Search for High Energy Astrophysical Neutrinos with the AMANDA Detector at the South Pole

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Elisa Bernardini
bernardi@ifh.de

DESY

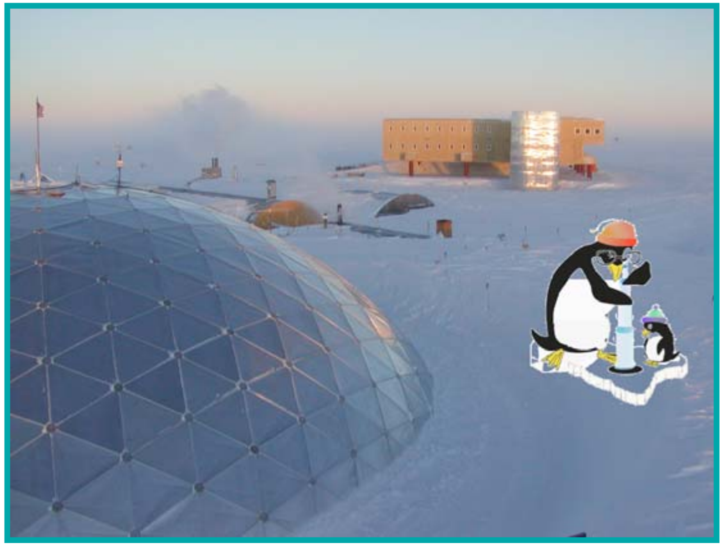
IceCube

http://amanda.uci.edu

http://icecube.wisc.edu

Contents

- Search Topics of the AMANDA scientific program
- Detection principles of the AMANDA Neutrino Telescope
- Status of search for astrophysical neutrinos with AMANDA:
  - Diffuse flux in different energy ranges
  - Search for point sources:
    - Steady
    - Transient
  - Other search topics



- The IceCube Project

AMANDA Physics Topics

Astrophysics / Cosmology / Particle Physics :

- **Cosmic Rays**

  Energy spectrum, composition (coincidence with air shower array SPASE)
  Flux measurements: atmospheric muons / neutrinos
  → also calibration of AMANDA

- **SuperNova monitor**

  90% coverage of Milky Way
  Participate in SNEWS

- **Dark matter / exotic particles**:

  → WIMPs
  → Magnetic Monopoles
  → Topological defects: extra-terrestrial UHE diffuse flux

- **High Energy Neutrino Astrophysics (this talk):**

  Acceleration sites / emission mechanisms / etc.:
  → limits to extra-terrestrial flux (diffuse / point-like – steady and transient)
  @ ≥ TeV energies

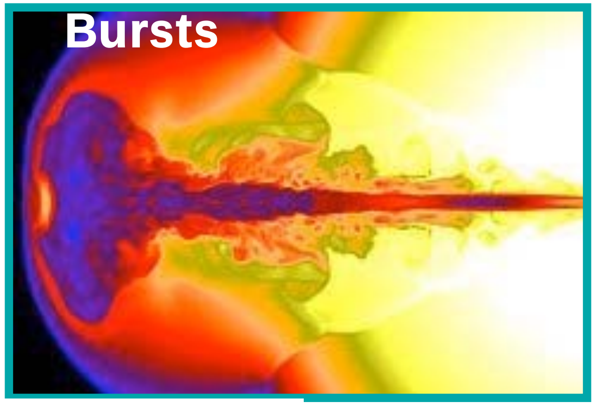
Neutrino Astrophysics in AMANDA

MeV GeV TeV PeV EeV ……

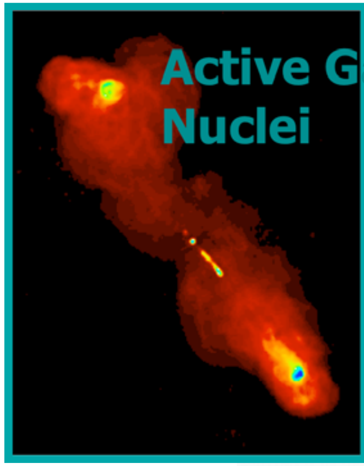
SuperNova explosions

Sources of Cosmic Rays

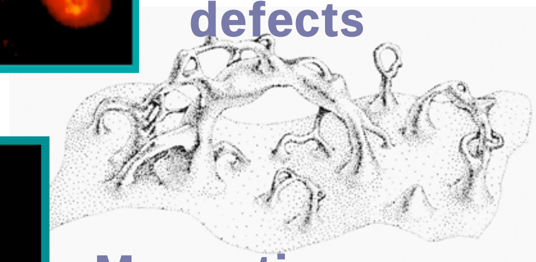
Gamma Rays Bursts



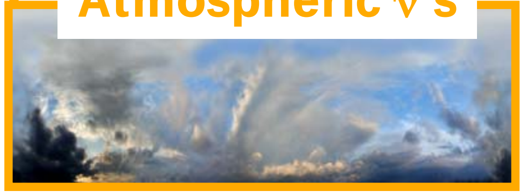
Active Galactic Nuclei



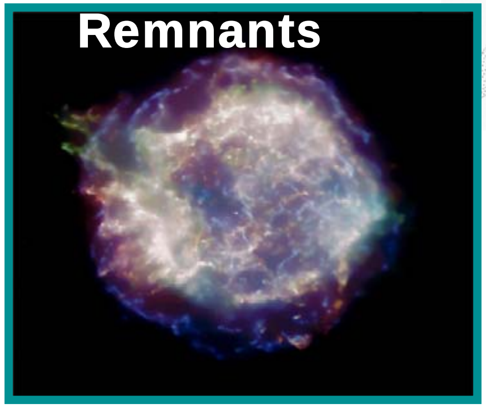
Topological defects



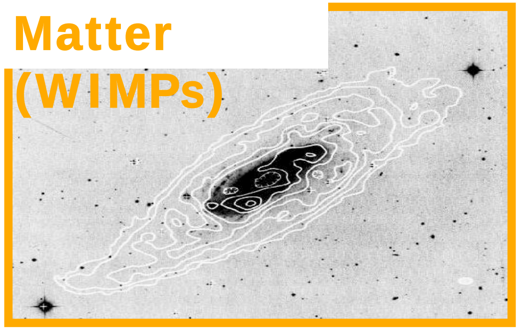
Atmospheric ν's



SuperNova Remnants



Dark Matter (WIMPs)



…

Magnetic Monopoles

…

High Energy Neutrino source candidates

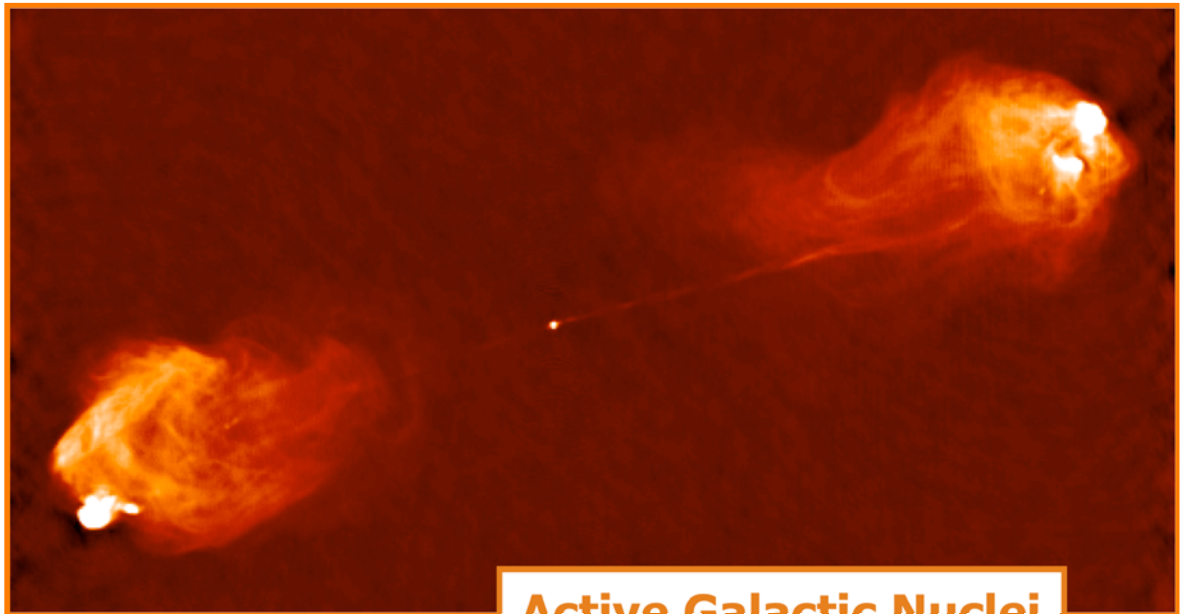
Galactic Sources:

- Supernova Remnants, Pulsars, neutron stars in binary systems, small mass black holes (e.g. Microquasars) ...

Extragalactic Sources:

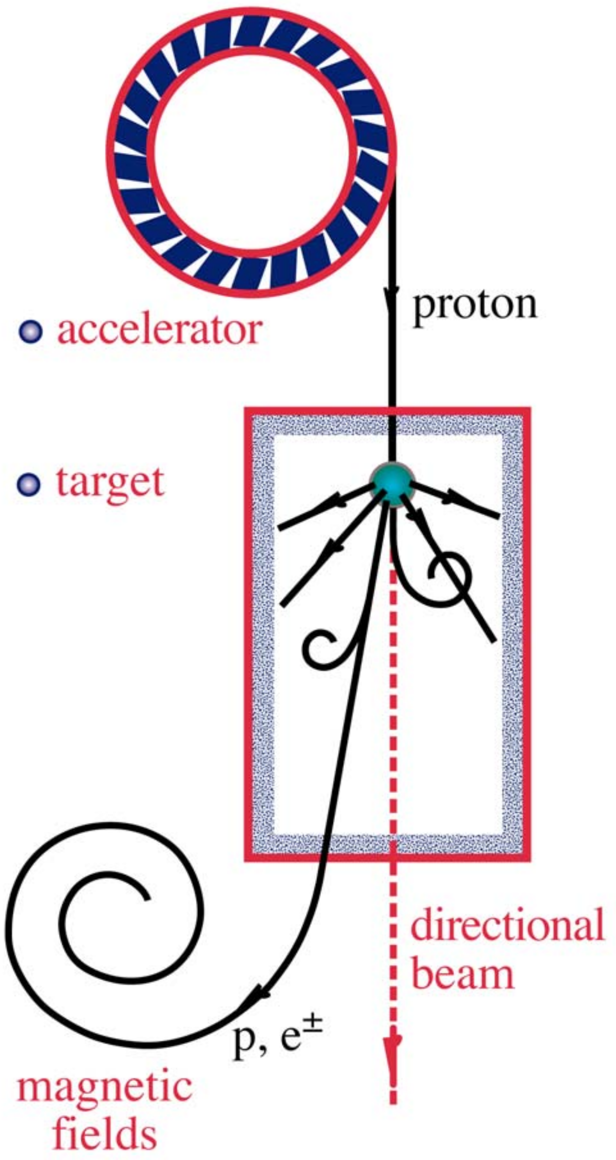
Active Galactic Nuclei (AGN), Gamma Ray Burst (GRB) ...

Microquasars
≈ Solar mass



Active Galactic Nuclei
~ 10^8 Solar masses

NEUTRINO BEAMS: HEAVEN & EARTH



→ **black hole**

→ **radiation enveloping black hole**

$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

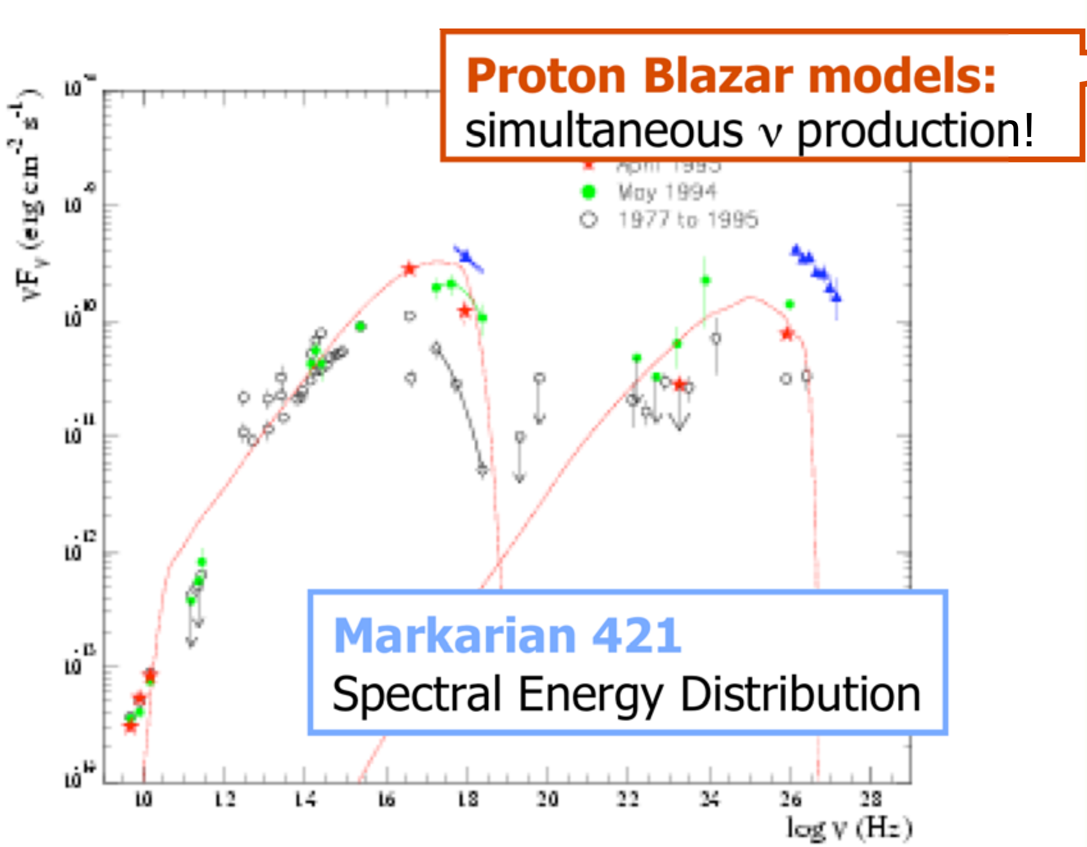
Transp. From F. Halzen

A reference example: Blazars (Active Galactic Nuclei)

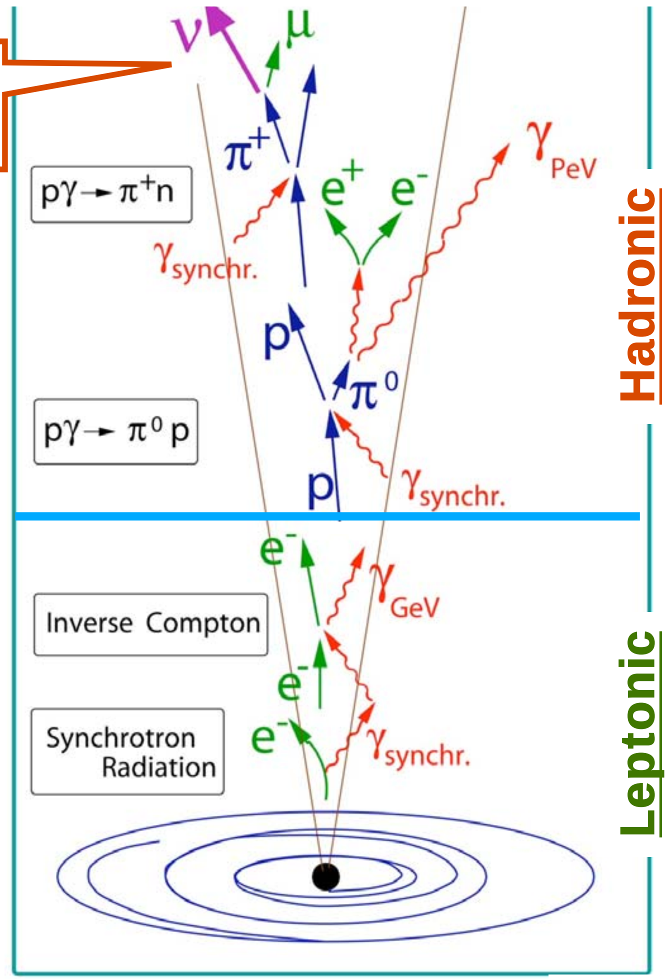
Emission:

Low energy (from radio up to UV / X-ray): non-coherent synchrotron radiation.
High energy (up to TeV) **under debate: leptonic** versus **hadronic** models.

Neutrinos provide the only unambiguous way to discriminate scenarios.

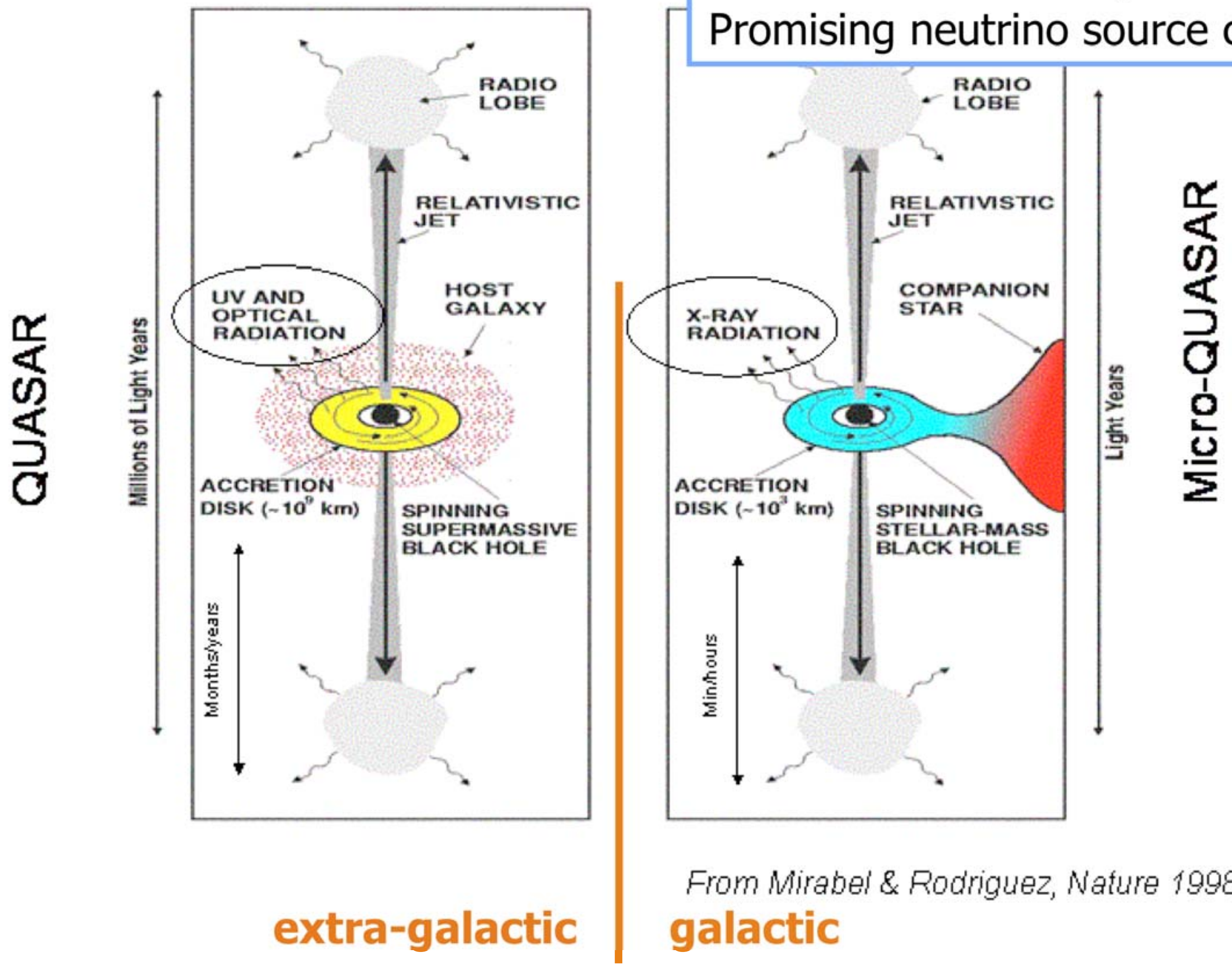


http://veritas.sao.arizona.edu/VERITAS_whipple_science.html



Analogy Quasar / Microquasar:

SS433:
Observational hints of hadronic acceleration from α-spectral lines
Promising neutrino source candidate



From Mirabel & Rodriguez, Nature 1998

Neutrino-Production and oscillations

Most models:

- Neutrinos produced in hadron-hadron (pp) and hadron-photon (pγ) interactions followed by meson decay, with different energy yields.

1. $p + p \rightarrow \pi + ...$

$$\rightarrow \mu + \nu_\mu$$

$$\rightarrow e + \nu_e + \nu_\mu$$

2. $p + \gamma \rightarrow n + \pi^+$

$$\rightarrow \mu + \nu$$

Neutrinos from neutron decay emerge with much lower multiplicity and energy.

Production

Spectrum

- Hadron spectrum at the source is expected to show a power-law shape (Fermi acceleration) → power law spectrum for neutrinos

Flavor ratio (case 1 and 2):

$\nu_e : \nu_\mu : \nu_\tau$ ~ **1:2:<10^{-5} @ the source**

$\nu_e : \nu_\mu : \nu_\tau$ ~ **1:1:1 @ the detector**

Propagation

The AMANDA Collaboration

United States:

Bartol Research Institute
UC Berkeley
UC Irvine
Pennsylvania State
UW Madison
UW River Falls
LBNL Berkeley

Europe:

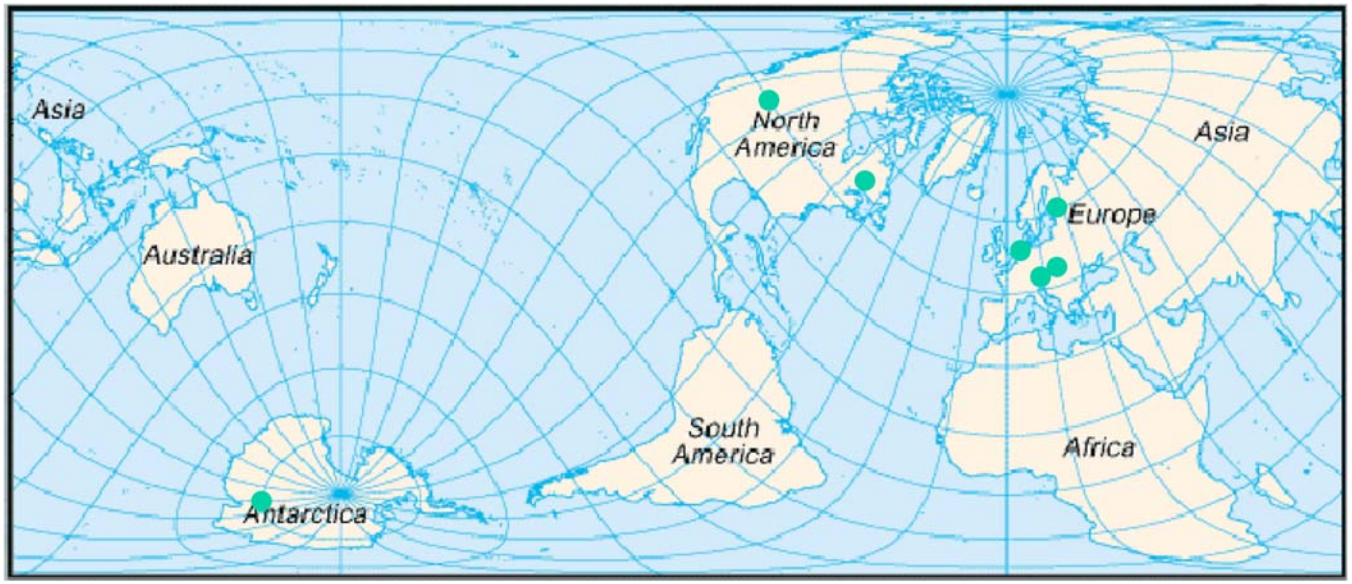
VUB-IIHE, Brussel
ULB-IIHE, Bruxelles
Université de Mons-Hainaut
Imperial College, London
DESY, Zeuthen

Universität Mainz
Universität Wuppertal
Universität Dortmund
Stockholms Universitet
Uppsala Universitet
Kalmar Universitet

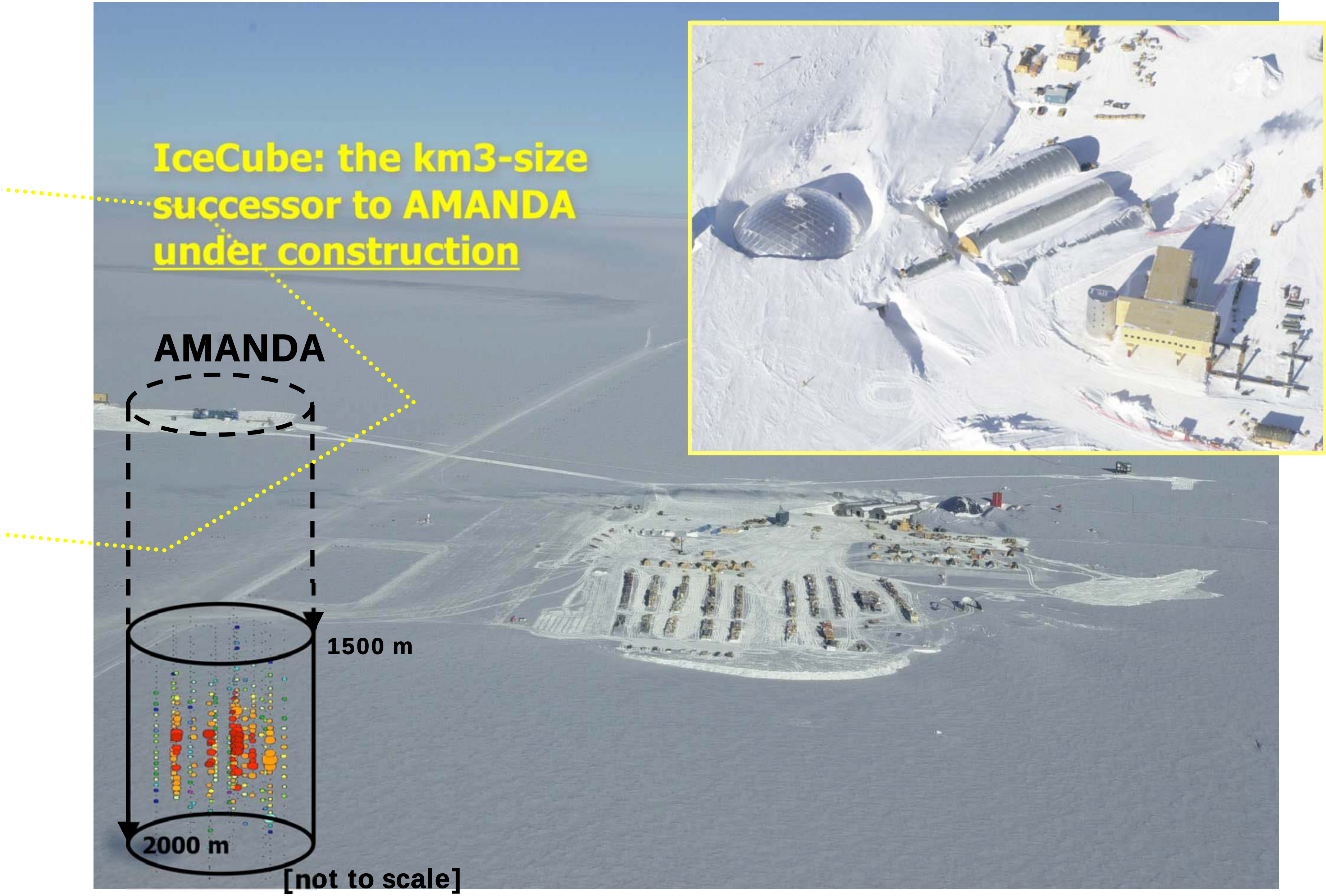
Antarctica:

South Pole Station

~150 members

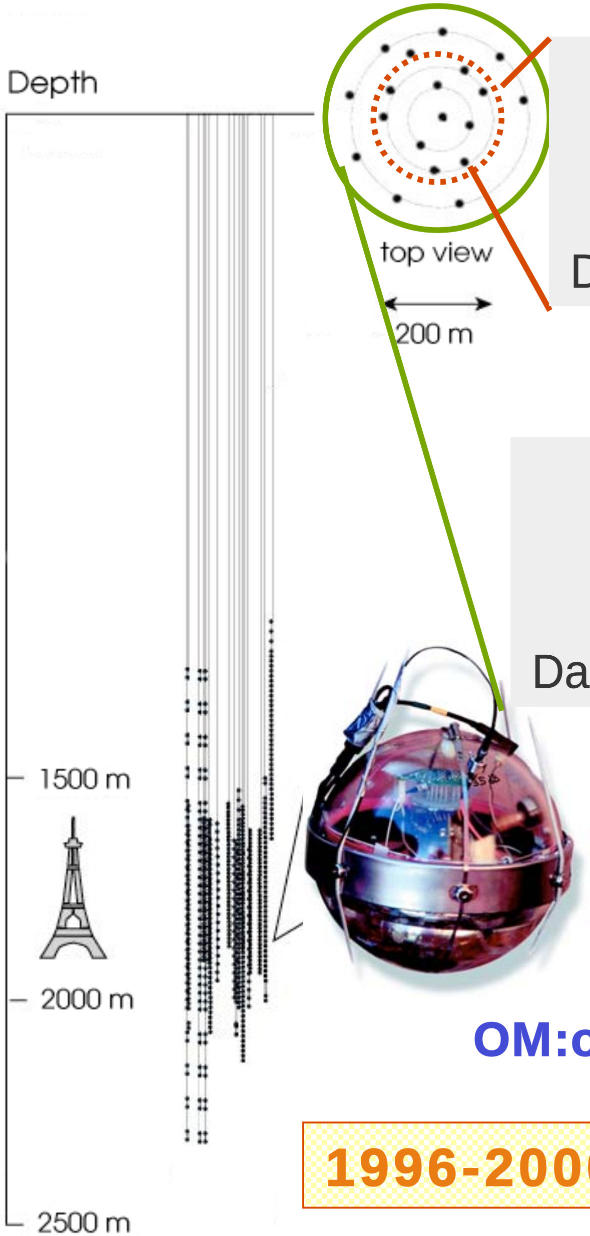


The AMANDA Site



Detection principles and Analysis strategies

The AMANDA Neutrino Telescope



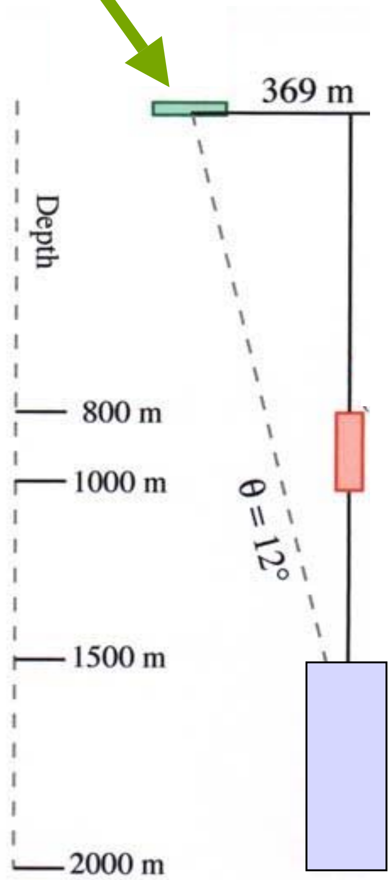
AMANDA-B10
Inner 10 strings
302 PMTs
Data years: 1997-99

AMANDA-II
19 strings
677 PMTs
Data years: 2000, ...

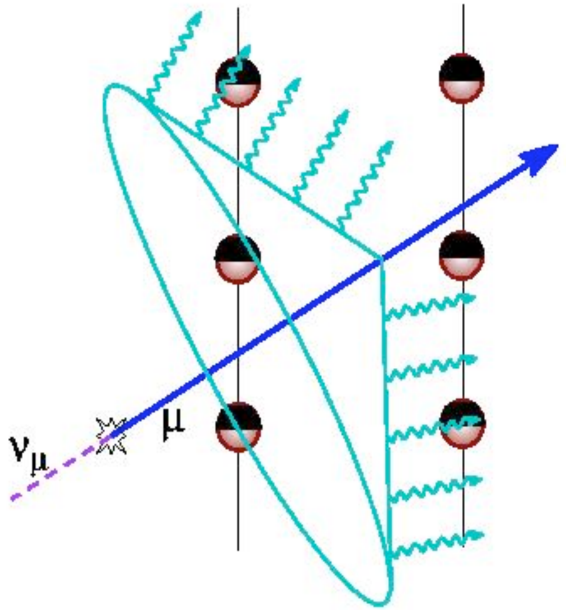
OM:optical module

1996-2000: deployment

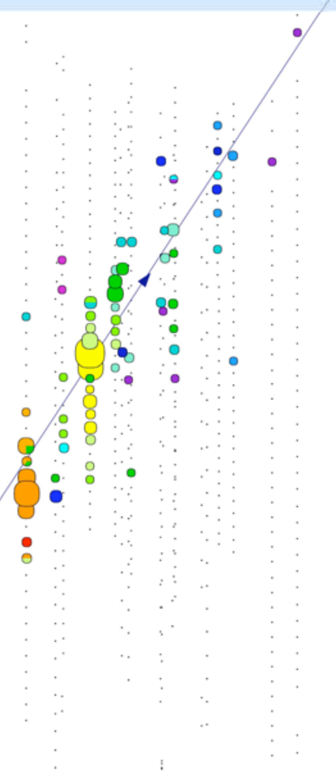
South Pole Air Shower Experiment -- **SPASE**

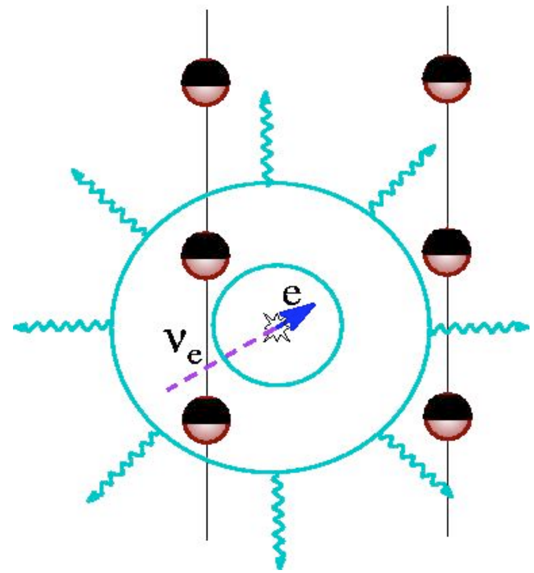


The AMANDA ν's detection principles



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

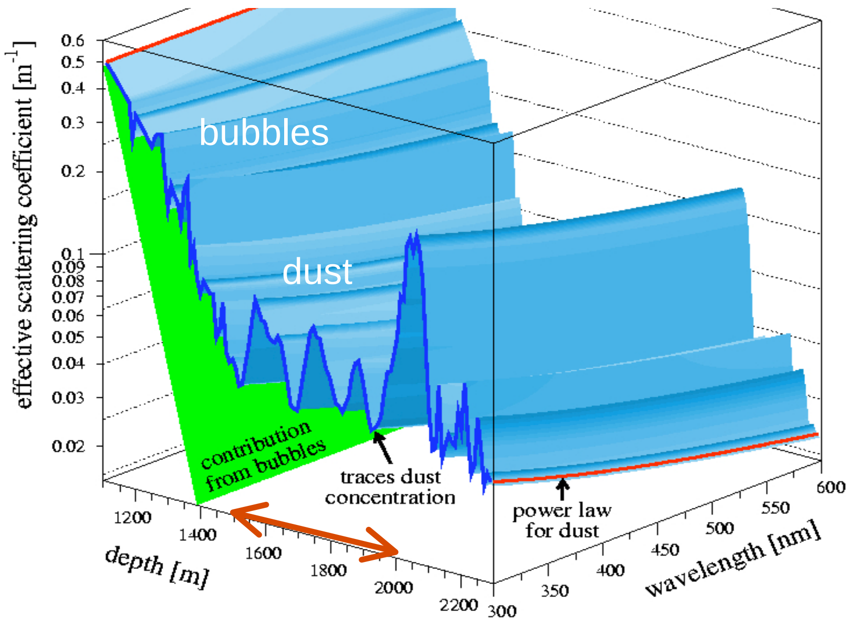
Event reconstruction:
Complex minimization procedures in a multidimensional space (e.g. 5) to find the best likelihood for a given signature hypothesis and the recorded hit times.

The AMANDA medium

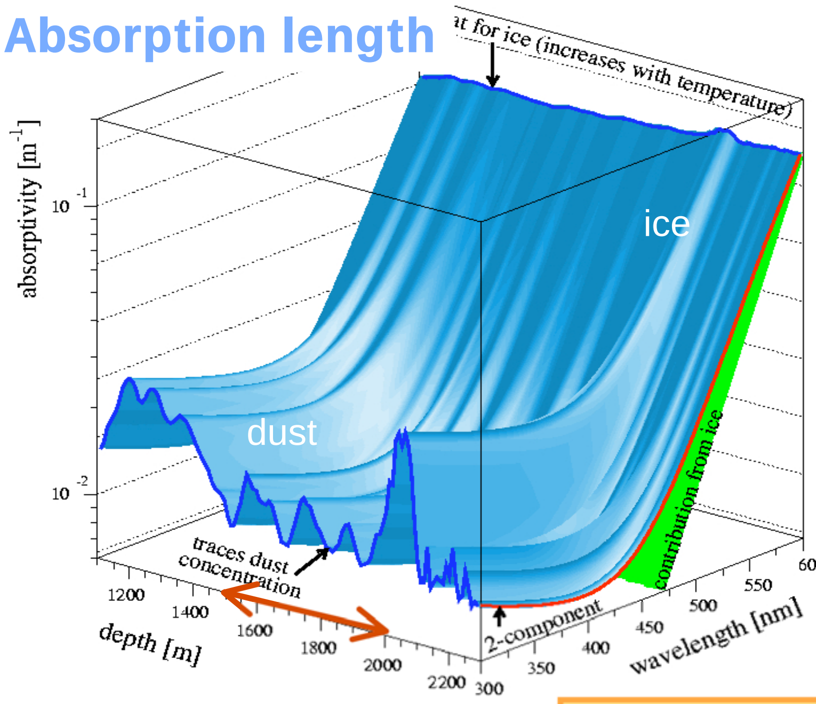
Optical properties:

Data from calibration light sources deployed along the strings and from cosmic rays.

Effective scattering coefficient



Absorption length



On average:

Absorption length @ 400 nm	Eff. Scattering length @ 400 nm
110 m	20 m

Noise Rate from Optical Modules

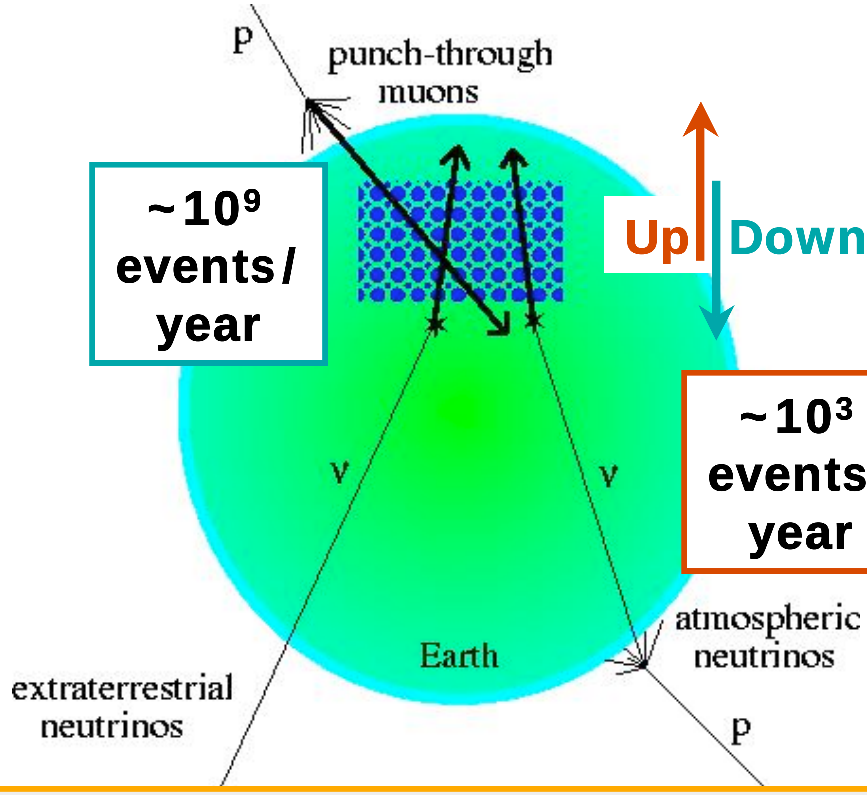
< 1 kHz

Operate as "SuperNova Watch" AMANDA contributes to SNEWS

Search for Astrophysical ν's: Analysis Strategy

Search for astrophysical ν's must cope with:

a. the background from atmospheric muons
b. the background from atmospheric ν's



~10^9 events / year

Up | **Down**: to reduce the background from (a)

~10^3 events / year

'Blind-Analysis principle':

Event selection and analysis procedures are optimized and tested on fraction of data or on a time-scrambled data set.

Atmospheric Neutrinos

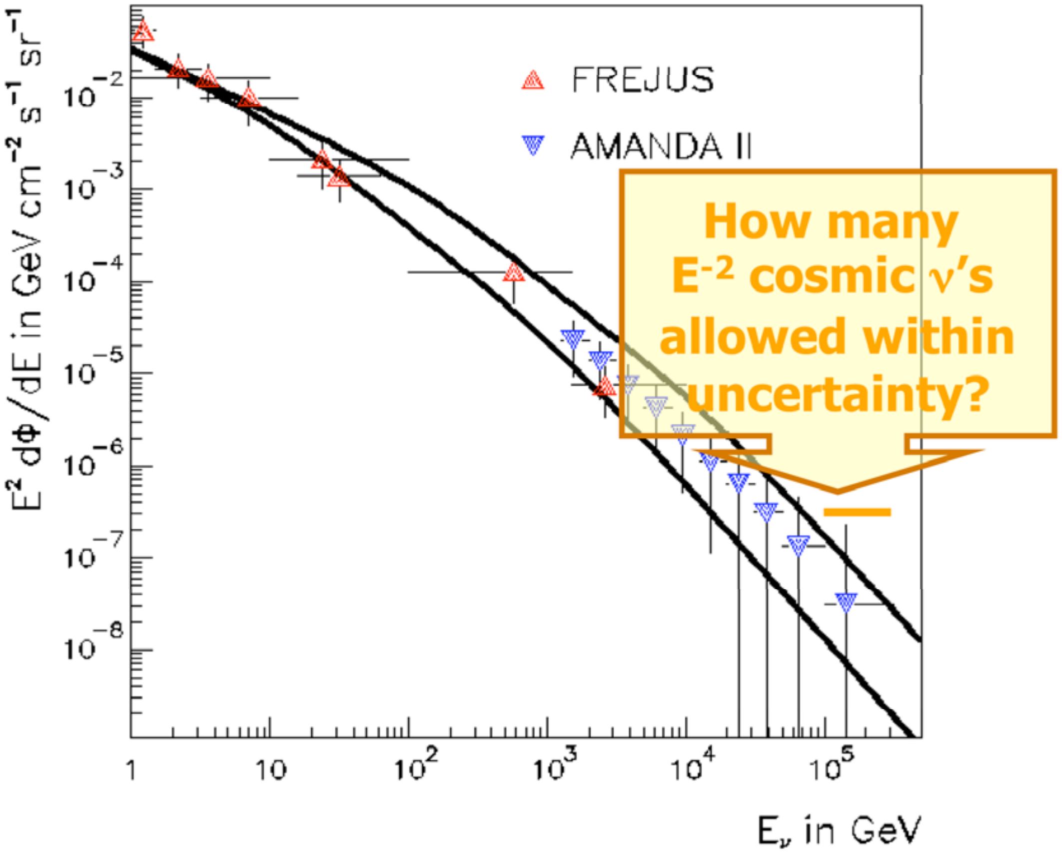
Atmospheric Neutrinos

Atmospheric ν_μ's as test-beam for AMANDA:

- Cross-check detector efficiencies.
- Energy reconstruction with Neural Network and Regularized Unfolding

First measurement of the atm. ν_μ's flux above TeV:

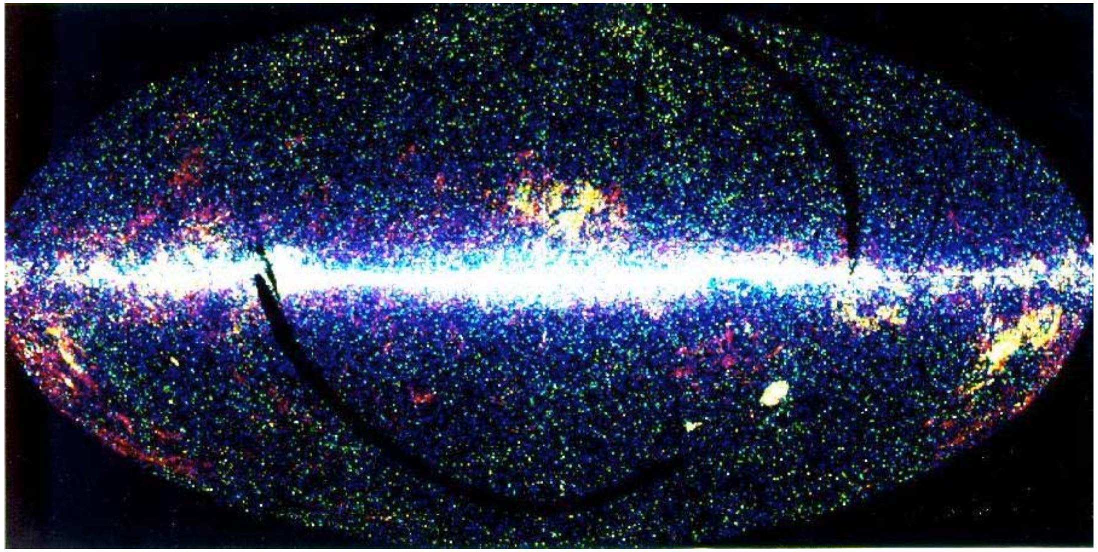
- Used about 600 selected up-going ν_μ events (year 2000)
- Spectral index compatible with –3.7 within errors.
- Agreement with Frejus data at lower energy



Flux of up-going atmospheric ν's AMANDA and Frejus results

Search for Astrophysical Neutrinos:

1. Diffuse Flux



Infrared all-sky map

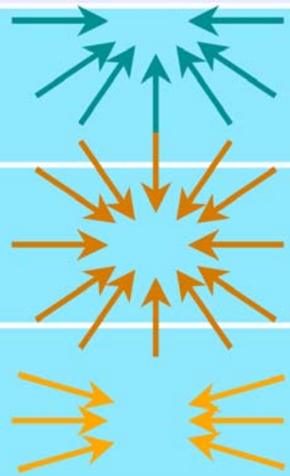
Search for a diffuse excess of High Energy ν's

Search for an integrated excess of ν's:

- Signal:
  from many unresolved extragalactic sources: **energy spectrum $dN/dE \sim E^{-2}$**
- Background:
  $dN/dE \sim E^{-3.7}$

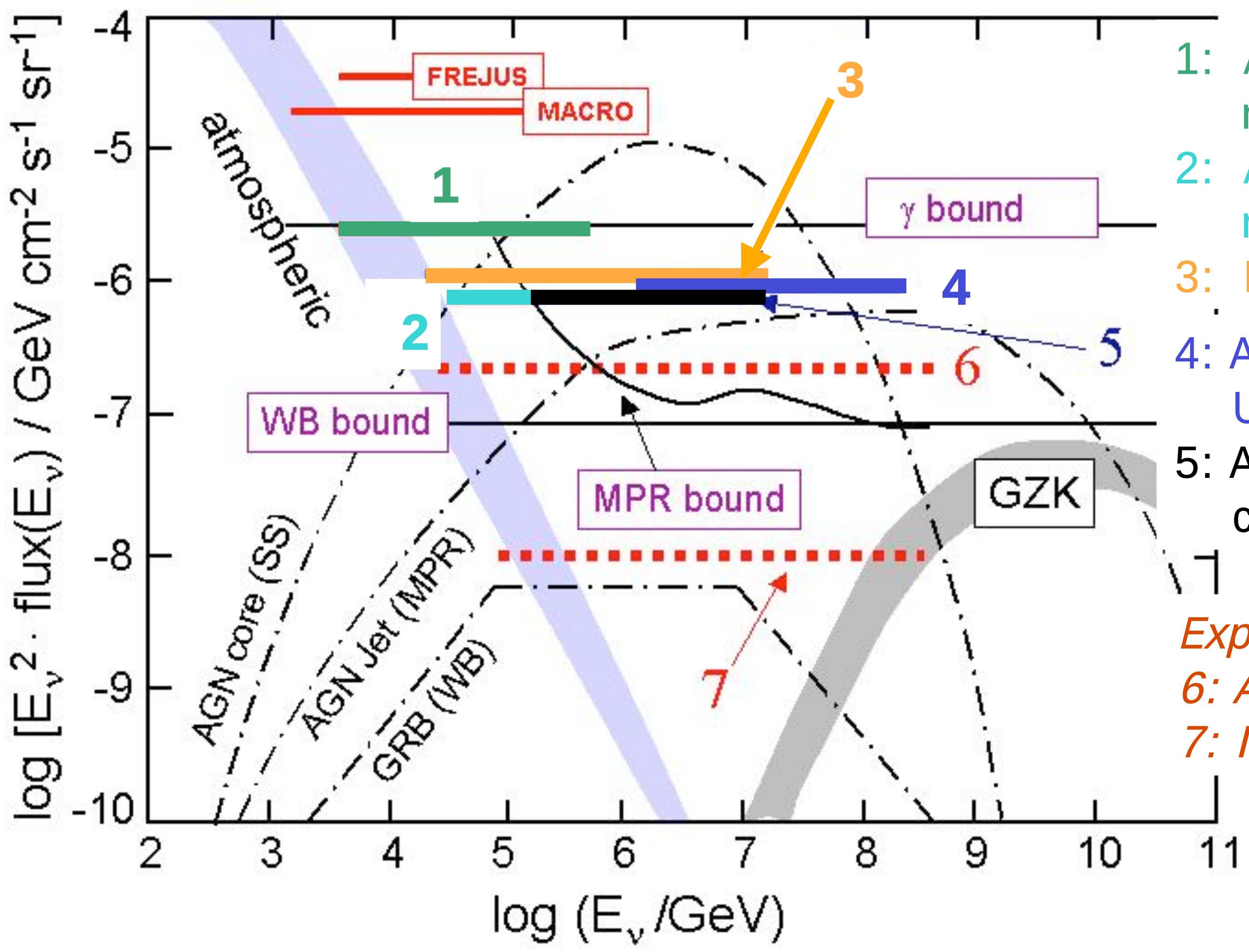
→ Use energy indicators or look for peculiar (not background-like) topologies.

Event class	Energy Range	Flavor sensitiviy	Angular coverage
Up-going μ's	hundreds GeV to PeV	ν_μ	
Cascades	TeV to PeV	all-flavor	
Ultra High Energy (UHE) events	> 1 PeV	all-flavor	



Search for a diffuse flux: Summary

Summary of upper limit to diffuse flux (all flavors):
- **Models:** factor 1.5 to correct for oscillations and all-flavor
- **Exp. Results:** factor 3 for limits derived for ν_μ



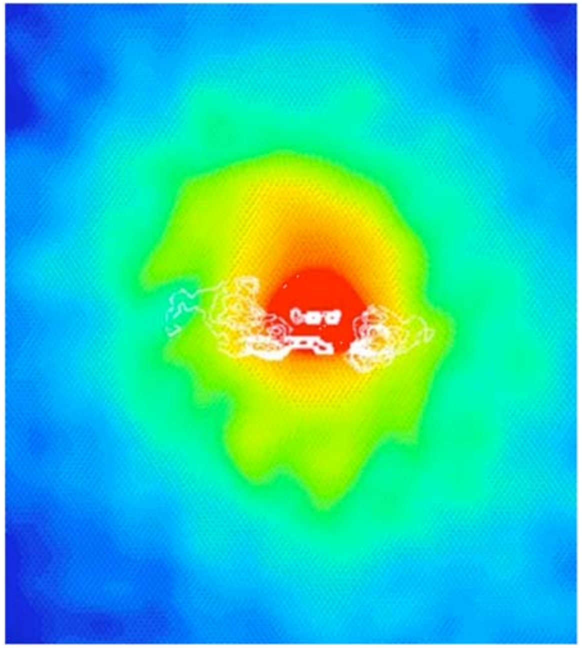
1: Amanda-B10 muons (174 d)
2: Amanda-II muons (193 d)
3: Baikal
4: Amanda-B10 UHE (174 d)
5: Amanda-II cascades (193 d)

Expected:
6: Amanda-II, 4 yr
7: IceCube 3 yr

Search for Astrophysical Neutrinos:

2. Point-like sources:

a) Search for Steady Sources

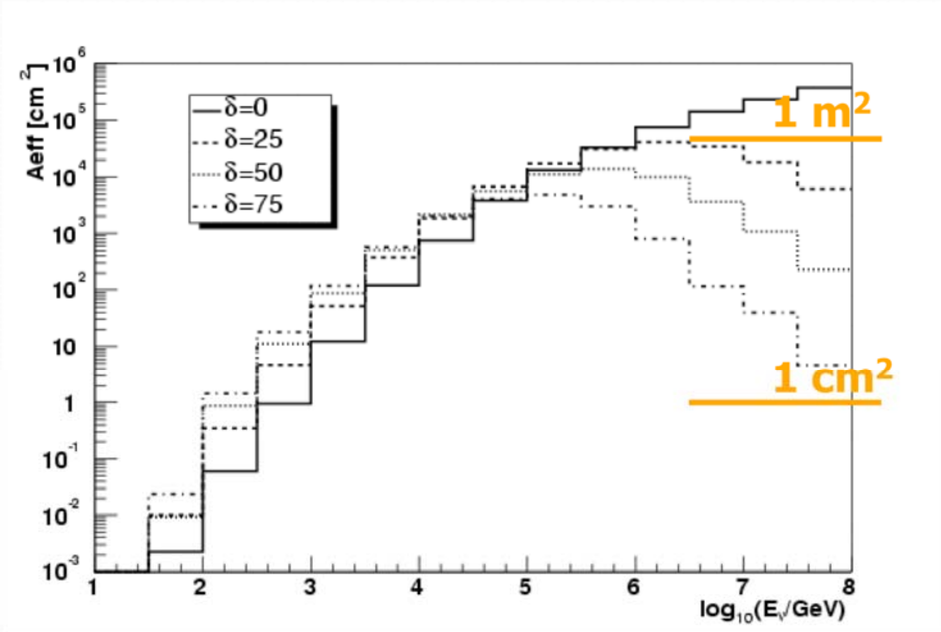


X-ray image and radio map of the Cluster Abell 400

Search for ν_μ point sources

Search for clusters of events from defined directions of the Sky:

- **Signal:** $dN/dE \sim E^{-2}$
- **Background:** atmospheric ν's



Large effective area:
long μ track length

$$n_{sig} = T_{life} \cdot \int_{\Omega} \int_{E_\nu} A^{\nu}{}_{eff}(E_\nu, \delta) \frac{d\Phi^{\nu}_{model}}{dE_\nu d\Omega} dE_\nu d\Omega$$

Blindness principle:
Event Selection optimized on distributions which only reflect the detection efficiency:
Randomize direction of events: Right Ascension (α) or time.

Search for ν_μ point sources – Previous results

Sensitivity:

Average flux upper limit in presence of no signal (Poisson statistics)
Energy spectrum: $dN/dE \sim E^{-2}$
Integrated in energy [10-10^8 GeV] and dependent on declination [$cm^{-2}\ s^{-1}$]

Data	Pointing resolution	Sensitivity	Reference
1997	3°↑ 5.8°→	$[10\text{-}30]\cdot10^{-8}$	ApJ 583, 1040 (2003)
2000	1.5°↑ 2.7°→	$2\cdot10^{-8}$	Phys. Rev. Lett. 92, 071102 (2004)
00-02	1.5°↑ 2.7°→	$0.9\cdot10^{-8}$	astro-ph/0412347

AMANDA-II
Higher ν
Aeff:
improvement
5-15

Multiple
years
Larger
livetime:
improvement
2.2

Data combined “a posteriori”
Improved event reconstruction capabilities not fully exploited
$E_{th} \sim 1$ TeV

No statistically significant excess of events above the background

Search for ν_μ point sources – Recent results

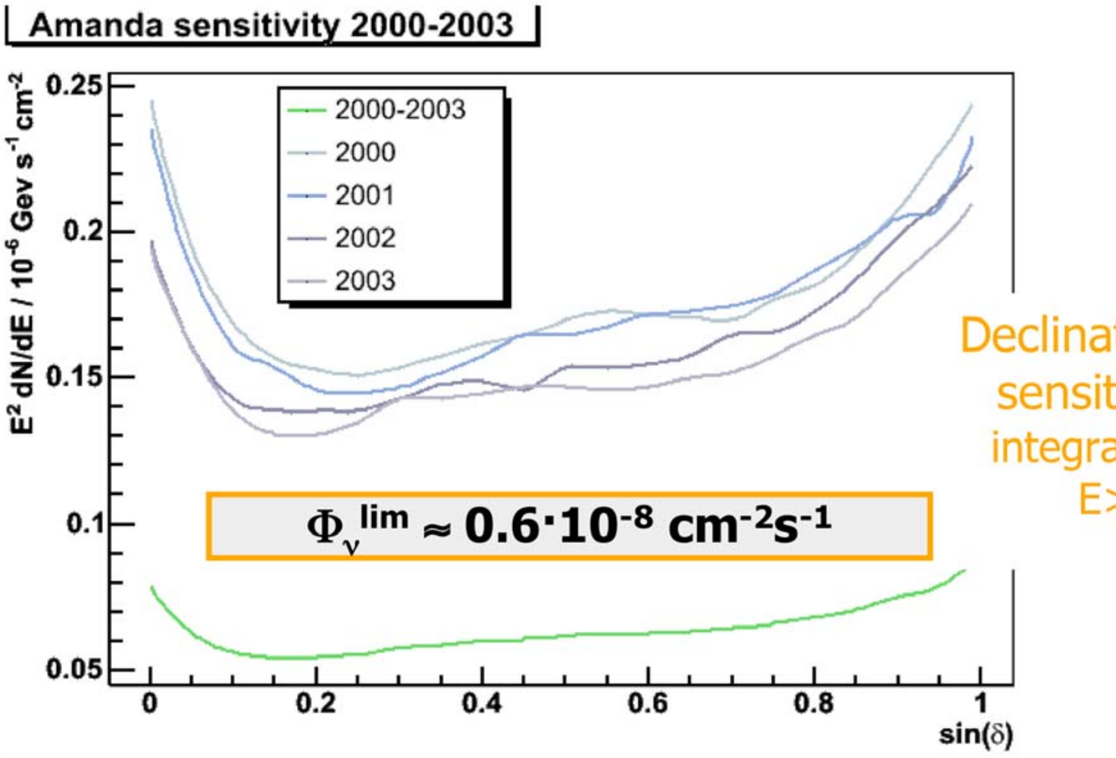
Unified data processing scheme, years 2000-2003:

- Data from years 2000, 2001, 2002, combined with 2003
- Improved event reconstruction

Point source event selection:

- Improved background rejection power
- Higher sensitivity to **lower energies** (target $E_{th} < 100$ GeV)

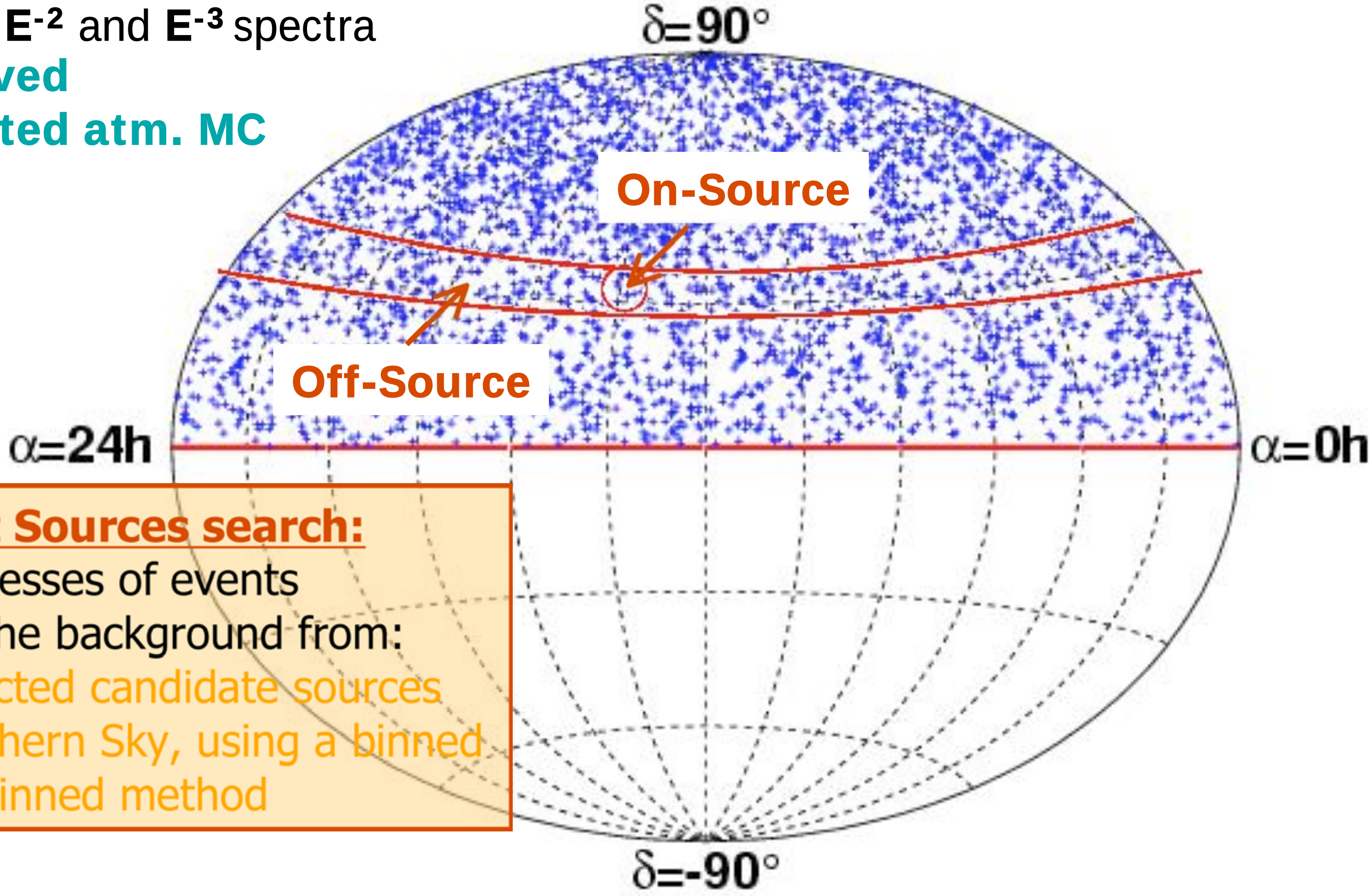
Factor 3 improvement in the Sensitivity compared to 2000



Declination averaged sensitivity (δ>0°), integrated in energy E>10 GeV:

2000-2003 selected neutrino candidates

The **Sky-plot (live-time 807 days)**:
3369 neutrino candidate events
Event selection optimized for each declination to both **dN/dE** ~ $\mathbf{E^{-2}}$ and $\mathbf{E^{-3}}$ spectra
3329 ↑ observed
3438 ↑ expected atm. MC



Steady Point Sources search:
Search for excesses of events compared to the background from:
- A set of selected candidate sources
- The full Northern Sky, using a binned and an un-binned method

Search for excesses in coincidence with known-objects

= 2.25°-3.75°

= 807 days

~ 4 events predicted [C.Distefano, 2002]

90% CL event upper limit of 2.03 AMANDA is testing optimistic models

33 Objects tested, a few results shown:

s. Blazars

Source	Total Obs. Events	Total Back. Events	Flux Upper Limit (90% CL)
Markarian 421	6	5.58	0.68
1ES...9+650	5	3.71	0.38
	2	4.50	0.21

AMANDA achieved the sensitivity to search for neutrinos from TeV γ-ray sources in high state:

Sensitivity Φ_ν/Φ_γ**~2** (**PRELIMINARY**) for Markarian 421, assuming:

- γ **spectral index** from HEGRA measurements (E_{th} few hundreds GeV) in 2000, 2001 "high states".
- **200 days** (out of 807) integral time of enhanced emission.

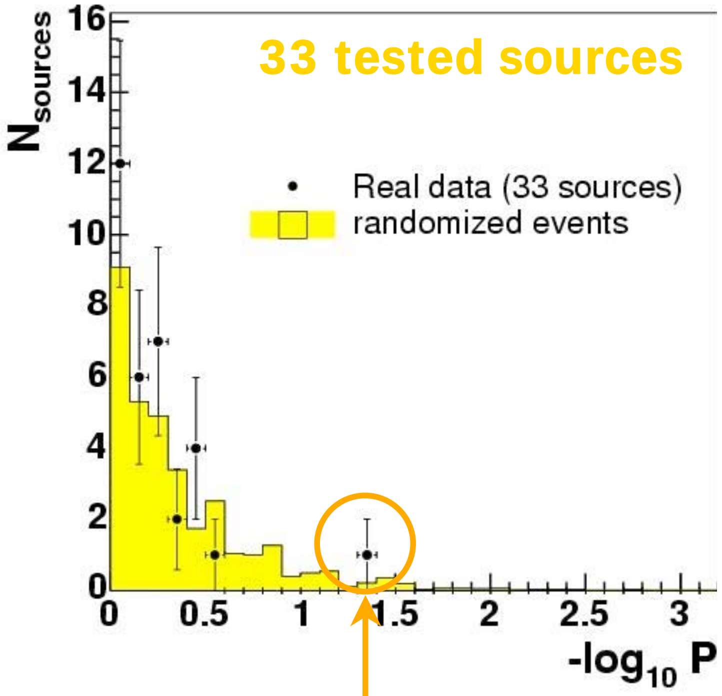
No sta... sign... ex...

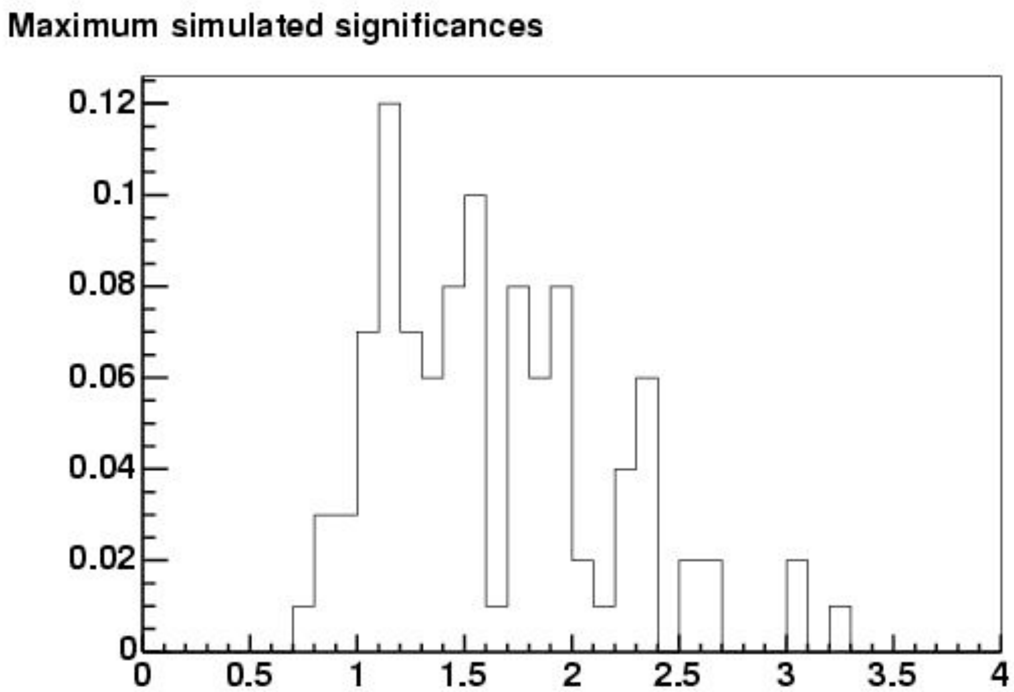
in units of $10^{-8}cm^{-2}s^{-1}$ integrated above E_ν=10 GeV

No systematic error included

Statistical significance evaluation:

Simulate repeated experiments using Right Ascension Randomization (accounts for trial factor and bin correlations).

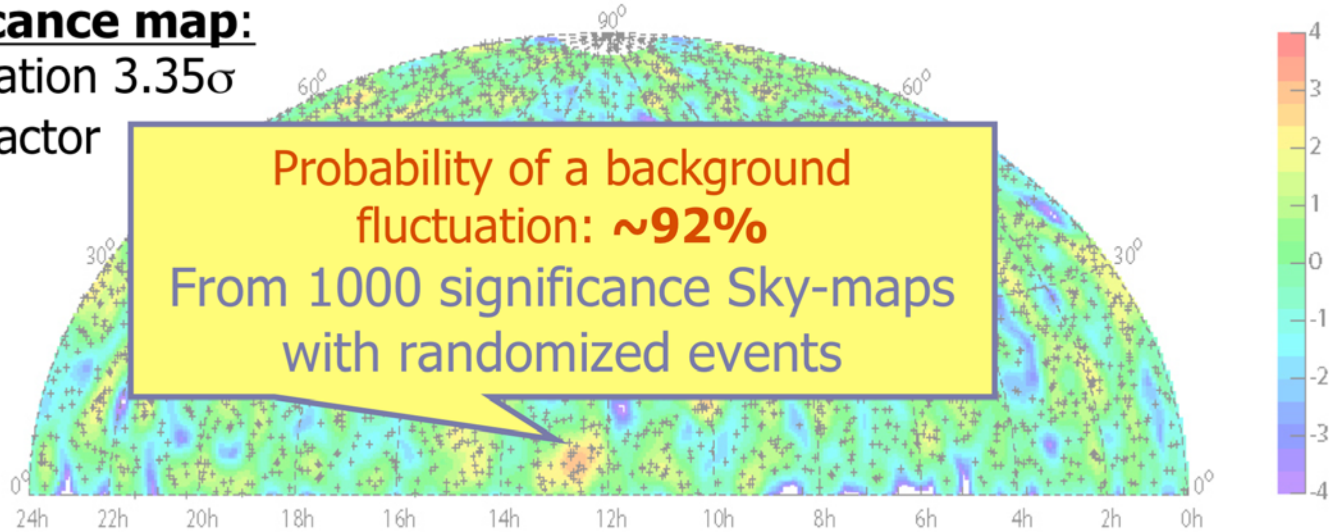




Crab Nebula: MC probability to obtain an entry with at least this excess significance is 64%.

Search for clusters of events in the Northern sky

The **Significance map**:
Highest deviation 3.35σ before trial factor correction



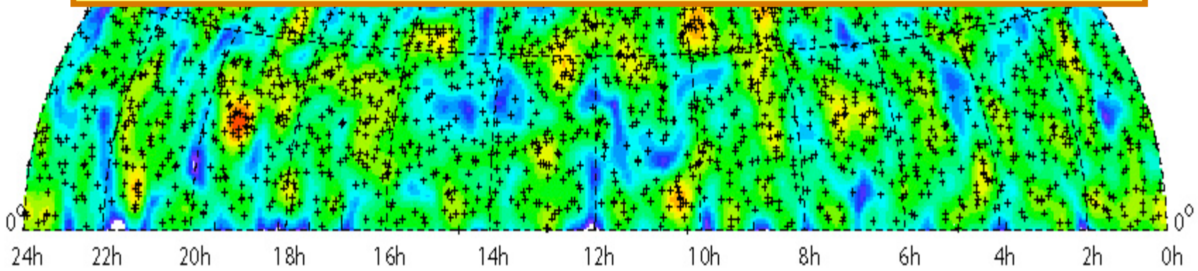
Probability of a background fluctuation: **~92%**
From 1000 significance Sky-maps with randomized events

Scrambled Sky

Randomize right ascension to evaluate overall probabilities

Search for steady Point Source Summary:

No statistically significant excess from steady point sources (4 years average)



Search for Astrophysical Neutrinos:

2. <u>Point-like sources:</u>

a) Search for <u>Transient</u> Sources

New!

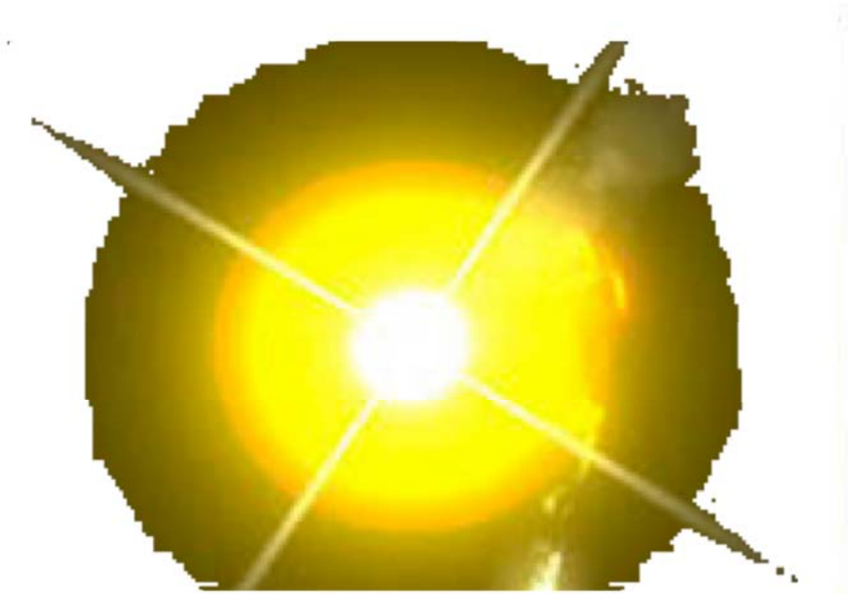


IMAGE CREDIT: NASA/Honeywell Max Q Digital Group, Dana Berry

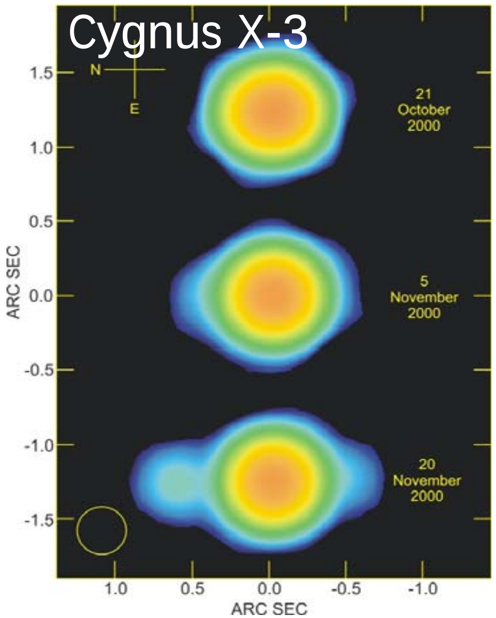
Search for event clusters in time

<u>Enhancing the detection chance</u> by reducing the S/N ratio using the time information:

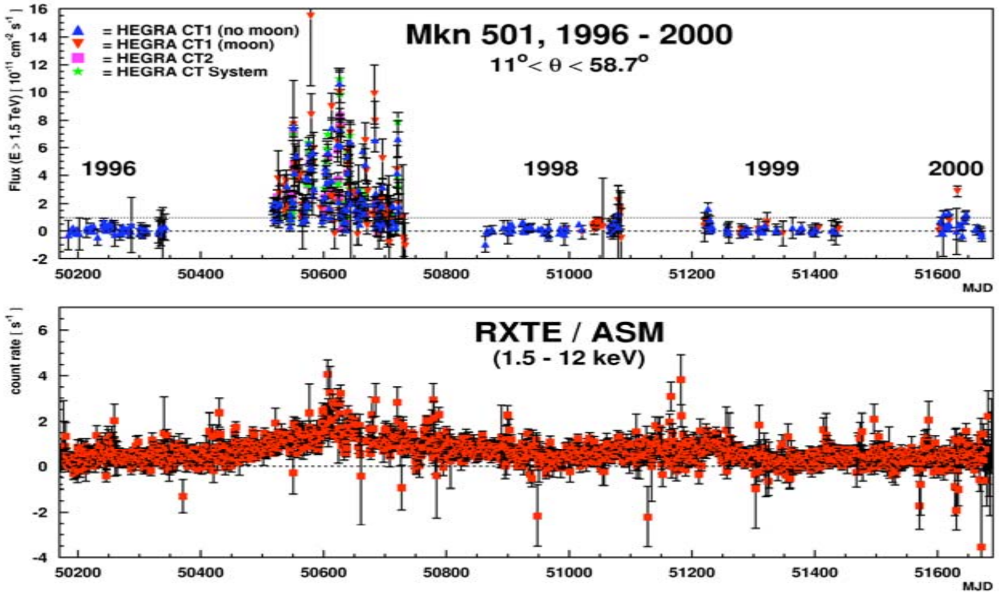
1. Many GeV and TeV ν candidate sources often show abrupt and significant enhancements in the electromagnetic emission

   If ν's are produced in the same processes, enhanced ν's emission is also possible

   Challenge: theoretical predictions are meager!



Radio image [Marti 2001]



TeV γ data (HEGRA) and X-ray (RXTE/ASM) data

2. Maximum flux increase in the electromagnetic emission is O(10)

   <u>Is a similar "flare" in ν's detectable in AMANDA?</u>

Analysis Strategies

Limit the search to favourable candidates:

Sources with **resolved photon emission** (steady / occasional) in **GeV/TeV** and evidence of variability

Two search approaches investigated:

1. Look at **known periods of enhanced emission** at the wavelength of interest:
   - **Radio** (indicate jets outbursts in MicroQuasars)
   - **γ and X-ray** (indicate beam-dump scenario in Blazars jets)

   Challenge:

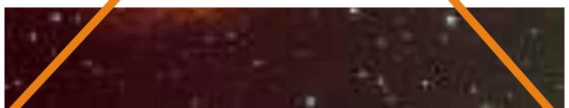
   too limited data and observations available at different wavelengths!

2. Search for **neutrino flares** **within sliding windows of fixed duration**

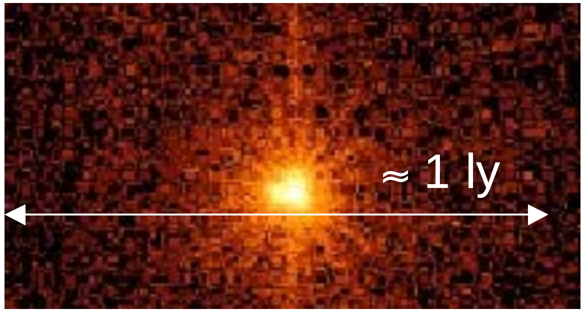
   Optimize the search window-length

Supernova remnants

~ Steady emission



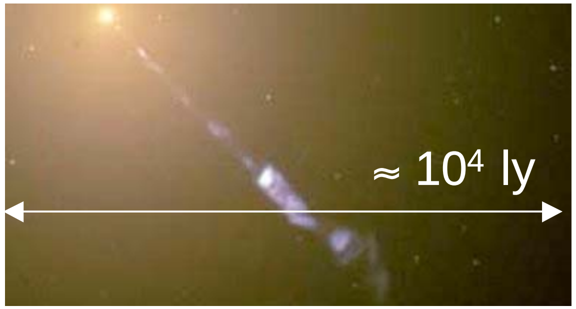
Microquasars



Variable (hours-weeks)

galactic

Active Galactic Nuclei



Variable (hours-months)

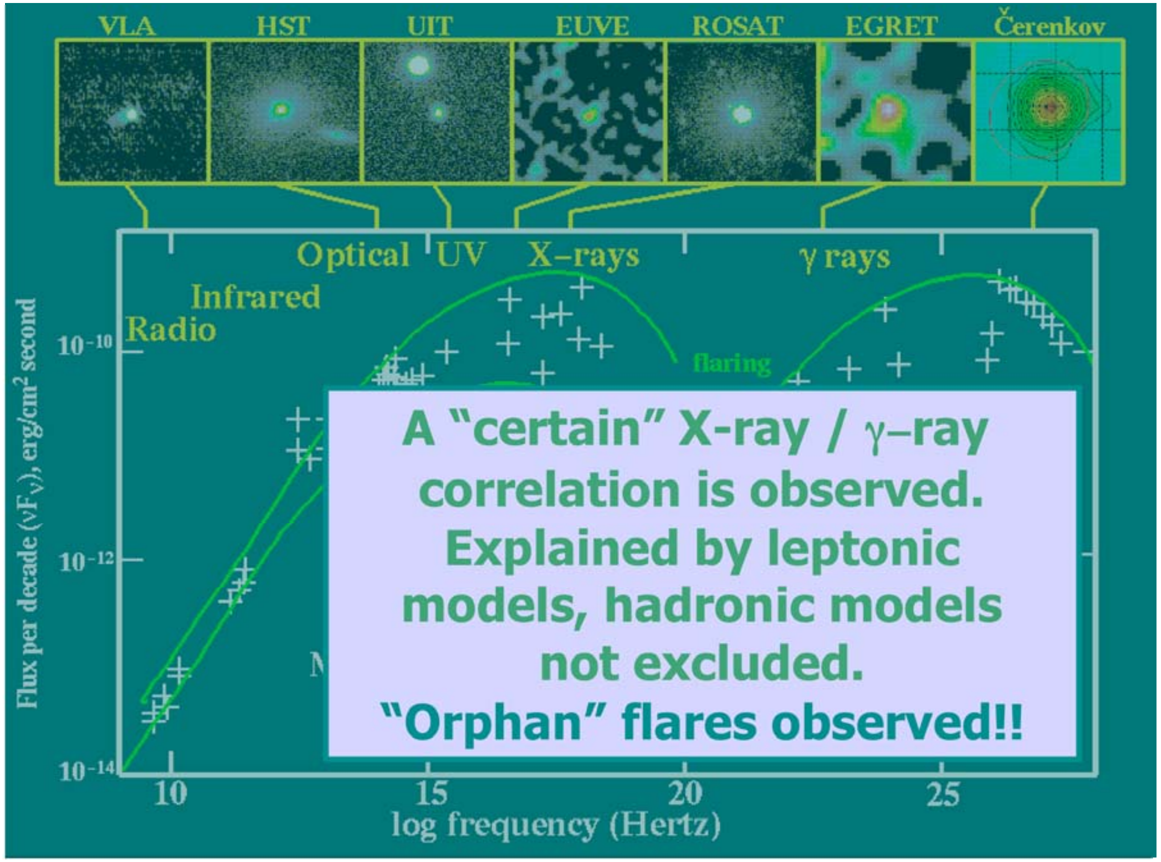
extra-galactic

1. Look at known periods (active states)

Search for ν's from the Blazars jets:
Look in coincidence with **γ-ray flares**:
- **too limited data** available
- observations often triggered by X-ray monitors (**bias**)

First "trial":
Look at periods of enhanced X-ray emission
Re-optimize event selection for shorter live-time.

Markarian 421: A Blazar "template"



A "certain" X-ray / γ–ray correlation is observed. Explained by leptonic models, hadronic models not excluded. "Orphan" flares observed!!

Source	Events	Backgr.
Markarian 421	0	1.63
1ES1959+650	2	1.57

Preliminary

2. Search for neutrino flares

Preliminary

= 2.25°-3.75°

= 20 / 40 days

12 Objects tested, a few results shown:

Source	Total Nr. Events (4 years)	Total Backgr. (4 years)	Period duration	Nr. of doublets	Probability for highest significance
Markarian 421	6	5.58	40 days	0	Close to 1
1ES1959+650	5	3.71	40 days	1	0.34
3EG J1227+43	[illegible]	[illegible]	[illegible]	[illegible]	0.43
QSO 0235+16	[illegible]	[illegible]	[illegible]	[illegible]	0.52
Cygnus X-3	[illegible]	[illegible]	[illegible]	[illegible]	Close to 1
GRS 1915+105	6	4.76	20 days	1	0.32
GRO J0422+32	5	5.12	20 days	0	Close to 1

No event triplet observed

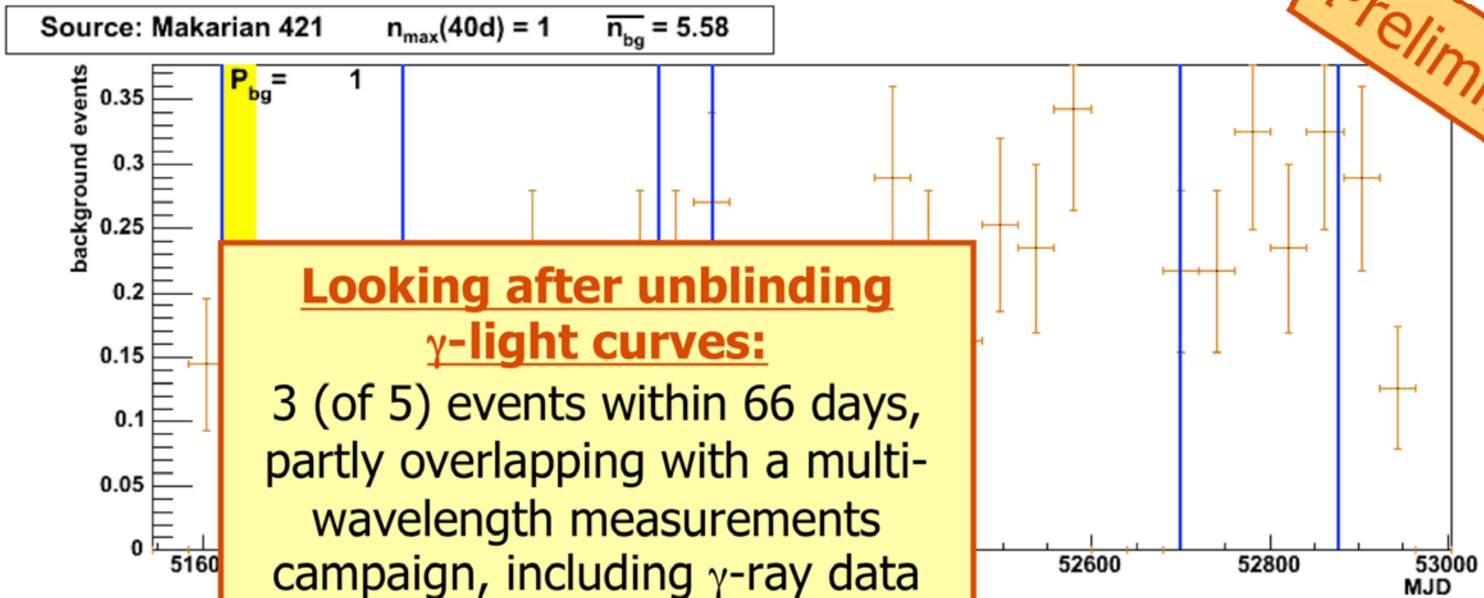
No statistically significant excess observed in any of the selected objects (blind-analysis)

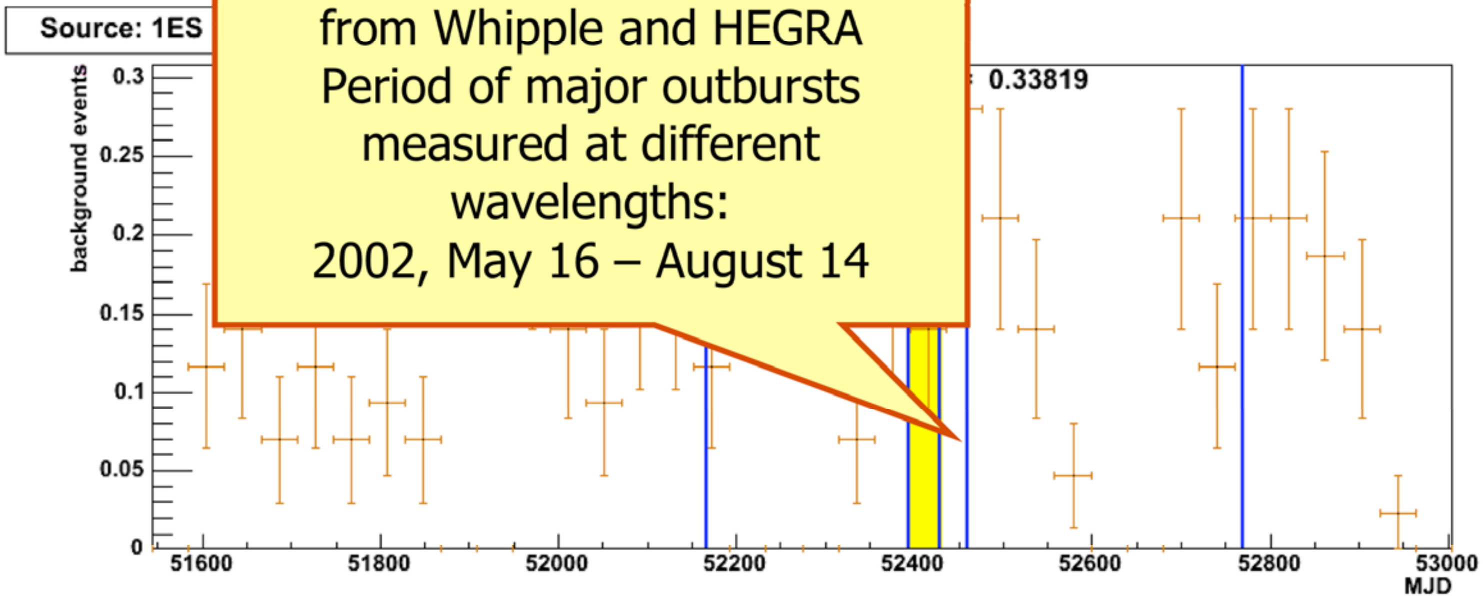
In Tab.: **Preliminary** results from the **search for neutrino flares within sliding windows** of fixed duration
Probability for a background fluctuation for the window with highest signficance are reported (not trial factor corrected)

”Blind” search for neutrino flares:

40 days Extragalactic Objects / 20 days Galactic Objects

Preliminary





Looking after unblinding γ-light curves:

3 (of 5) events within 66 days, partly overlapping with a multi-wavelength measurements campaign, including γ-ray data from Whipple and HEGRA

Period of major outbursts measured at different wavelengths:

2002, May 16 – August 14

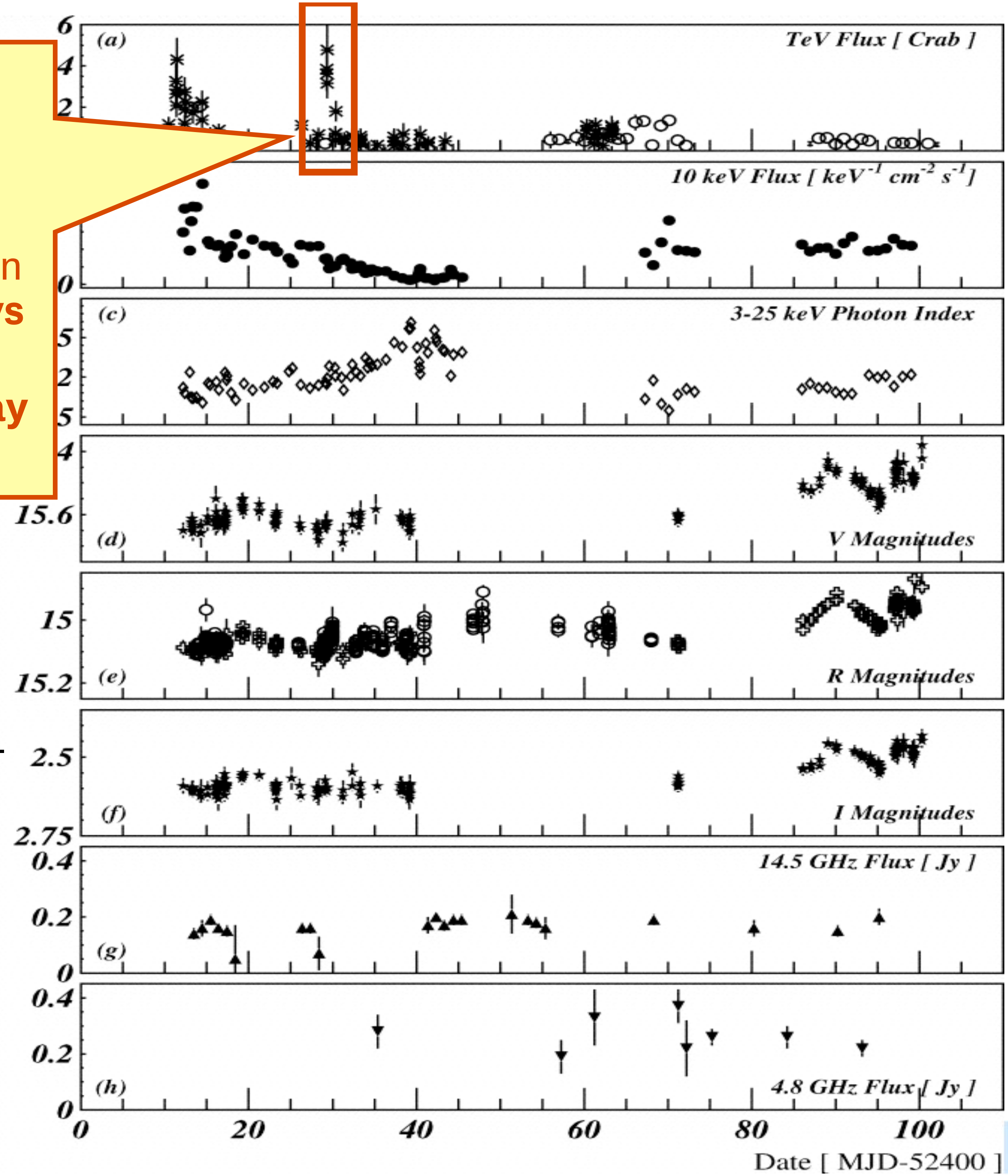
Yellow boxes: search window of highest significance

Blue lines: event times

Error bars: Off-Source background per 40 days

“**Orphan flare**”:
MJD 52429

Unique observation of a high flux γ-**rays flare without** corresponding **X-ray** counterpart



Results from the multi-wavelength campaign
(a) Whipple and HEGRA
(b-c) X-ray
(d-f) optical
(g-h) radio
ApJ 601, 151 (2004)

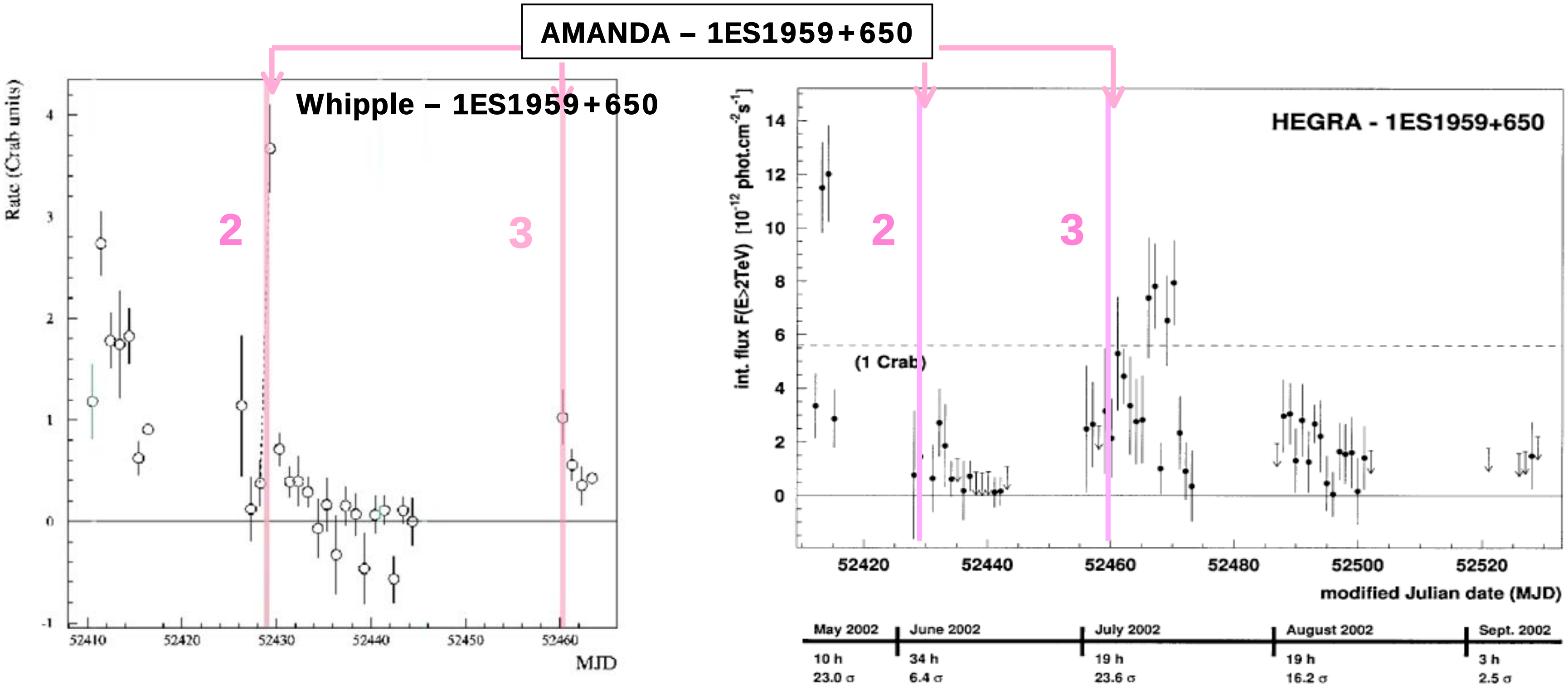


Fig1: Whipple data, E_{th}=600 GeV [2]

Fig2: HEGRA data, E_{th}=2 TeV [1]

"Orphan flare" visible in Whipple data but not in HEGRA data

Probability for a random coincidence with AMANDA events cannot be quoted:
blindess principle violation→ statistical significance should be evaluated "a posteriori"

Interesting hint for future search strategies
More data necessary for interpretations

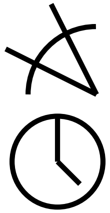
Other Astrophysics Search topics

- **Search for neutrinos in coincidence with GRBs**
- **Indirect WIMPs search**
- **…** http://amanda.uci.edu

Search for ν_μ correlated with GRBs

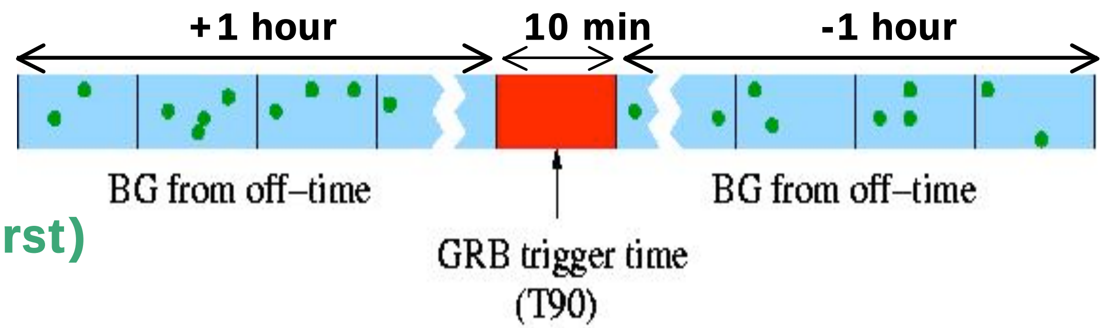
Point source analysis with space and time coincidence:

Use localization and trigger provided by Satellite Network.



= 20°

~ 3 minutes (depending on burst)



Preliminary

Data	# GRBs	Trigger	Obs.	Bck.
2001	13	IPN3 & GUSBAD	0	0.05
Precursor	13		0	0.04
2002	9	IPN3 &	0	0.04
Precurs				0.03
2003				0.05
Precurs				0.03
Total	31	IPN3 & GUSBAD	0	0.14
Precursor	30		0	0.09

Assuming WB type spectrum (E_B at 100 TeV and Γ =300):

Sensitivity:

$E^2\Phi_\nu \sim 4 \times 10^{-8}$ $GeV s^{-1} cm^{-2} sr^{-1}$

Indirect WIMPs search

Relic neutralinos accumulated at the center of the Sun:

Considered annhilitation into(*)

$\chi\chi \rightarrow b\bar{b}$ (soft channel)

$\chi\chi \rightarrow W^+W^-$ (hard channel)

Sun treated as a Point Source

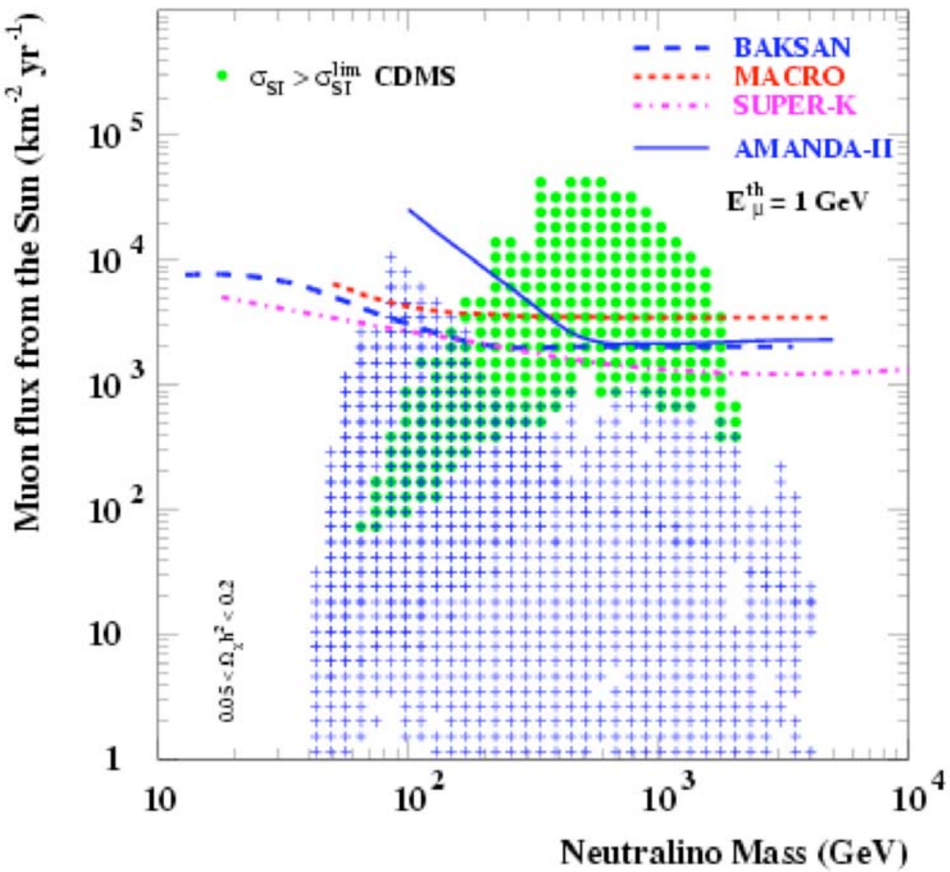
Select ~ horizontal tracks

Cuts optimized for masses 100-5000 GeV (blind analysis)

= **26° (soft) / 5.5° (hard)**

~ 144 days (year 2001)

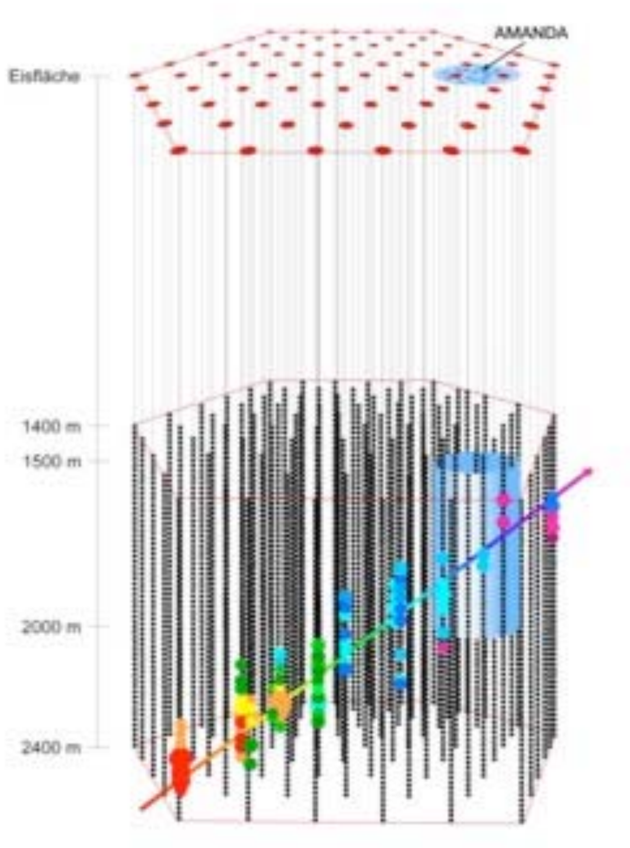
No statistically significant excess of events above the background



Upper limits on the muon flux from neutralino annhiliation into W^+W^- in the Sun

(*) DARKSUSY for theoretical flux predictions

Neutrino Astrophysics :
The new “Era” -- IceCube



The IceCube Project

A km³-size detector at the South Pole:

Goals:

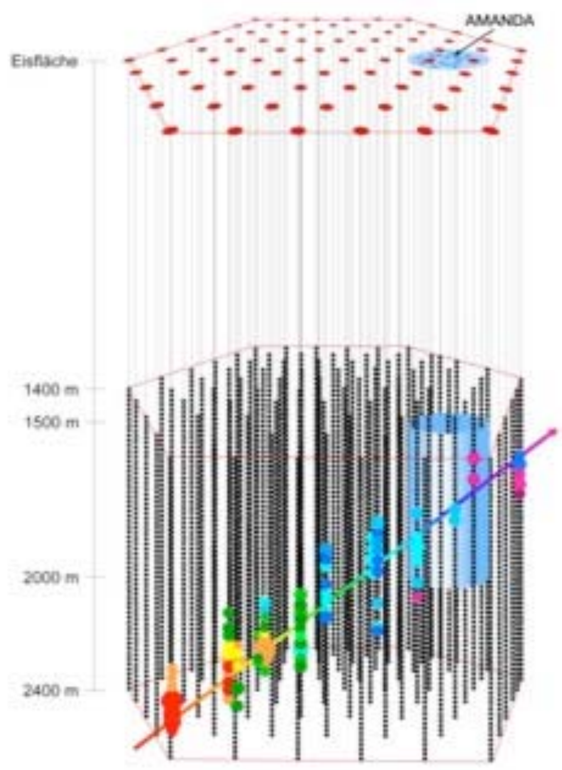
- Sensitivity to look for neutrinos from AGNs, GRBs ...
- Study the "knee" region of the cosmic ray spectrum
- ...

AMANDA as Pilot project

Extensive **technological development**

(e.g. digital readout)

Optimized for energies > TeV



Design:

4800 Optical Modules

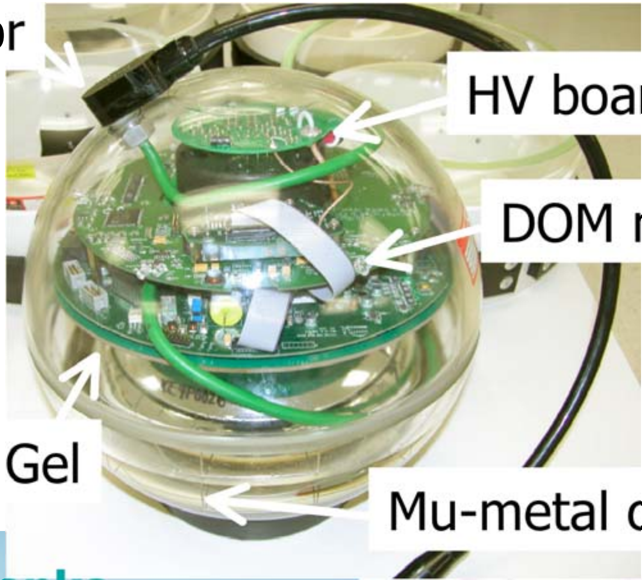
80 strings (@ 125 meters)

Depth: 1400-2400 m

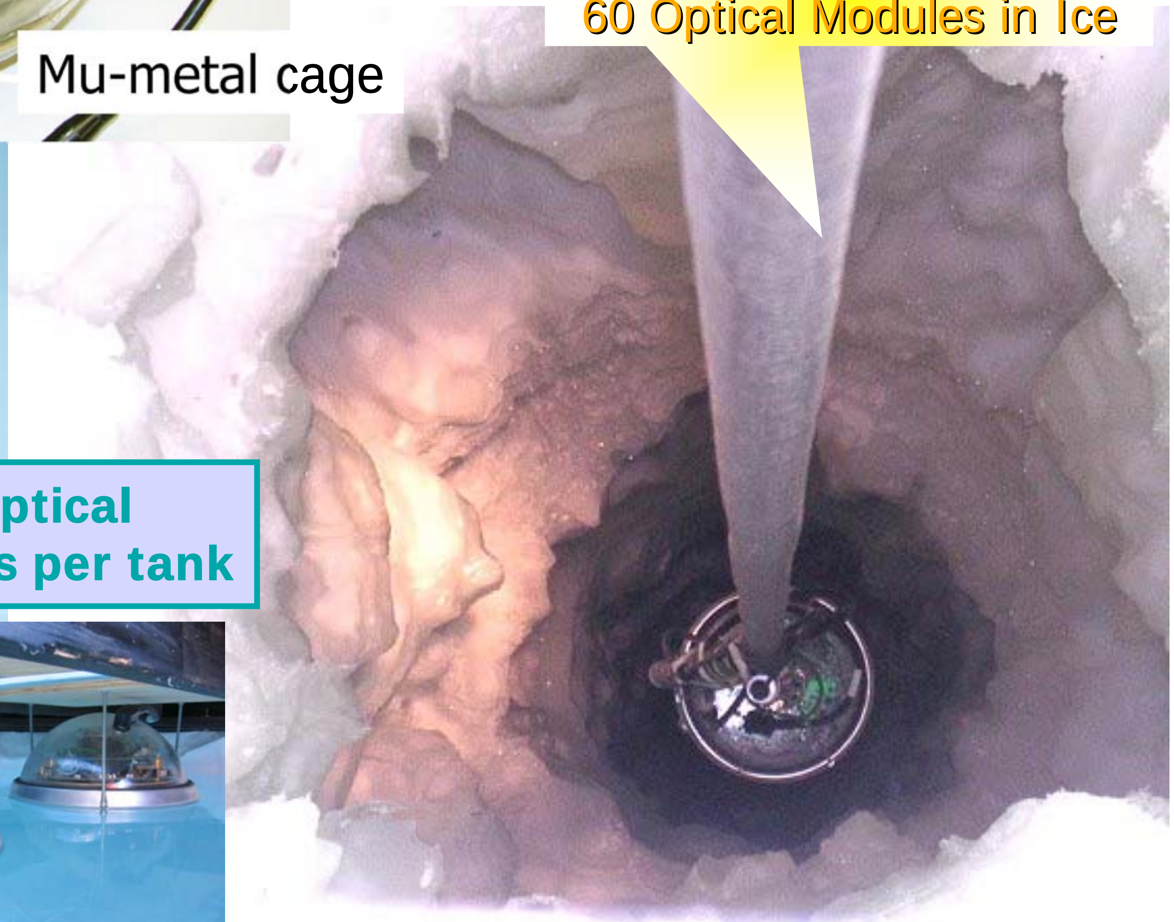
Extensive Air Shower Array @ surface: IceTop

Instrumented volume: 1 km^3

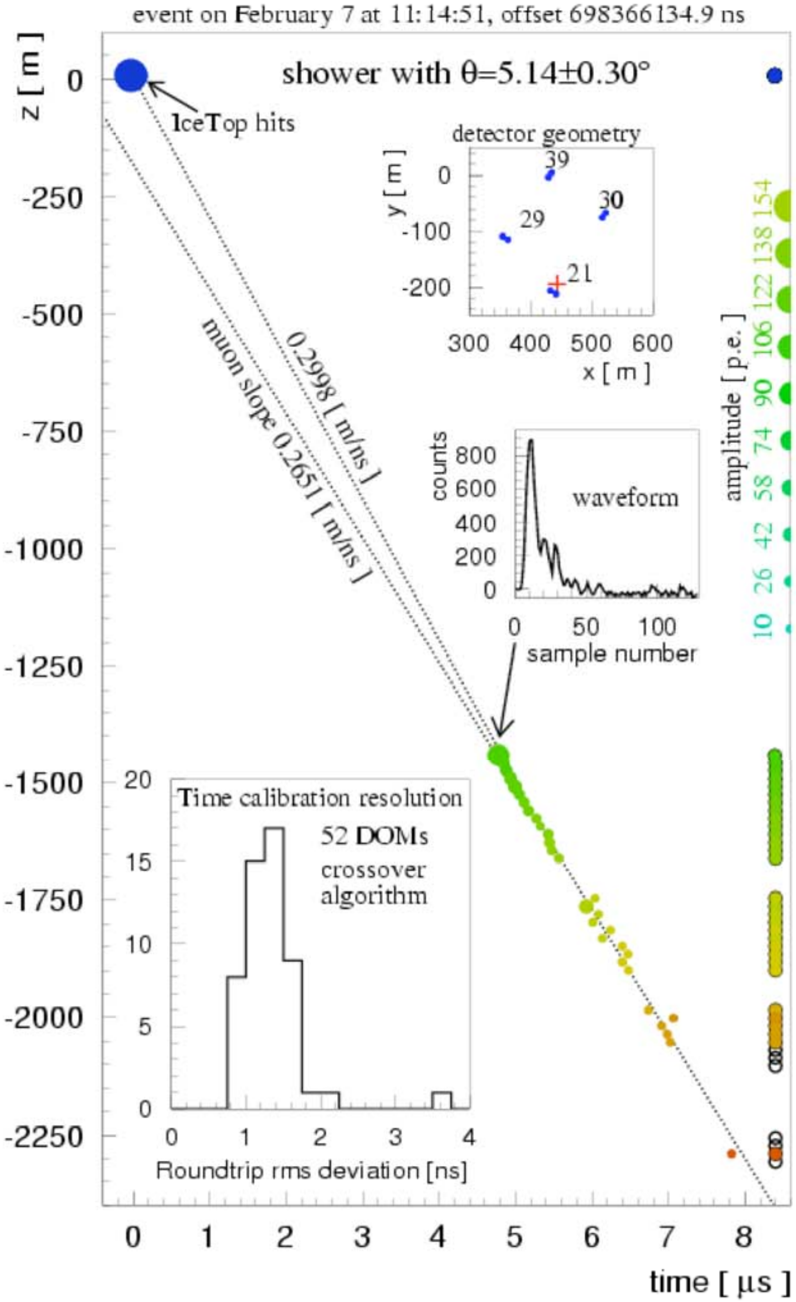
Installation: **2005**-2010, **started!**

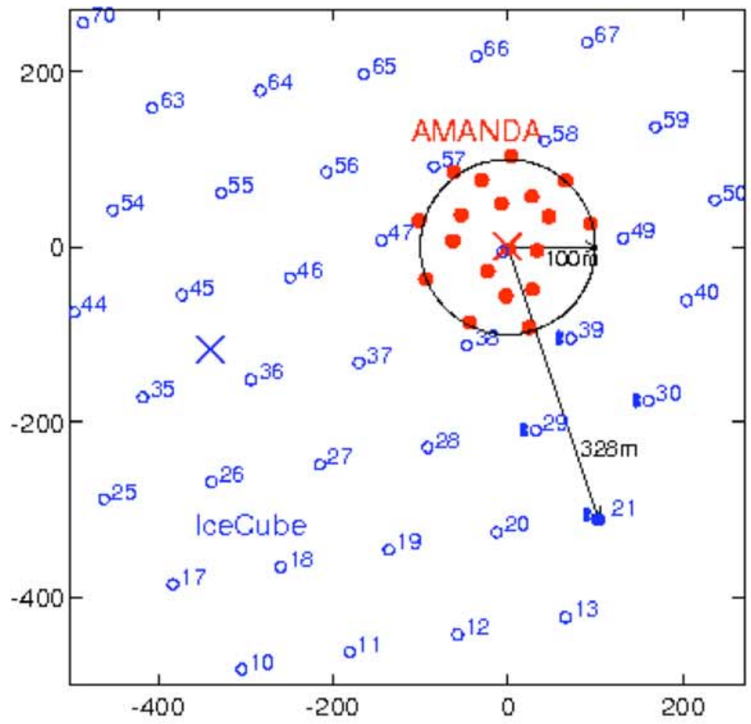

Penetrator
HV board
DOM main board
Optical Gel
Mu-metal cage
~300 Optical Modules built


8 IceTop tanks installed
2 Optical Modules per tank


27 January 2005
First IceCube string
(“string 21”)
successfully deployed
60 Optical Modules in Ice

First IceCube events





An almost vertical event:

12 IceTop DOMs hit (powered 16)

30 IceCube DOMs hit (powered 36)

Direction reconstruction of the shower from IceTop hits

Direction reconstruction in ice: different slope due to scattering

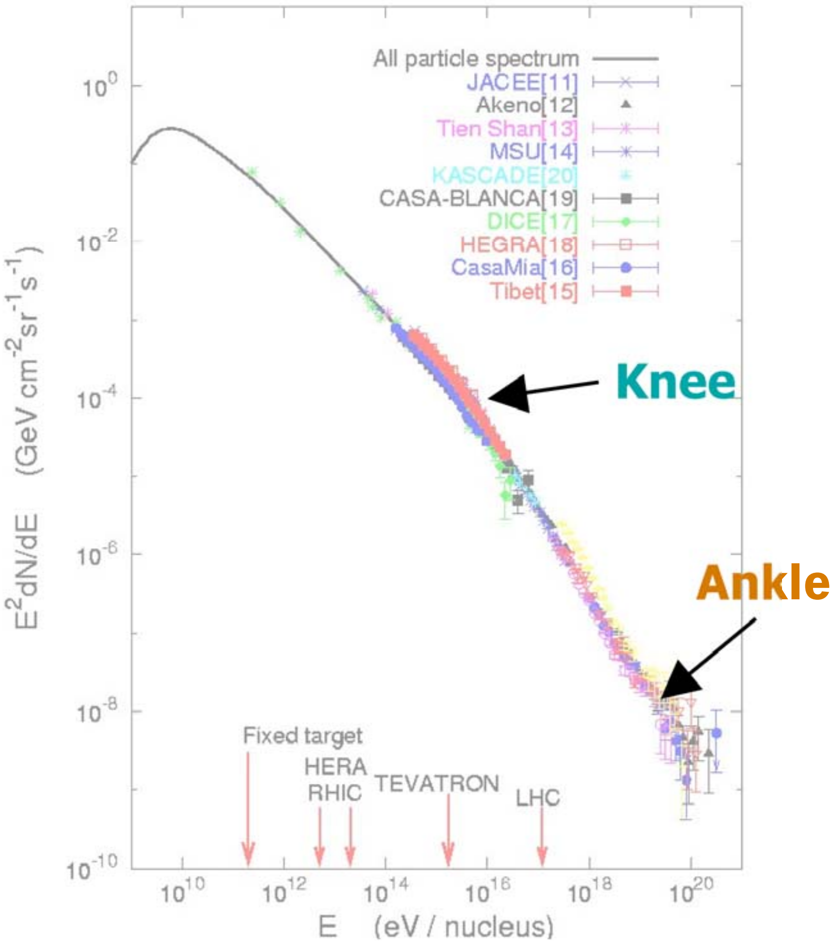
Summary

- Substantial progress in analysis of AMANDA data.
- Physics program covers **wide energy range and topics**.
- Search for **high energy cosmic neutrinos** reported in this talk:
  - **no statistically significant excess of high energy neutrinos observed so far and upper limits reported / published (diffuse, point-like).**
- Search for **time-variable point sources developed**: proof of principle encouraging.
  - **No statistically significant excess observed**
  - **More observations and extensive multi-wavelength collaborations are necessary in the future.**
- AMANDA paved the way to ν-Astronomy with IceCube
- **First string of IceCube successfully deployed January 2005**
- **March 2005 merging of the two Collaborations.**

High Energy Neutrino Astrophysics

High Energy Cosmic Rays Incognita:

1. Composition measurements at the cross-over energy galactic / extragalactic
2. **Acceleration mechanism: hadronic / electromagnetic**



Galactic origin:
$E_{max} \sim \beta \cdot B \cdot L$

"Knee" region:
transition
galactic/extragalactic?

Above the "ankle":
generally assumed
extragalactic origin

Search for ν flares: Method

Search for excesses of events in <u>sliding time windows of fixed size (Δt)</u>:

Method: Compare observed and background events in Δt.

In what follows is shown how to:

1. Select the **data sample: <u>use the 4 years data sample (807 days)</u>**
2. Select the **search window size (time duration): <u>40 d / 20 d (**)</u>**

→ Depend on signal strength, spectrum and duration (unknown!)

Constraints from steady point sources search results:

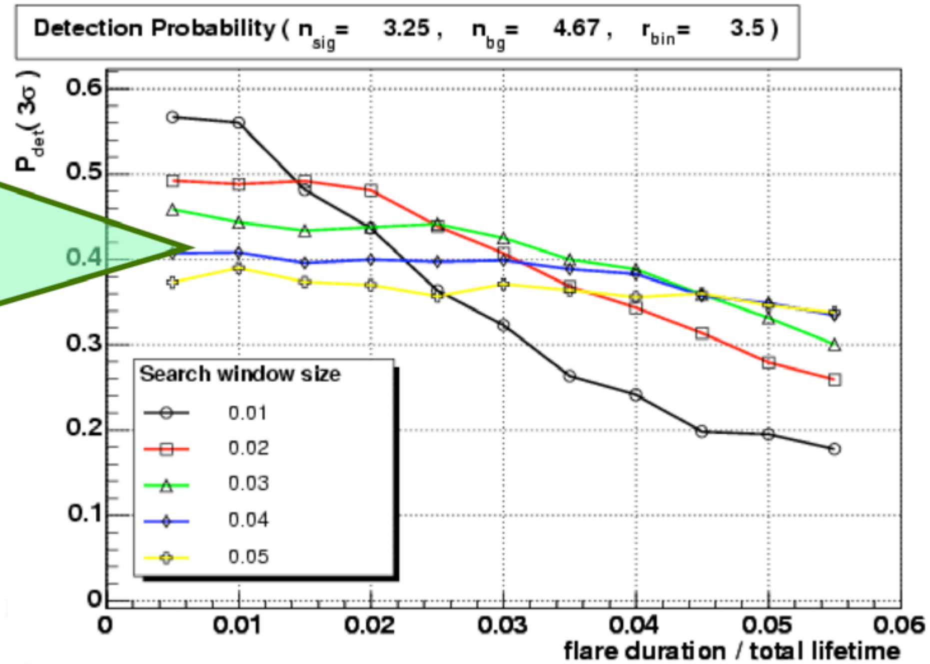
- **Upper limit:** Flares of duration Δt >100 days are almost excluxed
- **Lower limit:** Sensitivity ratio flares 10-day / 4-years: ~ 3
- Photon flux ratio flare/no-flare state: O(10) from multi-wavelength observations

2. Choose the window size:

- Detection probability not "too-low"
- Limited dependence on flare duration

Consideration from multi-wavelength observations:

- T_{flare}(galactic) < T_{flare}(extragalactic)

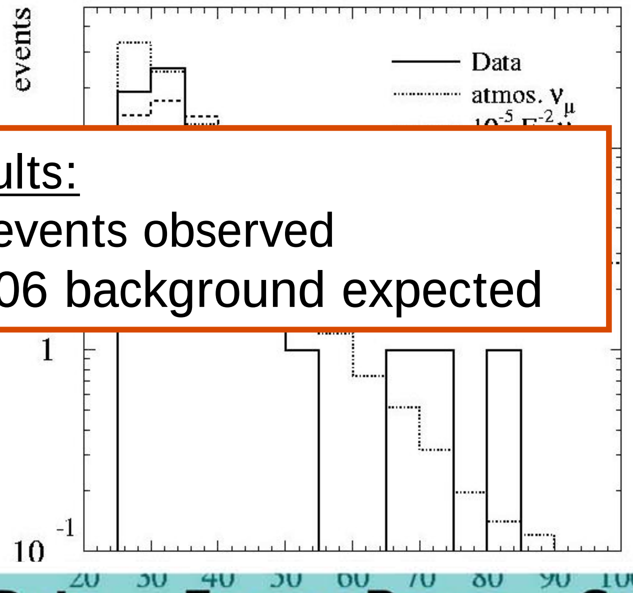


(**) 40 d: Extragalactic / 20 d Galactic sources

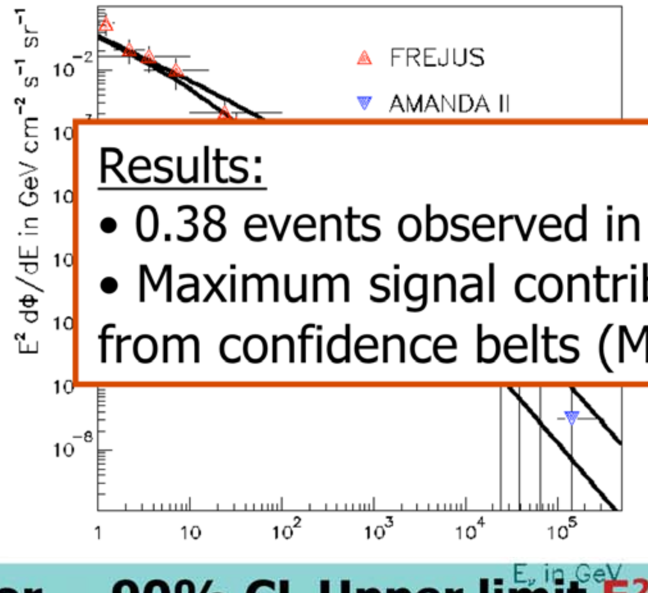
Diffuse flux: up-going ν_μ

Up-going events:

- Energy indicator: hit-channel multiplicity
- Optimize event selection for energy spectrum $dN/dE \sim E^{-2}$
- Full MC simulation event generation and signal/background propagation
  1. Counting experiment with Atm. ν normalization at Nch<50 (1997 data)
  2. Looking for distortions in the energy spectrum @ last bin (2000 data)



Results:
- 3 events observed
- 3.06 background expected



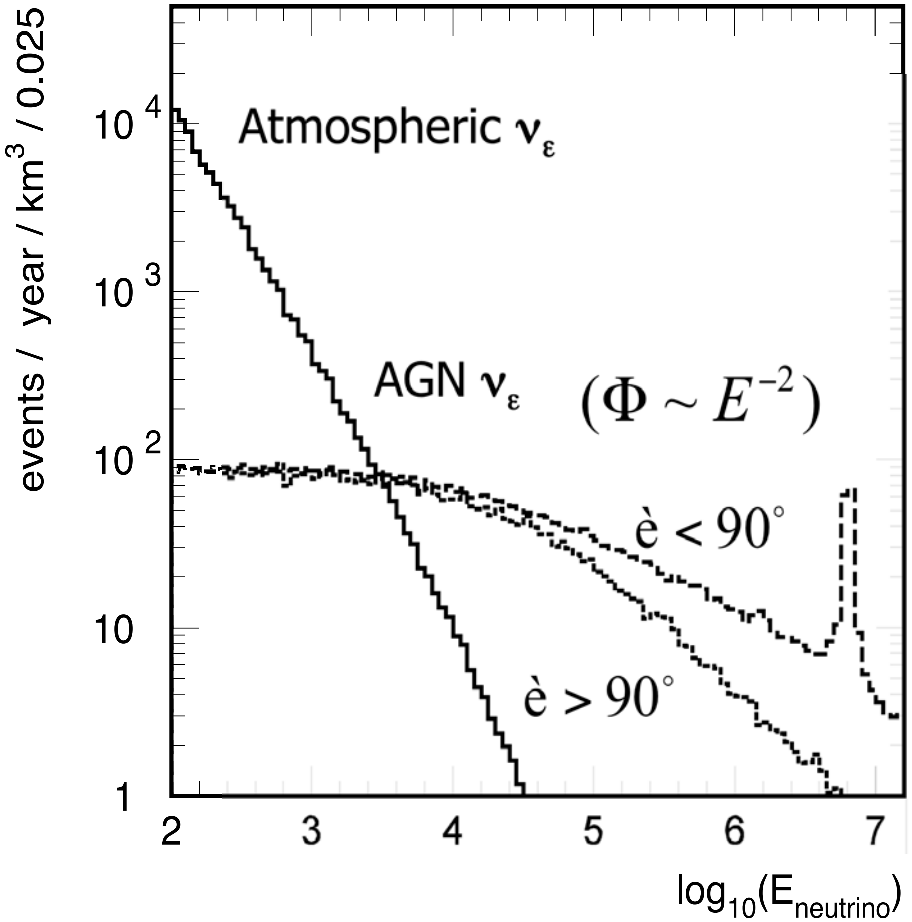
Results:
- 0.38 events observed in last bin
- Maximum signal contribution from confidence belts (MC)

Data	Energy Range	Syst. error	90% CL Upper limit $E^2\,\Phi_{\nu\mu}(E)$
1997	6 - 1000 TeV	25%	$8.4\cdot10^{-7}$ GeVcm^{-2} s^{-1}sr^{-1}
2000	100 - 300 TeV	33%	$2.6\cdot10^{-7}$ GeVcm^{-2} s^{-1}sr^{-1}

Diffuse flux: cascades

Cascade events:

- Sensitivity to all three flavors:
  - event rates 50% ν_e 30% ν_τ 20% ν (assuming 1:1:1 flavor ratio)



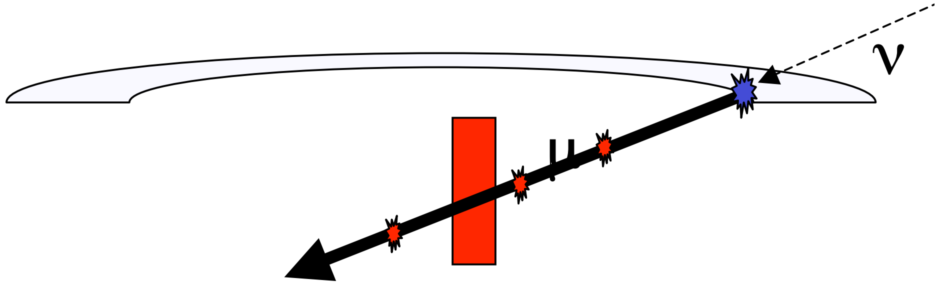
Results:

- 1 event observed
- $0.96^{+0.7}_{-0.3}$ background expected

90% CL upper limit:

- **$E^2\,\Phi_{all\ \nu}(E) < 8.6 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}**
  Energy region: 50 TeV – 5 PeV
- **$E^2\,\Phi_{\bar{\nu}e}(6.3\text{ PeV}) < 2 \cdot 10^{-6}$ GeV cm^{-2} s^{-1} sr^{-1}**

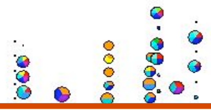
Diffuse flux: Ultra High Energy



UHE ν's:

- For $E_\nu > 1$ PeV:
  - the $\nu_{e,\mu}$ range < $R_\oplus$
  - Atmospheric μ and ν rate is low
- μ range is > 10 km

→ Select ← and ↓ events, large effective areas, assume $dN/dE \sim E^{-2}$



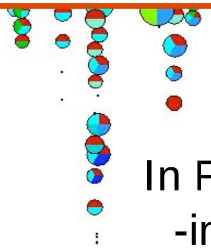
Results (1997 data):

- 5 events observed
- 4.6 ± 1.2 ± 36% (syst) background expected

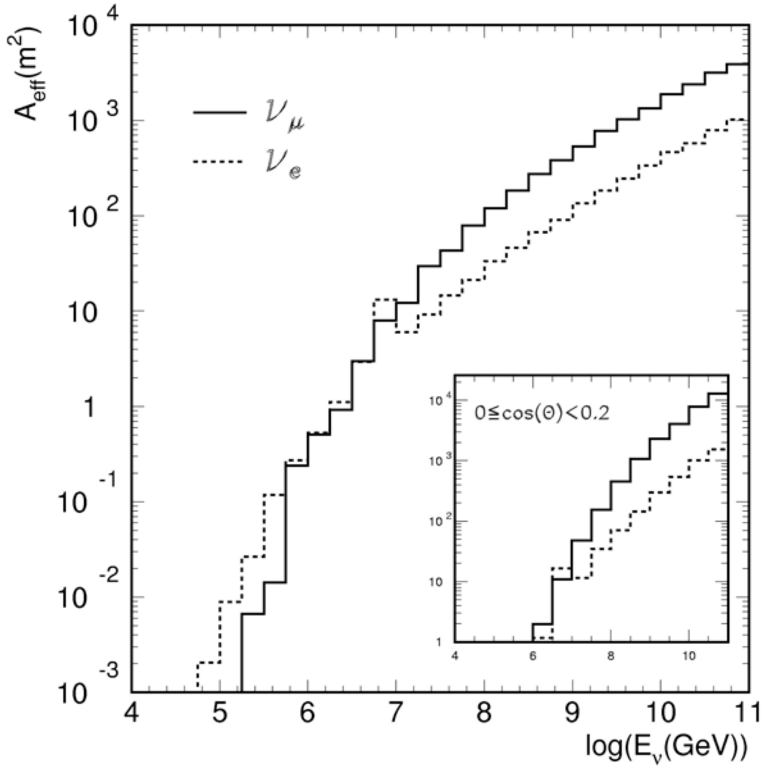
90% CL upper limit:

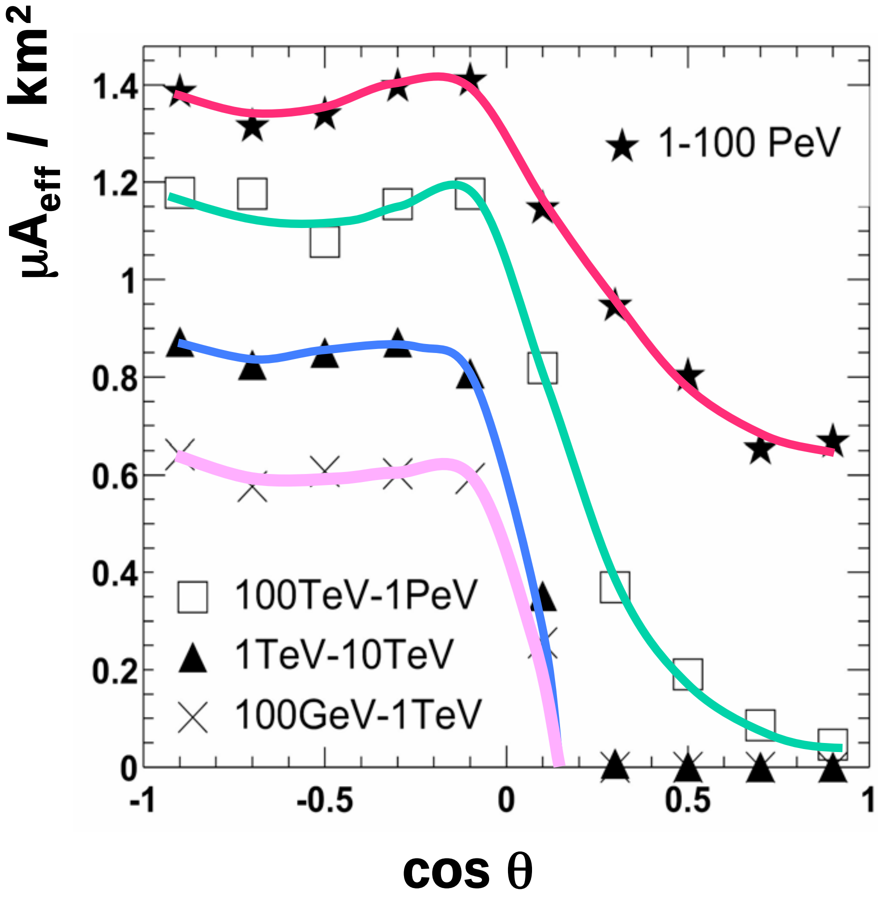
$E^2 \Phi_{all\ \nu}(E) < 9.9 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

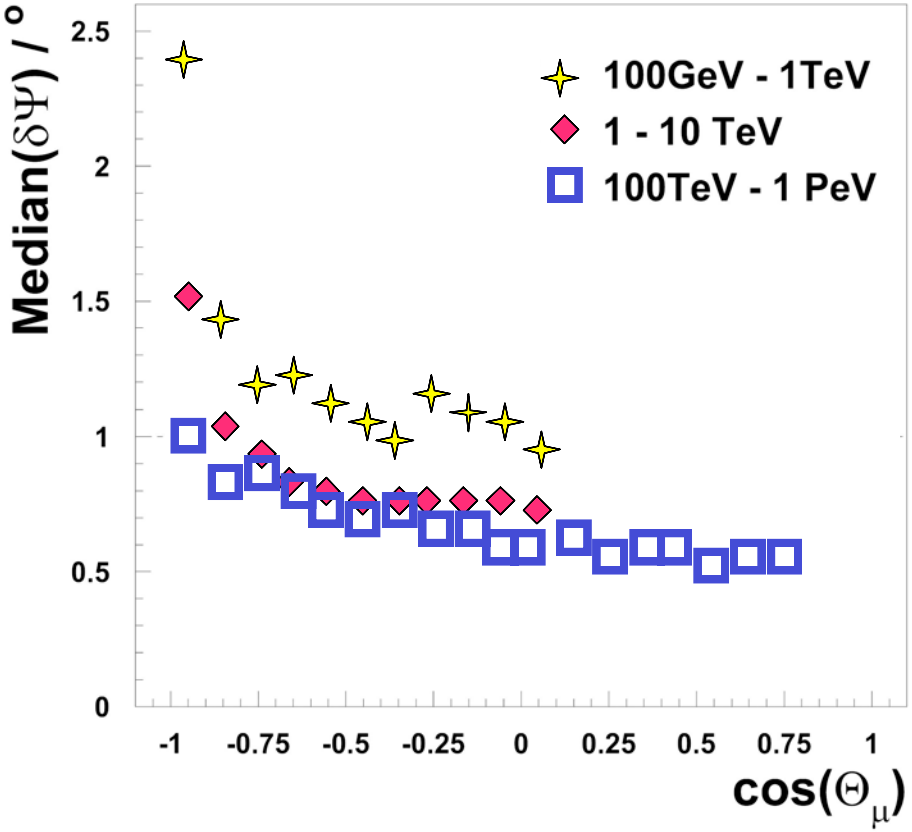
Energy region: 1 PeV – 3 EeV



In Fig.: A MC simulated UHE ν -induced event in AMANDA



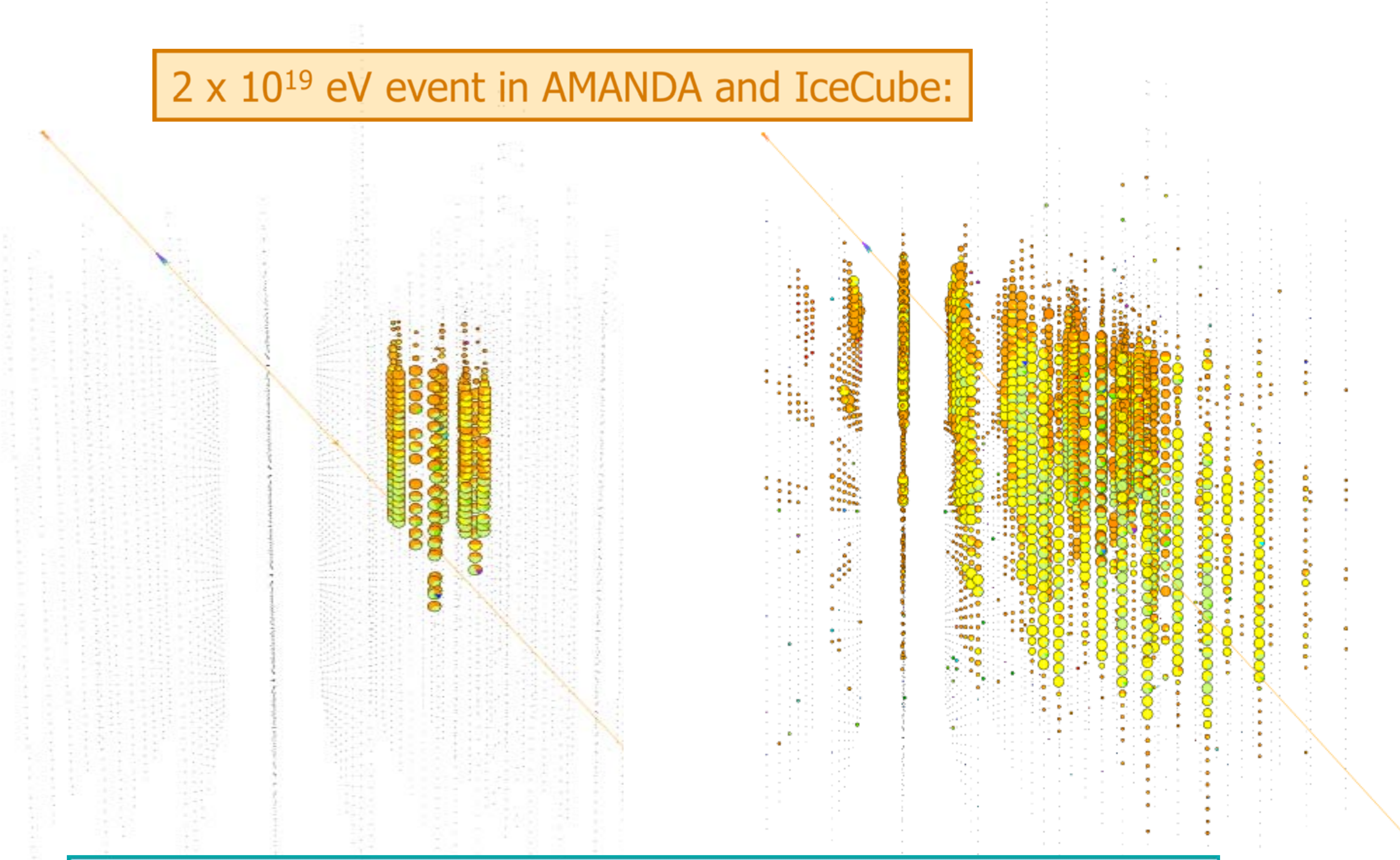




Effective Area vs. zenith angle after rejection of background from downgoing atmospheric Muons.

Angular resolution (point source analysis), but using standard AMANDA reconstruction and selection procedures (improvement from full Waveform information)

2×10^{19} eV event in AMANDA and IceCube:



PeV ν_τ cascade events: capability to separate vertex cascade and τ decay ("double bang" signature) above tens PeV.

Data filtering and event reconstruction 00-03

	Filtering/Fit	Event Selection	P.Rate
			7.14 billion events
L1	**Hit & Optical Module selection**		**1**
	Two fast first-guess reconstructions (*):		
	Direct-Walk	$Zenith_{DW} > 70^o$	**3.7%**
	JAMS		
L2		$Zenith_{JAMS} > 80^o$	**0.39 %**
	Cross-talk hit-filter		**0.39 %**
	Up-going Likelihood (UL) reconstruction (**)		
L3		$Zenith_{UL} > 80^o$	**0.11%**
	Topological parameters calculation		
	Hits distributions along the tracks		
	Single track angular resolution		
	Down-going Likelihood (DL) reconstruction (**)		
			7.85 million muon tracks

(*) "Moderate" CPU-time consumptive ~ 10^{-3} s/events for a 2.5 GHz CPU

(**) Intensively CPU-time consumptive, up to ~ 1 s/events, First guess results as "seeds", 32 iterations for up-going, 64 for down-going hypothesis

Source	Total Nr. Events	Total Backgr.	Period duration	Nr. of doublets	Probability for highest significance
Markarian 421	6	5.58	40 days	0	Close to 1
1ES1959+650	5	3.71	40 days	1	0.34
3EG J1227+4302	6	4.37	40 days	1	0.43
3EG J0450+1105	6	4.67	40 days	1	0.47
QSO 0235+164	6	5.04	40 days	1	0.52
QSO 0528+134	4	4.98	40 days	0	Close to 1
Cygnus X-3	6	5.04	20 days	0	Close to 1
Cygnus X-1	4	5.21	20 days	0	Close to 1
GRS 1915+105	6	4.76	20 days	1	0.32
GRO J0422+32	5	5.12	20 days	0	Close to 1
3EG J1828+1928	3	3.32	20 days	0	Close to 1
3EG J1928+1733	7	5.01	20 days	1	0.35

Candidate	Dec(°)	RA(h)	1997 Φ_ν	2000 Φ_ν	2000-2003 N_{obs}/N_{bg}	2000-2003 Φ_ν
Markarian 421	38.2	11.1	11.2	3.5	6 / 5.58	0.68
Markarian 501	39.8	16.9	9.5	1.8	5 / 4.96	0.61
1ES 1426+428	42.7	14.5		1.7	4 / 4.29	0.54
1ES 2344+514	51.7	23.8	12.5	2.0	3 / 4.86	0.38
1ES 1959+650	65.1	20.0	13.2	1.3	5 / 3.71	1.01
QSO 0528+134	13.4	5.5		2.0	4 / 4.98	0.39
QSO 0235+164	16.6	2.6		1.7	6 / 5.04	0.70
QSO 1611+343	34.4	16.2		0.8	5 / 5.24	0.56
QSO 1633+382	38.2	16.6		1.7	4 / 5.58	0.37
QSO 0219+428	42.9	2.4		1.6	4 / 4.31	0.54
QSO 0954+556	55.0	9.9		1.7	2 / 5.23	0.22
QSO 0716+714	71.3	7.4		4.4	1 / 3.25	0.30
SS433	5.0	19.2		0.7	2 / 4.50	0.21
GRS 1915+105	10.9	19.2		2.2	6 / 4.76	0.71
GRO J0422+32	32.9	4.4		2.9	5 / 5.12	0.59
Cygnus X-1	35.2	20.0		2.5	4 / 5.21	0.40
Cygnus X-3	41.0	20.5	4.9	3.5	6 / 5.04	0.77
XTE J1118+480	48.0	11.3		2.2	2 / 5.40	0.20
CI Cam	56.0	4.3		0.8	5 / 5.11	0.66
LS I +61 303	61.2	2.7		1.5	3 / 3.65	0.60
SGR 1900+14	9.3	19.1		1.0	3 / 4.27	0.35
Crab Nebula	22.0	5.6	4.2	2.4	10 / 5.36	1.25
Cassiopeia A	58.8	23.4	9.8	1.2	4 / 4.59	0.57
Geminga	17.9	6.6	6.8	3.3	3 / 5.17	0.29