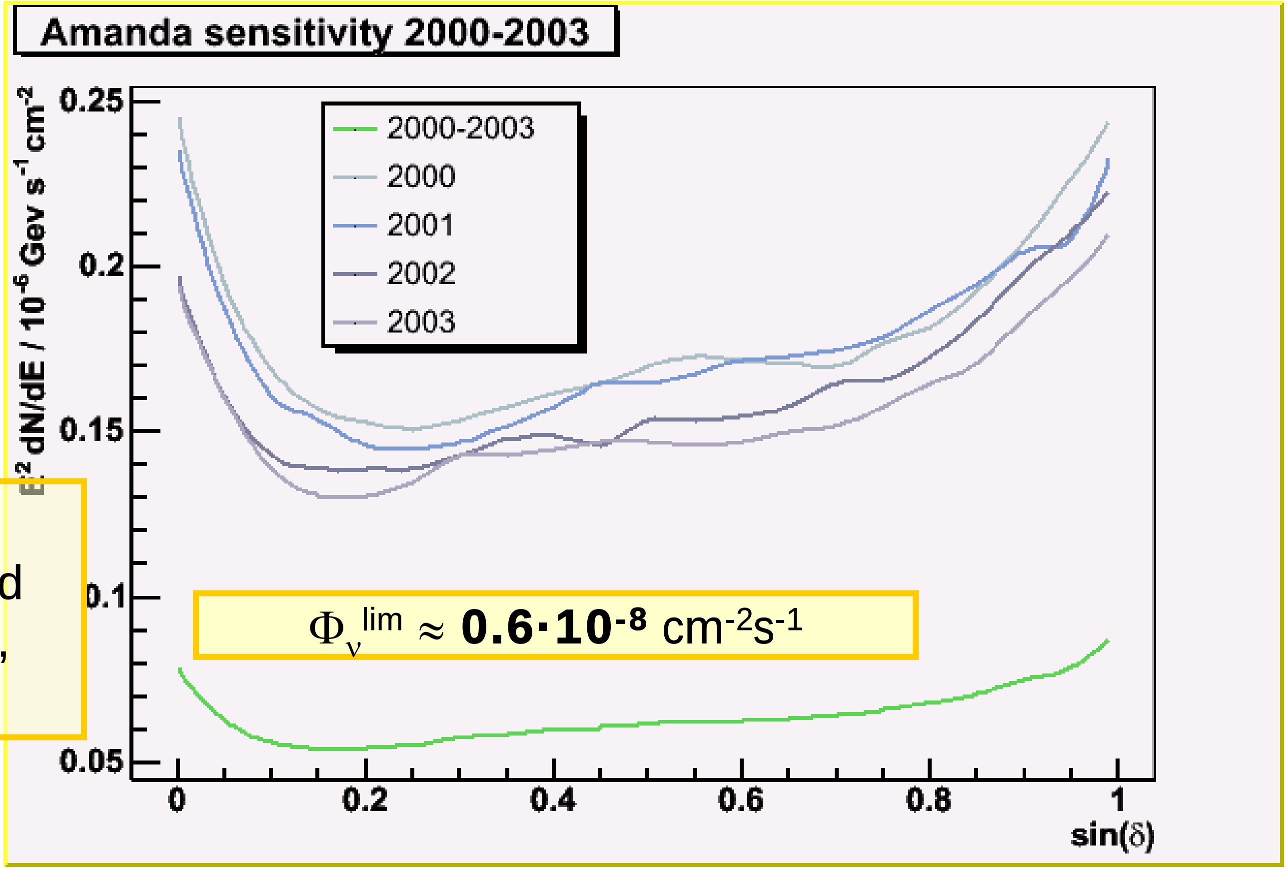
Searches in the Northern Sky:
Angular cuts are applied to the reconstructed events to reject atmospheric (i.e. down-ward going) muons

ApJ 583, 1040 (2003)
Phys. Rev. Lett. 92, 071102 (2004)
Astropart. Phys. 22, 339 (2005)

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 spectum proportional to both **dN/dE** ~ $\mathbf{E^{-2}}$ and $\mathbf{E^{-3}}$

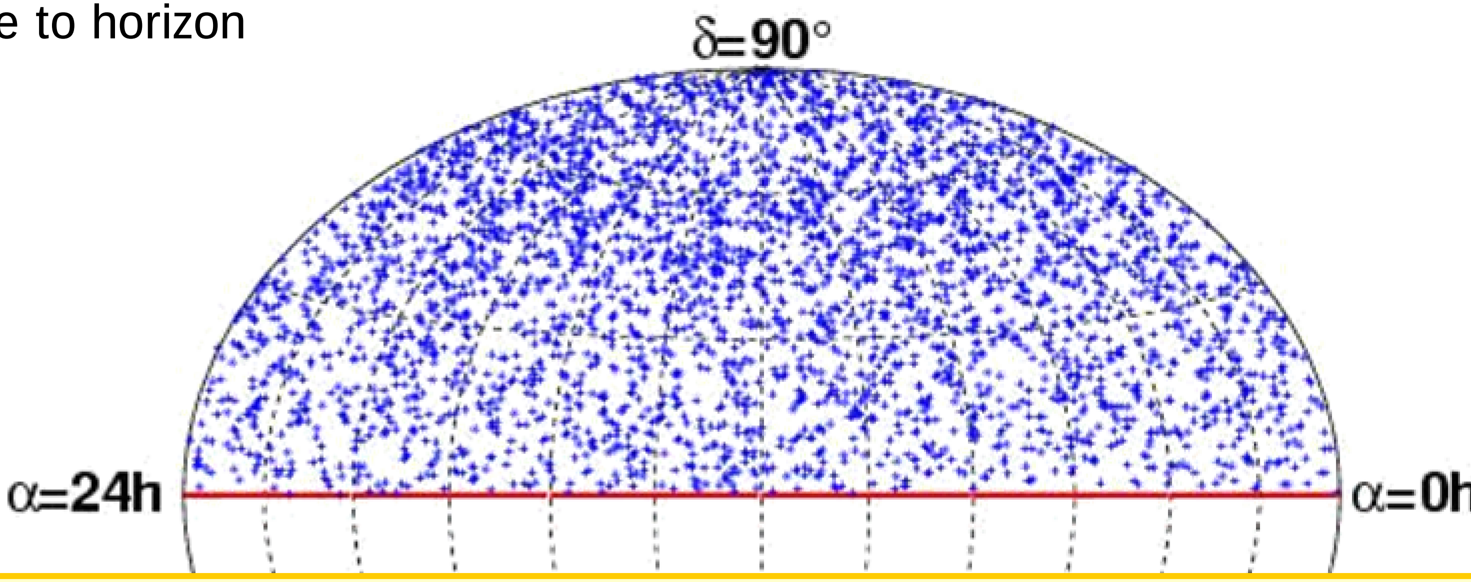


Declination averaged **sensitivity**, integrated in energy (E>10 GeV), **dN/dE** ~ $\mathbf{E^{-2}}$:

Selected events between 2000 and 2003

3329 ↑ observed neutrinos in the Northern Sky

Contamination from fake-events
(mis-reconstructed) < 5%
close to horizon

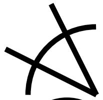


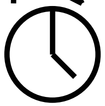
Point Sources search:

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

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


= 2.25°-3.75°


= 807 days

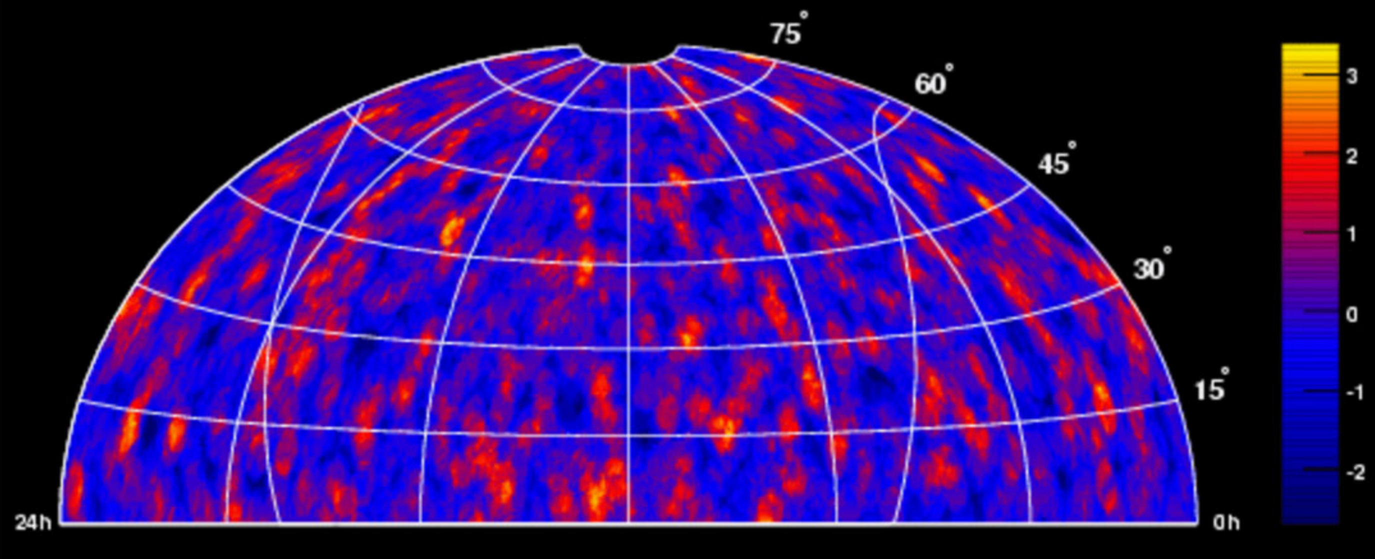
The statistical significance is evaluated with MC experiments on events with randomized right ascension

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



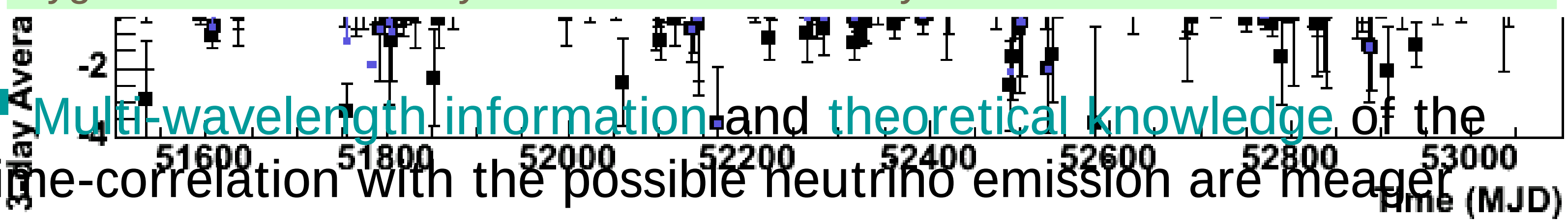
Highest deviation **3.4** σ

The probability of this excess (or higher) in any of the sky bins, due to a background fluctuation is **92%**

Search for 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

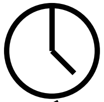
Source	EM light curve source	Livetime in periods of high activity	Nr. of ν events in high state	Expected backgr. in high state
Markarian 421	ASM/RXTE	141 days	0	1.63
1ES1959+650	ASM/RXTE	283 days	2	1.59
Cygnus X-3	Ryle Telesc.	114 days	2	1.37

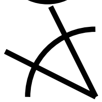


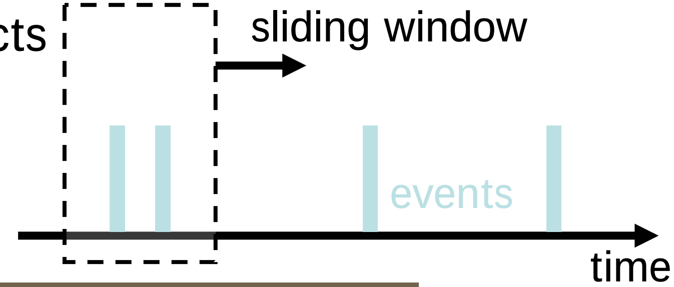
- Multi-wavelength information and theoretical knowledge of the time-correlation with the possible neutrino emission are meager

Search for time variable signals – Part 2: ν flares

Search for ν flares using time-sliding windows:

 = 40/20 days for Extragalactic/Galactic Objects

 = 2.25°-3.75°

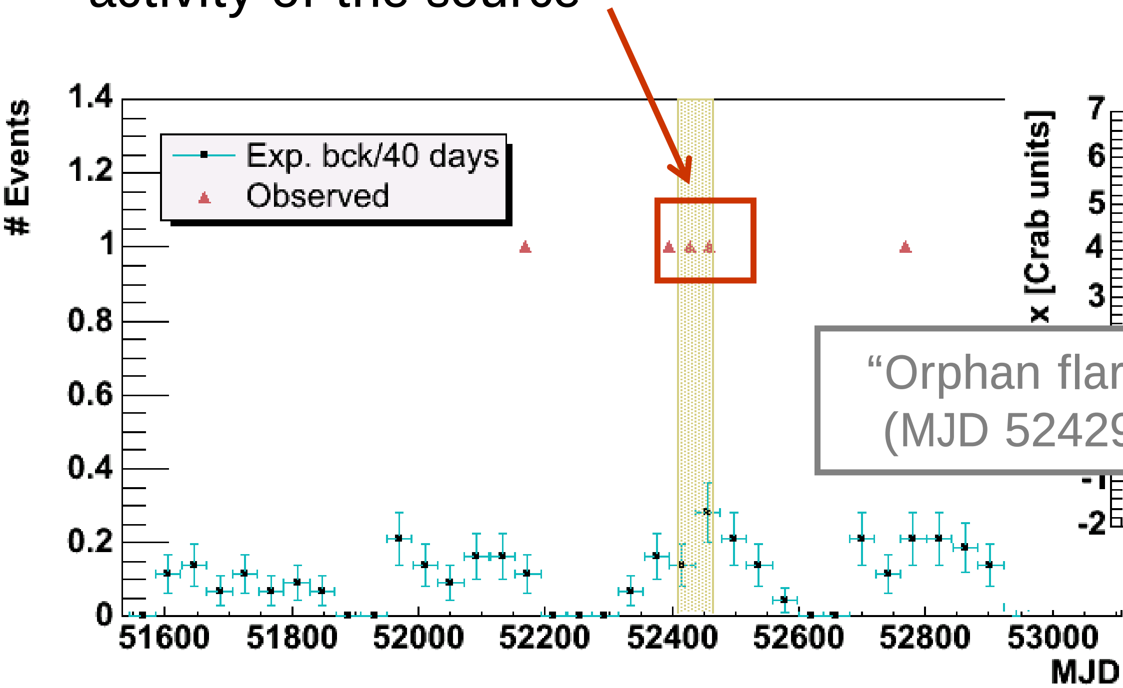


Source	Period duration	Nr. of doublets	Probability for highest multiplicity
Markarian 421	40 days	0	Close to 1
1ES1959+650	40 days	1	0.34
3EG J1227+4302	40 days	1	0.43
3EG J0450+1105	40 days	1	0.47
QSO 0235+164	40 days	1	0.52
QSO 0528+134	40 days	0	Close to 1
Cygnus X-3	20 days	0	Close to 1
Cygnus X-1	20 days	0	Close to 1
GRS 1915+105	20 days	1	0.32
GRO J0422+32	20 days	0	Close to 1
3EG J1828+1928	20 days	0	Close to 1
3EG J1928+1733	20 days	1	0.35

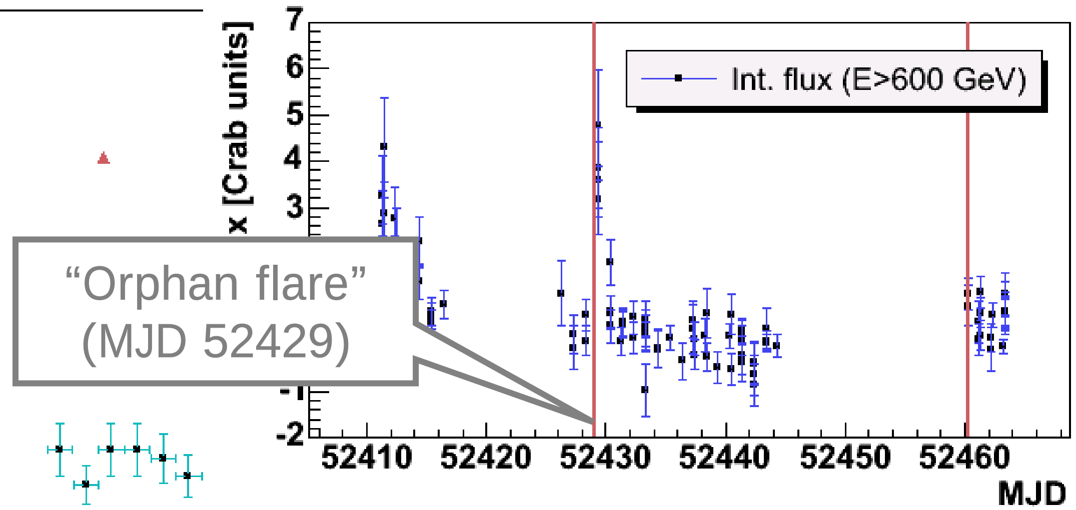
An interesting coincidence with a gamma-ray flare:

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 2.25º from the direction of 1ES 1959+650



Whipple light curve [Holder et al 2003]

Results from the search for neutrino Point Sources

- 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

	Data Analysis	Data input
Search for ν's in coincidence with observed (known) active states	Based on data on the electromagnetic emission **sources candidates** and **periods of interest** are selected	▪ **Combined light curves** at different wavelengths ▪ **Sample of ν's** optimized for the duration of the periods of interest
Search for ν's flares	▪ Based on data on the electromagnetic emission **sources candidates** are selected ▪ Search for **clusters in time** of **ν's**	▪ **Combined light curves** at different wavelengths (define the time-scale) ▪ **Sample of ν's** optimized for the expected time-scale(s)

A Neutrino-based alarm as Target Of Opportunity?

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***

Constraints for the neutrino-based alarm

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 ν-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 ν-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):

Source	δ(°)	n_{obs}	n_{bck}
Markarian 421	38.2	6	5.6
Markarian 501	39.8	5	5.0
1ES 1959+650	65.1	5	3.7

Expected alarm rate:
~10 /year, to be matched with the operation time of the gamma-ray telescopes

To be considered in addition:

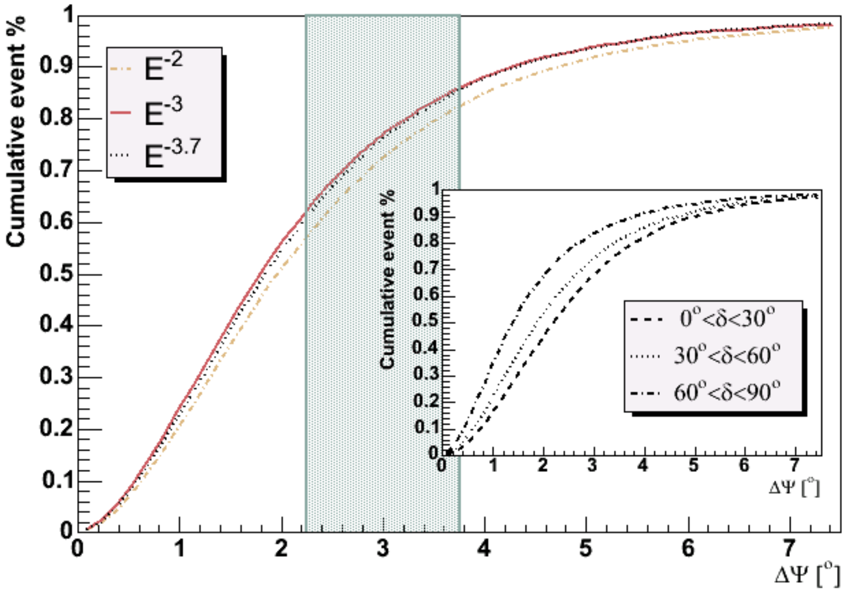
- GeV Blazars **3C 273** and **3C 279**
  currently non in the list of (33) selected neutrino candidate sources
- Variable Micro-quasars **LSI +61 303** + ?

Neutrino events (alarm) rates

- 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

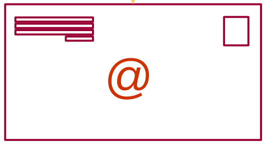
ON-LINE DATA FILTERING AND RECONSTRUCTION

MONITORING

Events at final level (point source selection)

IceCube alert trigger reference

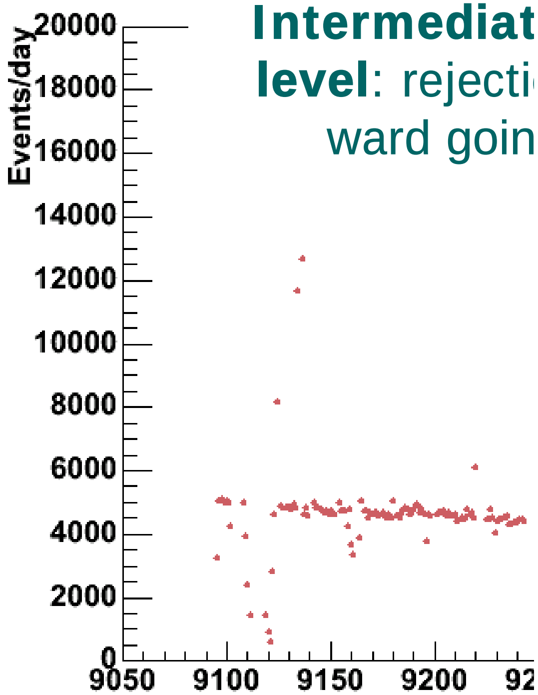
DETECTOR STABILITY TESTS
(Correlated noise rate, OMs stability ...)



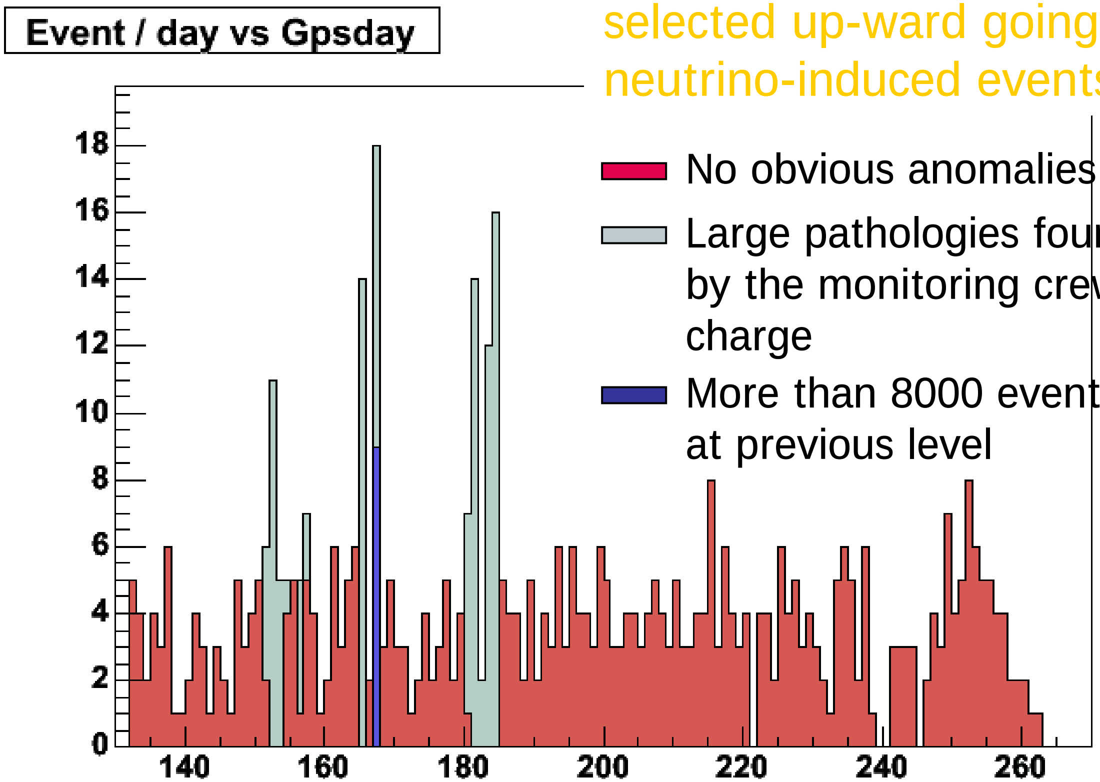
Modem

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:

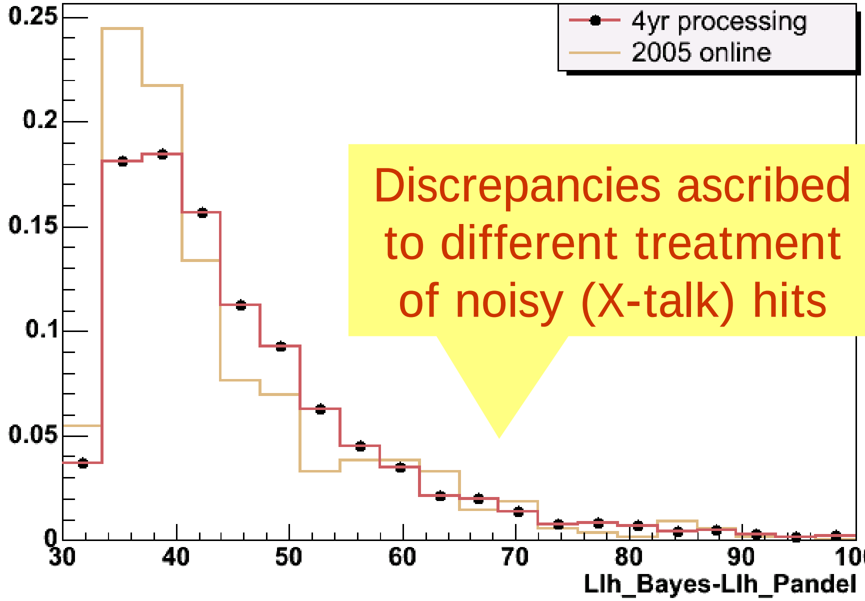


Intermediat **level**: rejecti ward goin

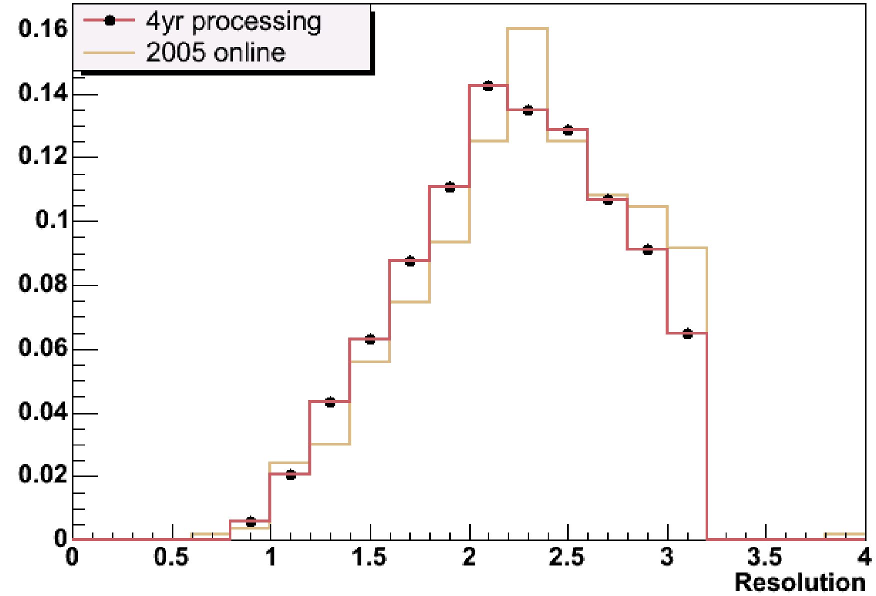


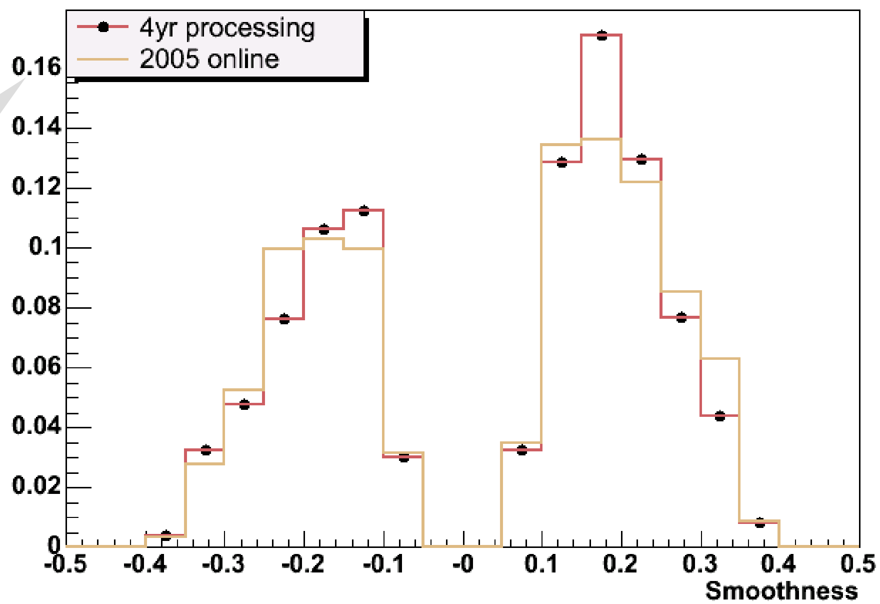
Final level: selected up-ward going neutrino-induced events

Final level distributions (all runs)



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!)

ν to γ-ray correlation: the statistical test

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 ν signal

3. **Probability of random coincidences**

    Based on the **measured ν rates** and **expected gamma-ray flares rates**

Feasibility study for a Target of Opportunity program

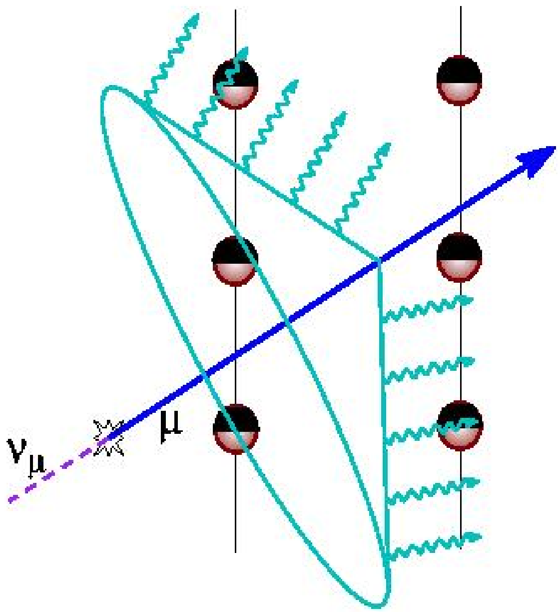
- Assessment of the performance of the AMANDA on-line event filtering procedures and automatic data-quality tagging (in progress)
- Create multi-messenger working groups
- Compile a proposal clarifying:
  1. Case studies (physics potential)
  2. Selected targeted sources
  3. Partner experiments
  4. 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
- ....

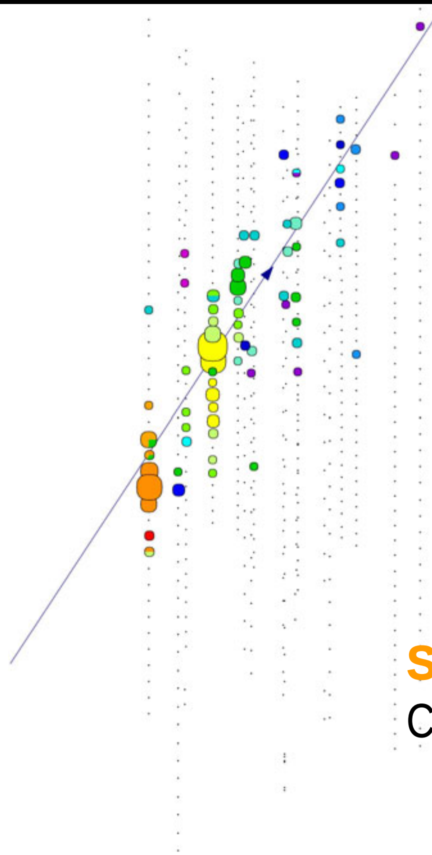
Thank you!

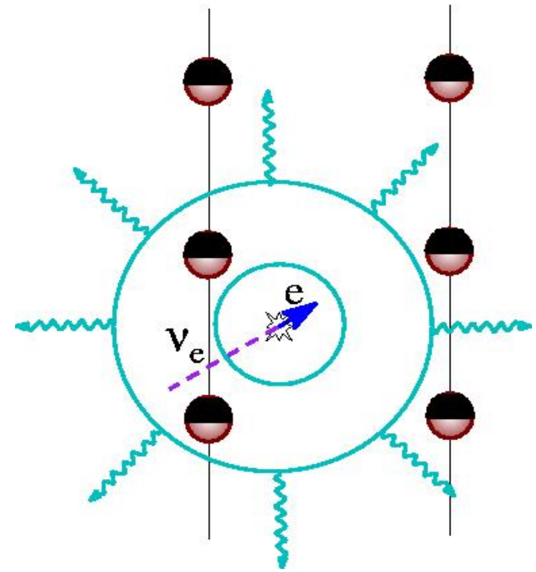
ON-LINE filtering (point source stream)

	Reconstruction / filtering step	Event cut	
Class 1 noise rejection	BAD/dead OM selection (dynamical)		
	Pulse shape cuts (OM-wise)		
	Correlated noise checks		
Re-triggering (multiplicity 24)			
Class 2 noise rej.	ADC cleaning (reject <0.1 p.e.)		
	Isolated hits and early/late hits rejection		
Fits	Direct Walk ("first guess (*)")	$\theta>70^o$	
	JAMS ("first guess")	$\theta>80^o$	**L1**
	32-fold likelihood reconstruction (**)	$\theta>80^o$	
		Smooth<0.4	**L3**
	16-fold bayesian reconstruction (**)		
	Track resolution (shape of the likelihood valley)		**Final level**

(*) ~ 10^{-3} s/events for 2.5 GHz (**) ~ 1 s/events







First ν_μ signature:
up-going μ track

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

Channel	Pointing Resolution	$\sigma[\log_{10}(E/TeV)]$	Coverage
↑ μ-tracks	1.5° - 2.5°	~ 0.4 (>1 TeV)	2π
Cascades	30° - 40°	0.1 – 0.2	4π