High energy neutrino astronomy*

Steve Barwick
UC- Irvine

ICFA, Oct 5, 1999
Fermilab

* SuperK, current lower E_ν detectors → see A. Bettini

Multi-messenger Astronomy

Take advantage of the complete suite of information carriers that nature has to offer

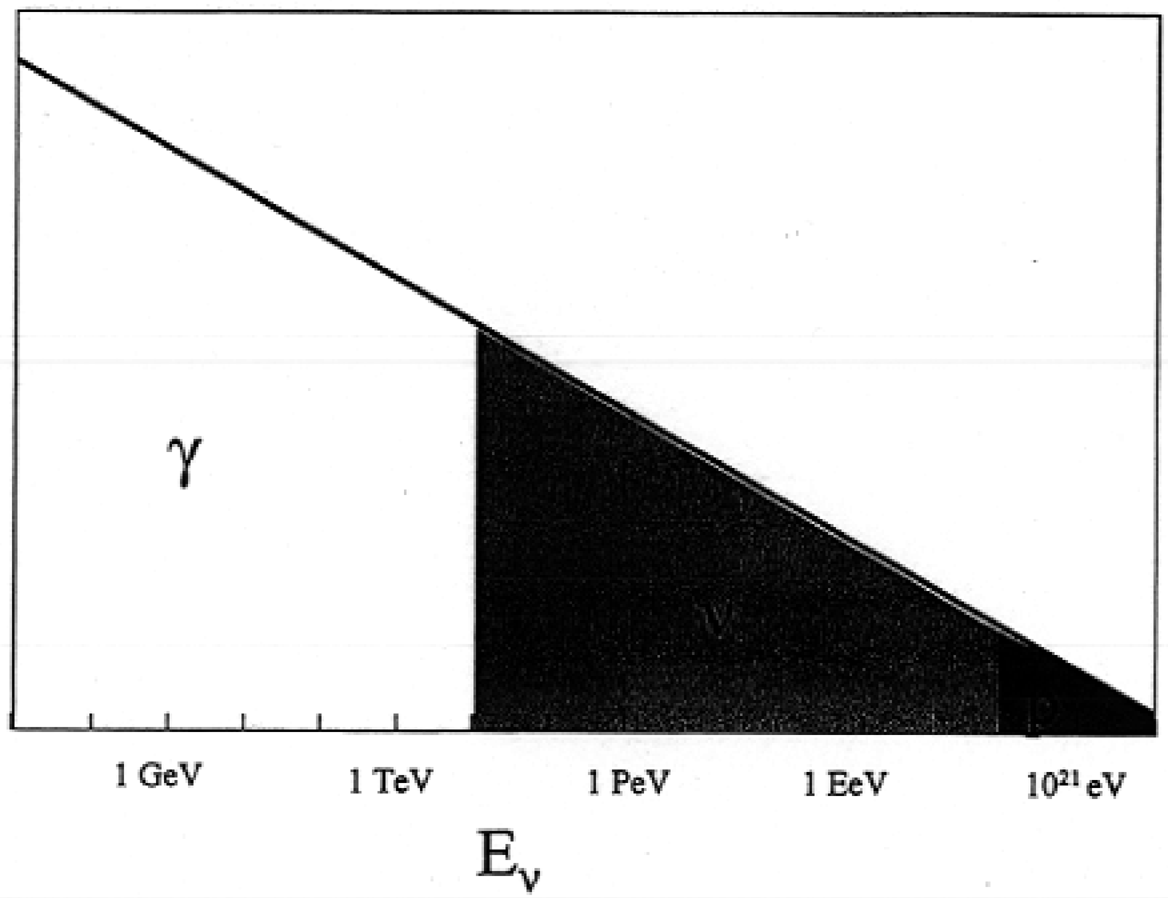
- Particle probes
  - Neutrino Telescopes (AMANDA, IceCube)
  - High energy cosmic ray (Auger, OWL)
- Gravity wave detectors
  - LIGO, LISA
- Multi-wavelength photon studies
  - "TeV" -STACEE, MILAGRO, VERITAS

Coincidence studies are planned, and may offer the most powerful tool to understand the most powerful objects in the Universe.

IceCube Science

- **Overwhelmingly motivated by "discovery" potential**
- **Astronomy**
  - GRB and AGNs
    - **Do they accelerate protons?**
      - ν's provide unequivocal proof
    - **Are they the sources of highest energy CRs?**
      - A few dramatic events may produce the answer
    - **Diffuse vs point**
      - Depends on geometric distribution
      - Depends on distribution of fireball paramaters
  - Galactic Plane
    - **Not prominent, but visible (~10-100/yr)**
    - **Rate depends on details of CR energy spectrum**
  - Dark matter search
    - **Important probe for $M_{DM} > 0.5$ TeV**

Searching for remote sources



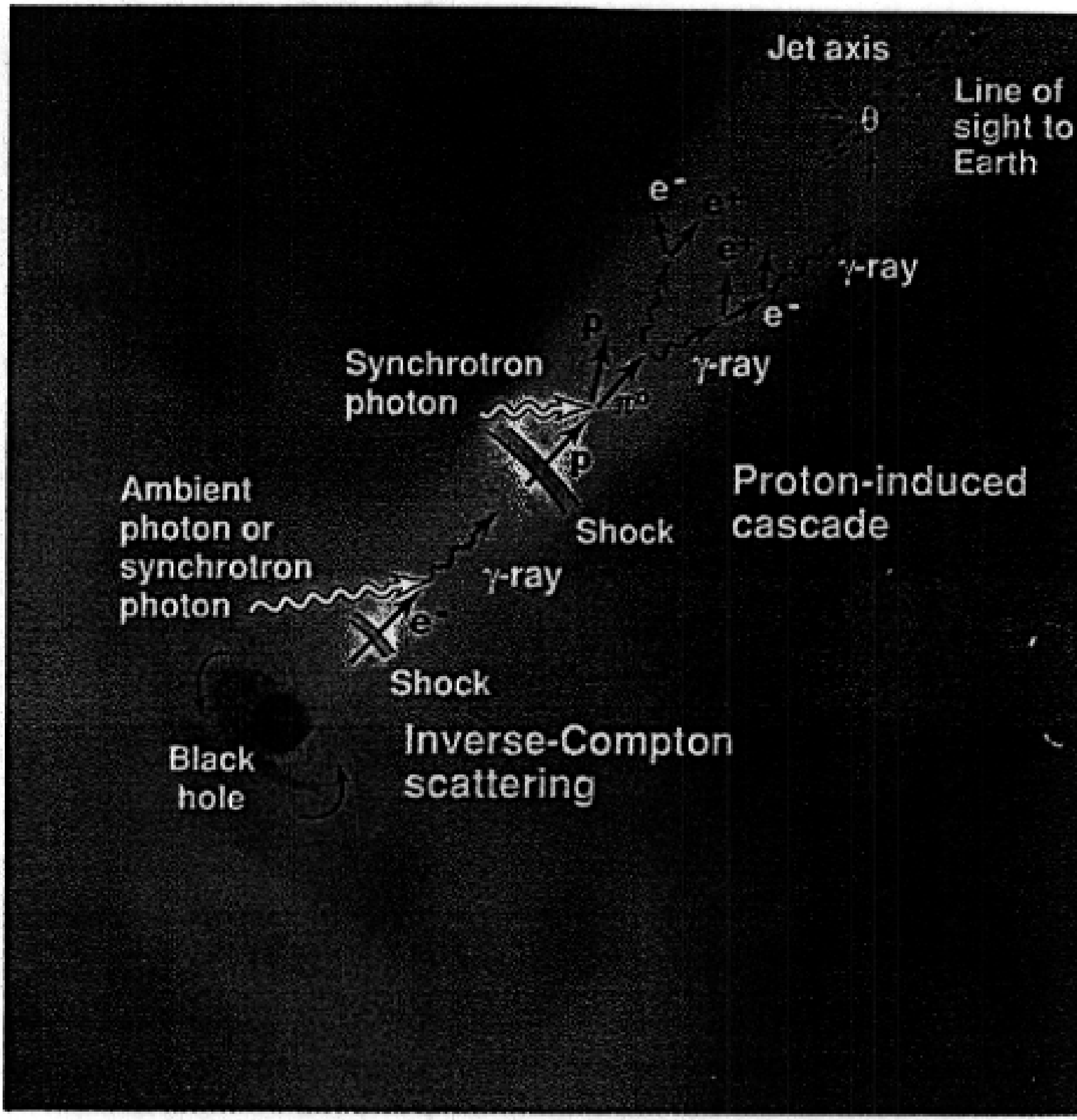
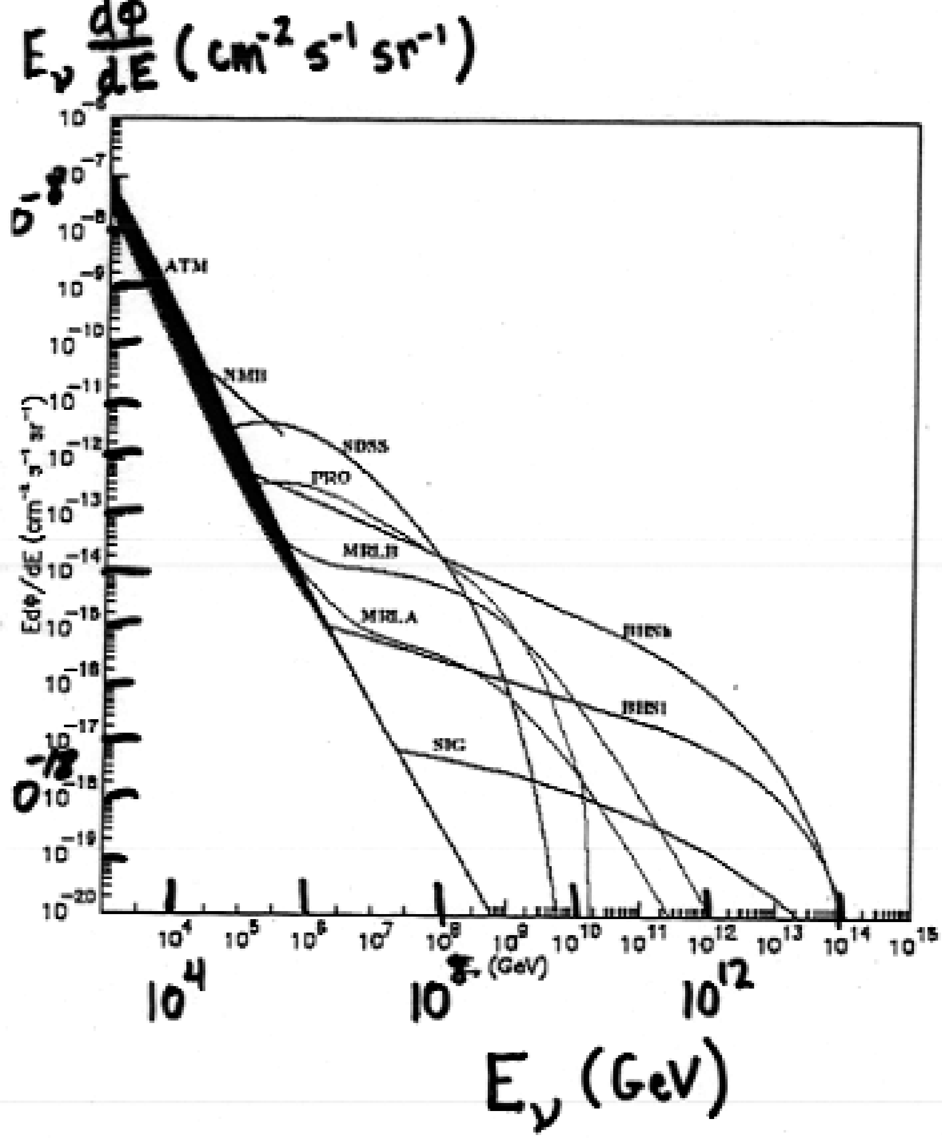


ILLUSTRATION K. SUTLIFF

Cosmic cascade. Artist's conception of the nucleus of an active galaxy. Two possible scenarios for the production of the high-energy gamma rays in a relativistic jet are indicated.

IceCube: diffuse ν-signals



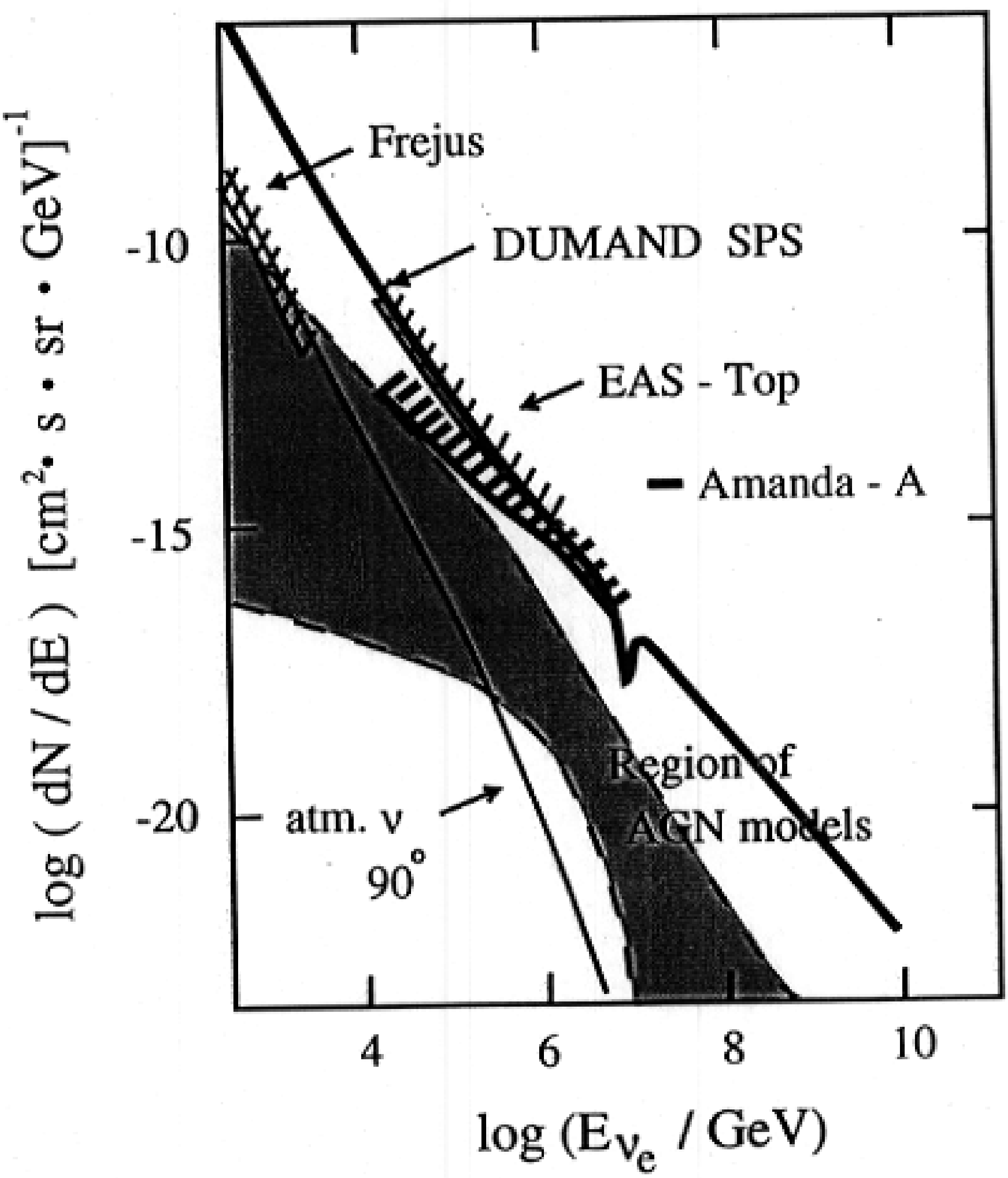
AGN = Active Galactic Nuclei

Events/year

SOURCE	E_ν^{REC} 10 TeV	E_ν^{REC} 100 TeV
Atmospheric		
ATM	**680**	**8**
Generic AGN		
SDSS	**2500**	**1300**
NMB	**2100**	**640**
Blazars		
PRO	**340**	**210**
MRLB	**78**	**26**

$\frac{0.1}{10^5}$

Experimental Limits on H.E. ν_e cascades



HPBA11, FEB04/17:10

Survey of Event Rate Predictions

- Point Sources

Source	Rate (/km^{2}yr) $E_\nu \geq 1$ TeV
SNa Remnant	3
AGN (3C273)	1-100
Mk421, Mk501	1-10 from γ flux
GRB	~3/burst

- Diffuse Sources

Source	Rate (/km^{2}yr sr) $E_\nu \geq 1$ TeV
AGN	400-800
AGN jets	45
GRB	10
Atm ν	1000

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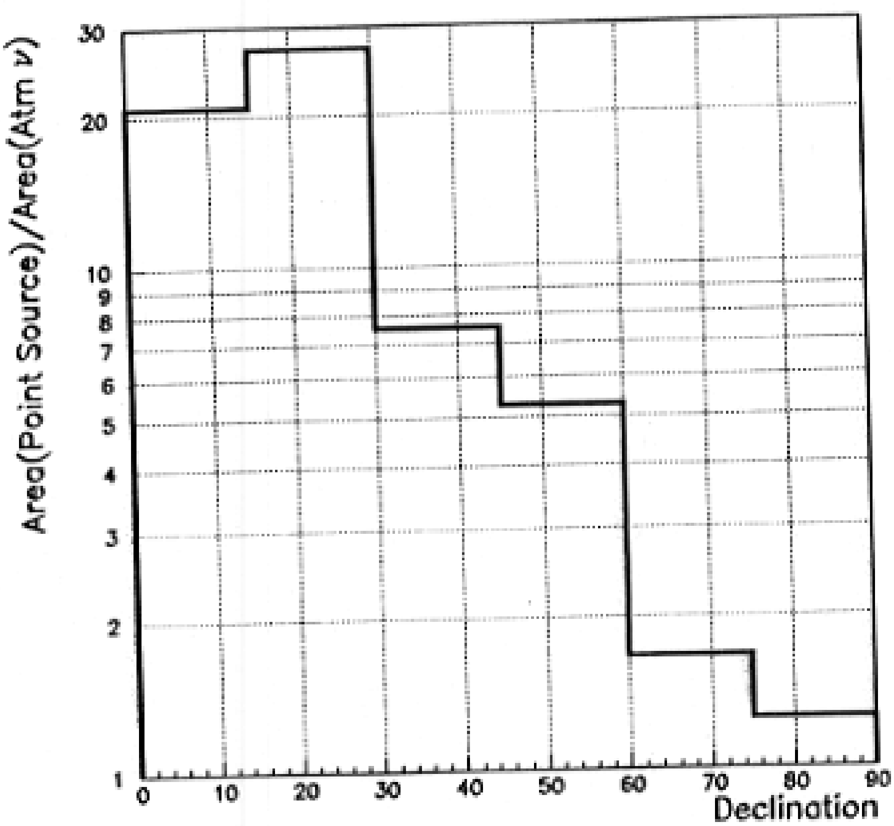
AMANDA

Point Source Search

(J.Kim, ICRC '99)

- Optimize selection criteria for hard (E^{-2}) spectra
- Goals:
  - Improve acceptance over zenith angle
  - Search for clustering in space
- Key development: ENERGY FIT
  - Utilizes charge information (N_{pe} vs distance)
  - Fit sensitive to track reconstruction



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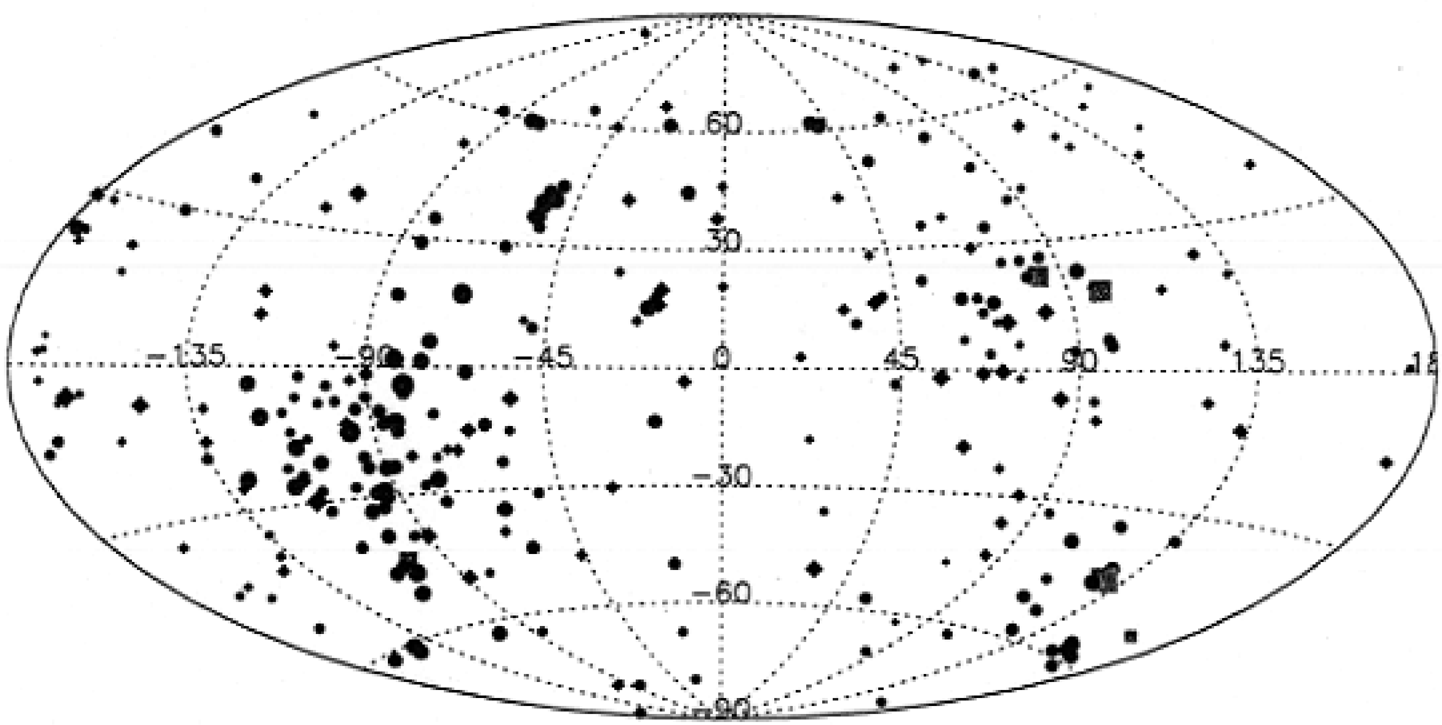
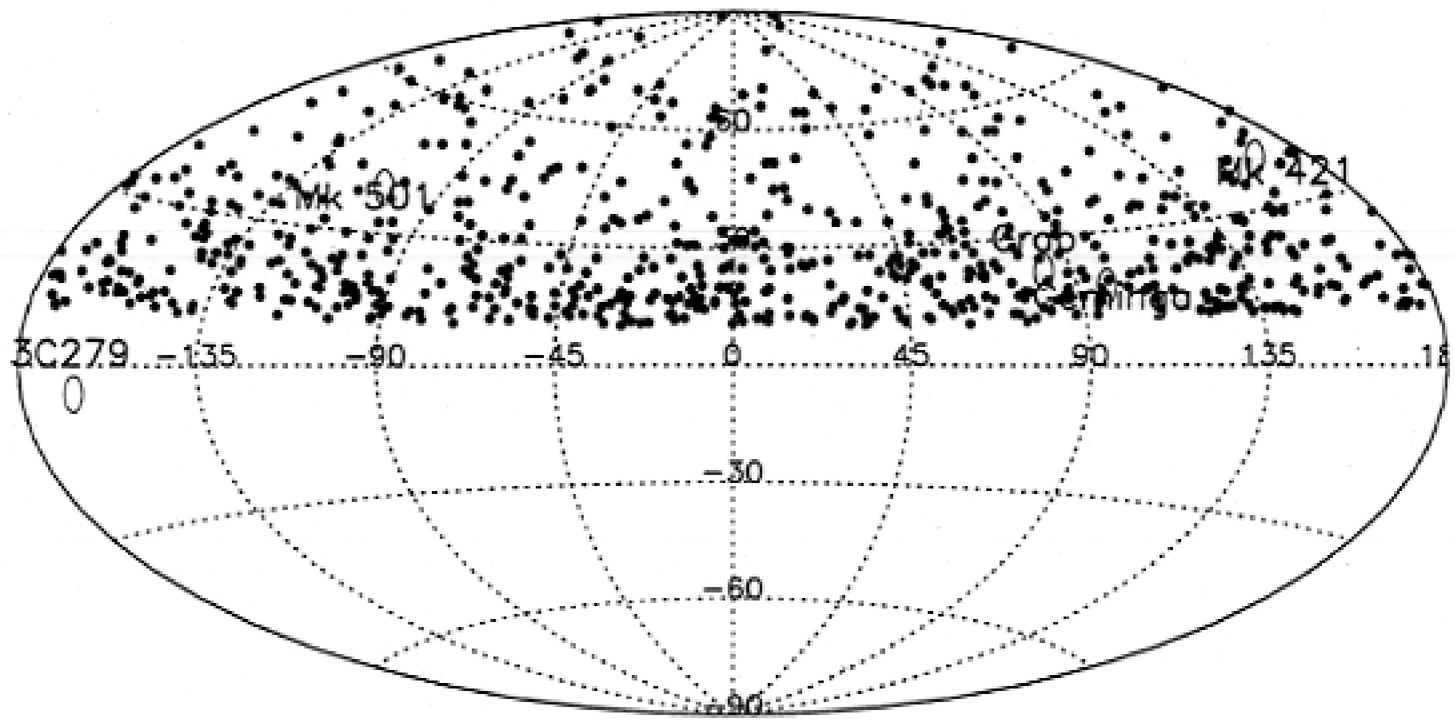
EGRET 3rd – Equatorial Coordinates



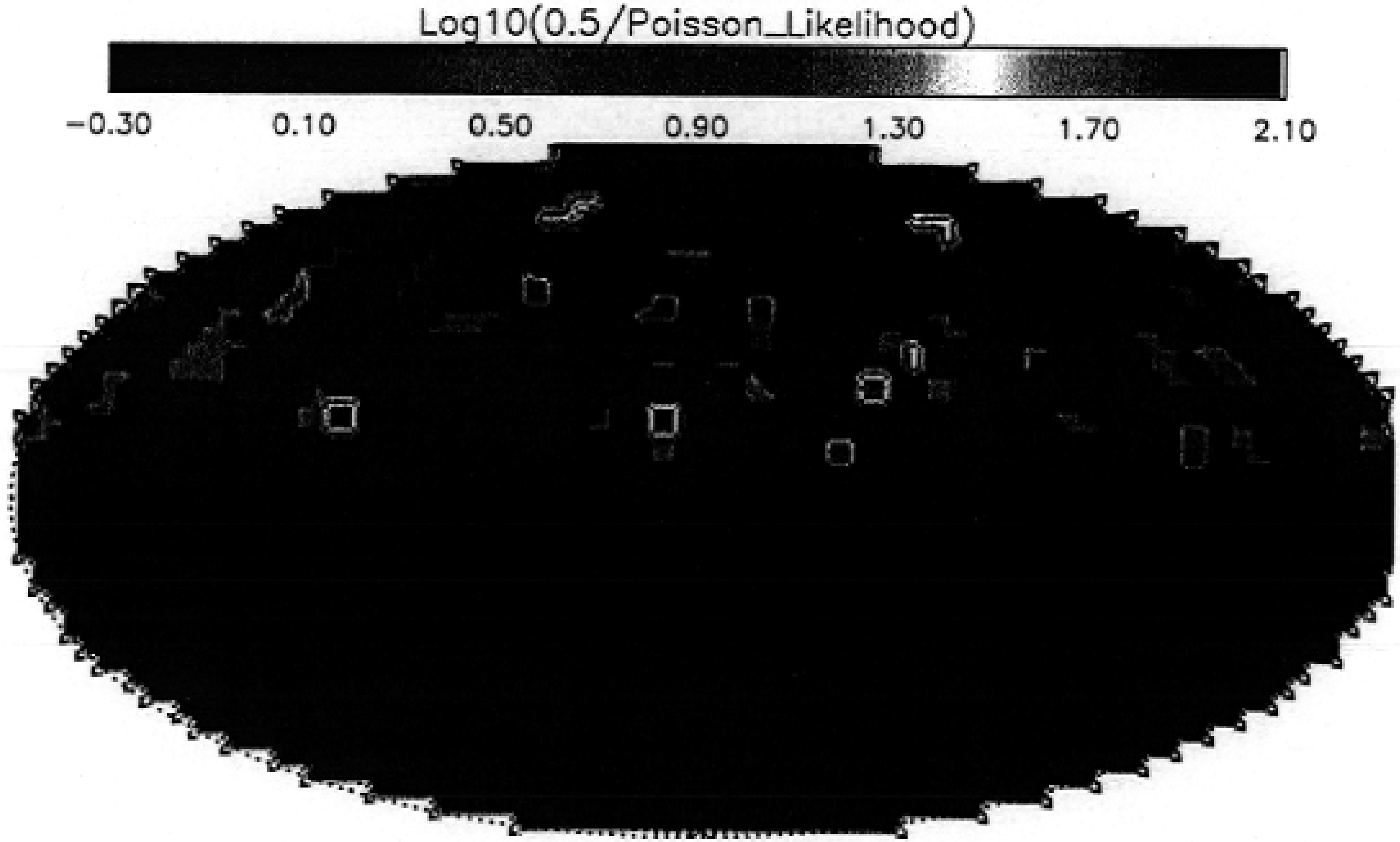
AMANDA Sky Plot

AMANDA Sky Map – Equatorial Coordinates



AMANDA Signal Significance

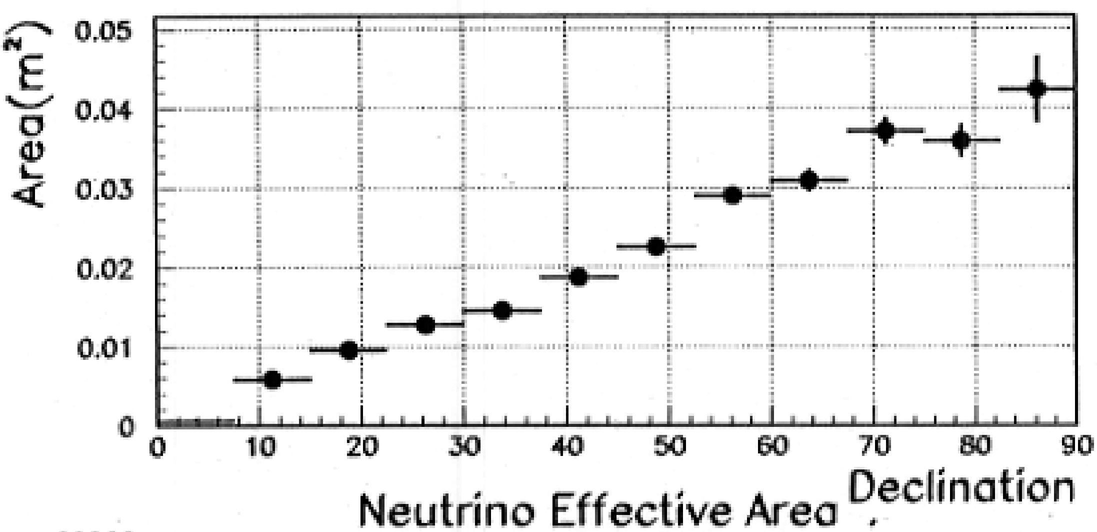
-Log(0.5/Poisson_Likelihood)

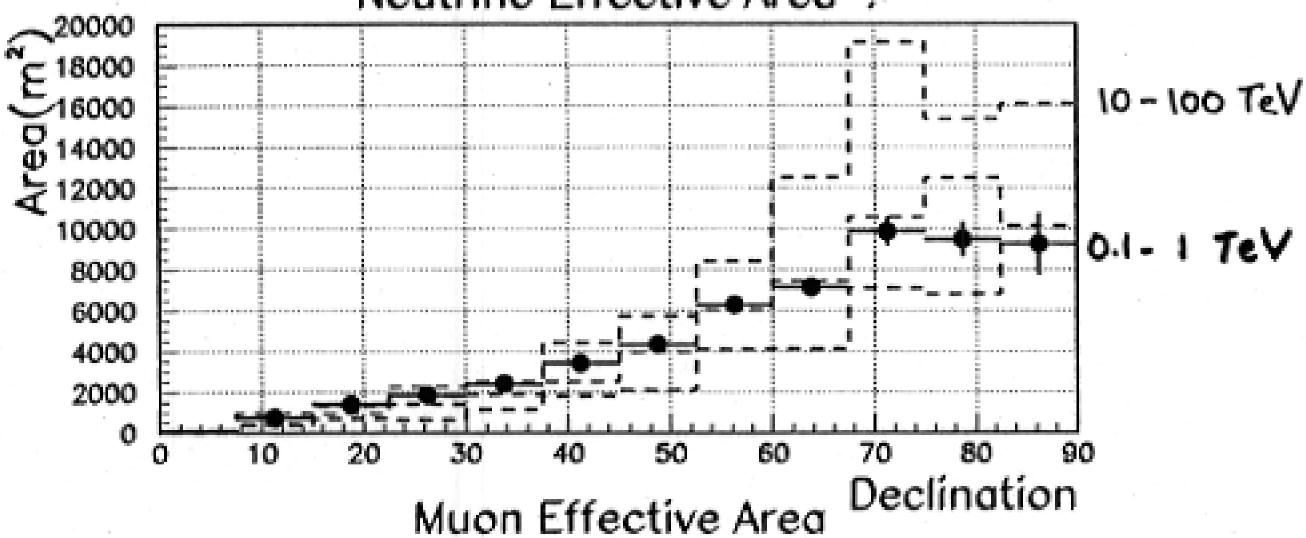


AMANDA

B10 Effective Area ~ 10^4 m^2

- Data points weighted by energy spectrum (E_ν^{-2})





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AMANDA: Flux limits

(preliminary)

90% CL, units $10^{-14}\ cm^{-2}\ s^{-1}$

Muon flux induced by muon neutrinos

Source	AMANDA (80 days)	MACRO	Baksan	IMB
Cyg X-3	2.4	7.6		4.1
MRK 421	3.4	5.4		3.3
Her X-1	4.9	4.2		4.3
Crab Nb	11.1	2.2	2. 6	4.3
Geminga	13.9	1.2	4.0	3.1

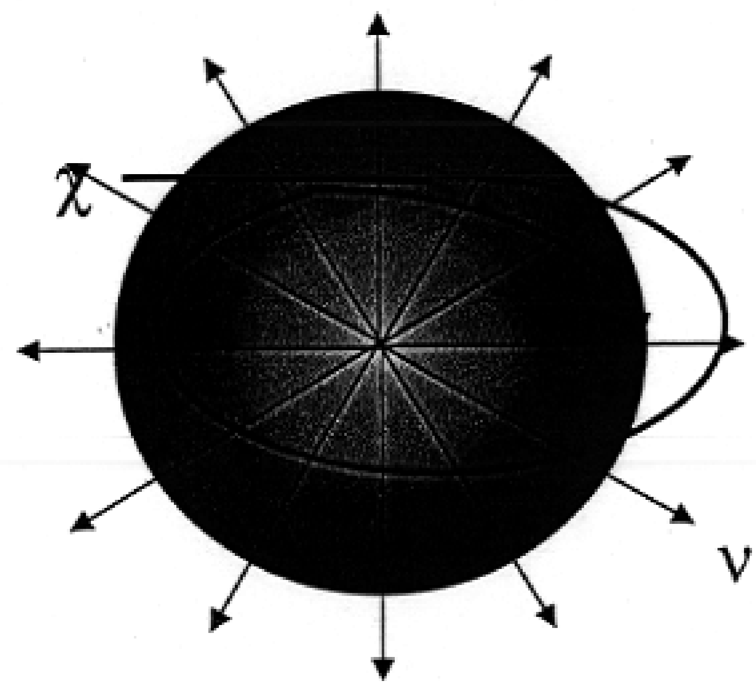
Search for neutralinos

- Energy loss by elastic scattering

- Concentration in the center of sun or earth

  $\chi\chi \rightarrow X \rightarrow \nu$

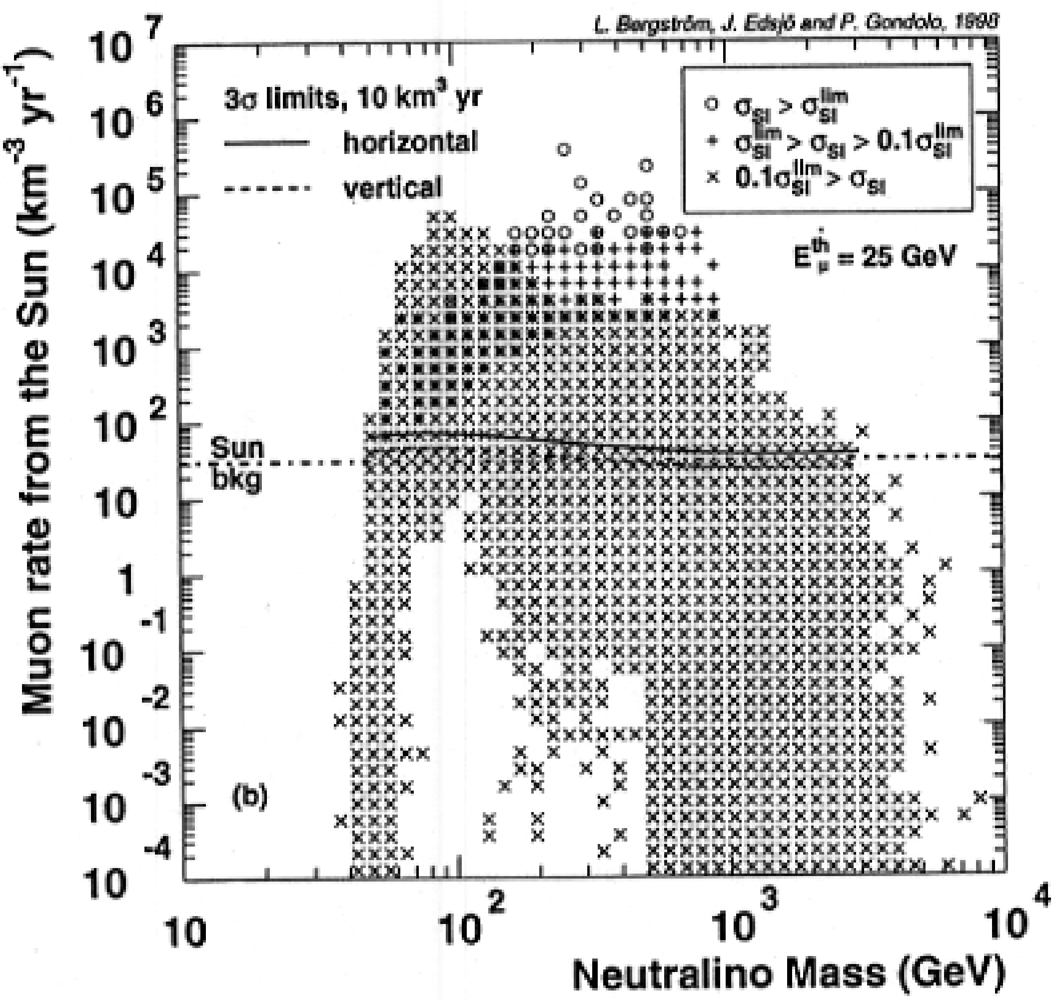
  $E_\nu \approx M_\chi$



•In the earth, we are background limited: $\sigma_\theta \approx \frac{23^\circ}{\sqrt{M_\chi / GeV}}$

•Sun complements direct search

WIMP searches (Sun)

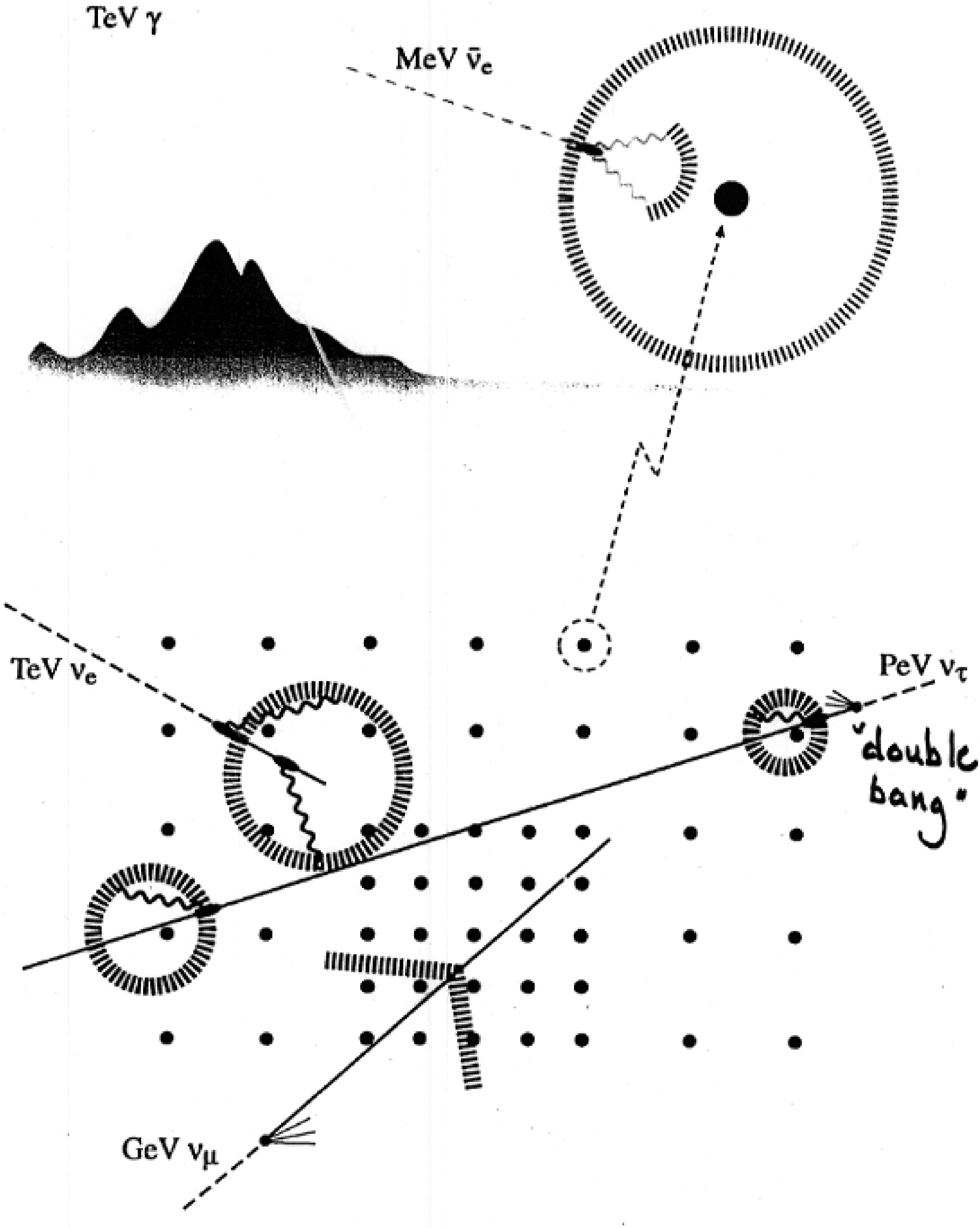


IceCube Science

- **Particle Physics**
  - ν-mass provides window beyond stand. model
    - **Pev -scale ν_τ appearance via "double bang" mechanism or upward going ν's**
  - Atm ν's: $\nu_\mu \to \nu_\tau$?
    - **If accelerator experiments fail to resolve issue, then Amanda-II can be augmented to lower energy threshold. IceCube provides veto.**
  - Search for topological defects
  - Monopoles
- **Multi-disciplinary studies**
  - Glaciology studies of dust, soot, acids vs depth
  - Optical properties, mechanical properties of ice
  - Hot water drill technology
    - **In-situ radio receivers for E> PeV**
    - **Large scale seismic array at seismically quite rotation axis**
    - **Facilitate search for elementary life forms in lakes below Antarctic Ice Sheet**

GRB Science

- Origin of highest energy cosmic rays
- Verify fireball models
- ν_τ appearance $\Delta m^2 > 10^{-17}$ eV^2
- Test of relativity: $(c_\gamma - c_\nu)/c_\gamma < 10^{-16}$



TeV γ
MeV $\bar{\nu}_e$
TeV ν_e
PeV ν_τ
"double bang"
GeV ν_μ

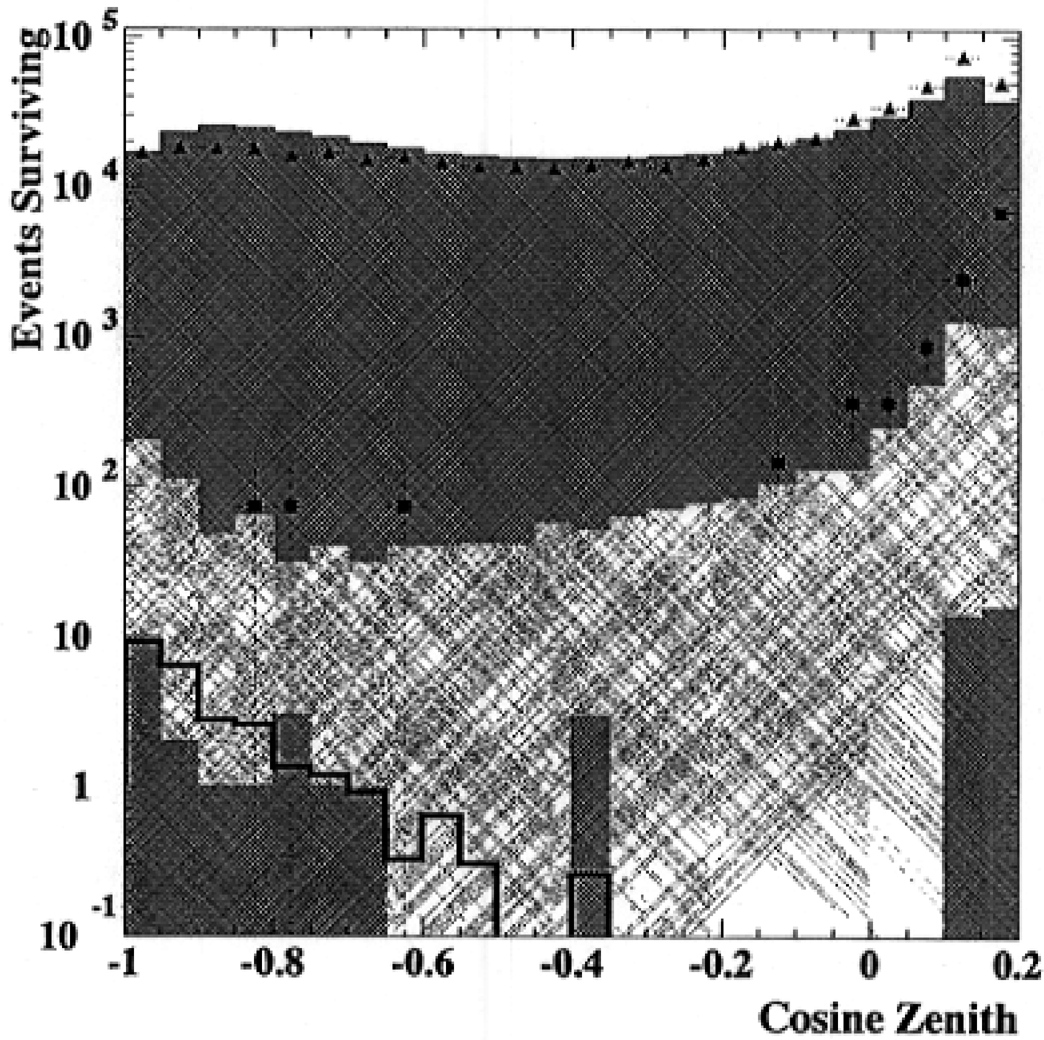
Atm. Neutrino Analysis

- Evolving analysis (steep learning curve)
  - Improve efficiency
  - Improve sensitivity over zenith angle

- Analysis of odd days of 1997
  - Initial reconstruction (ppandel)
    - **17 events**
  - Improved calibration and reconstruction (upandel)
    - **38 events , but 8 look suspicious**
  - Improved filtering and quality criteria
    - **~50 events, in progress**
  - Add amplitude information
    - **Used in point source work, better uniformity**

➜ Statistical tests become important discriminant

Angular Distributions



histo = data
symbol = MC bkg
solid line = atm
MC

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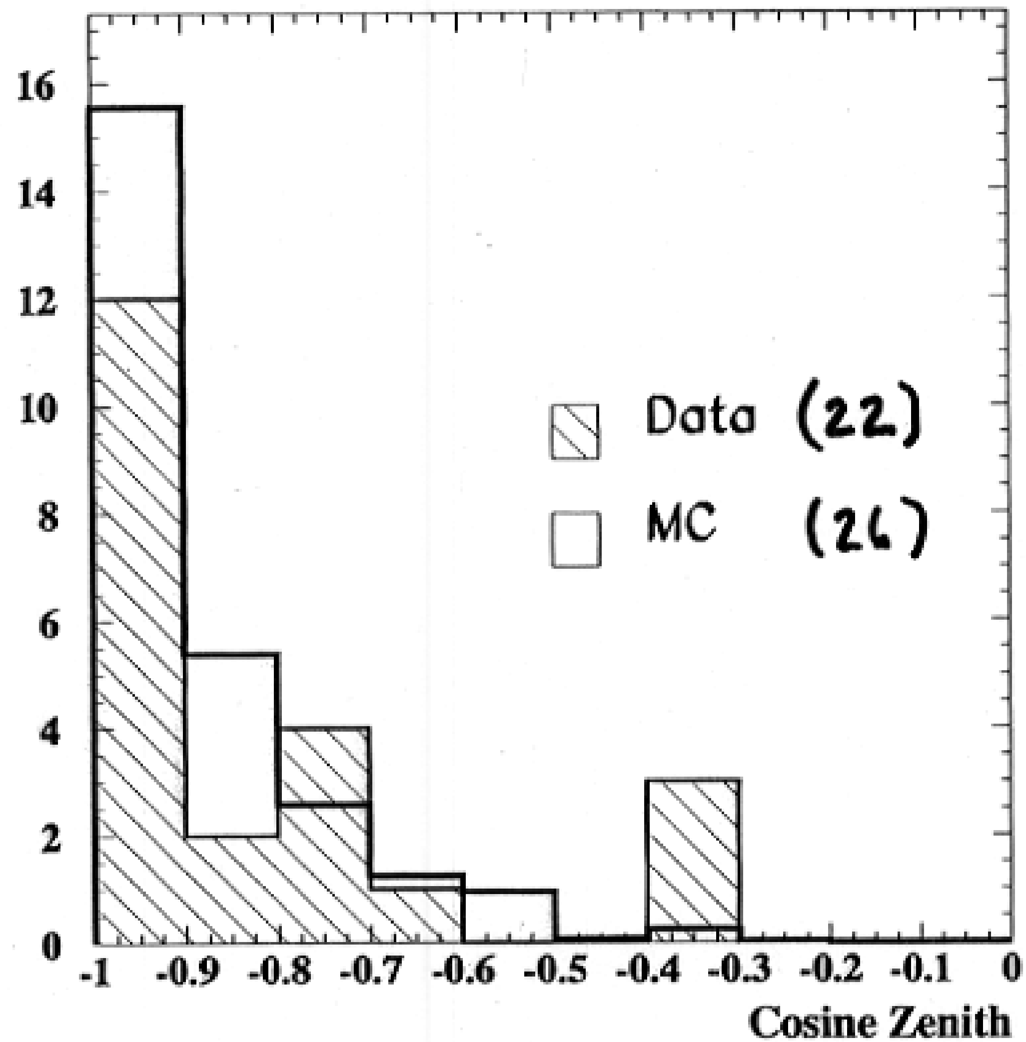
Angular distribution of Atm. ν candidates



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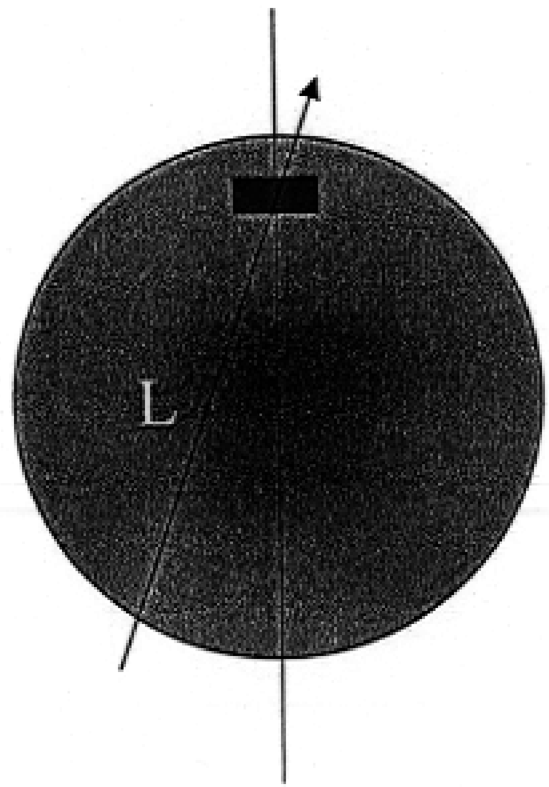
Neutrino oscillations using atmospheric neutrinos



$L \cong 2R_{\approx} \cos\theta_Z$

$P_{surv} = 1 - \sin^2 2\theta \, \sin^2(1.27\, L\, \Delta m^2/E)$

L in km

Δm^2 in eV^2

E in GeV

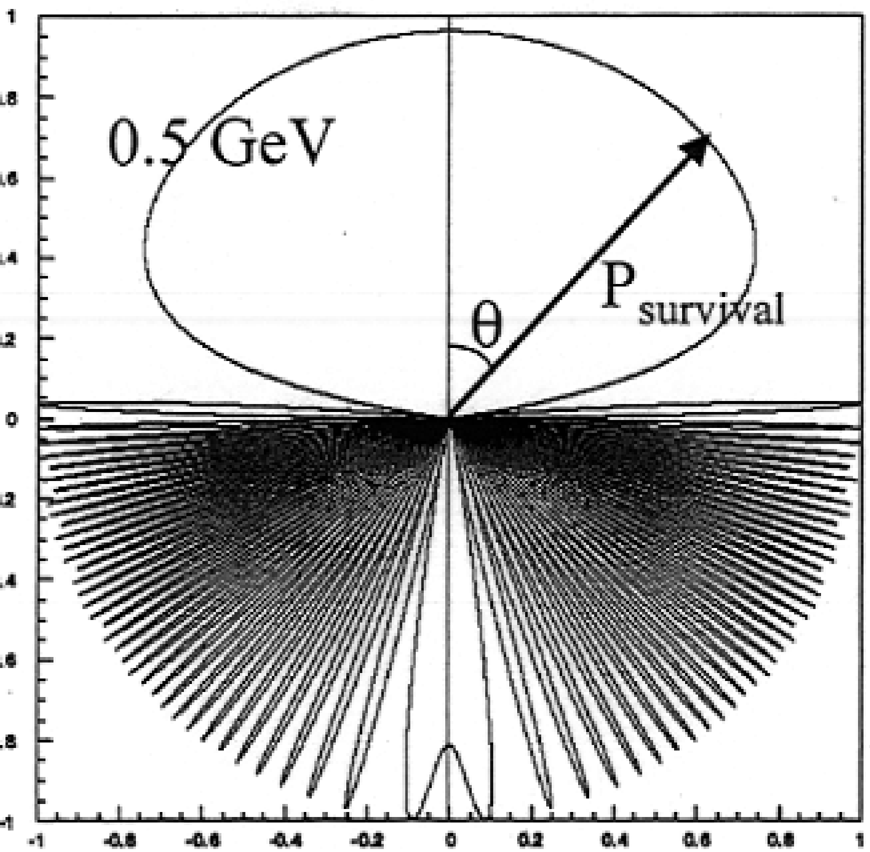
- Different L/E due to higher E_{thresh} than SK
- Energy resolution of contained events may be good enough to observe suppression feature

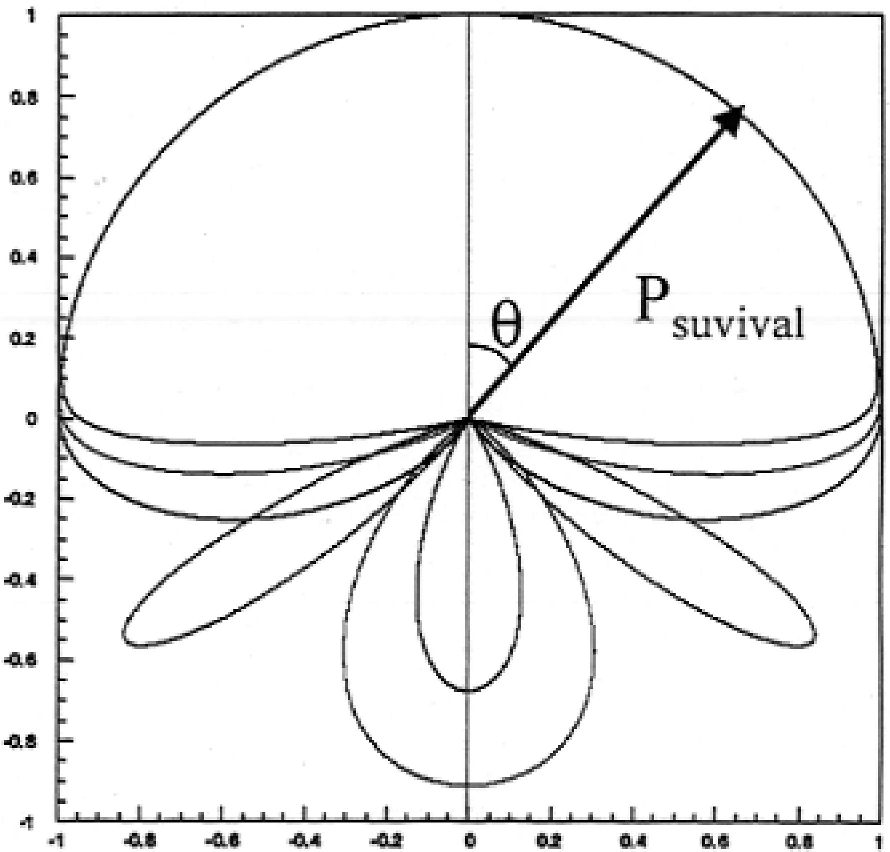
Atmospheric neutrinos

$P_{survival}$ = vector magnitude
θ = zenith angle pointing to the ν origin

E_ν = 10GeV
20 GeV
35 GeV

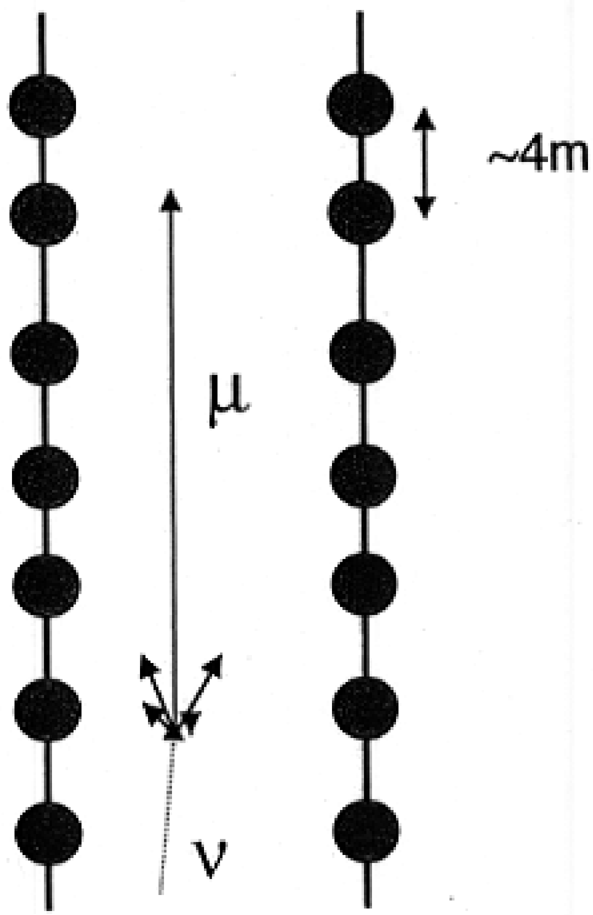
"Contained" events
Energy given by the muon range





Neutrino Oscillation Study

- For vertical Atm ν events
  - $E_{GeV}=L_{km}\delta m^2(eV^2)/1.2$ ~ 27 GeV
- Use high density in-fill of AMANDA-II
  - Utilize string architecture of HE ν-telescopes
  - Measure E_ν of contained events with calorimetry
  - Calibrate efficiency of vertical events with Am-A



-Use Am-II to veto atm muon background

-measure cascade and muon cherenkov light

-AMANDA 500m tall (E_μ < 100 GeV)

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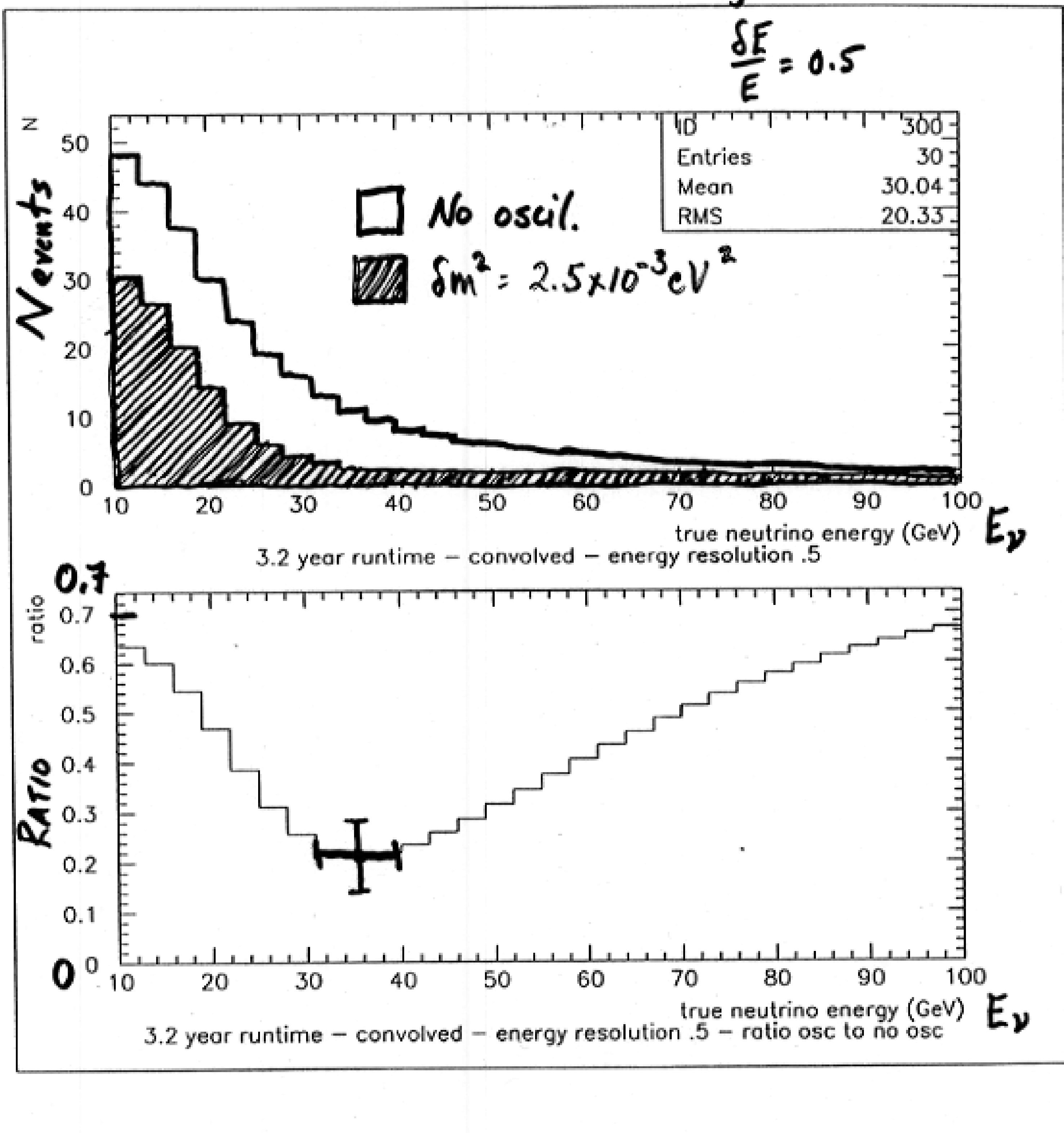
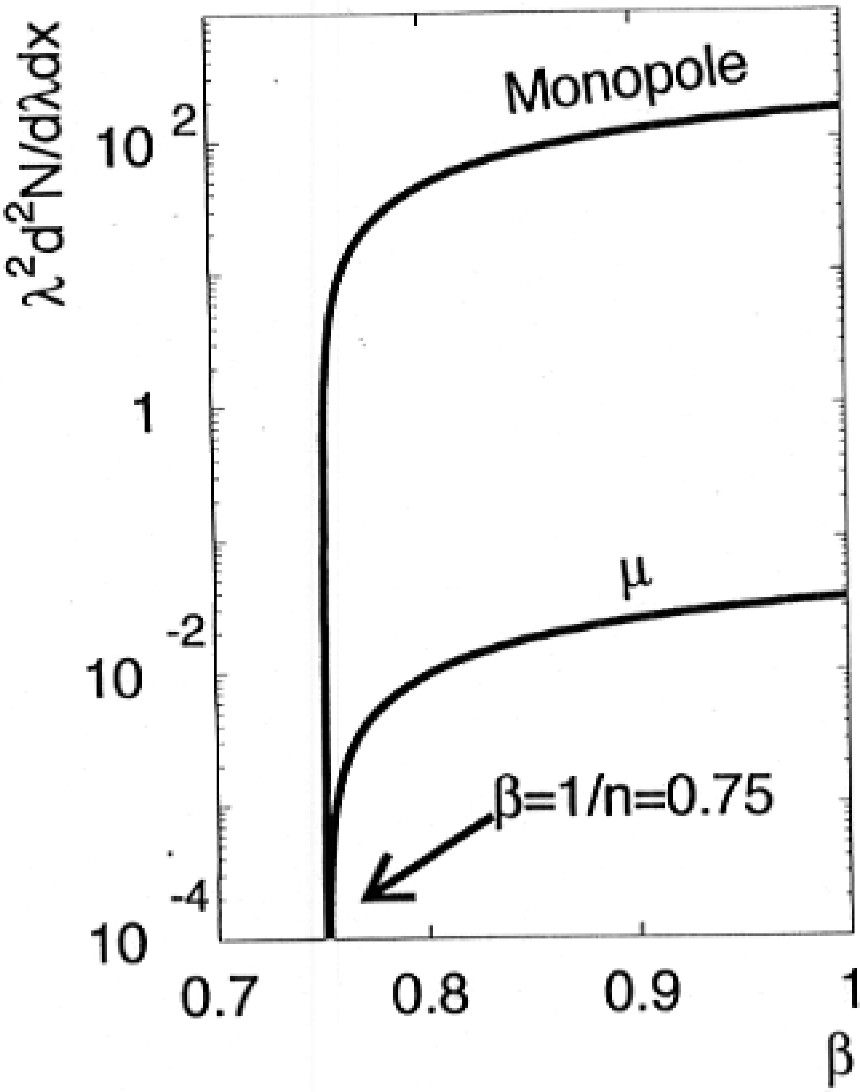
Atm ν : 26 string



Light Yield

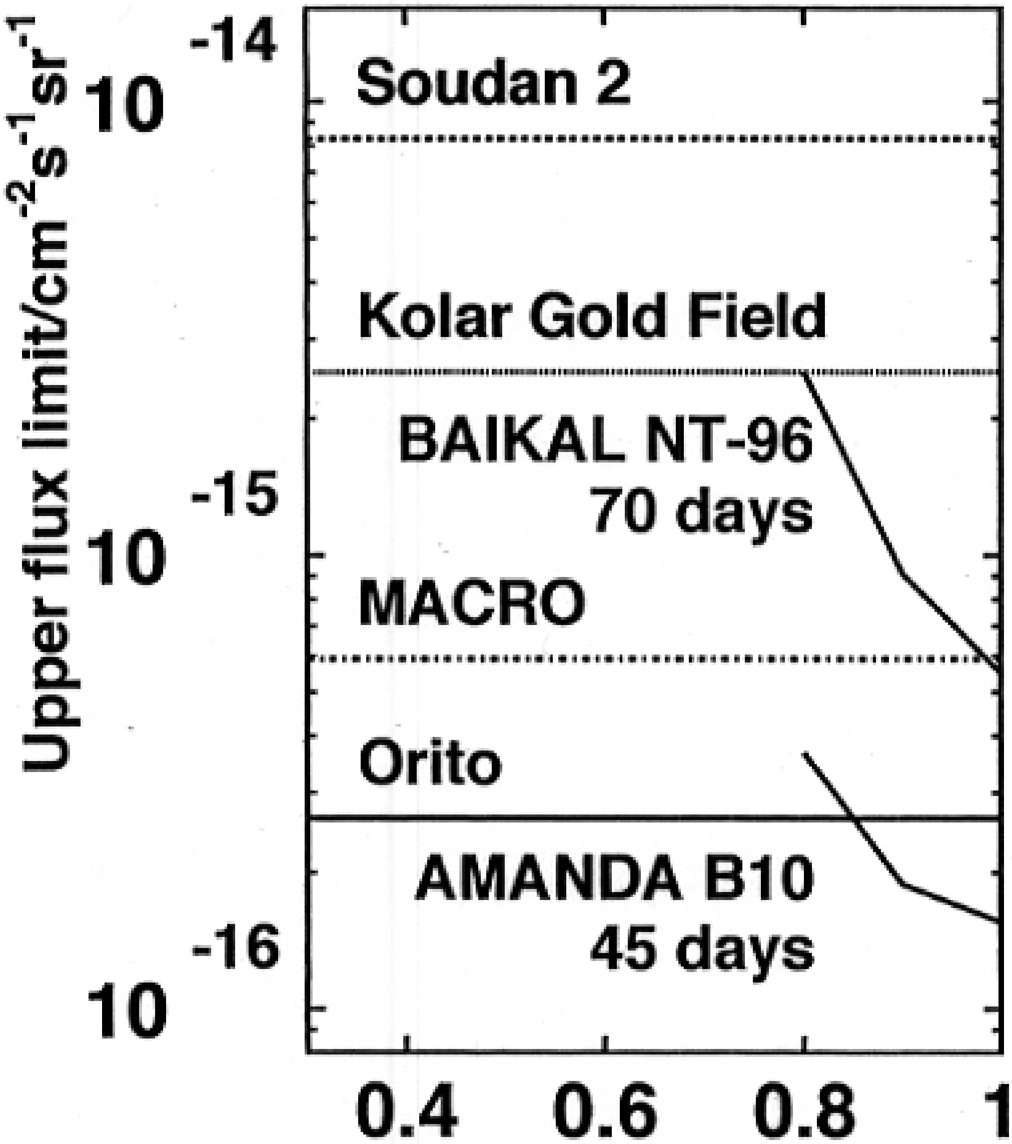
Due to $n^2(g/e) \approx 8300$, light production is highly enhanced above electrically charged particles.

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha n^2(\lambda)(g/e)^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$



Monopole and μ light yield

Upper flux limits (90%C.L.)



Supernova/GRB System

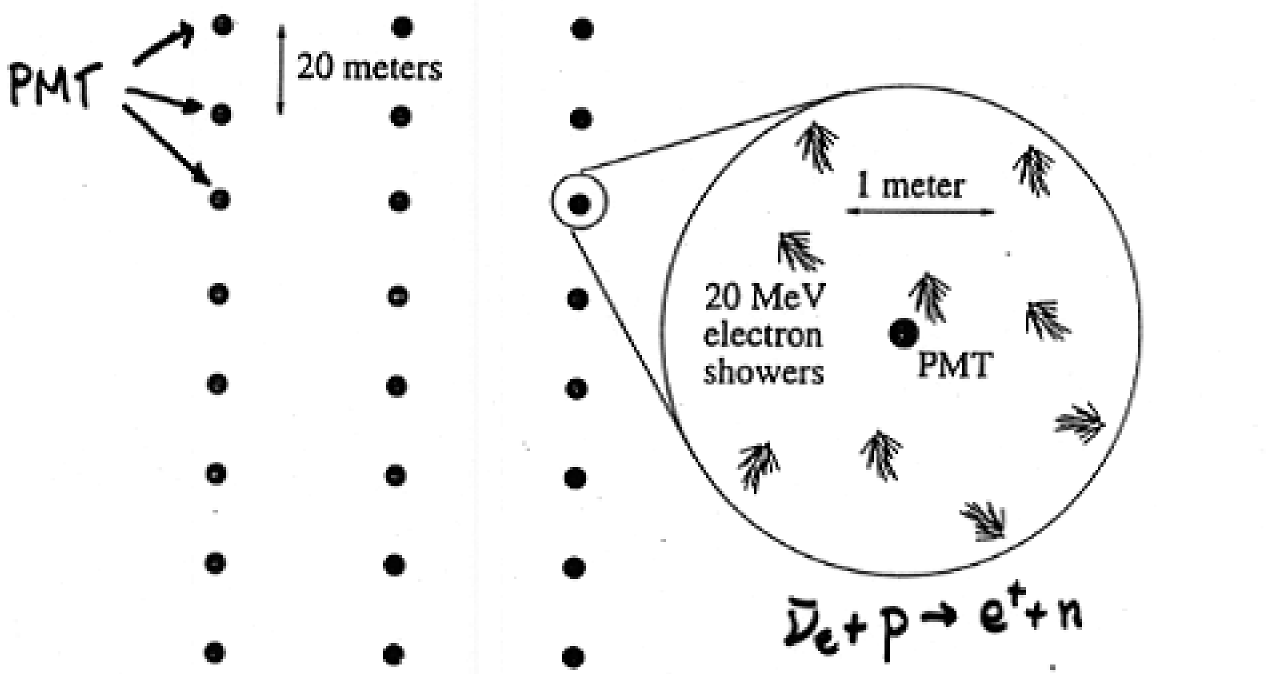
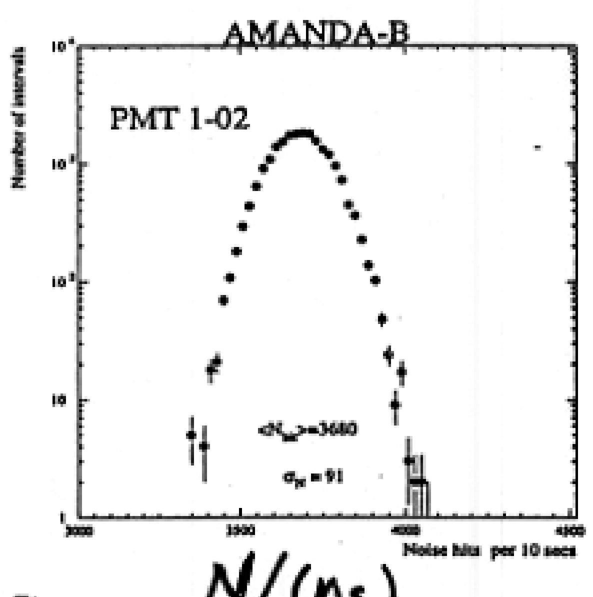
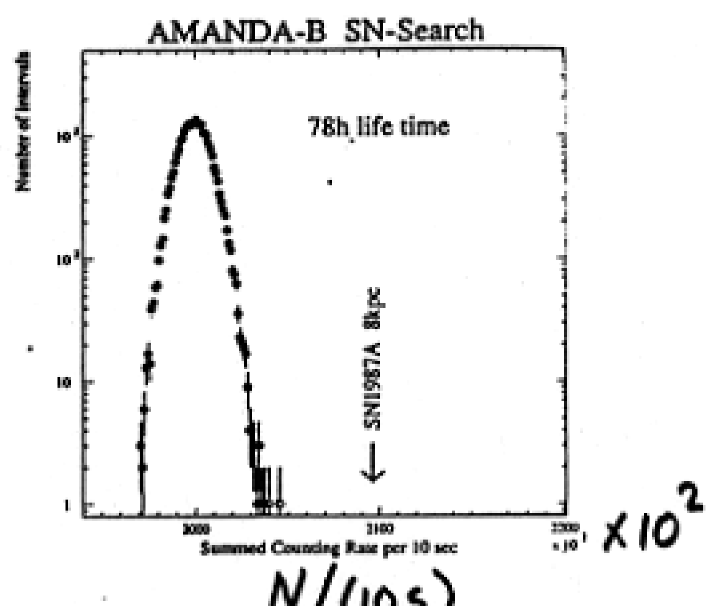


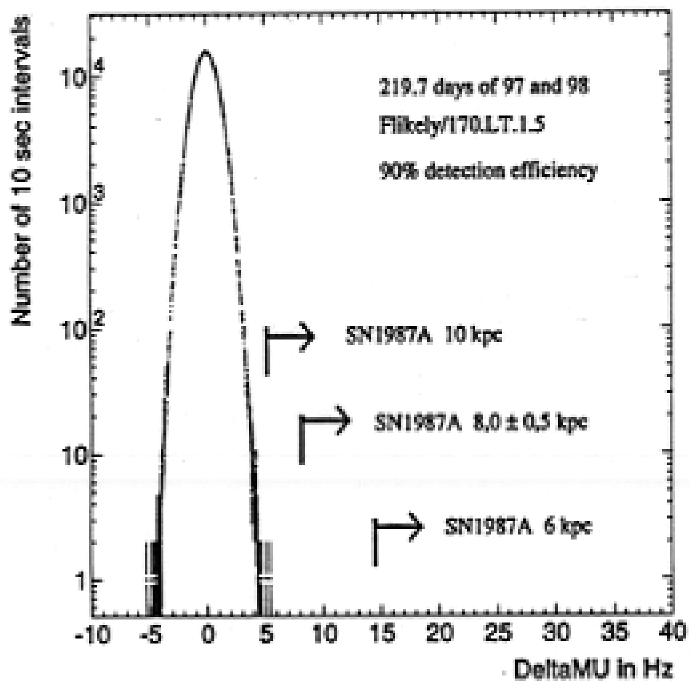
Figure 4: Underwater/ice detector as rate counters for burst like events. Note that the events shown in the insert do not appear simultaneously but are distributed over the duration of the burst.





AMANDA - Supernova ν-Search

SN-Search 1997/1998



$\Rightarrow$ **No Supernova seen in 1997/98.**

- **SN detectable up to center of galaxy with Amanda-B10**

  For 5000 PMTs we find $R_{MAX} \sim 25\text{kpc} \rightarrow$ full galaxy.

HE Neutrino Programs

AMANDA

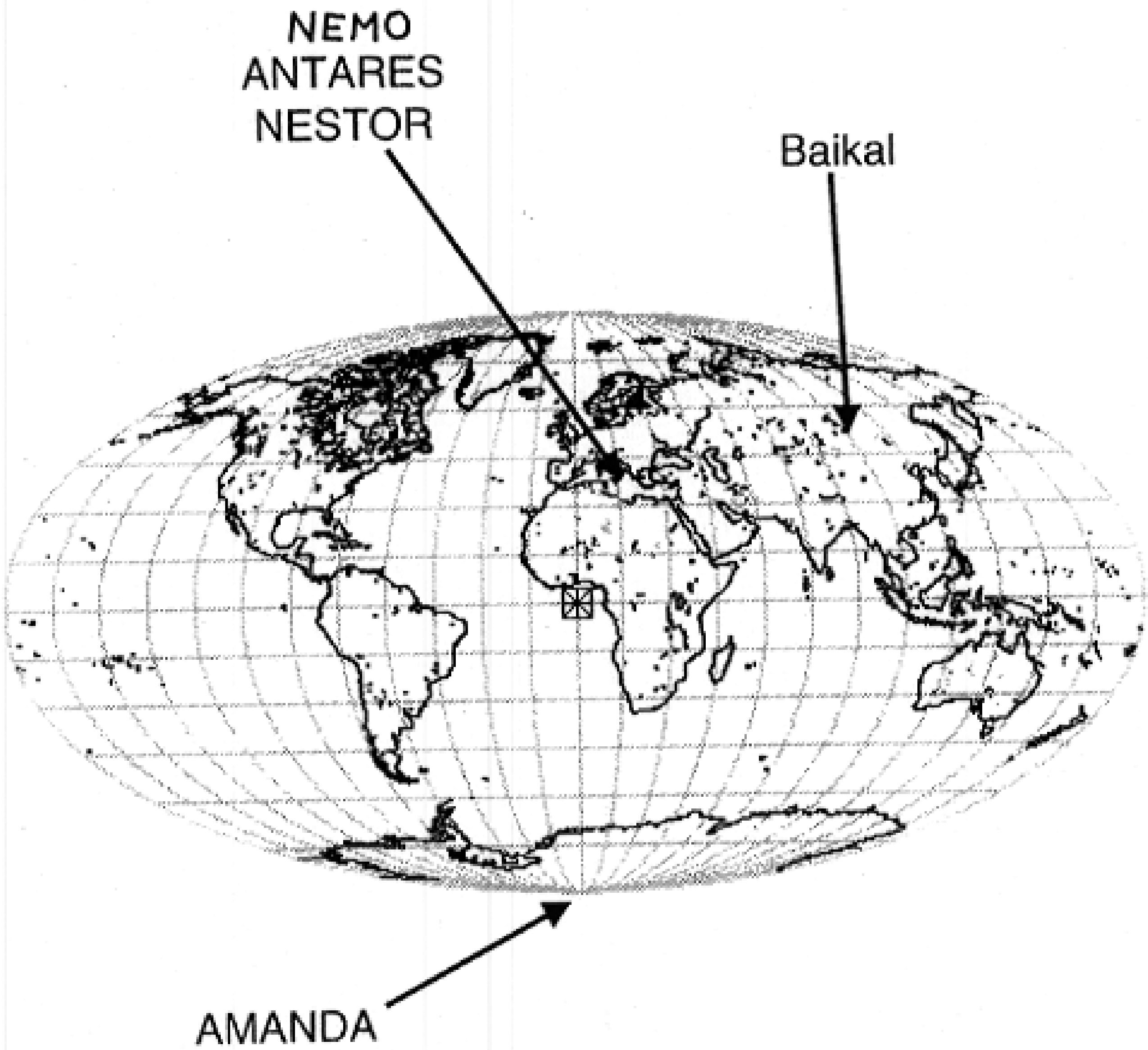
ANTARES

Baikal

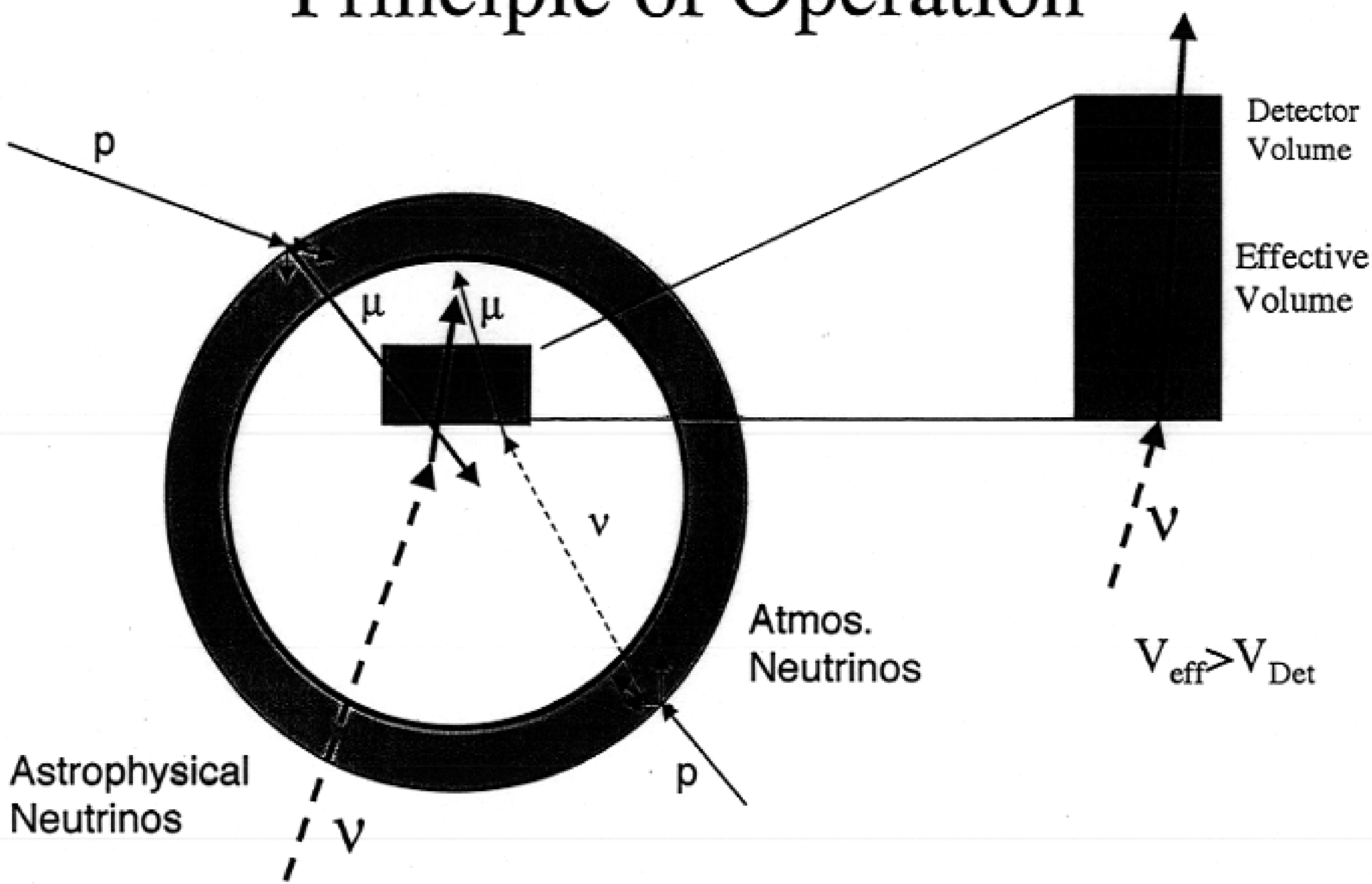
NT-200

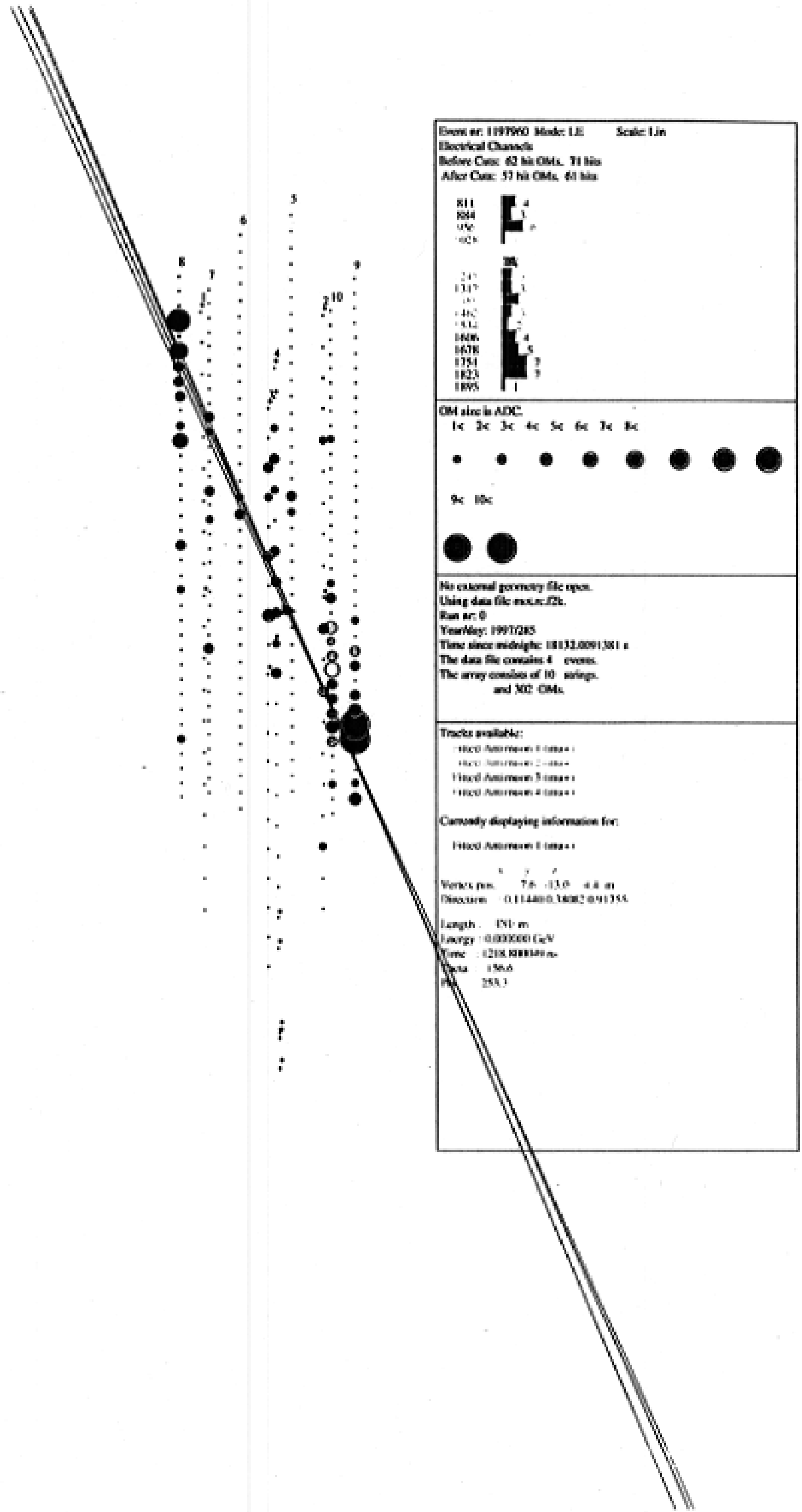
N E S T O R

Location of HE ν-detectors

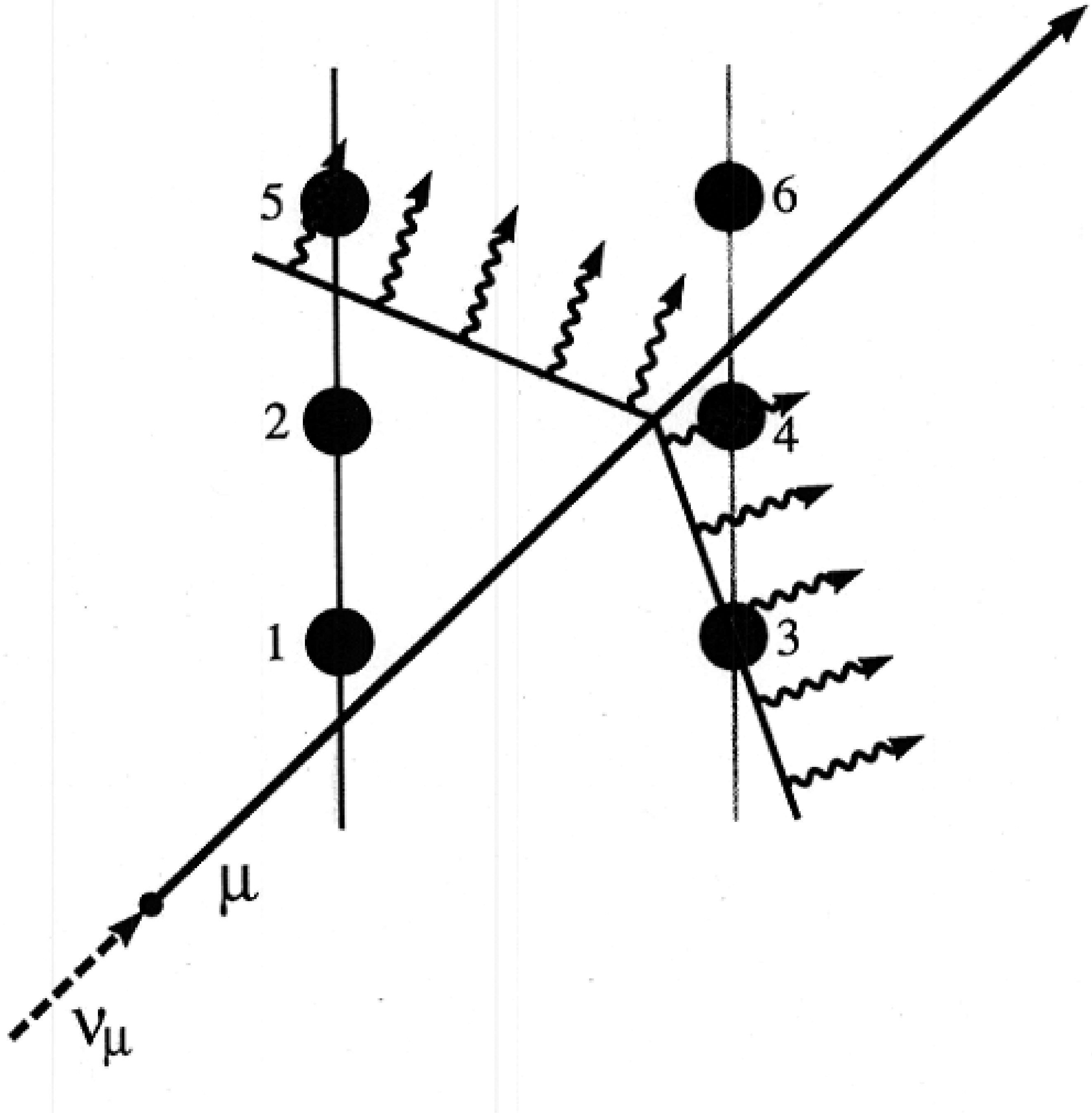


Principle of Operation

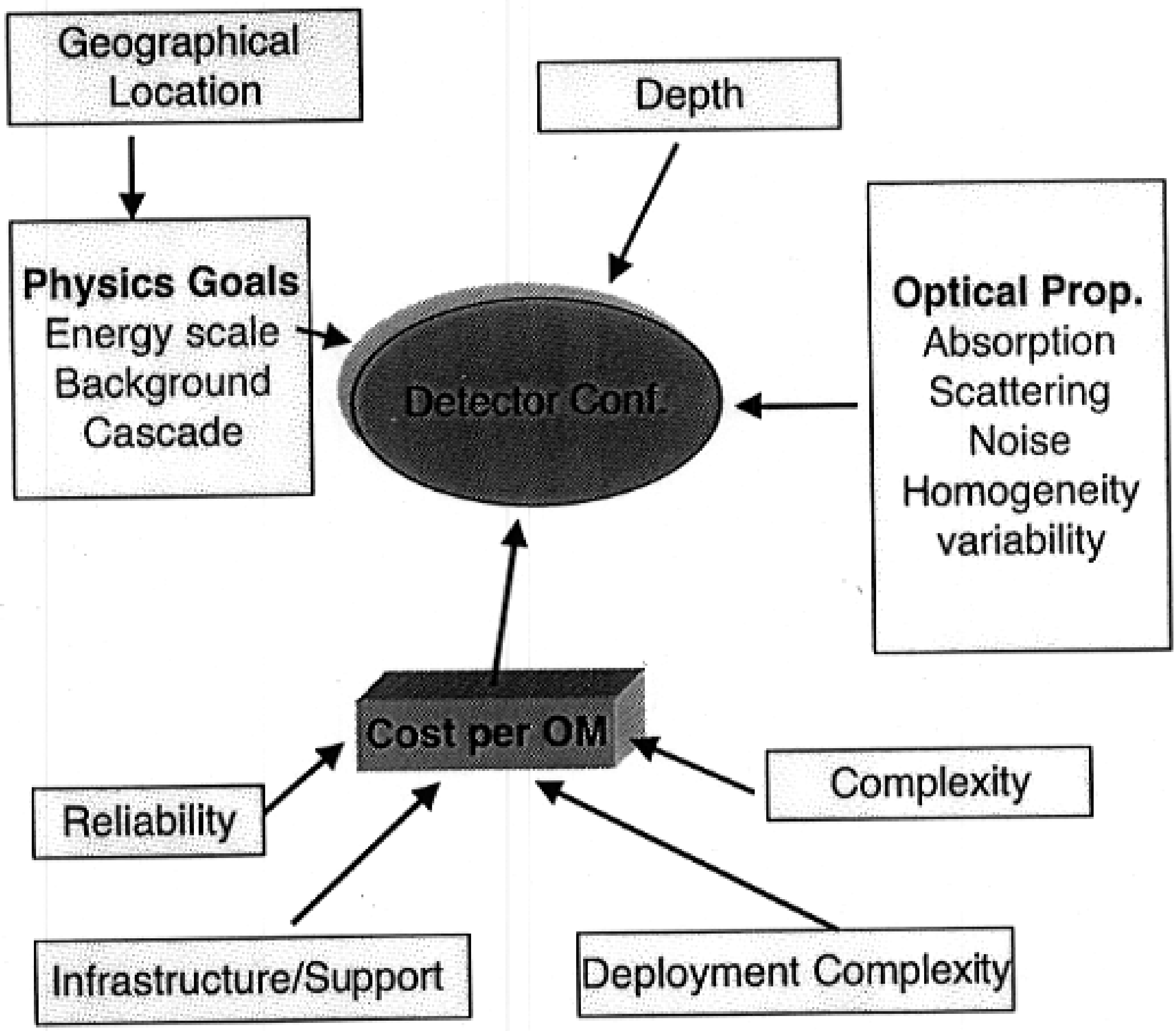



Scale: Lin
Electrical Channels
Before Cuts: 62 hit OMs, 71 hits
After Cuts: 57 hit OMs, 61 hits
OM size in ADC
1c 2c 3c 4c 5c 6c 7c 8c
9c 10c
No external geometry file open.
Using data file mor.ev.f2k.
Run nr: 0
Year/day: 1997/283
Time since midnight: 18132.0091381 s
The data file contains 4 events.
The array consists of 10 strings.
and 302 OMs.
Tracks available:
Currently displaying information for:
Vertex pos. 7.6 -13.0 -4.4 m
Length
Time : 1218.8000000 ns
5
6
8
7
9
10

Arrival times of Cherenkov wavefront give direction of muon



Parameters of ν-arrays



Search Strategies

Source	Rejection method	Background
Point Source (e.g., AGN)	1. up-down 2. direction 3. energy?	$(10^9$ /yr)(M) $x(d\Omega/2\pi)$
Bursts (e.g., GRB)	[illegible] 2. dire[illegible] [illegible] 4. energy?	[illegible]
Diffuse flux (e.g. Atm. ν)	1. up-down	$(10^9$/yr)(M)

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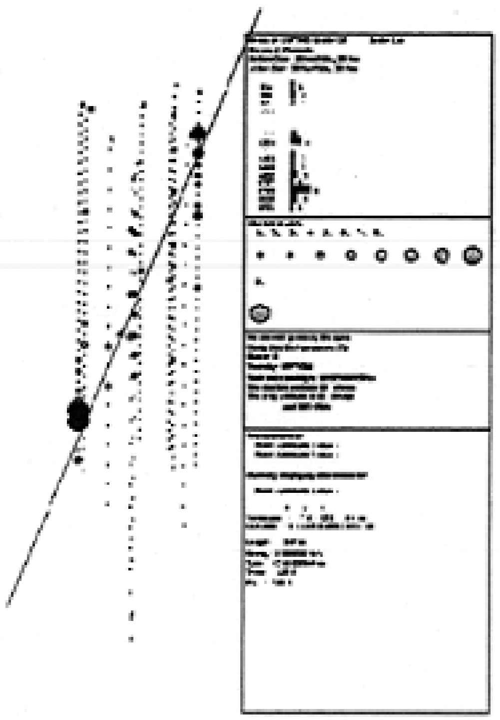
AMANDA Neutrino Telescope



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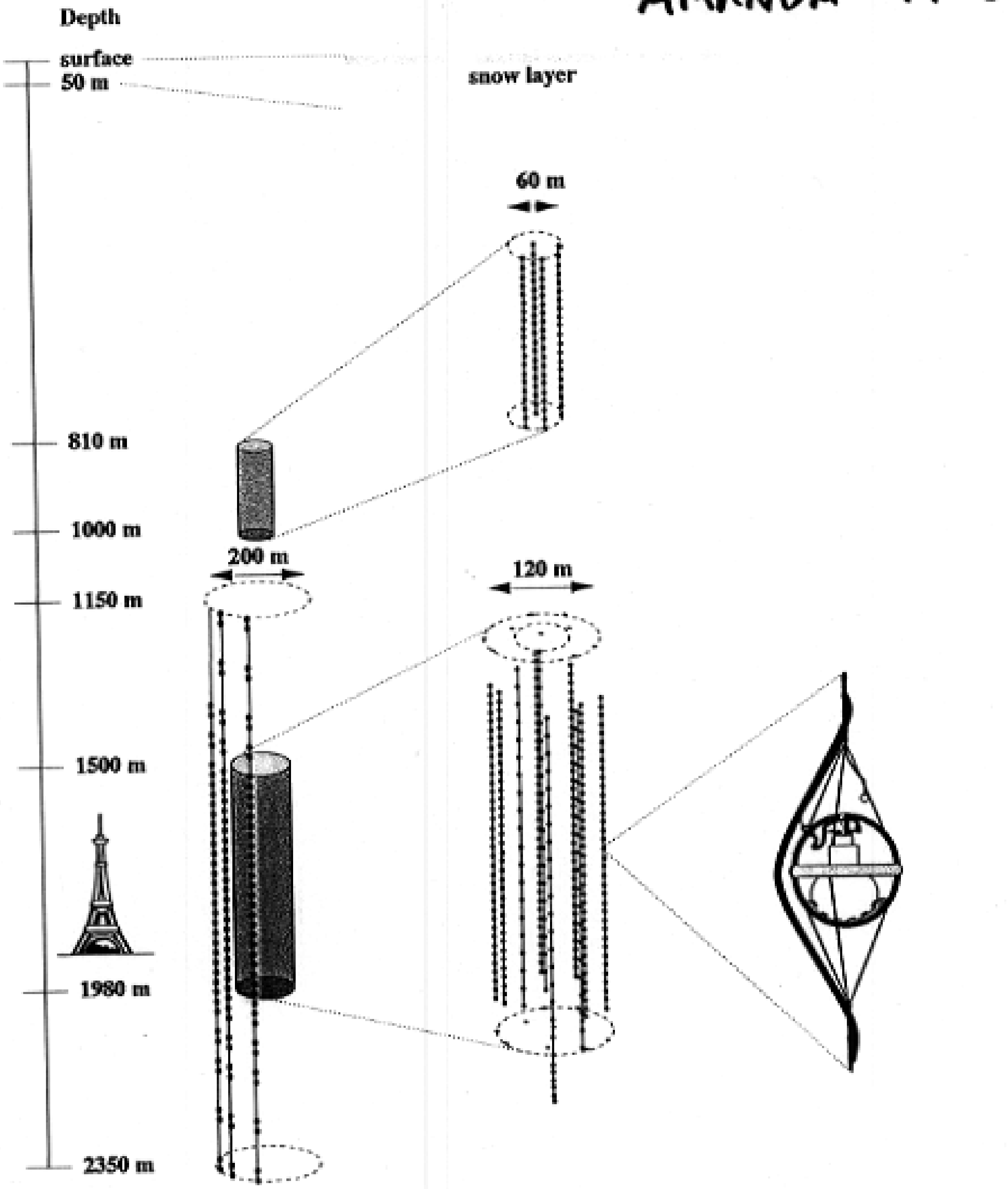
TAUP99 - Paris

AMANDA '99 CONFIG.



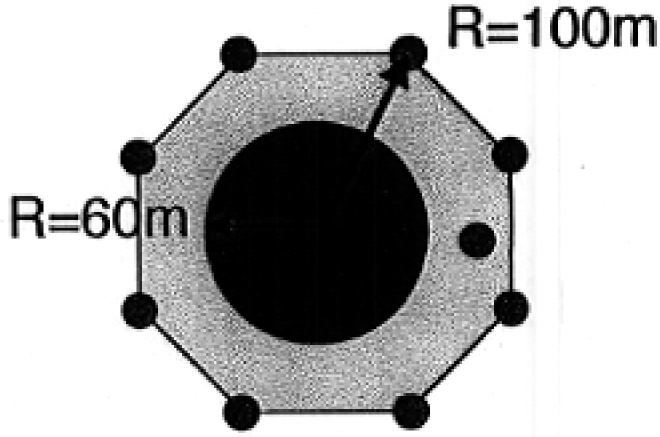
AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

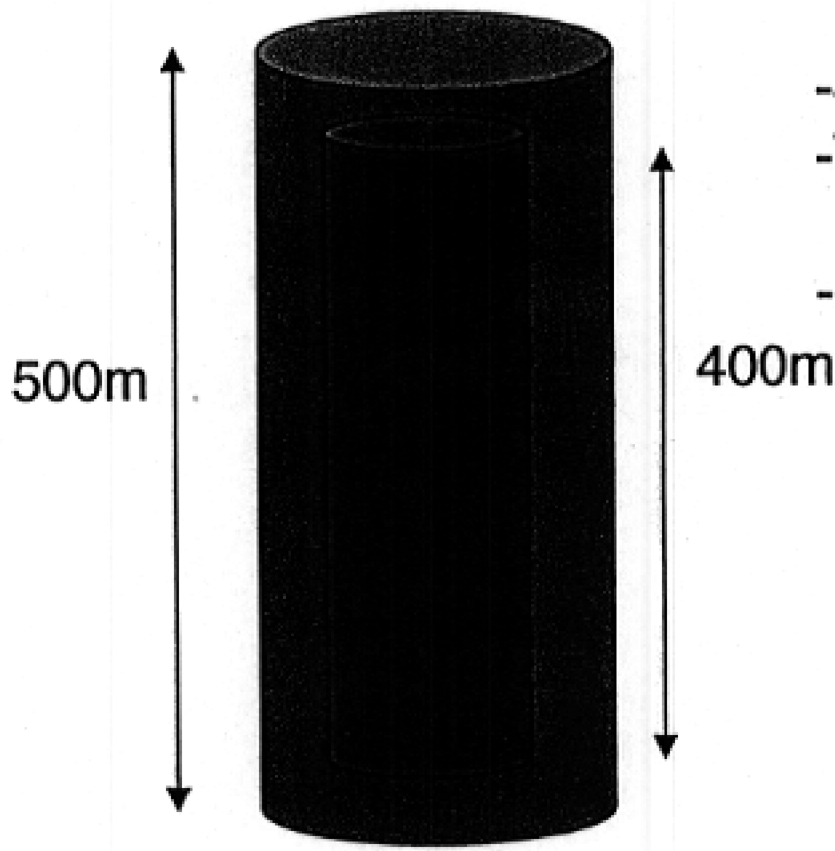
zoomed in on one
optical module (OM)

- 15 institutions from US and Europe

AMANDA-II



- AM-II string ('00)
- Am-B array ('97)



-42 Hybrid OMs/string
-Test bed for new technology
-Good ice 1400m-2300m

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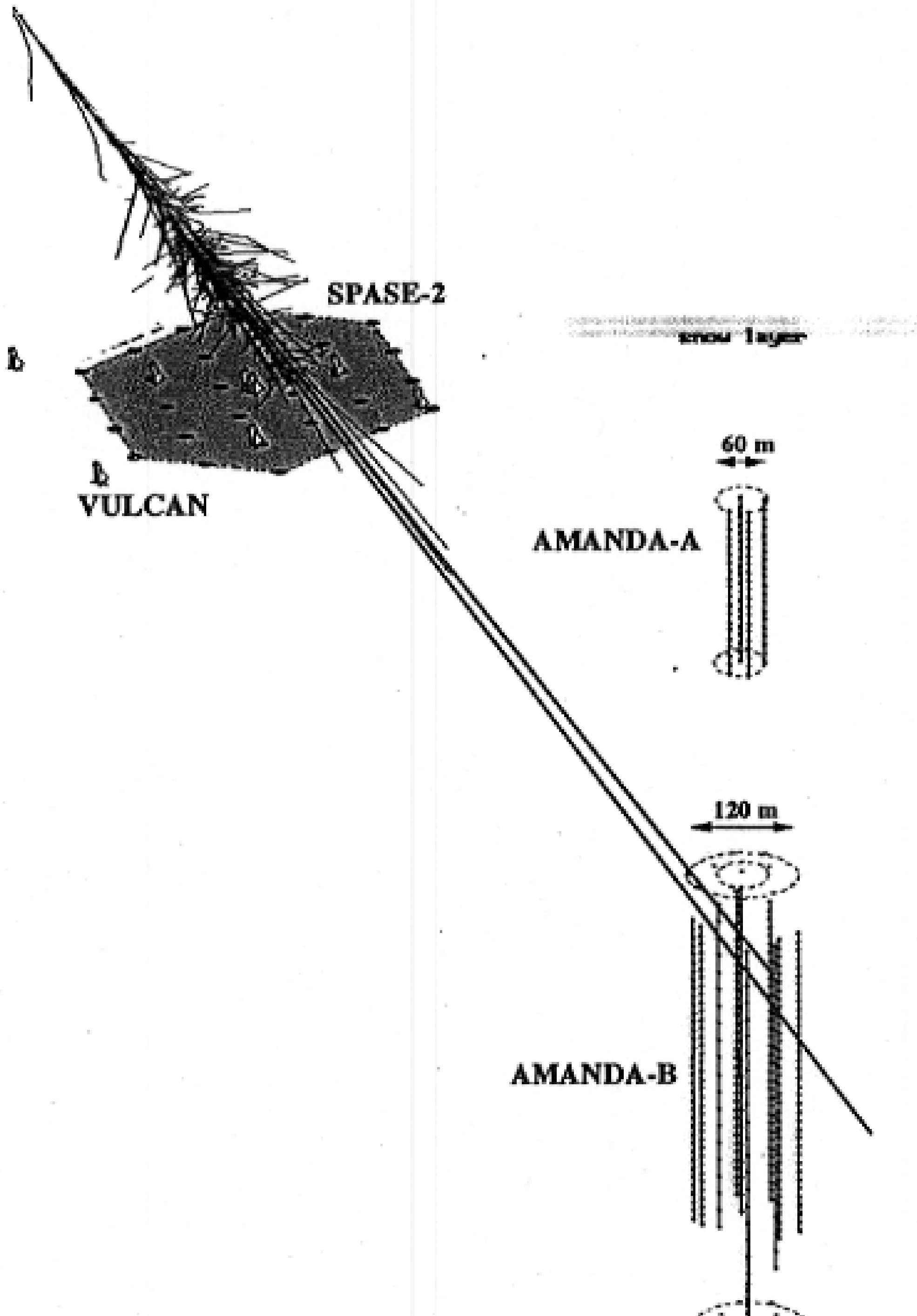
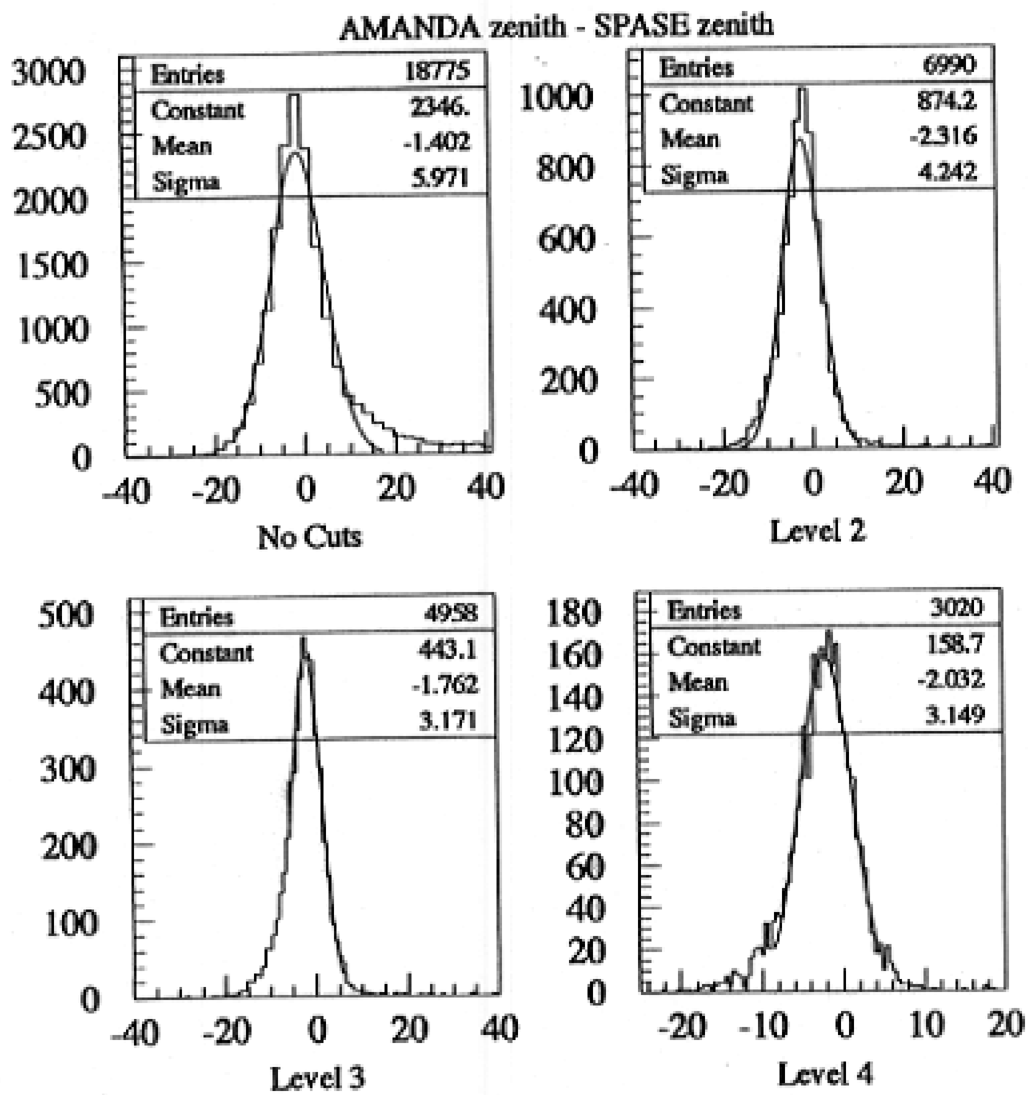
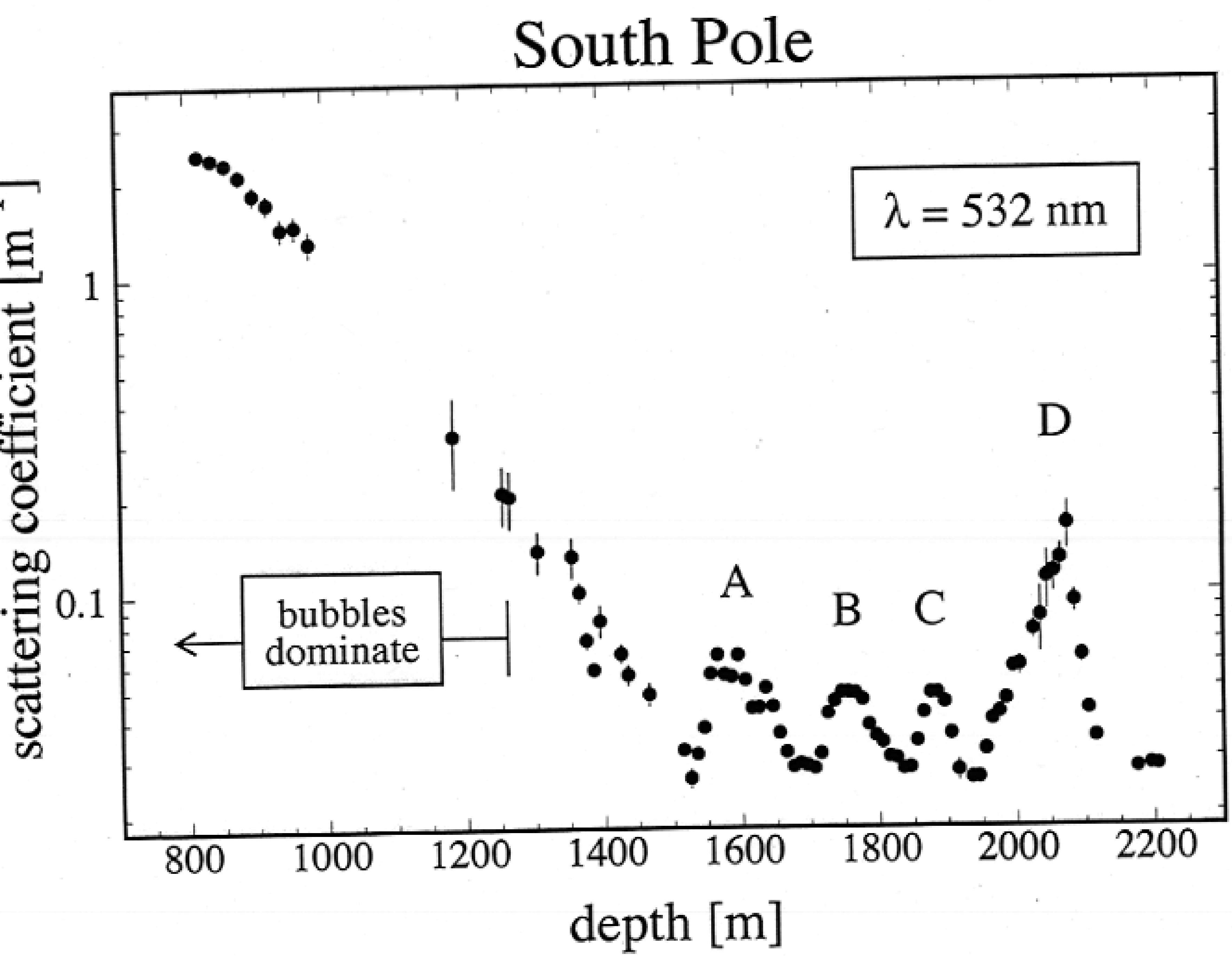

SPASE-2
snow layer
VULCAN
60 m
AMANDA-A
120 m
AMANDA-B

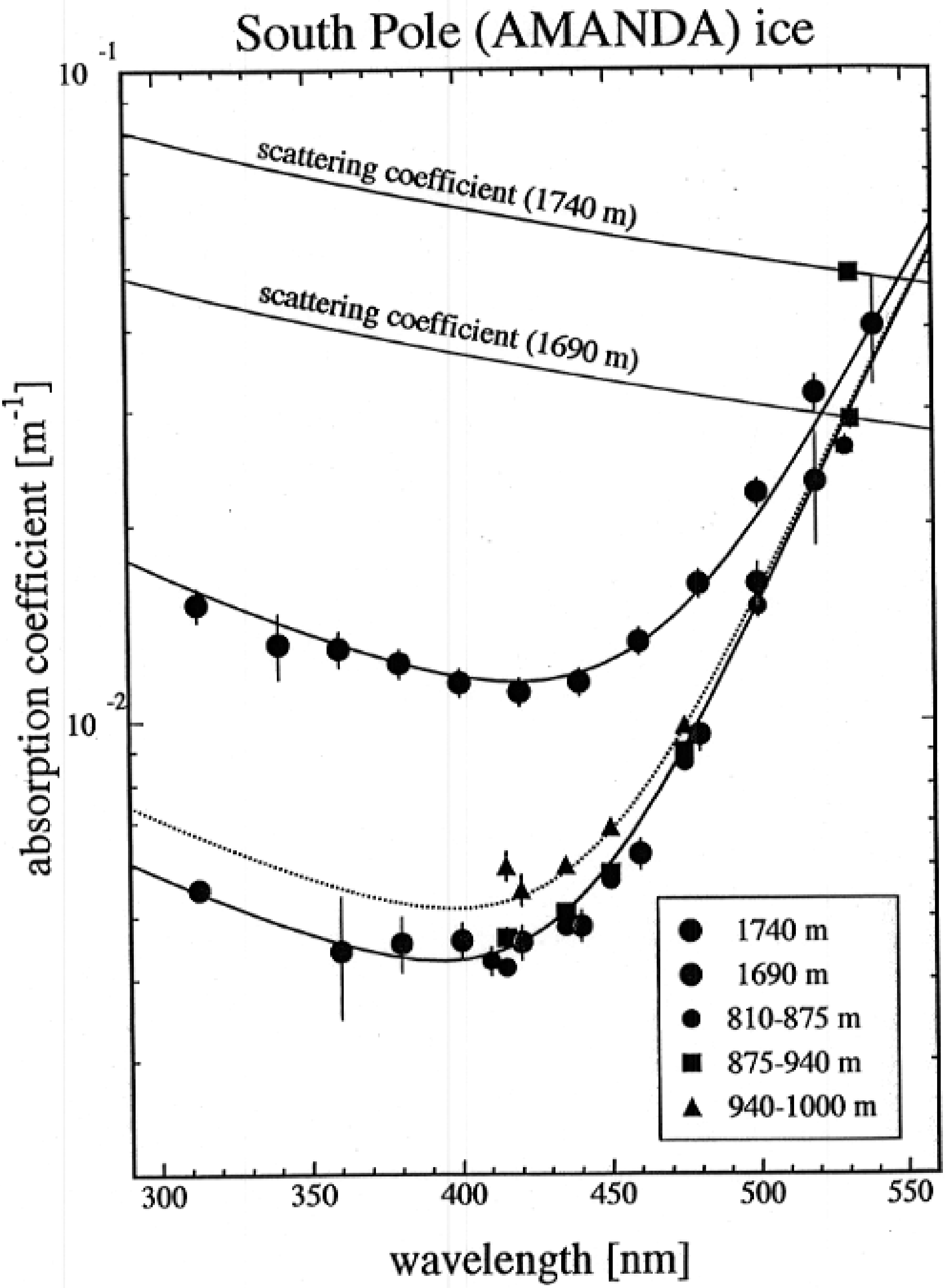
Pointing Calibration Spase-2/Amanda-B10

1 **Standard AMANDA Cuts defined in HE 6.3.02**

- **σ (at Level 4) = 3.1 $\pm$ 0.1 °**
- **Mean = -2.0 $\pm$ 0.1 °**




South Pole
λ = 532 nm
scattering coefficient [m^-1]
1
0.1
bubbles dominate
A
B
C
D
800
1000
1200
1400
1600
1800
2000
2200
depth [m]


South Pole (AMANDA) ice
scattering coefficient (1740 m)
scattering coefficient (1690 m)
1740 m
1690 m
810-875 m
875-940 m
940-1000 m
absorption coefficient [m^{-1}]
wavelength [nm]
10^{-1}
10^{-2}
300
350
400
450
500
550

Baikal - NT200

http://www.ifh.de/baikal/baikalhome.html

Located at Lake Baikal, Siberia

1100 m depth

Absorption ~20m and seasonally dependent

Status:

Completed NT-200 : Apr 98

~2000 m² detector for E_μ ~ 1 TeV

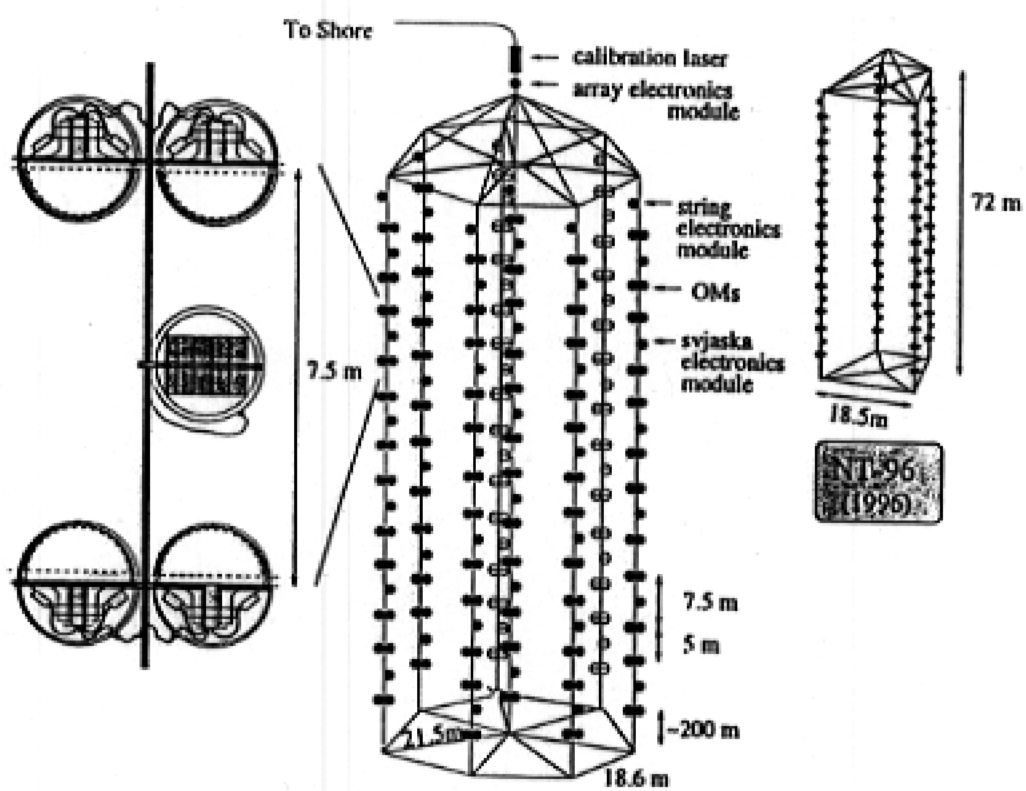
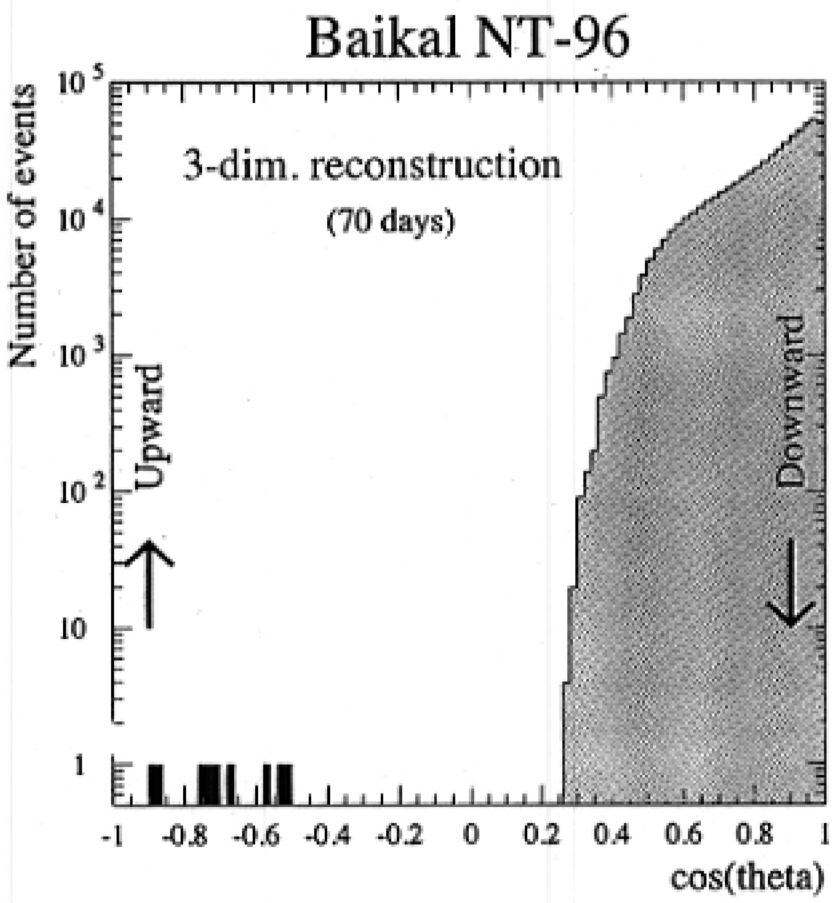


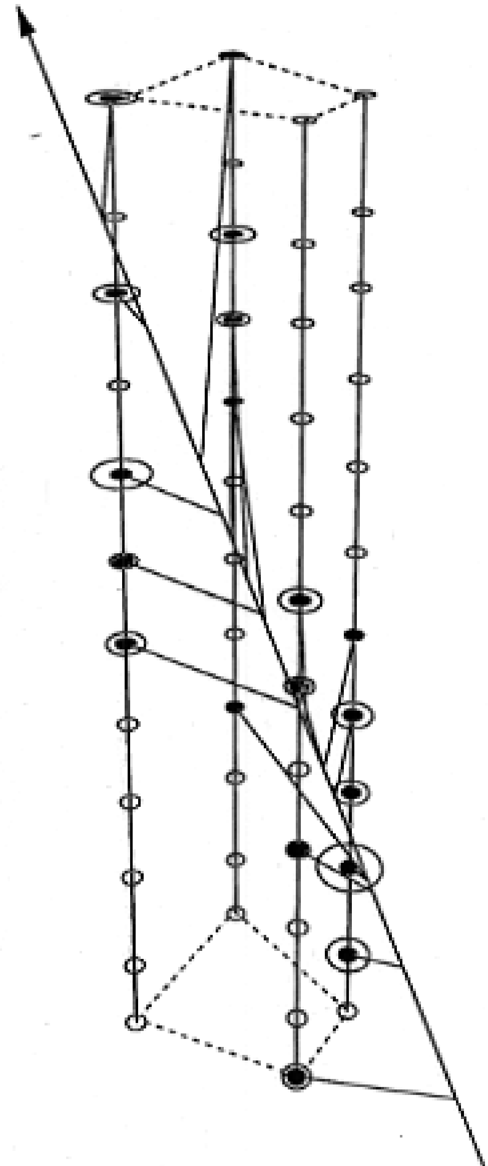
Figure 2: Sketch of the NT-200 detector. Top right the 1996 stage NT-96 is shown.

Baikal ν-events

First clear evidence for HE neutrino detection

9 events in 70 days using NT-96





ANTARES demonstrator

http://antares.in2p3.fr/antares/

40 km off-shore from Toulon, France

2400m depth

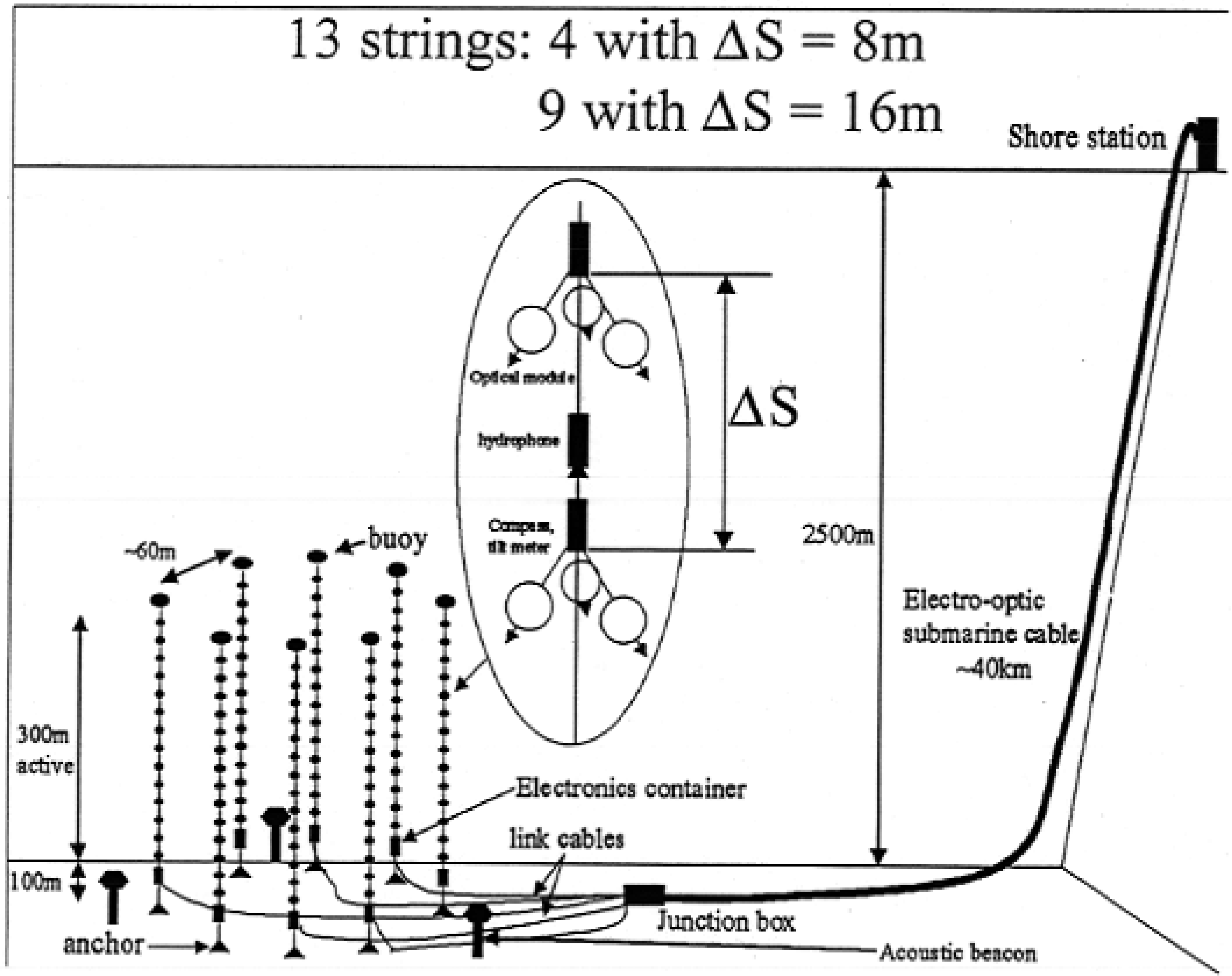
Nearly complete tests of environment at site

- ~100 days of in-situ data
- Biofouling a problem only for upfacing OMs
- Sea current and optical noise OK
- Attenuation length = 41+- 1m @ 466 nm

Schedule:

40 km electro-optical cable:	May 98	Broke '98
Mechanical tests of a full string:	Jun 98	✓
Connection with submarine:	Sep 98	✓
Partially equipped string (8 OMs):	~~End 98~~	Oct '99
Deploy full equipped string:	~~End 99~~	TBD

ANTARES

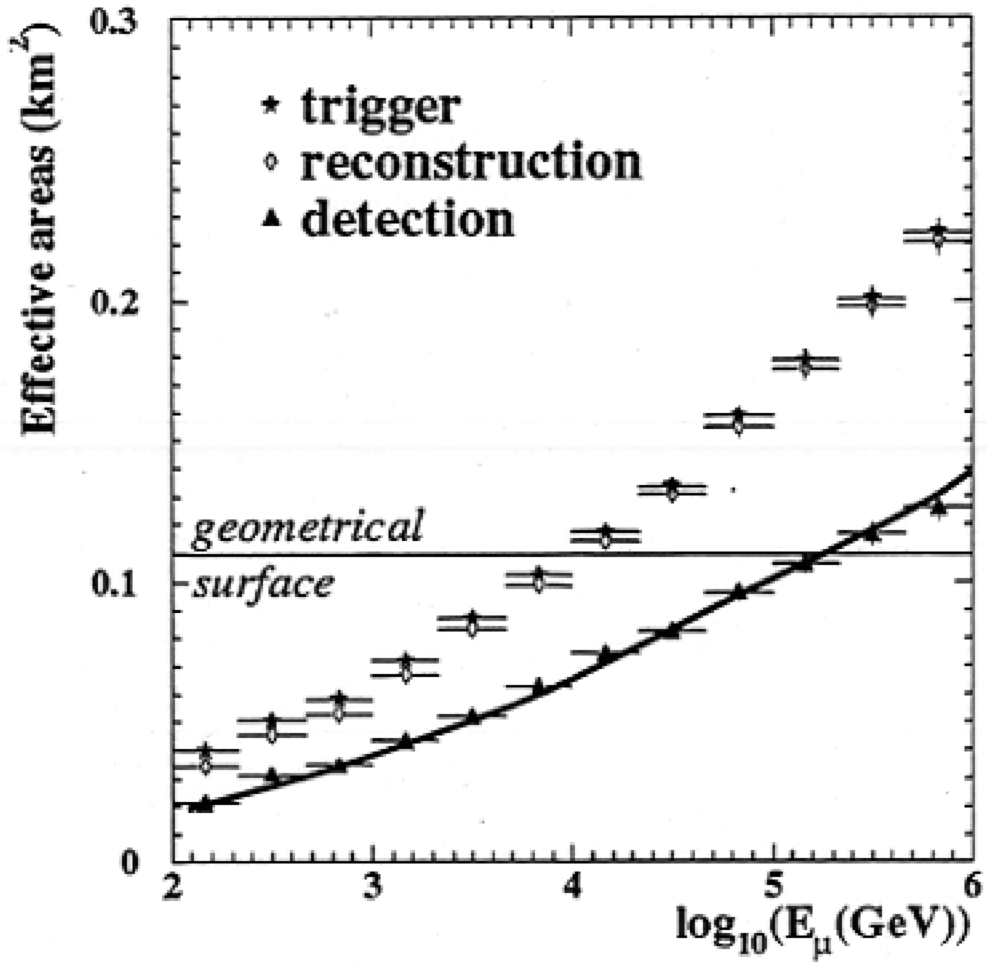

13 strings: 4 with ΔS = 8m
9 with ΔS = 16m
Shore station
Optical module
hydrophone
Compass, tilt meter
ΔS
2500m
~60m
buoy
Electro-optic submarine cable ~40km
300m active
100m
Electronics container
link cables
Junction box
anchor
Acoustic beacon

Effective area for ANTARES

Convolution of the generation area and detector efficiency

$A_{eff} = 0.03\ km^2$ @ 1 TeV

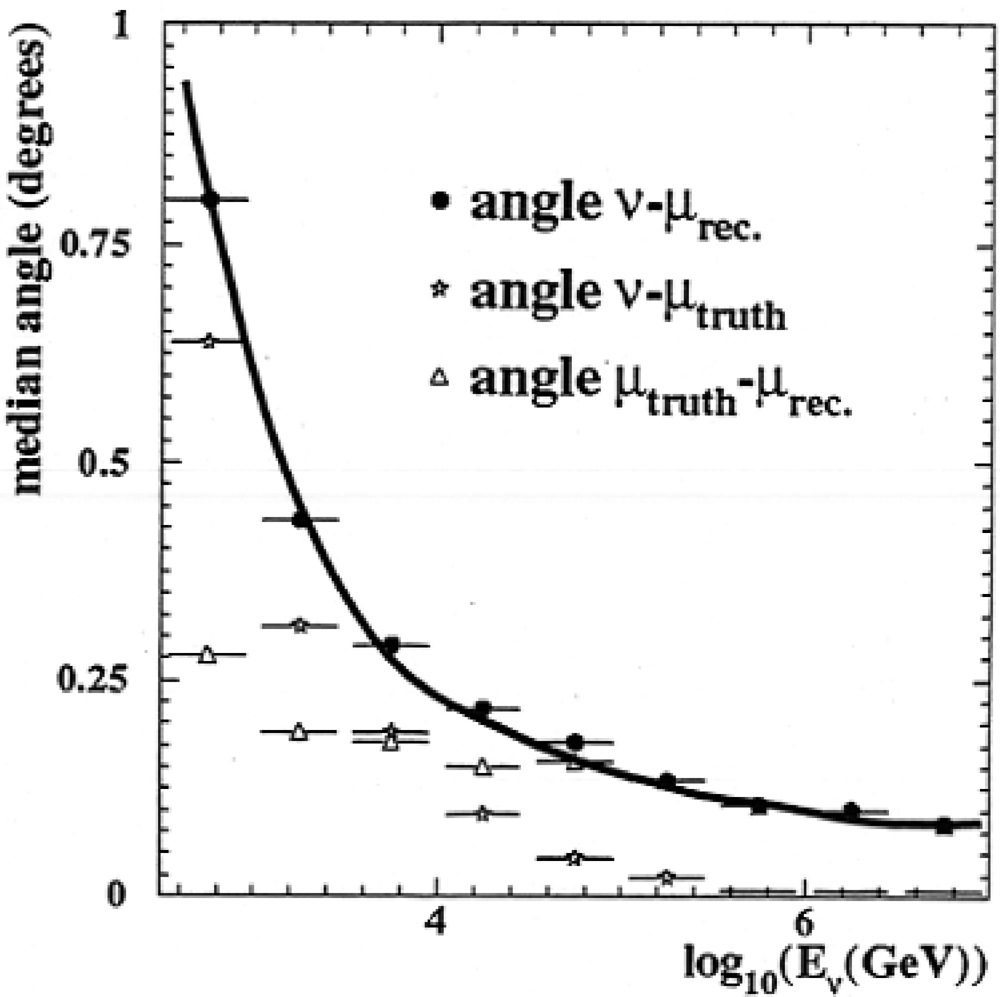
$A_{eff} = 0.1\ km^2$@100 TeV



ANTARES: angular resolution

Excellent angular resolution is expected from simulations, so absolute pointing mus[t] be demonstrated

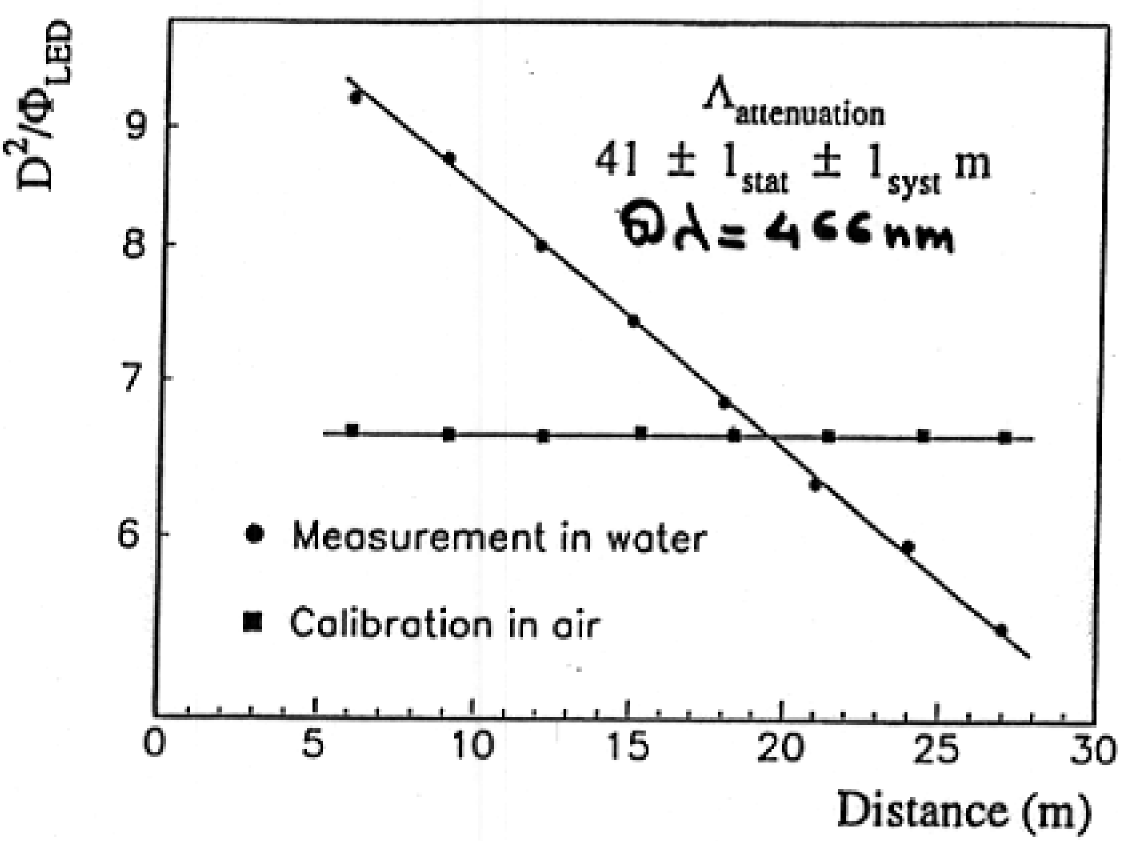
θ = angle between the true direction of the ν and the reconstructed direction of the μ



Optical atten. len. @ Antares

Wavelength = 466 nm

Determination of $\Lambda_{attenuation}$



D: Distance between LED and PMT

Φ_{LED}: LED luminosity to obtain a constant current on PMT

NESTOR

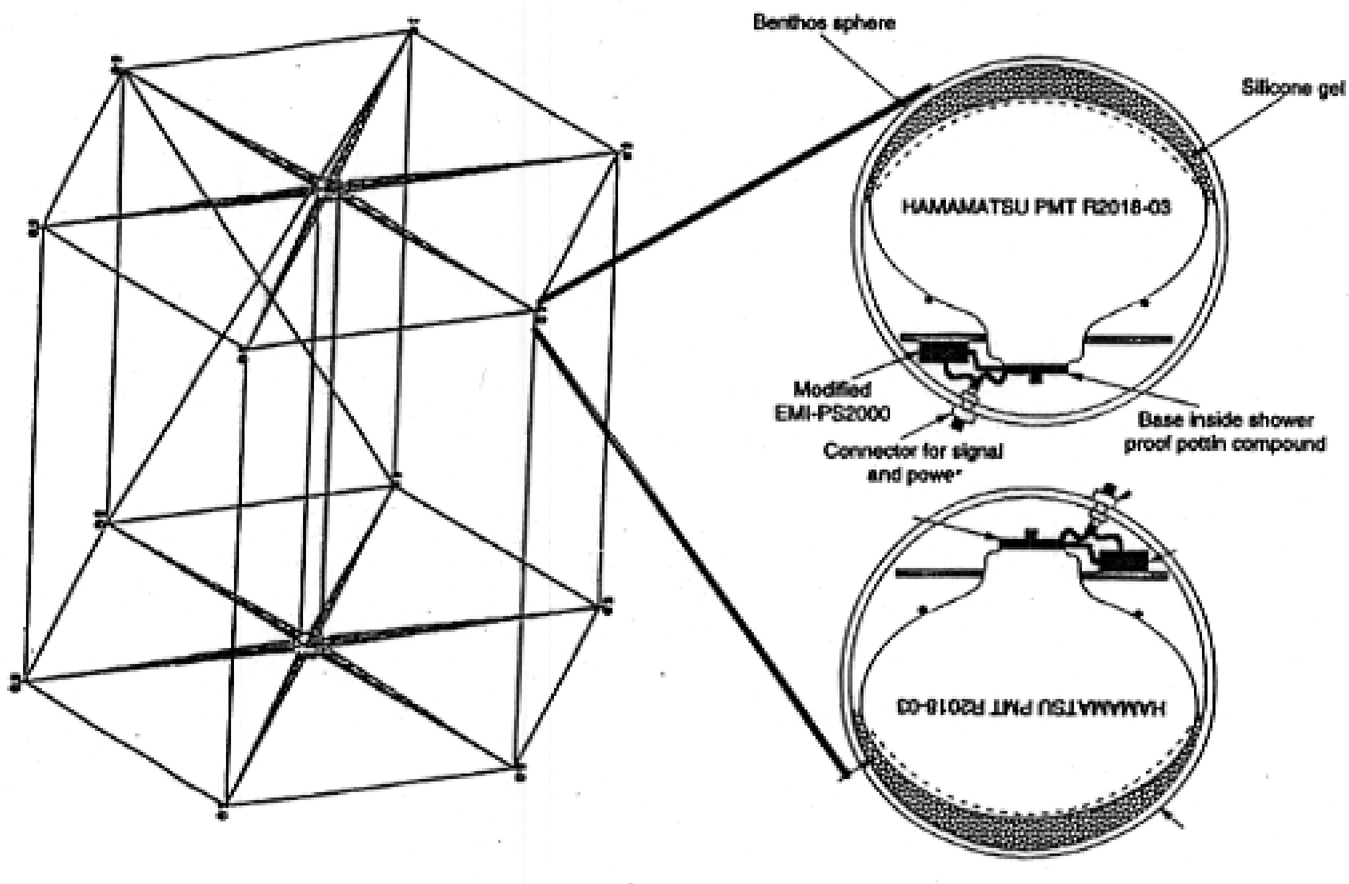
http://abyss.hepl.uoa.ariadne-t.gr

Site ~16 km off-shore of Pylos, Greece

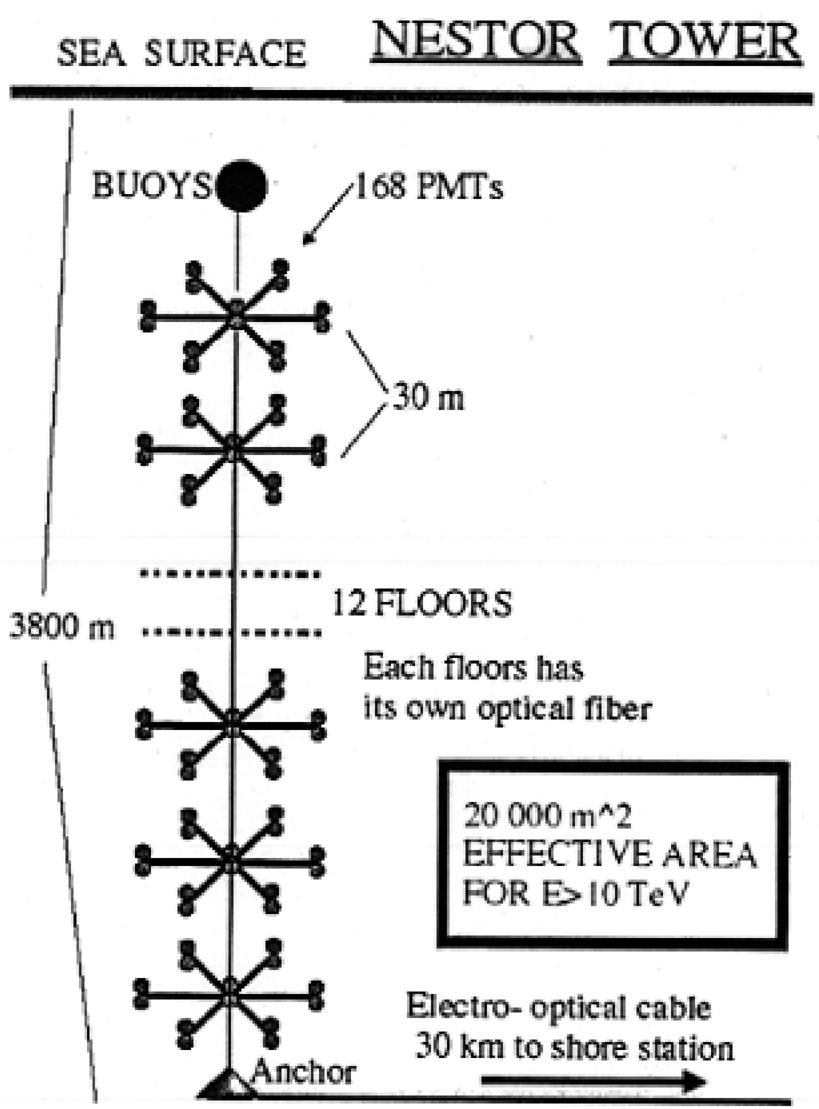
3800m depth

Status:

Bay station operational :	Jun 98	
Practice deployment in shallow bay:	Jul 98	Elec. failu
Electro-Optic cable ordered:		
Deploy 2 of 12 floors at site :	~~Sep 98~~	Early '00
Deploy complete 12 floors :	~~~May 99~~	TBD



NESTOR



Main components	Need (1 Tower)	Have
PMTs (15")	168	248
BENTHOS spheres	268	350
Mechanics (Floors)	12	5 (3 Al, 2 Ti)
Electronics (Floor module)	12	Only prototypes
E/O cable (18 fibers)	1	Ready in Pylos To be deployed

TEST STATIONS:

BAY STATION	ACTIVE
DEEP SEA STATION	READY

NEMO

(Italy)

- (Another) study of deep sea optical properties in selected sites of Ionian and South Tyrrhenian Sea
- R&D on undersea electronics

Detection of >PeV ν's: Radio and Acoustic

- Coherent Cherenkov emission at radio wavelengths + low attenuation in ice
- Acoustic is less efficient than Radio
- Signal size unverified; backgrounds starting to be studied

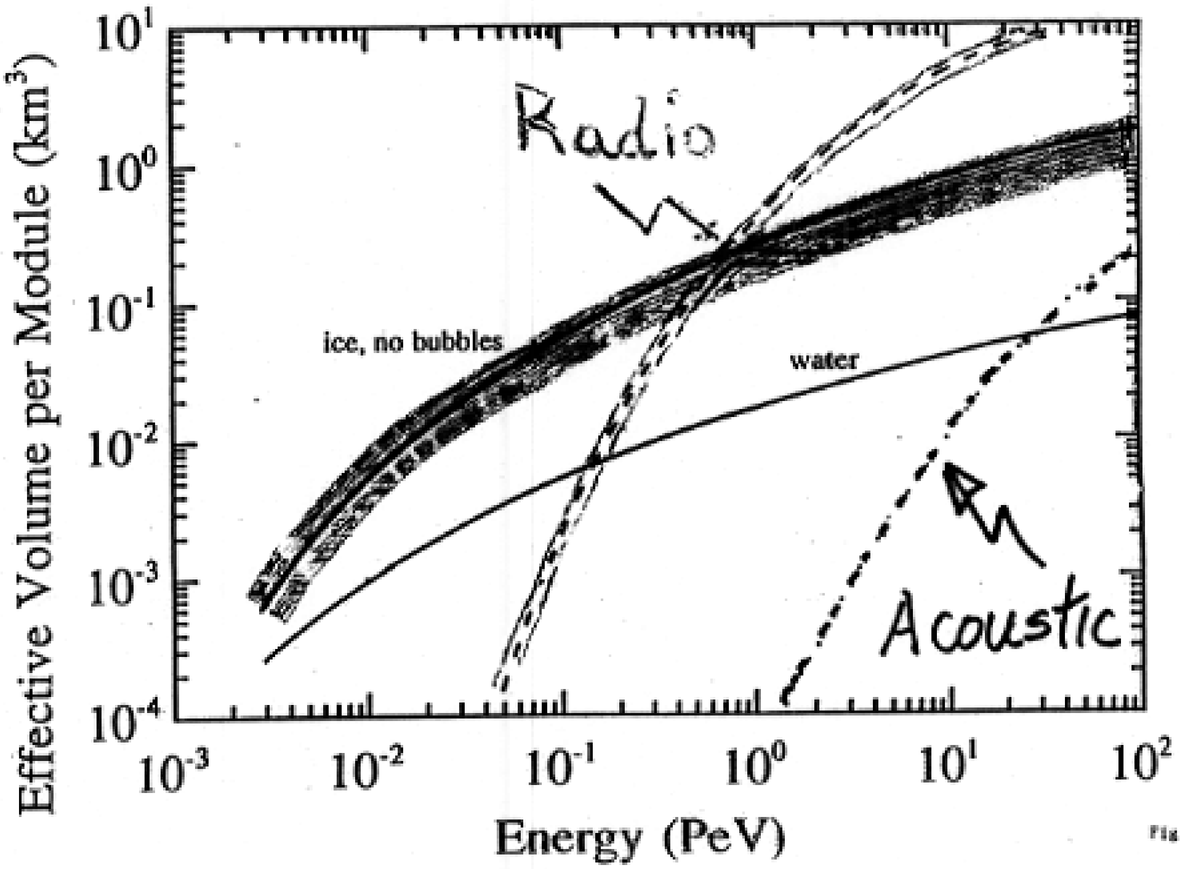
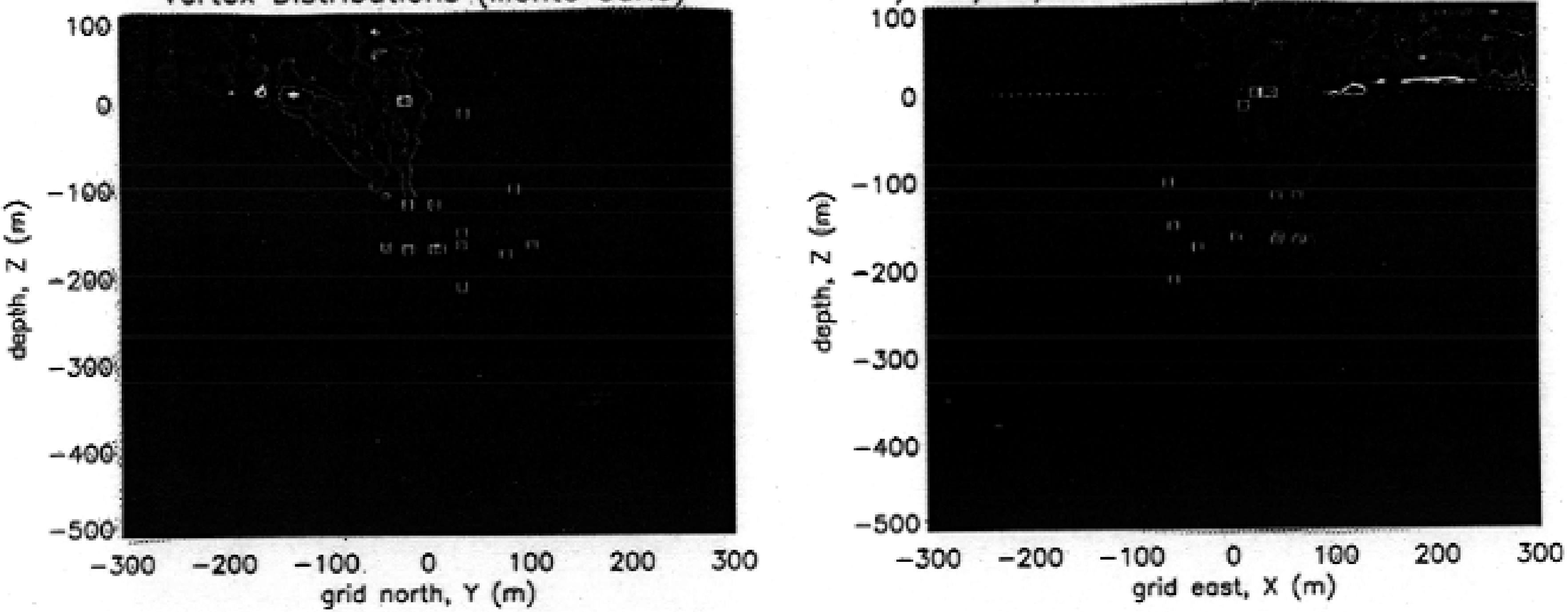
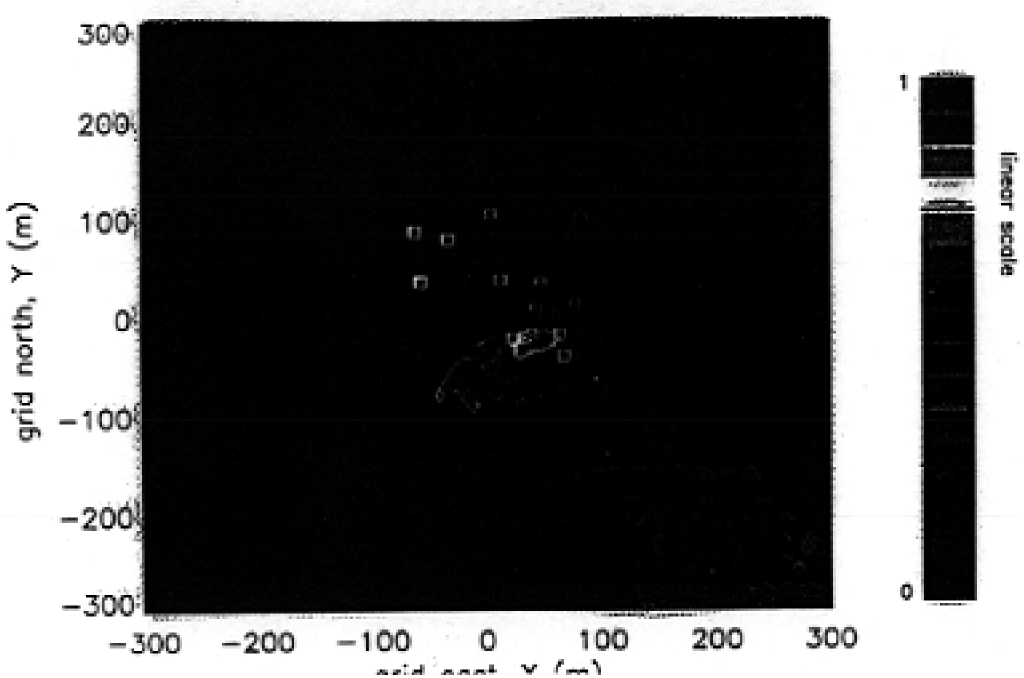


Fig. 1

RICE Collaboration

Vertex Distributions (Monte Carlo) /rice/99/vertex_test/general0_10.location



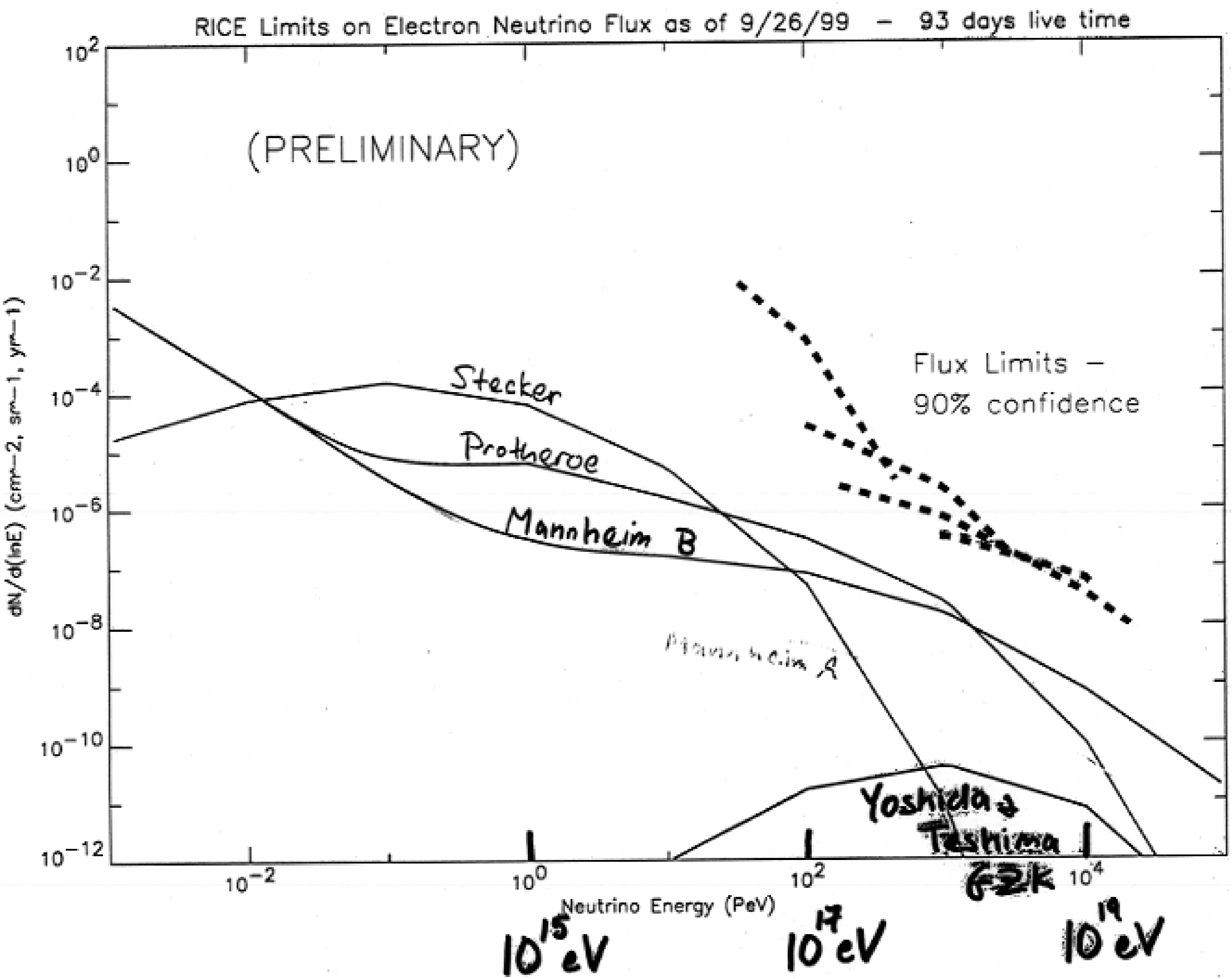


Events occuring from day: 0.00000 to 0.00000 = 9997

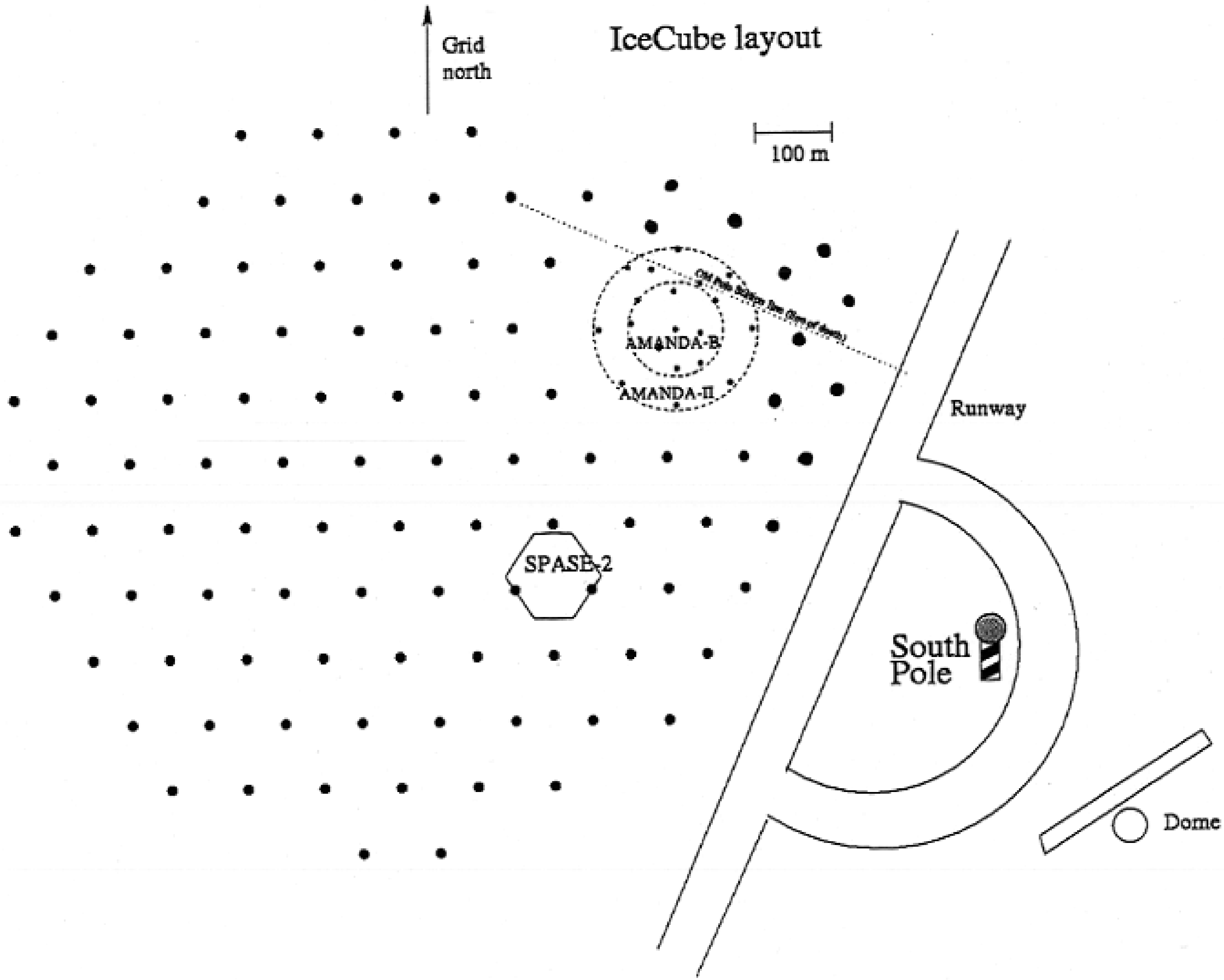
Chi-squared cut: 0.000500000 to 10.0000 = 6666

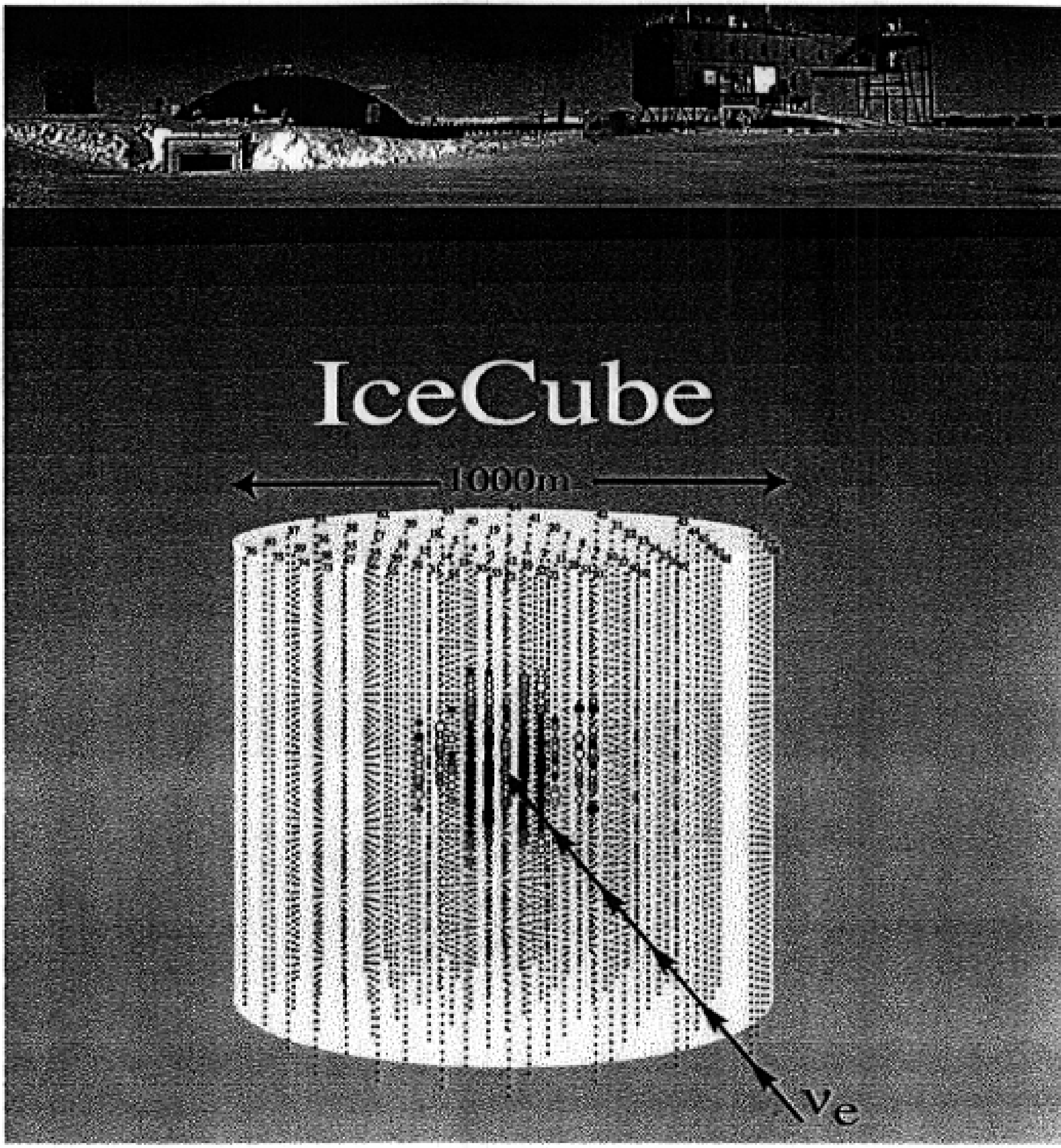
Depth cut (m): -500.000 to 100.000 = 6666

98Rx1 0.997750
98Rx2 0.957246
98Rx3 0.951695
98Rx5 0.946445
98Rx4 0.921992
98Rx6 0.895590
96Rx6 0.350285
97Rx7 0.230573
96Rx2 0.188269
97Rx3 0.176268
96Rx3 0.141464
97Rx4 0.141164
98Hn3 0.00000
98Hn2 0.00000
98Hn1 0.00000
97RxG 0.00000



RICE Limits on Electron Neutrino Flux as of 9/26/99 – 93 days live time
(PRELIMINARY)
Flux Limits – 90% confidence
Stecker
Protheroe
Mannheim B
Mannheim A
Yoshida & Teshima
GZK
dN/d(lnE) (cm^-2, sr^-1, yr^-1)
Neutrino Energy (PeV)
10^{15} eV
10^{17} eV
10^{19} eV


IceCube layout
Grid north
100 m
AMANDA-B
AMANDA-II
SPASE-2
Runway
South Pole
Dome

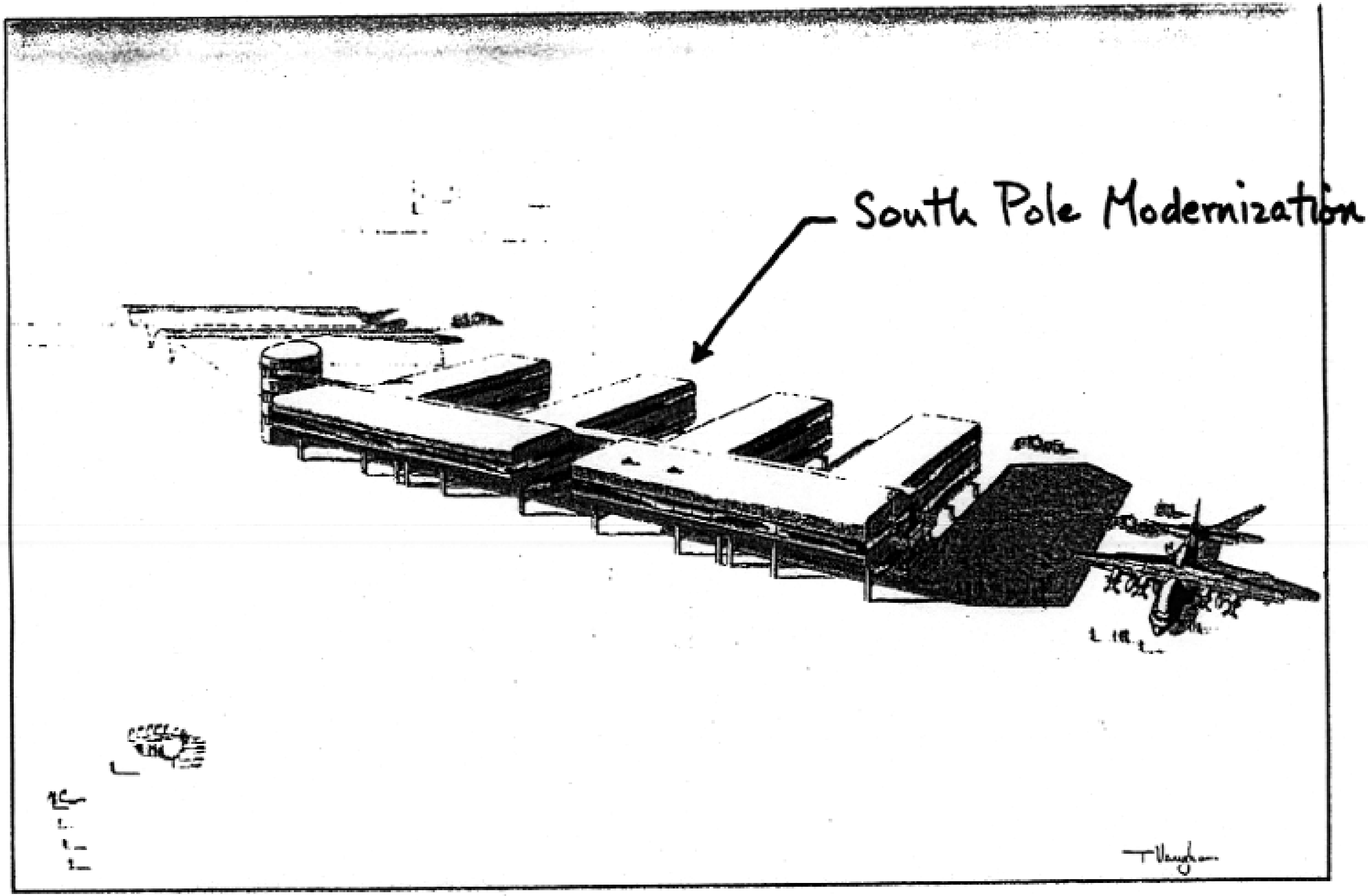

IceCube
1000m
νe

IceCube Budget (Summary)

Hardware (Strings, surface equip.)	\$35M
Logistics(drilling, fuel, summer camp)	\$20M
Personnel (US only)	\$20M
Total	\$75M

* No contingency, No inflation
No operating costs after construction

University of California-Irvine
S. Barwick


South Pole Modernization

IceCube Milestones

• FY99	B10-analysis papers (ICRC)
• FY00	Complete Am-II array (demo 8 holes/season), submit IceCube proposal
• FY01	Start IceCube ($$), Distant drilling, pre-deployment procedures, integration of drill team in deploy., Semi-automated calibration
• FY02	Start construction of 16 strings, deploy 8
• FY03	Deploy 16 strings per season
• FY04	Deploy next 16 strings
• FY05,06,07	Complete IceCube

Conclusions and Comments

HE ν- arrays are extremely flexible instruments

- Wide range in E sensitivity
  - **10 GeV - 10 PeV, perhaps more**
- Wide range in source location
  - **atmosphere - cosmologic**
- Neutrino flavor ID is possible
- Wide range of physics opportunities

Detector development has been steady

- Baikal and AMANDA - taking data
- NESTOR and ANTARES - water studies completed
  - **Beginning crucial deployment tests**

Considerable interest and uncertainty in acceleration mechanisms

- What is the source of > PeV CRs?

  $> 10^{15}$ eV CRs

Multi-messenger observations of sources

- γ, ν, gravity waves, EHE CRs
- Dramatic advance in knowledge