Neutrino Telescopes

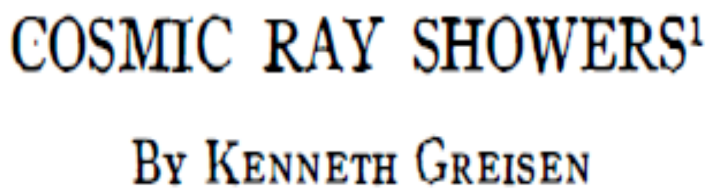
a Journey

Christian Spiering

Deep is the fountain of the past – couldn‘t we call it bottomless?

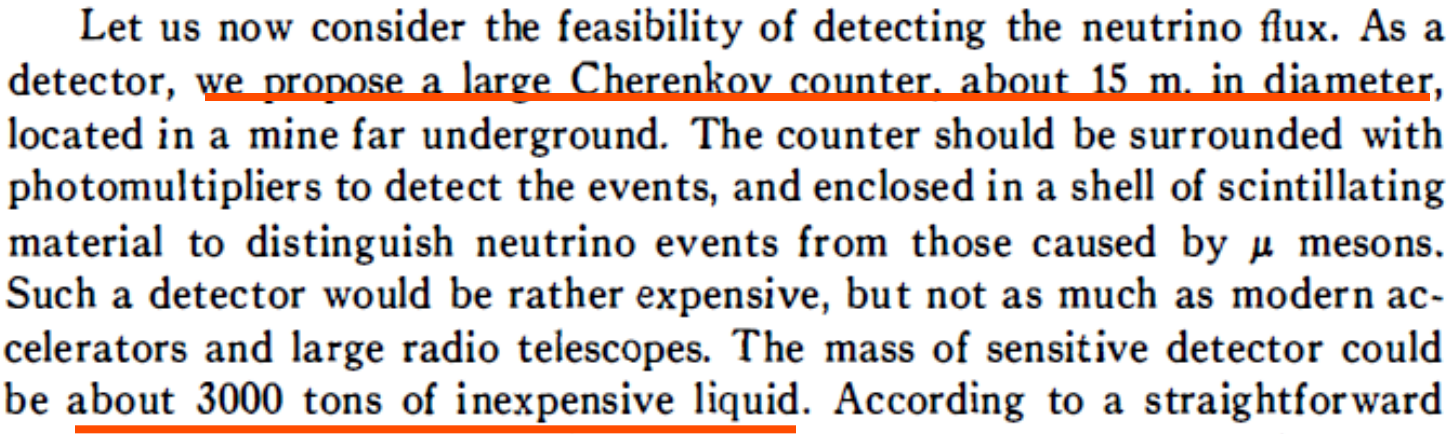
Thomas Mann, Joseph and his brothers

Ann.Rev.Nucl.Sci
10 (1960) 63

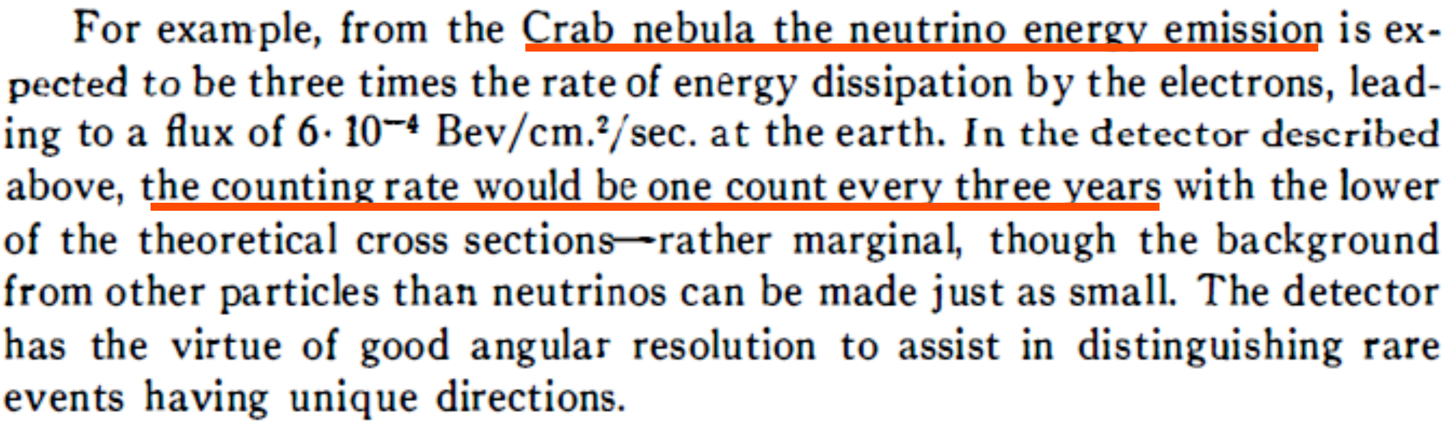


COSMIC RAY SHOWERS[1]

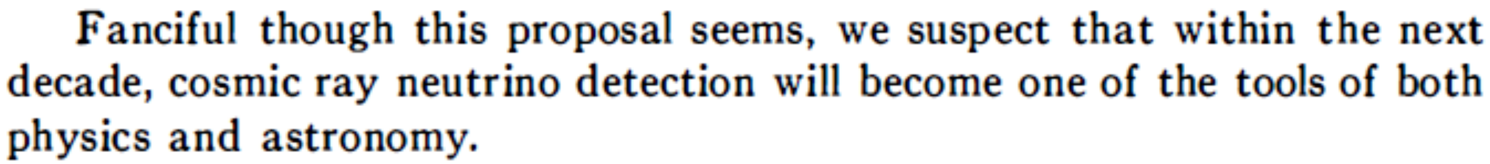
By Kenneth Greisen



Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward

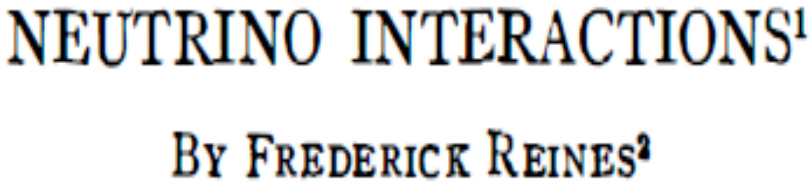


For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6\cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with the lower of the theoretical cross sections—rather marginal, though the background from other particles than neutrinos can be made just as small. The detector has the virtue of good angular resolution to assist in distinguishing rare events having unique directions.



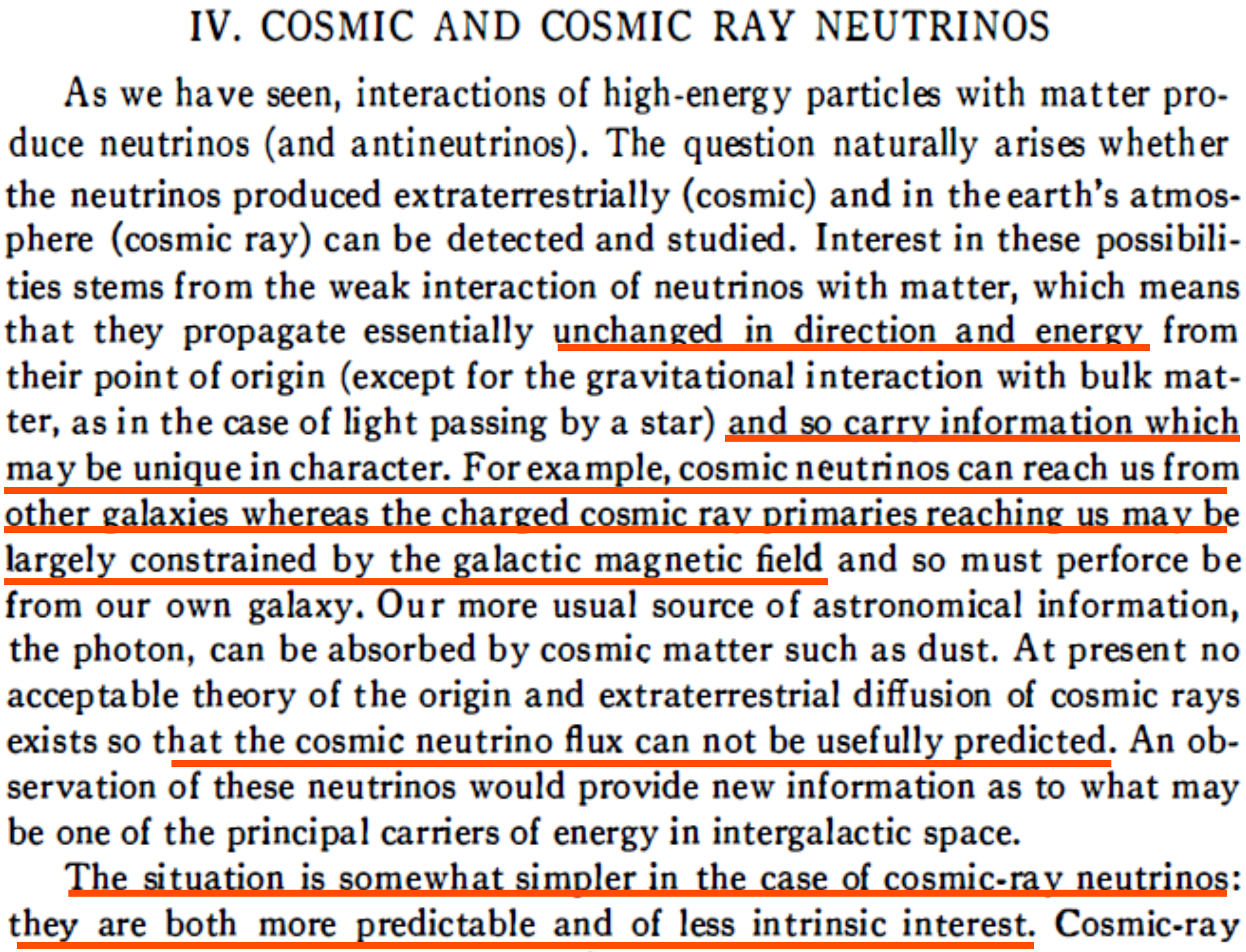
Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

Ann.Rev.Nucl.Sci
10 (1960) 1



NEUTRINO INTERACTIONS[1]

By Frederick Reines[2]



IV. COSMIC AND COSMIC RAY NEUTRINOS

As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies whereas the charged cosmic ray primaries reaching us may be largely constrained by the galactic magnetic field and so must perforce be from our own galaxy. Our more usual source of astronomical information, the photon, can be absorbed by cosmic matter such as dust. At present no acceptable theory of the origin and extraterrestrial diffusion of cosmic rays exists so that the cosmic neutrino flux can not be usefully predicted. An observation of these neutrinos would provide new information as to what may be one of the principal carriers of energy in intergalactic space.

The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

Frederick Reines, 1965

Detection of nearly horizontal atmospheric neutrinos in a South African Gold mine.

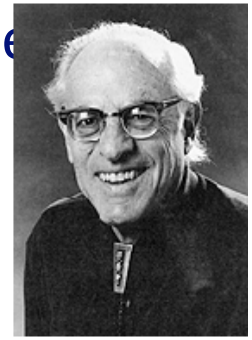
M.Markov, **1960**:

„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation“ Proc. 1960 ICHEP, Rochester, p. 578.

DUMAND

See also: A.Roberts: The birth of high-energy neutrino astronomy: a personal history of the DUMAND project, Rev. Mod. Phys. 64 (1992) 259.

- 1973 ICRC, Reines, Learned, Shapiro, Zatsepin, Miyake: a deep water detector to clarify puzzles in muon depth-intensity curves
- Puzzles faded away, but there remained the awareness that such a detector could also work as neutrino detector
- The name: DUMAND (Deep Underwater Muon And Neutrino Detector), proposed by Fred Reines
- 1975: First DUMAND Workshop in Washington State College
- DUMAND Steering Committee, chaired by F.Reines, J. Learned A.Robe



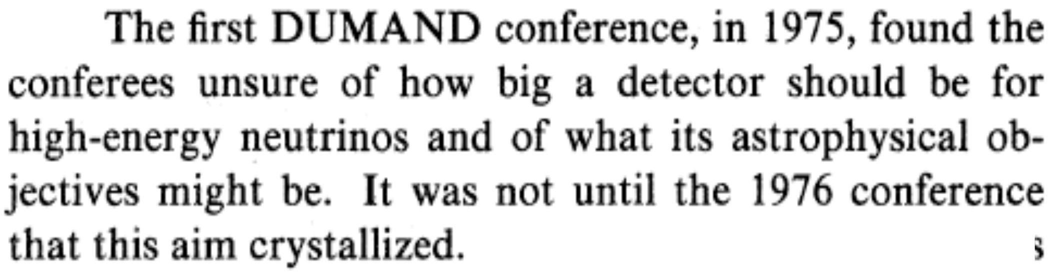
The DUMAND Workshops

- An unbelievable source of basic ideas
  (including crazy ones which are sometimes the most exciting)
- 1976 Honolulu
- 1978 Scripps
- 1979 Khabarovsk/Baikal
- 1978 Honolulu
- Plus dedicated workshops on deployment, acoustic detection, signal procressing and ocean engineering

Which physics?

- UNDINE: UNderwater Detection of Interstellar Neutrino Emission
    - i.e. Supernova → too rarely to optimize an ocean detector for it (→ IMB)
- ATHENE: ATmospheric High-Energy Neutrino Experiment
    - Better with underground experiments

A. Roberts:



The first DUMAND conference, in 1975, found the conferees unsure of how big a detector should be for high-energy neutrinos and of what its astrophysical objectives might be. It was not until the 1976 conference that this aim crystallized.

- UNICORN: UNderwater Interstellar COsmic Ray Neutrinos
    - The high energy option
    - preferred option, but: how large are the fluxes ?
    - → think as big as possible !

1978: 1.26 km³

22,698 OMs

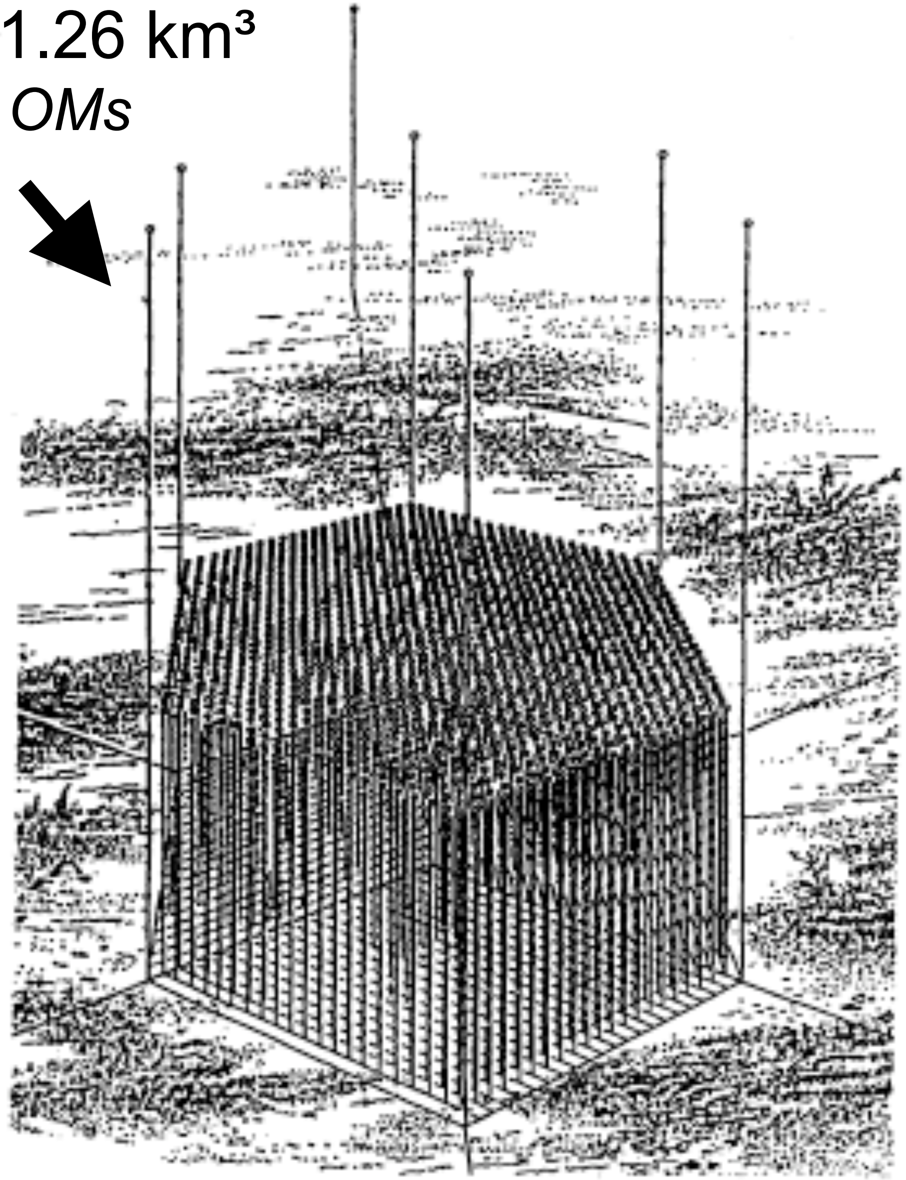
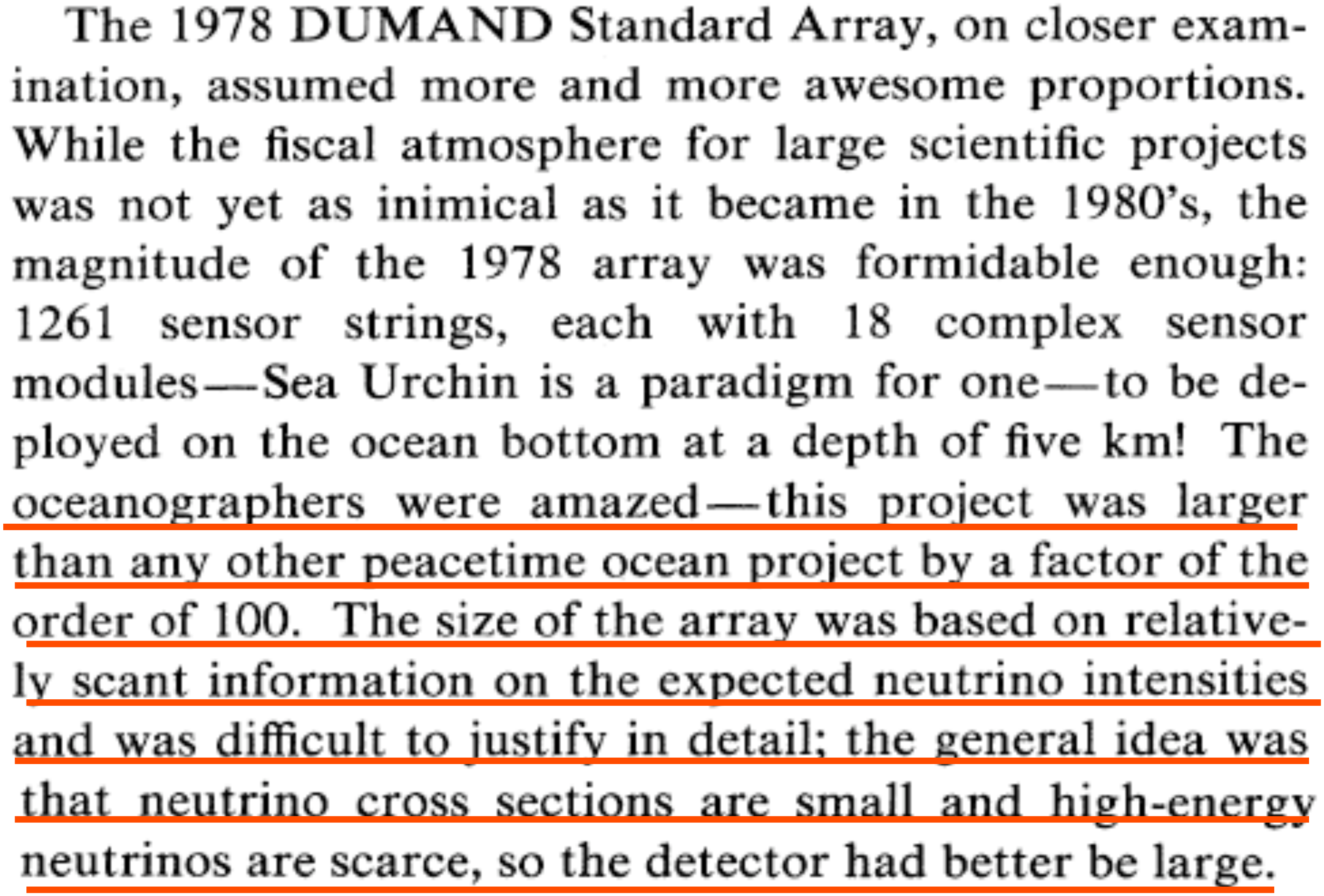
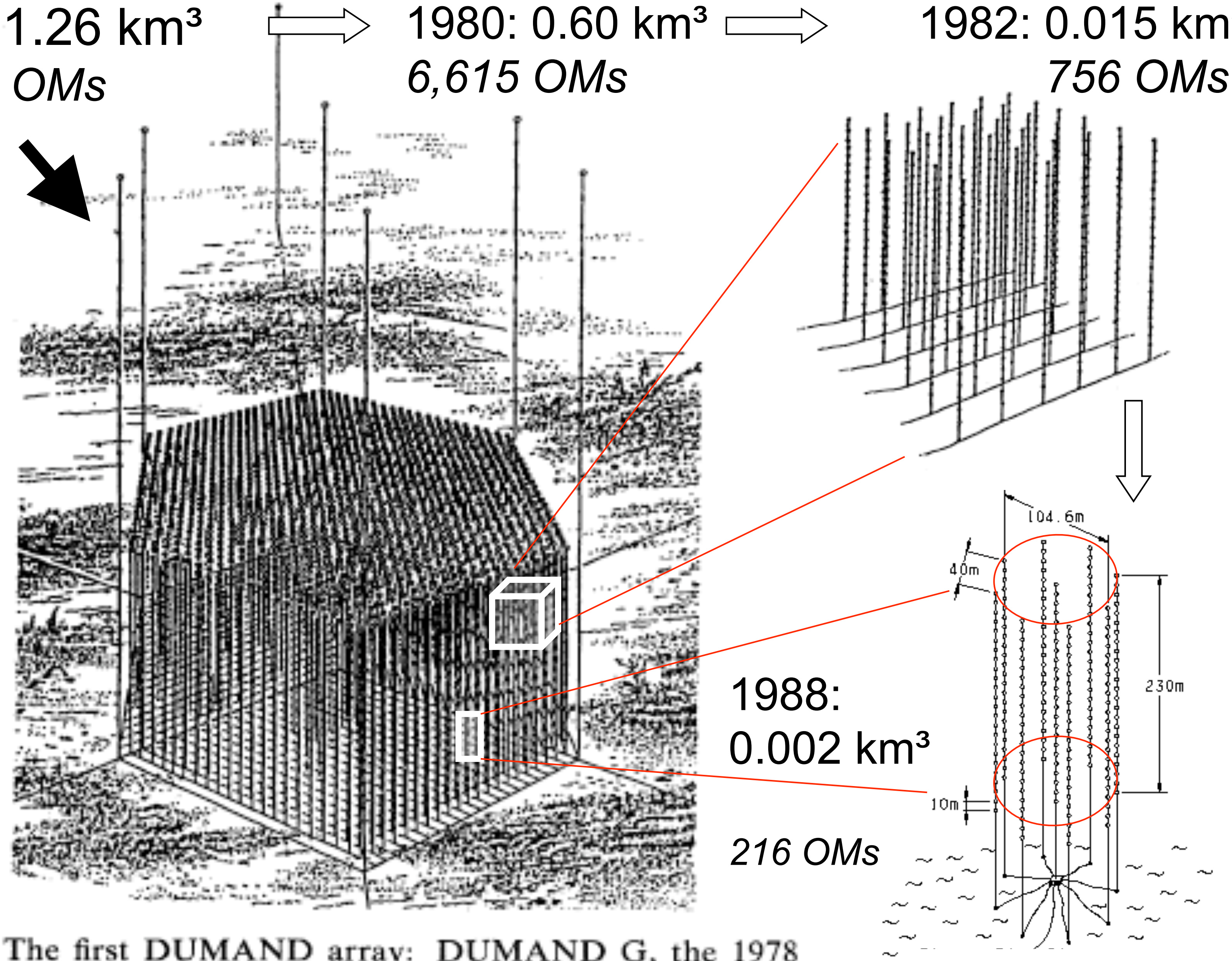


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

Financial and technological reality!



The 1978 DUMAND Standard Array, on closer examination, assumed more and more awesome proportions. While the fiscal atmosphere for large scientific projects was not yet as inimical as it became in the 1980's, the magnitude of the 1978 array was formidable enough: 1261 sensor strings, each with 18 complex sensor modules—Sea Urchin is a paradigm for one—to be deployed on the ocean bottom at a depth of five km! The oceanographers were amazed—this project was larger than any other peacetime ocean project by a factor of the order of 100. The size of the array was based on relatively scant information on the expected neutrino intensities and was difficult to justify in detail; the general idea was that neutrino cross sections are small and high-energy neutrinos are scarce, so the detector had better be large.



1978: 1.26 km³
22,698 OMs

1980: 0.60 km³
6,615 OMs

1982: 0.015 km³
756 OMs

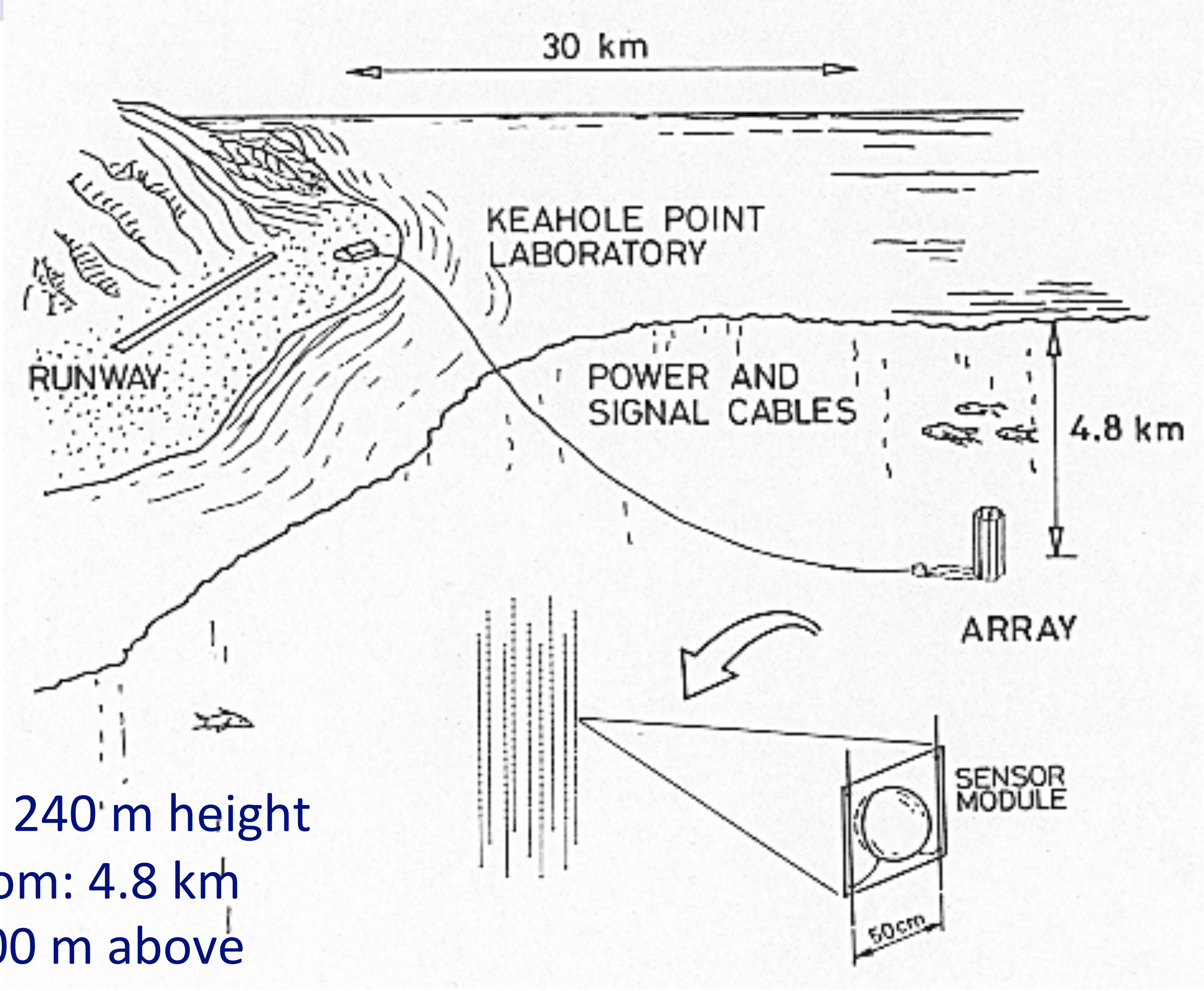
1988:
0.002 km³

216 OMs

FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

DUMAND-II

DUMAND-II (The Octagon)



- 9 strings
- 216 OMs
- 100 diameter, 240 m height
- Depth of bottom: 4.8 km
- Lowest OM 100 m above bottom

Point sources, DUMAND-II (0.002 km³) expectations in the eighties

!!!

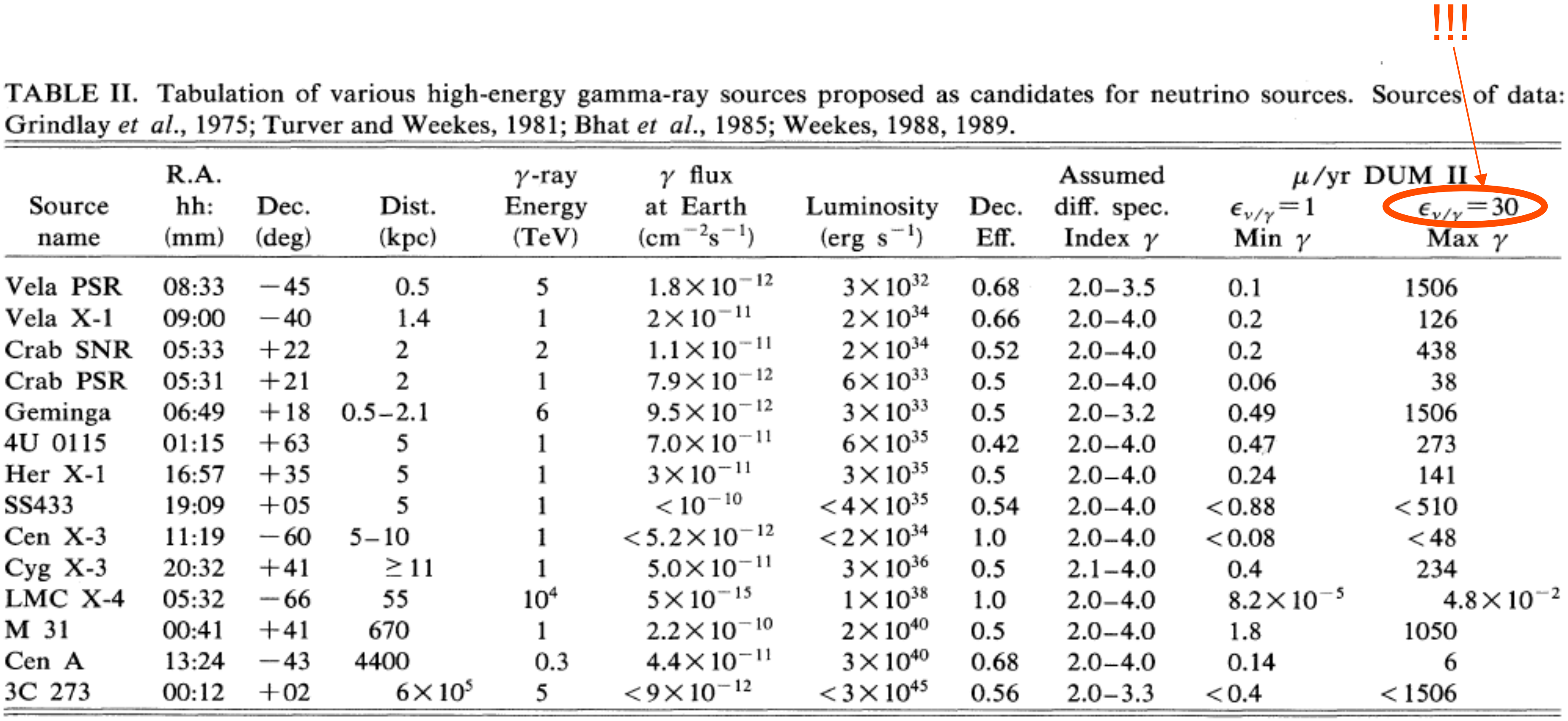


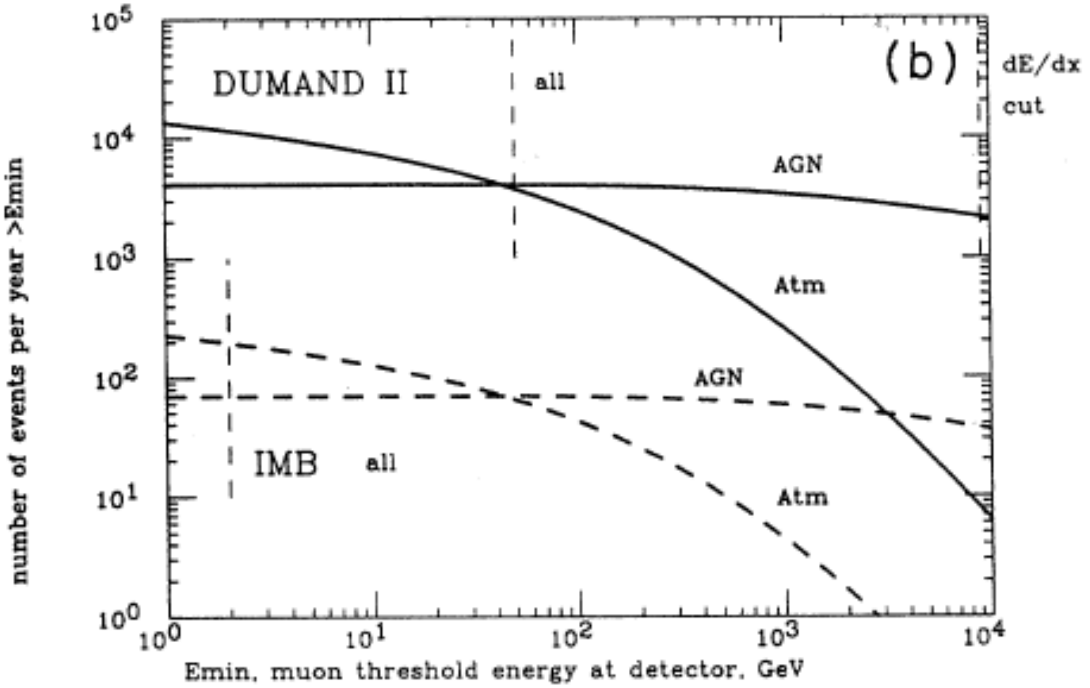
TABLE II. Tabulation of various high-energy gamma-ray sources proposed as candidates for neutrino sources. Sources of data: Grindlay *et al.*, 1975; Turver and Weekes, 1981; Bhat *et al.*, 1985; Weekes, 1988, 1989.

Source name	R.A. hh: (mm)	Dec. (deg)	Dist. (kpc)	γ-ray Energy (TeV)	γ flux at Earth ($\mathrm{cm^{-2}s^{-1}}$)	Luminosity ($\mathrm{erg\ s^{-1}}$)	Dec. Eff.	Assumed diff. spec. Index γ	μ/yr DUM II $\epsilon_{\nu/\gamma}=1$ Min γ	μ/yr DUM II $\epsilon_{\nu/\gamma}=30$ Max γ
Vela PSR	08:33	-45	0.5	5	1.8×10^{-12}	3×10^{32}	0.68	2.0–3.5	0.1	1506
Vela X-1	09:00	-40	1.4	1	2×10^{-11}	2×10^{34}	0.66	2.0–4.0	0.2	126
Crab SNR	05:33	$+22$	2	2	1.1×10^{-11}	2×10^{34}	0.52	2.0–4.0	0.2	438
Crab PSR	05:31	$+21$	2	1	7.9×10^{-12}	6×10^{33}	0.5	2.0–4.0	0.06	38
Geminga	06:49	$+18$	0.5–2.1	6	9.5×10^{-12}	3×10^{33}	0.5	2.0–3.2	0.49	1506
4U 0115	01:15	$+63$	5	1	7.0×10^{-11}	6×10^{35}	0.42	2.0–4.0	0.47	273
Her X-1	16:57	$+35$	5	1	3×10^{-11}	3×10^{35}	0.5	2.0–4.0	0.24	141
SS433	19:09	$+05$	5	1	$<10^{-10}$	$<4\times10^{35}$	0.54	2.0–4.0	<0.88	<510
Cen X-3	11:19	-60	5–10	1	$<5.2\times10^{-12}$	$<2\times10^{34}$	1.0	2.0–4.0	<0.08	<48
Cyg X-3	20:32	$+41$	≥ 11	1	5.0×10^{-11}	3×10^{36}	0.5	2.1–4.0	0.4	234
LMC X-4	05:32	-66	55	10^4	5×10^{-15}	1×10^{38}	1.0	2.0–4.0	8.2×10^{-5}	4.8×10^{-2}
M 31	00:41	$+41$	670	1	2.2×10^{-10}	2×10^{40}	0.5	2.0–4.0	1.8	1050
Cen A	13:24	-43	4400	0.3	4.4×10^{-11}	3×10^{40}	0.68	2.0–4.0	0.14	6
3C 273	00:12	$+02$	6×10^5	5	$<9\times10^{-12}$	$<3\times10^{45}$	0.56	2.0–3.3	<0.4	<1506

Note: in 1989, the only proven TeV γ source was the Crab SNR!

With these assumptions, a km³ detector would have discovered 5-50 (worst scenario) up to several ten thousand events (best scenario) per source

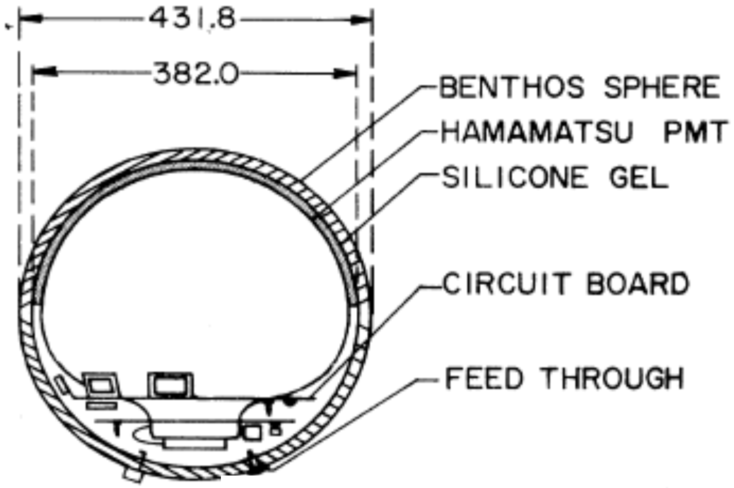
Diffuse sources, DUMAND-II (0.002 km^3) expectations in the eighties



The expected event rate in the DUMAND II and IMB detectors due to active galactic nuclei (AGN). The number of expected events per year above energy *E* is plotted against energy. Detector energy threshold are indicated by vertical dotted lines: 2.5 GeV for IMB, 25 GeV for DUMAND. The *dE/dx* cut at 10 TeV, the average AGN muon energy, indicates the probable threshold above which rough energy measurements should be possible from the total amount of light in the event (Learned and Stanev, 1991).

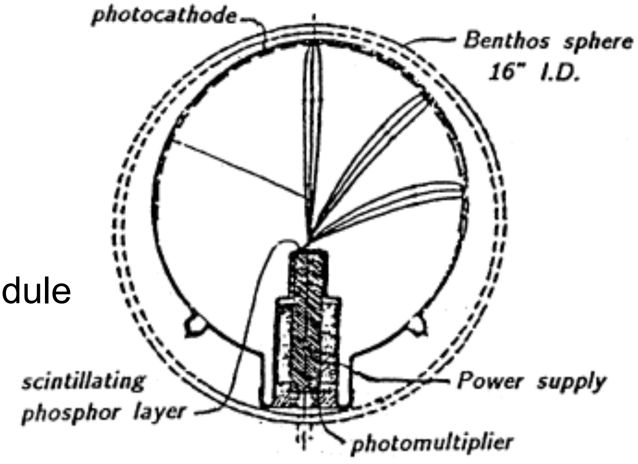
Technology boosts

- Optical fibers with < 12 db attenuation over 40-km length and data rates of hundreds of MBaud (Nobel prize 2009!)
- Appearance of 16“ Hamamatsu PMT
- Appearance of 14“ „smart“ Philips PMT



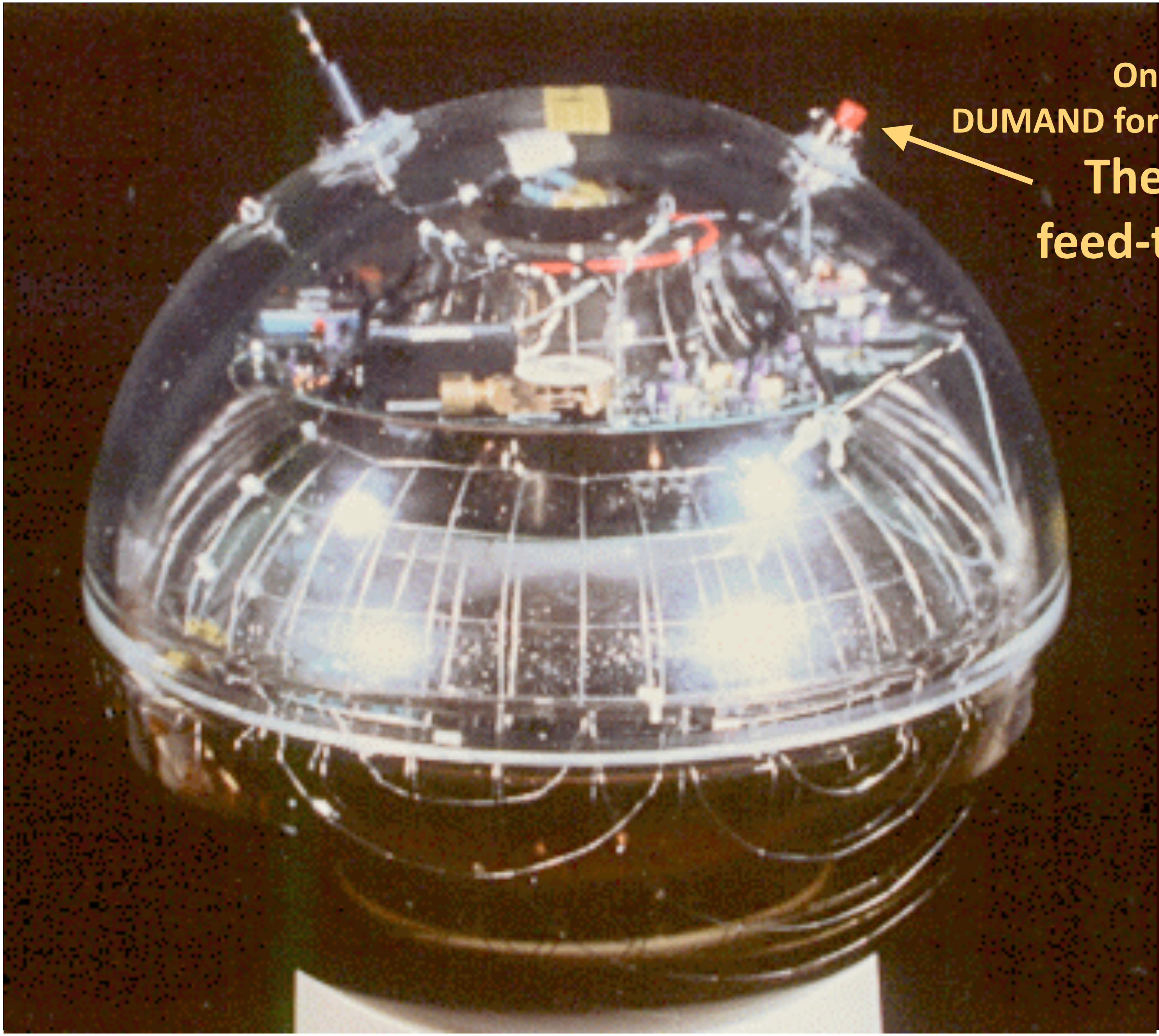
JOM

Japanese Optical Module



EOM

European Optical Module

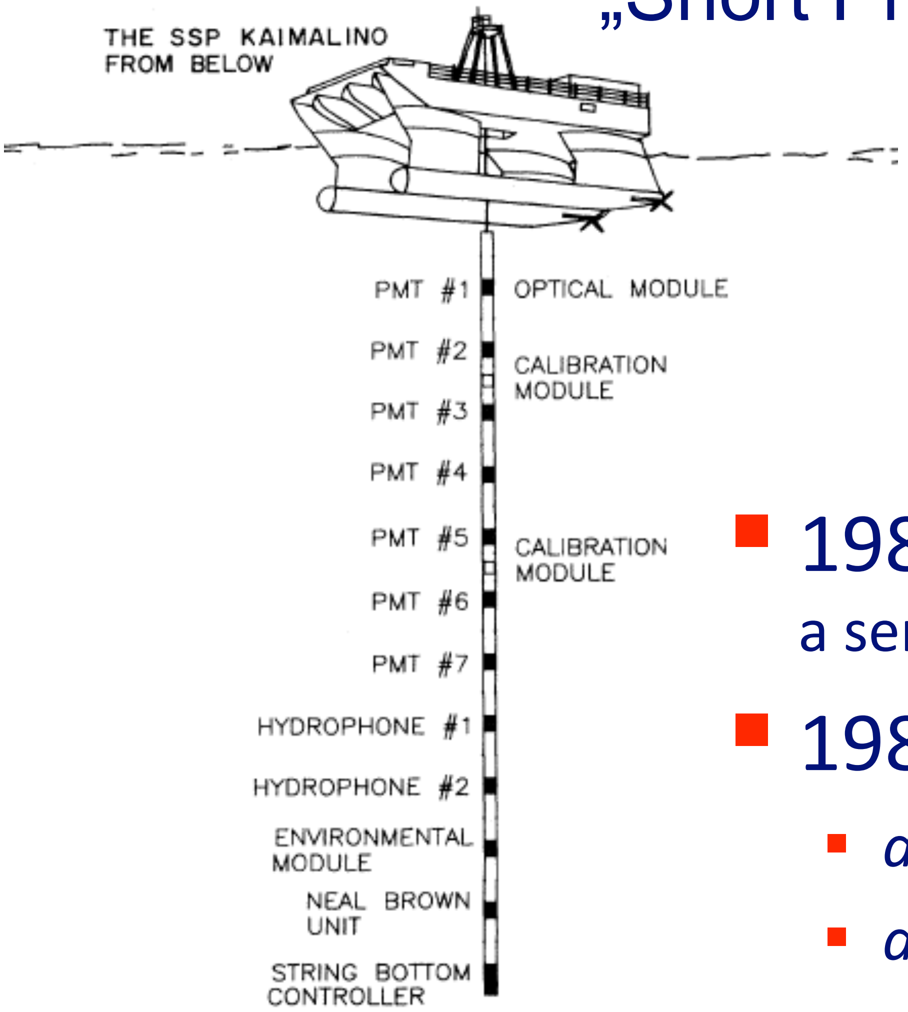


One legacy of DUMAND for AMANDA:

The optical feed-through

1987: The SPS

„Short Prototype String“



- 1982-87:
  a series of 14 cruises, with two lost strings
- 1987: success !
  - *depth-intensity curve*
  - *angular distributions*
  - *attenuation length (47±22 m)*

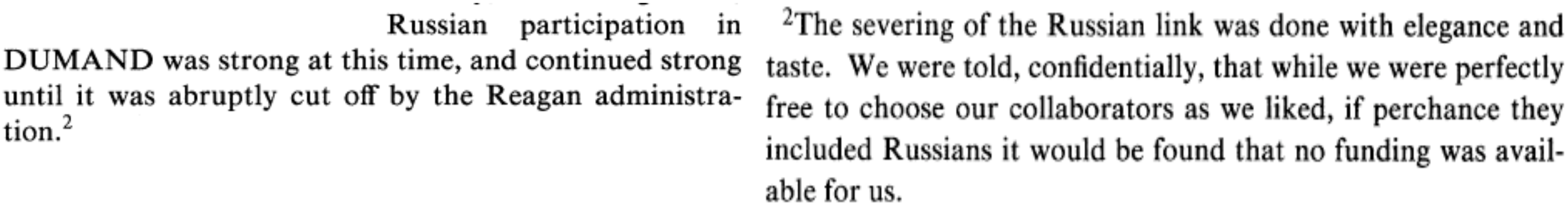
DUMAND after the SPS

- 1989: HEPAP supports DUMAND-II
- 1990: DOE allocates funds for DUMAND-II
- Further financial cuts → TRIAD (3 strings)
- 1993: shore cable laid
- December 1993: deployment of first string and connection to junction box. Failure after several hours
- 1995: DUMAND project is terminated

Russia

- Very active during early DUMAND workshops
- Kicked out of DUMAND after Russian Afghanistan invasion

A. Roberts:



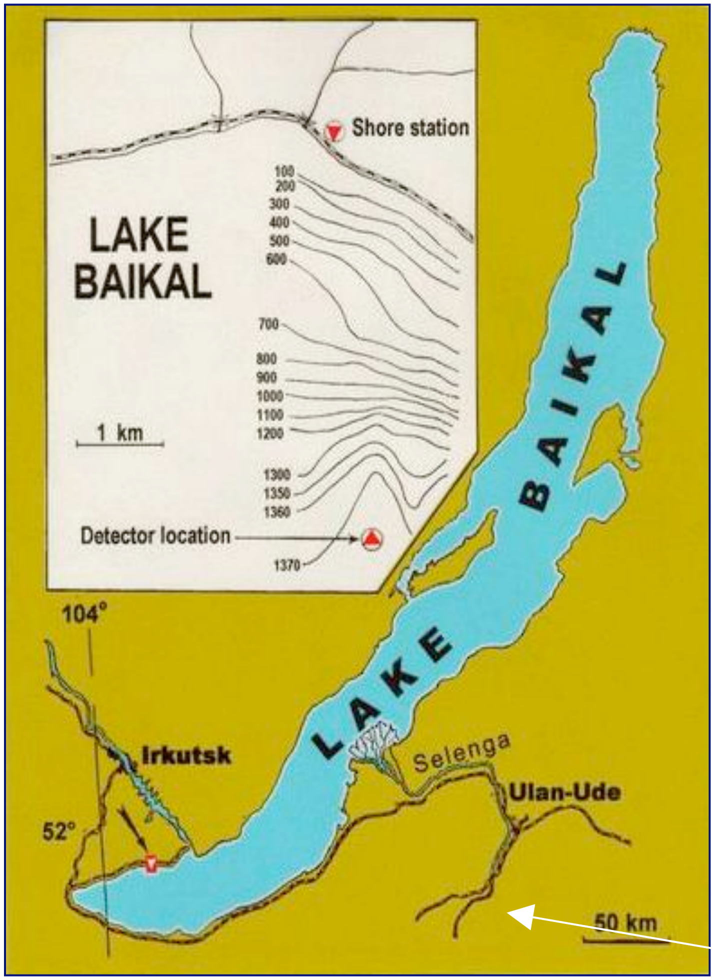
Russian participation in DUMAND was strong at this time, and continued strong until it was abruptly cut off by the Reagan administration.[2]

[2]The severing of the Russian link was done with elegance and taste. We were told, confidentially, that while we were perfectly free to choose our collaborators as we liked, if perchance they included Russians it would be found that no funding was available for us.

- 1980: Chudakov proposes exploration of Lake Baikal as possible site for a neutrino telescope
- 1981: start of site investigations at Lake Baikal (Domogatksy, Bezrukov)
- Exploration of Atlantic, Black Sea, Indian Ocean, Pacific and Mediterranean sites (Zheleznyk, Petrukhin)

The Lake BAIKAL experiment

Bezrukov, Domogatsky, Berezinsky, Zatsepin

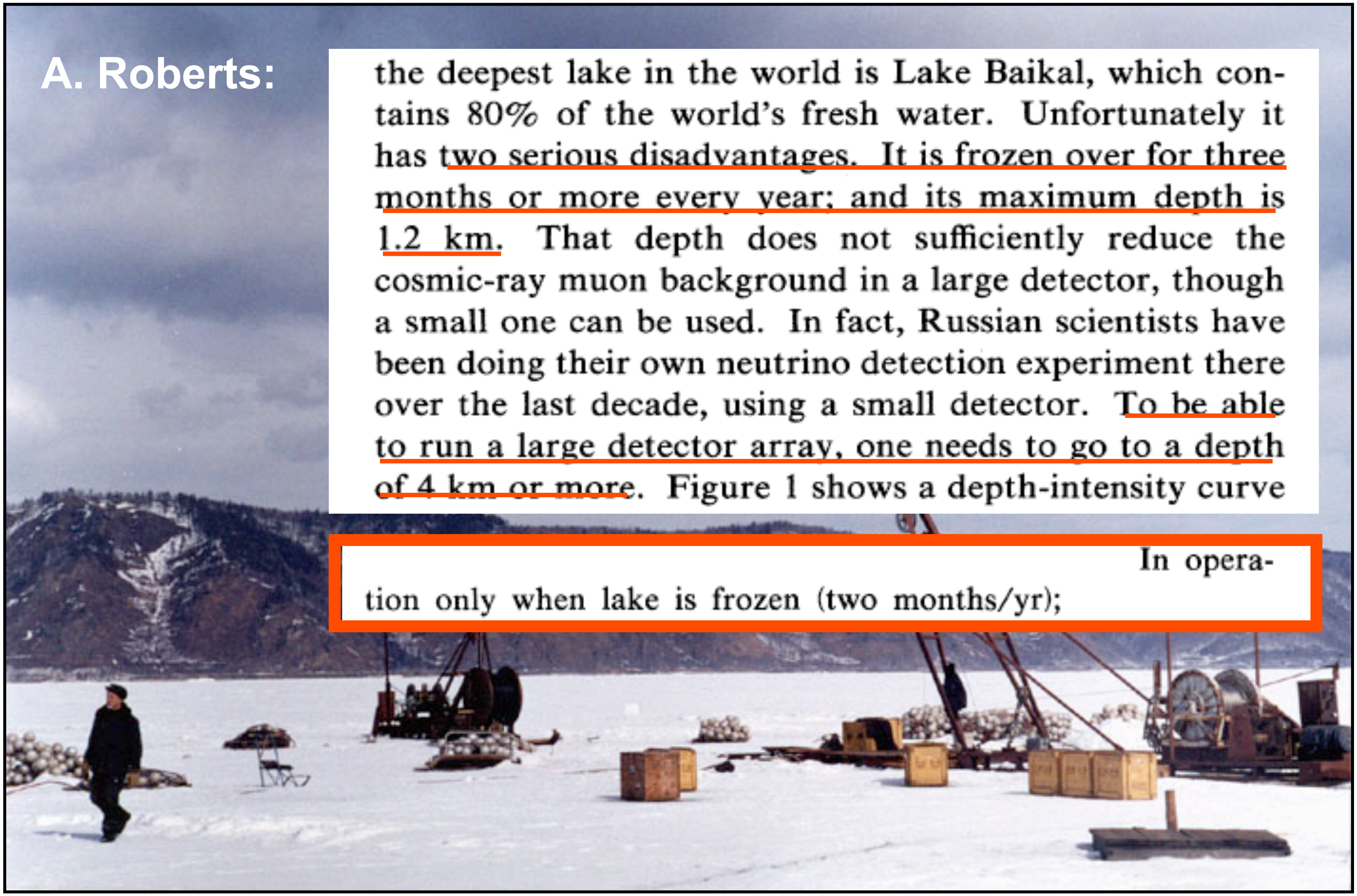


G. Domogatsky

- Largest fresh water reservoir in the world
- Deepest Lake (1.7 km)
- Choosen site 3.6 km from shore, 1.3 km depth

Ice as a natural deployment platform

… and its mis-interpretation:



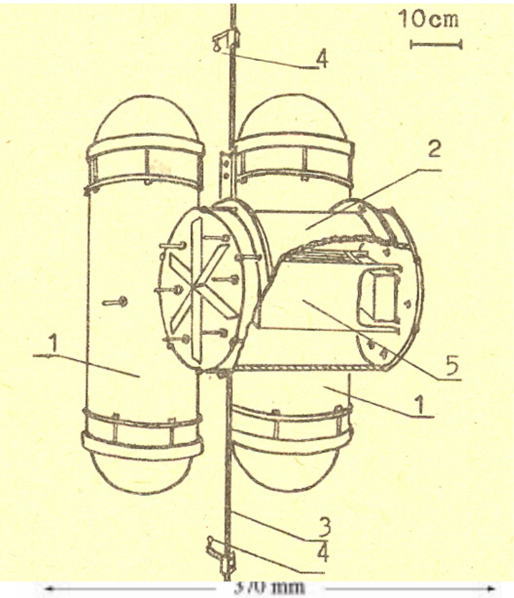
A. Roberts:

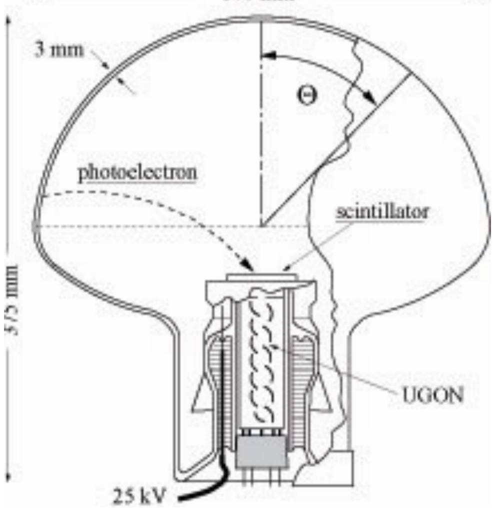
the deepest lake in the world is Lake Baikal, which contains 80% of the world's fresh water. Unfortunately it has two serious disadvantages. It is frozen over for three months or more every year; and its maximum depth is 1.2 km. That depth does not sufficiently reduce the cosmic-ray muon background in a large detector, though a small one can be used. In fact, Russian scientists have been doing their own neutrino detection experiment there over the last decade, using a small detector. To be able to run a large detector array, one needs to go to a depth of 4 km or more. Figure 1 shows a depth-intensity curve

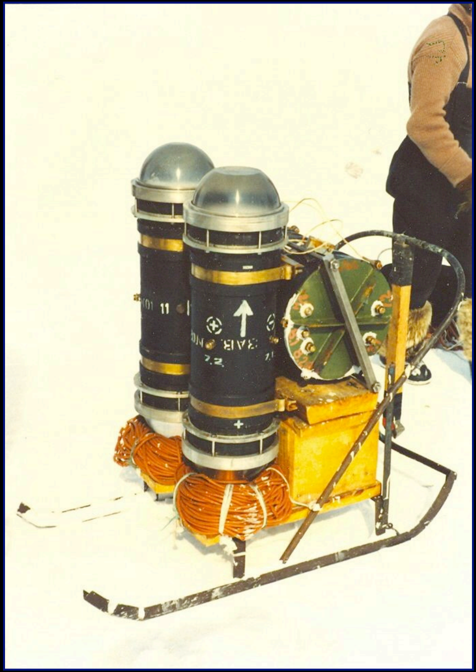
In operation only when lake is frozen (two months/yr);

Lake Baikal: the eighties

- 1984: first stationary string
    - Muon flux measurement
- 1986: second stationary string (Girlyanda 86)
    - Limits on GUT magnetic monopoles
- All that with 15-cm flat-window PMT FEU-49
- Development of a Russian smart phototube (Quasar)







1989: The fall of the Berlin wall

Shortly
later:

The Soviet empire
collapses


НЕ БРОСАТЬ!!
СТЕКЛО!
DESY - IfH
9
OBEN
НЕ БРОСАТЬ!!
СТЕКЛО!
DESY - IfH
11
OBEN
НЕ БРОСАТЬ!!
OBEN
ВВЕРХ
НЕ БРОСАТЬ!!
НЕ БРОСАТЬ!!
СТЕКЛО!
DESY - IfH
10
OBEN
ВВЕРХ
НЕ БРОСАТЬ!!
СТЕКЛО!
DESY - IfH
12
OBEN
DESY - IfH
МОСКВА

60 kg butter
40 kg margarine
25 liters oil
200 kg sugar
200 kg rice
20 kg coffee
10 kg tee
300 packages chocolade
50 kg cheese
300 kg meet products
Vitamins and medicaments

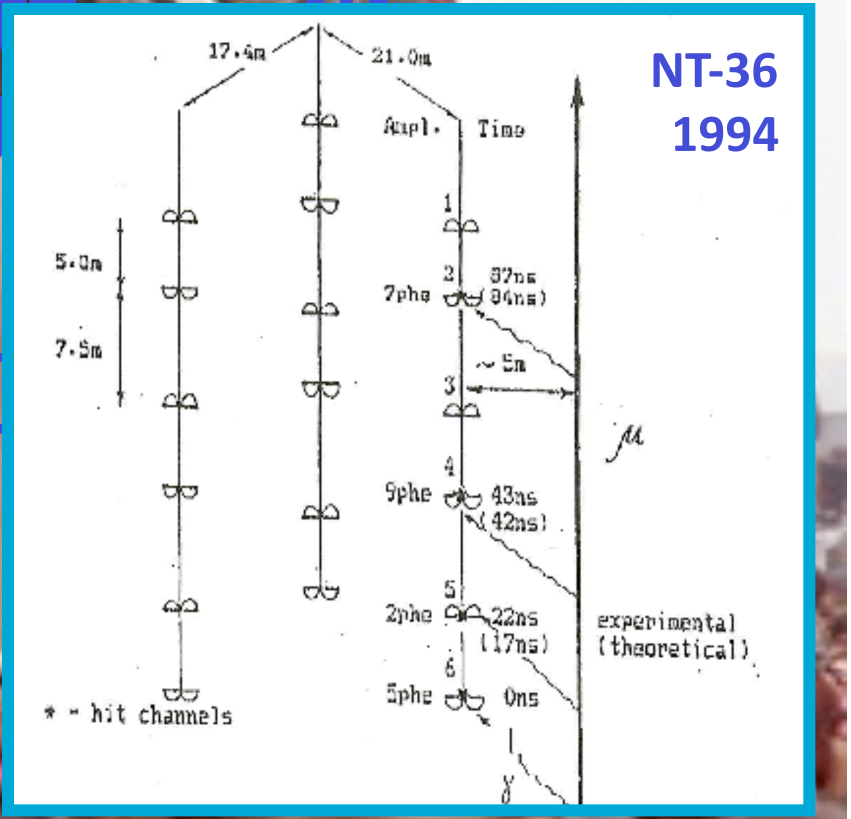
Towards NT-200

- 1988: Germany joins
- 1989/90: design of NT-200
- 1993 + 1994: NT-36
  - 18 channels at 3 strings
  - first underwater array
  - first 2 neutrino candidates

J. Learned to C.Spiering:
„Congratulations for winning the 3-string race!“
(NT-36 vs TRIAD vs AMANDA

1996: The fall of another wall

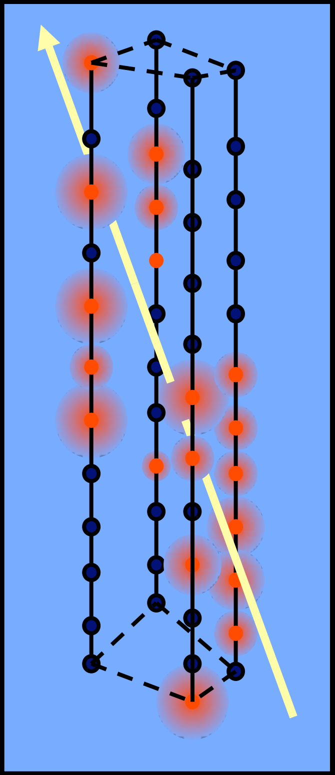
The first neutrino events underwater



Towards NT-200

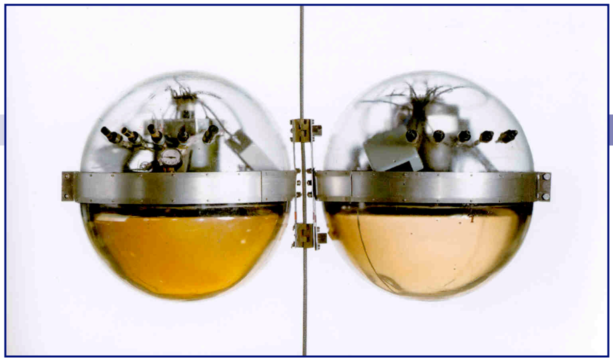
- 1988: Germany joins
- 1989/90: design of NT-200
- 1993 + 1994: NT-36
  - 18 channels at 3 strings
  - first underwater array
  - first 2 neutrino candidates
- 1995: NT-72
  - 38 channels at 4 strings
- 1996: NT-96
  - 48 channels at 4 strings
  - clear neutrinos
- 1998: NT-200
  - 96 channels at 8 strings

J. Learned to C.Spiering:
„Congratulations for winning the 3-string race!“
(NT-36 vs TRIAD vs AMANDA

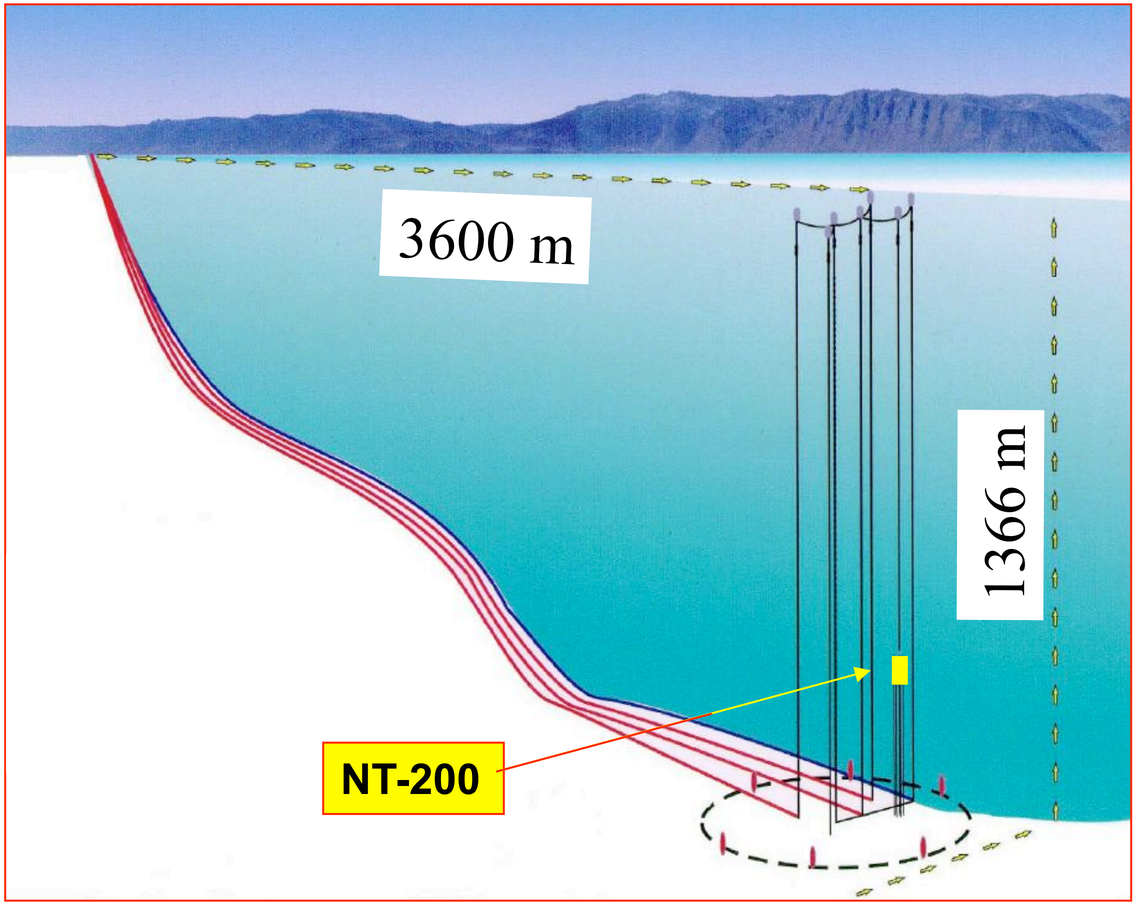


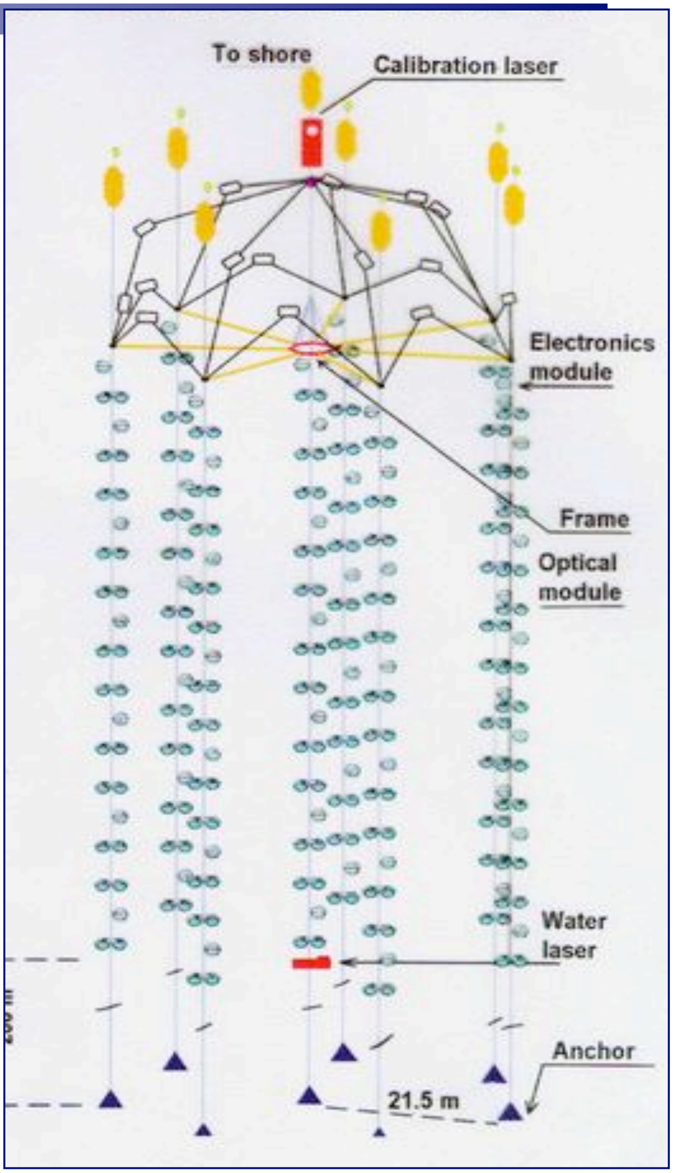
4-string stage (1996)

NT-200



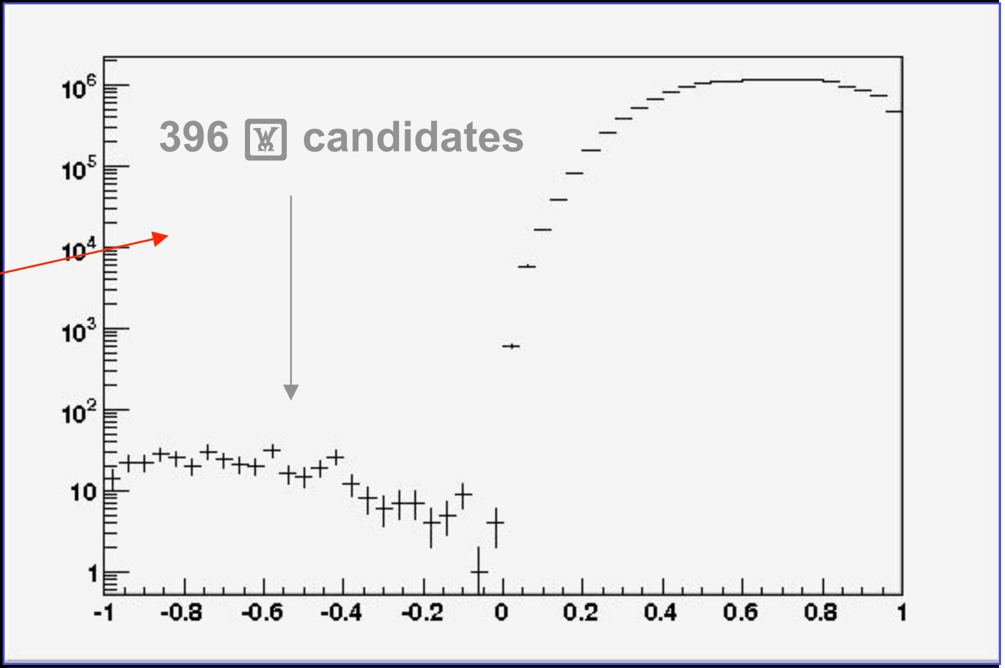
2 PMTs in coincidence
to surpress background





NT200 results

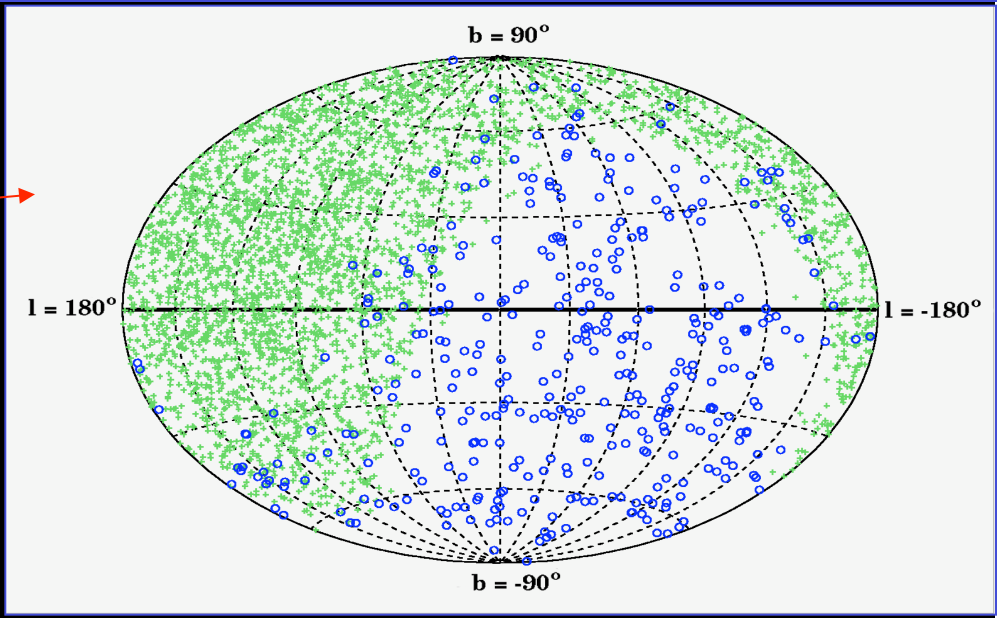
- Atmospheric neutrinos



- WIMP search
- Diffuse neutrino fluxes

Amanda 4 years
Baikal 5 years

- Skymap



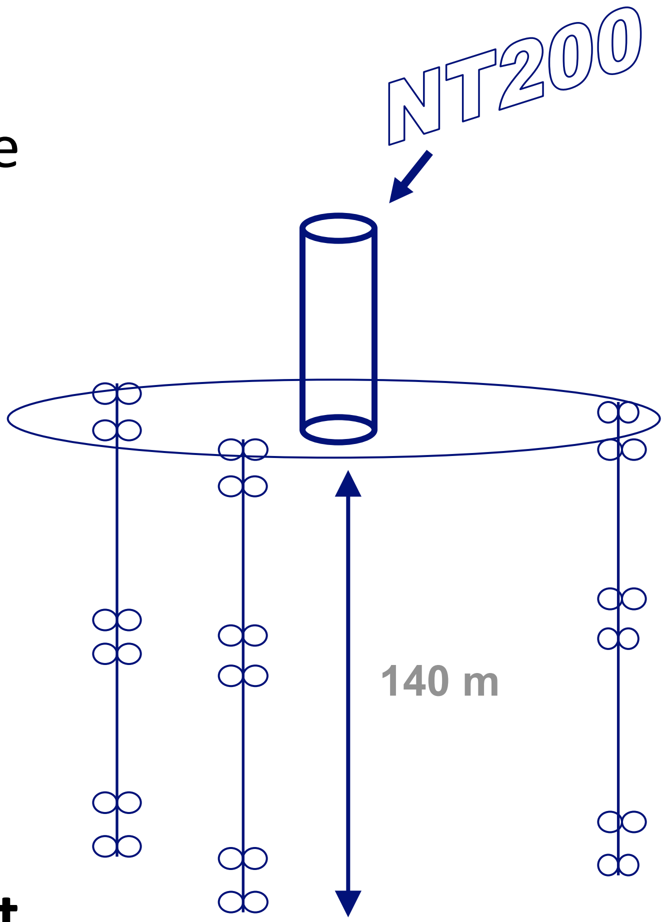
- GRB coincidences
- Magnetic monopoles

NT200+

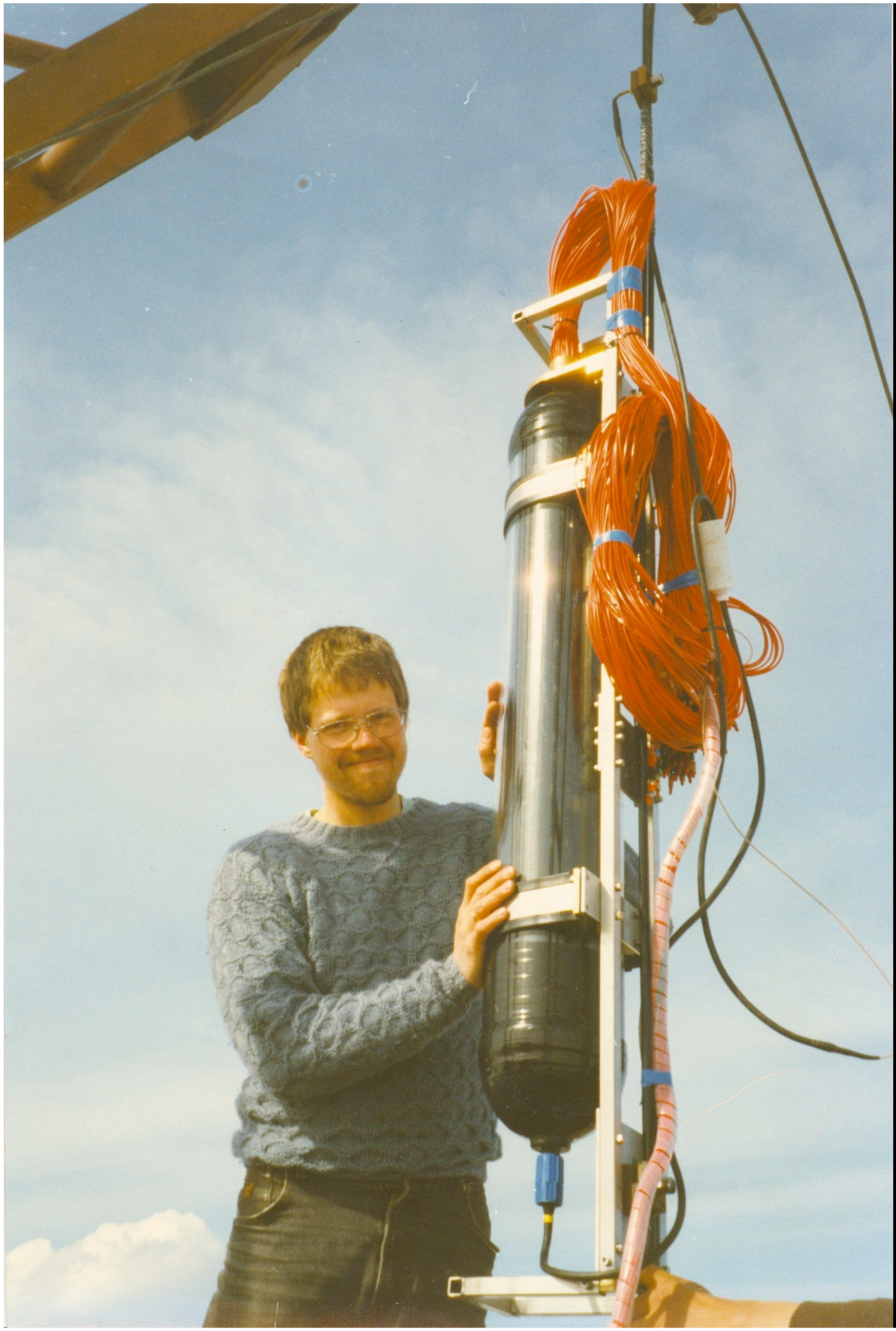
For searches of diffuse neutrino fluxes, the small NT200 could compete with the much larger Amanda by monitoring a large volume below the detector.

NT200+ fences this volume.
- upgrade 2005/06
- 4 times better sensitivity than NT200 for PeV cascades – on paper...

But alas! It never worked for longer than a few months per year and did not provide any physics result !



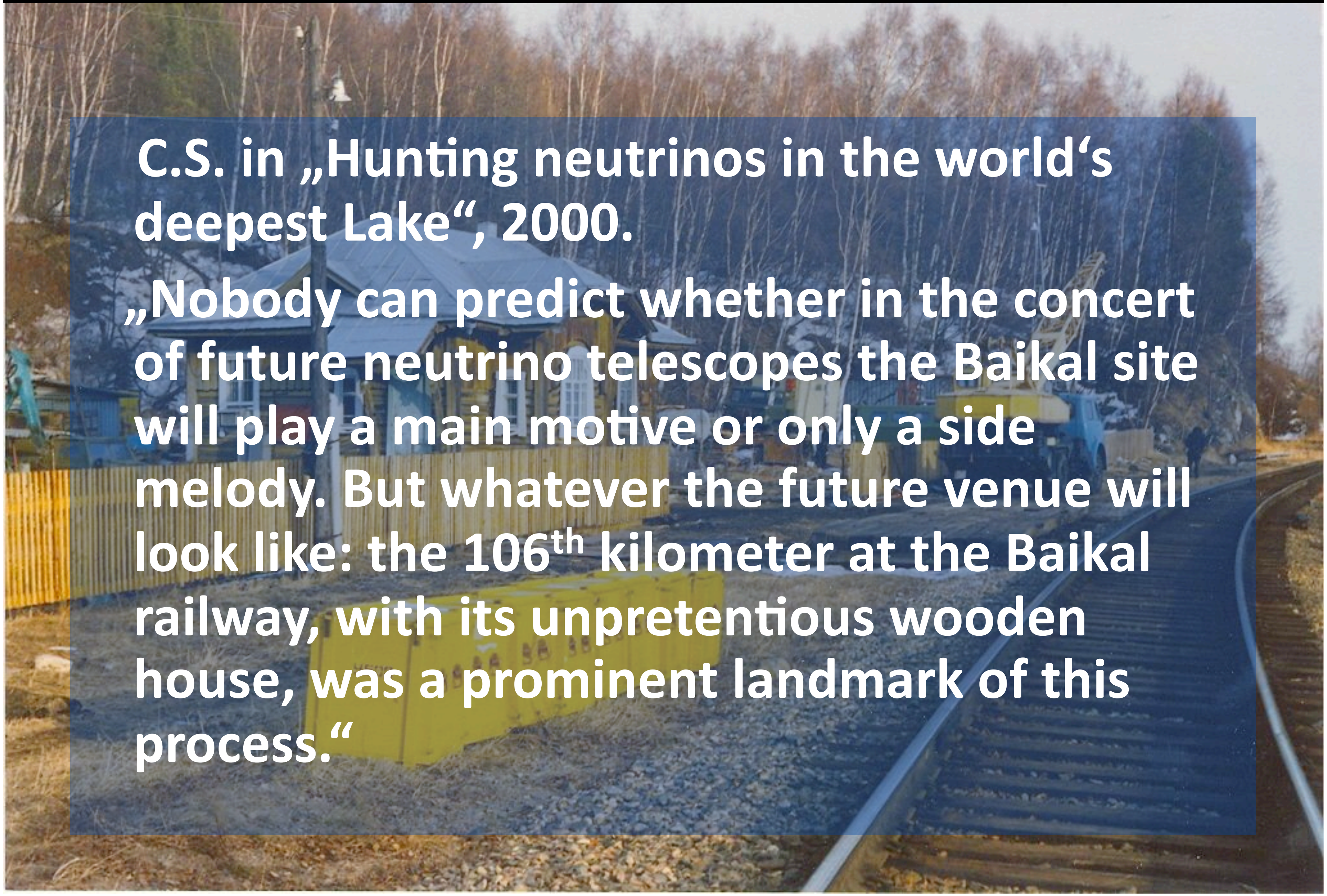

'93 2 1



ТОРОЖНО
ТЕКЛО


2-1

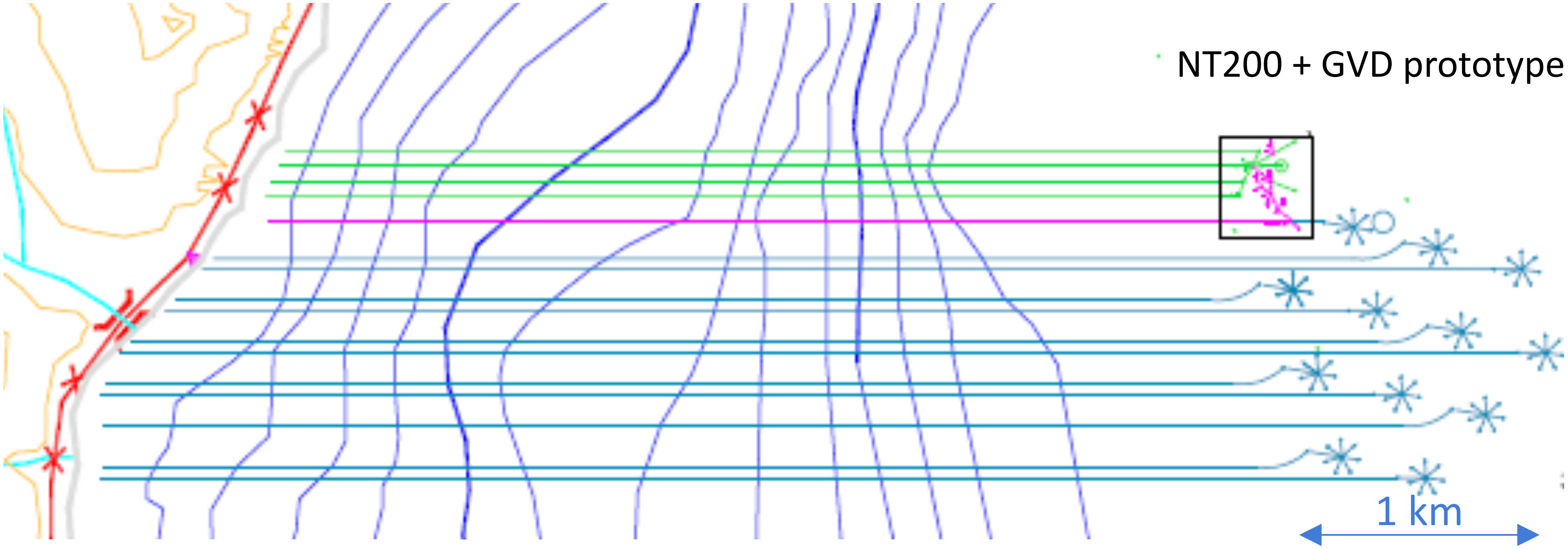
km106 of the Baikal Railway: The NT200 shore station



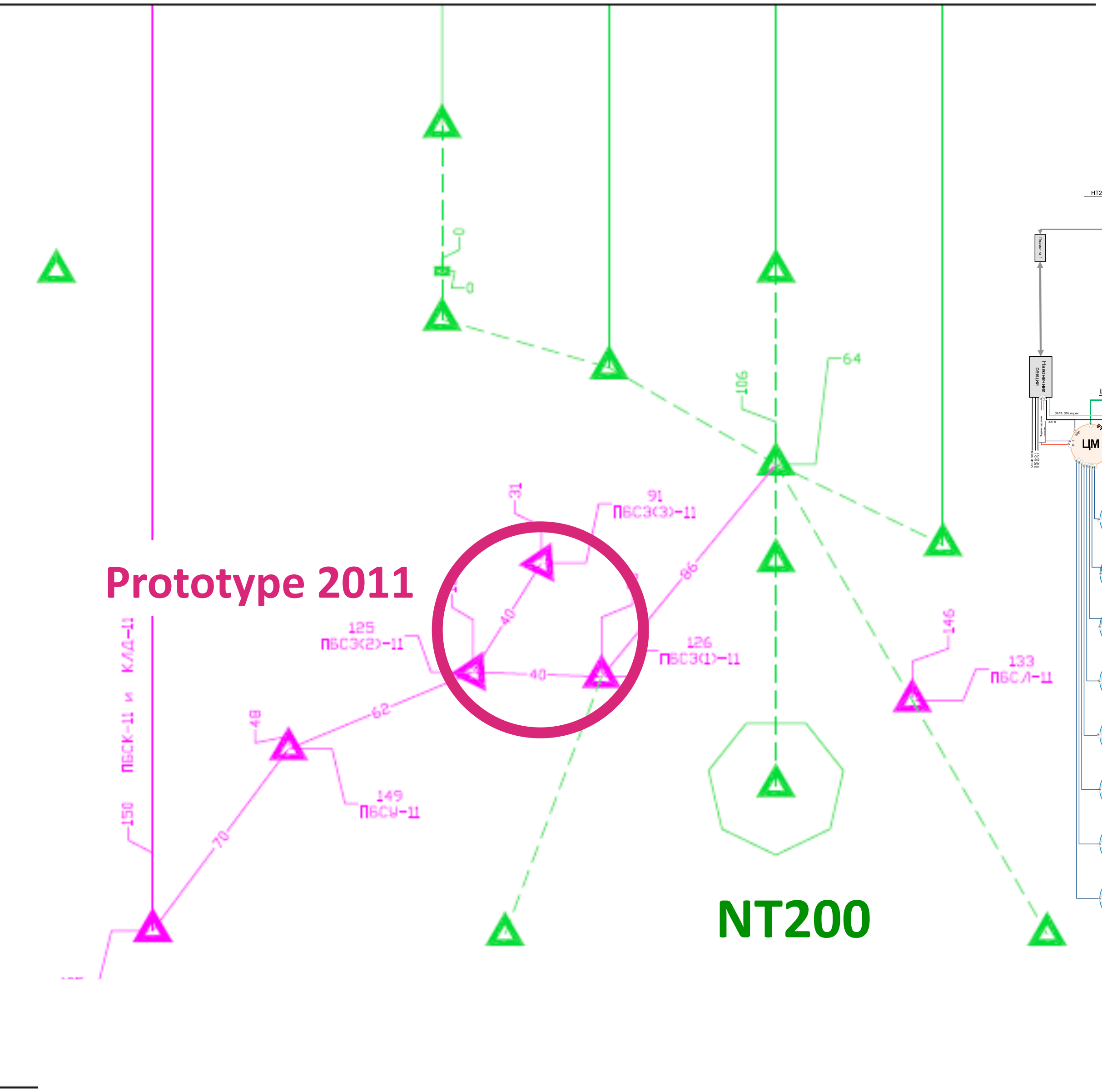
C.S. in „Hunting neutrinos in the world‘s deepest Lake“, 2000.

„Nobody can predict whether in the concert of future neutrino telescopes the Baikal site will play a main motive or only a side melody. But whatever the future venue will look like: the 106th kilometer at the Baikal railway, with its unpretentious wooden house, was a prominent landmark of this process.“

A Gigaton Volume Detector at Lake Baikal ?

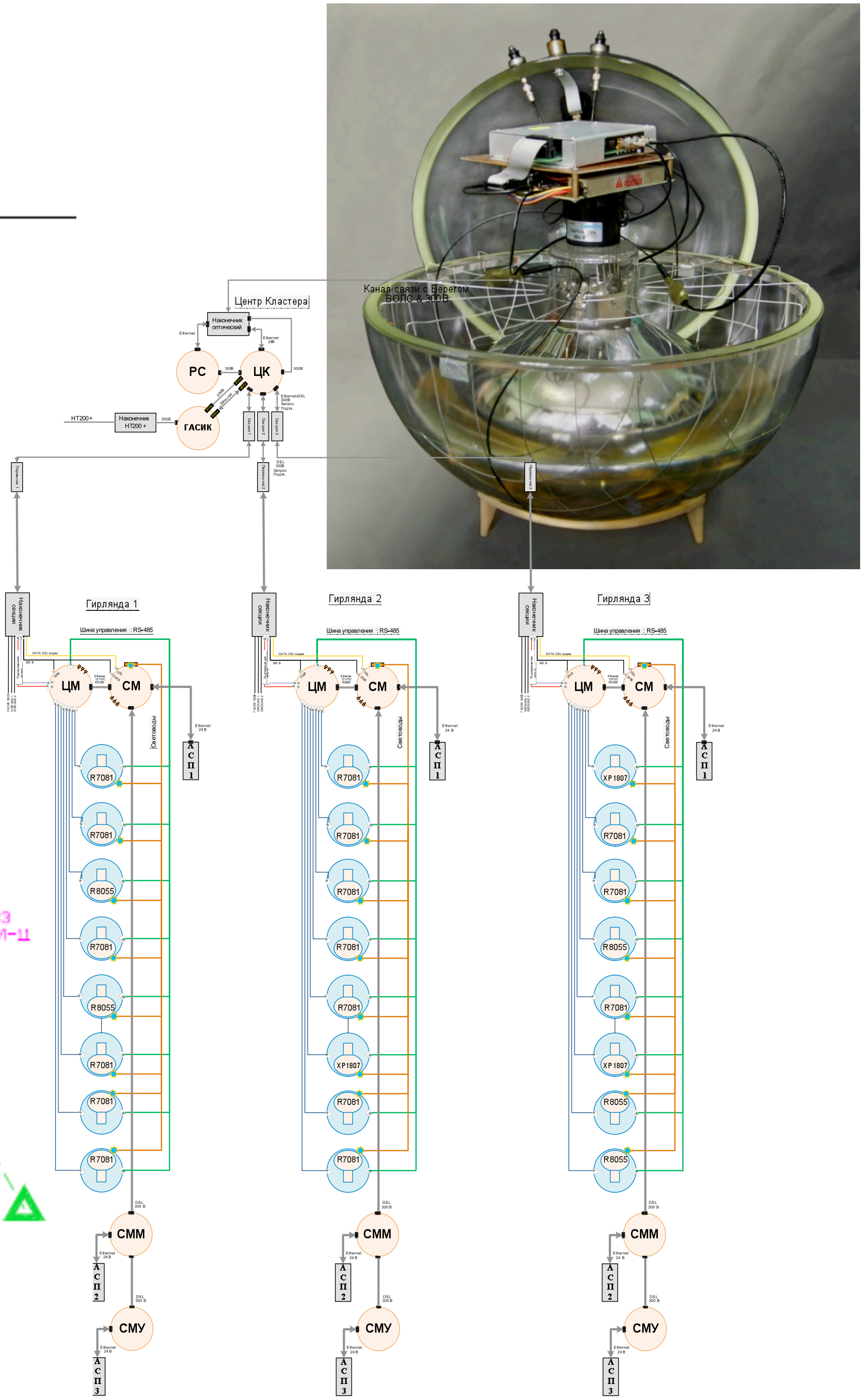


GVD



Prototype 2011

NT200



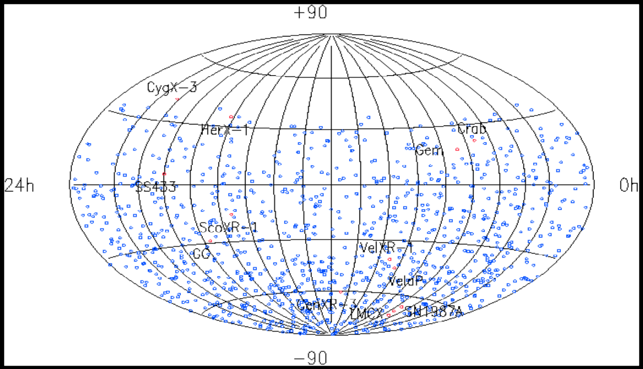
All other deep water/ice detector projects started around 1990 or later.

In the eighties /early nineties, shallow detectors have been proposed but never built.

- GRANDE (Arkansas)
- LENA (Italy)
- SINGAO (Italy)
- Swedish Lakes

On the other hand, deep underground detectors reached their full blossom:

- solar neutrinos
- supernova neutrinos
- limits on proton decay
- first hints to ν oscillations
- sky maps



MACRO, 1356 upgoing muons

See the talk
of Paschal Coyle

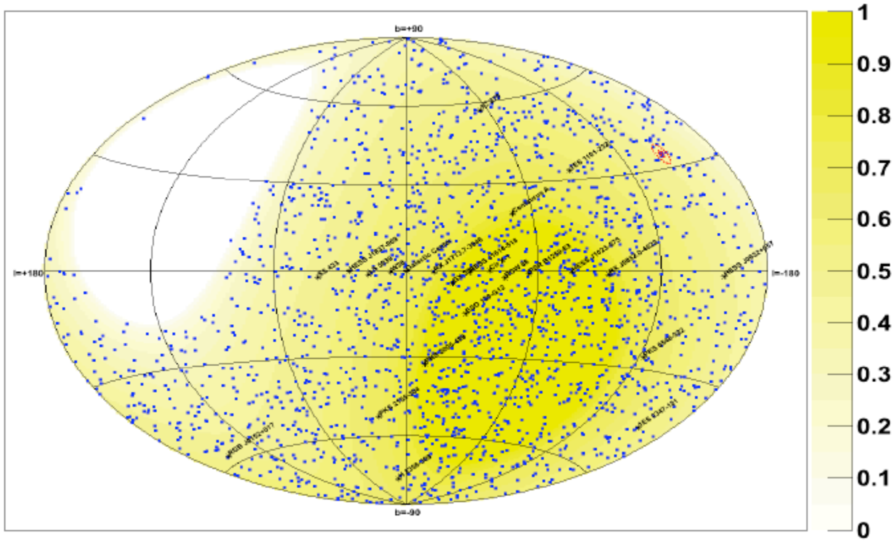
Mediterannean projects

NESTOR

ANTARES

NEMO

Antares sky map

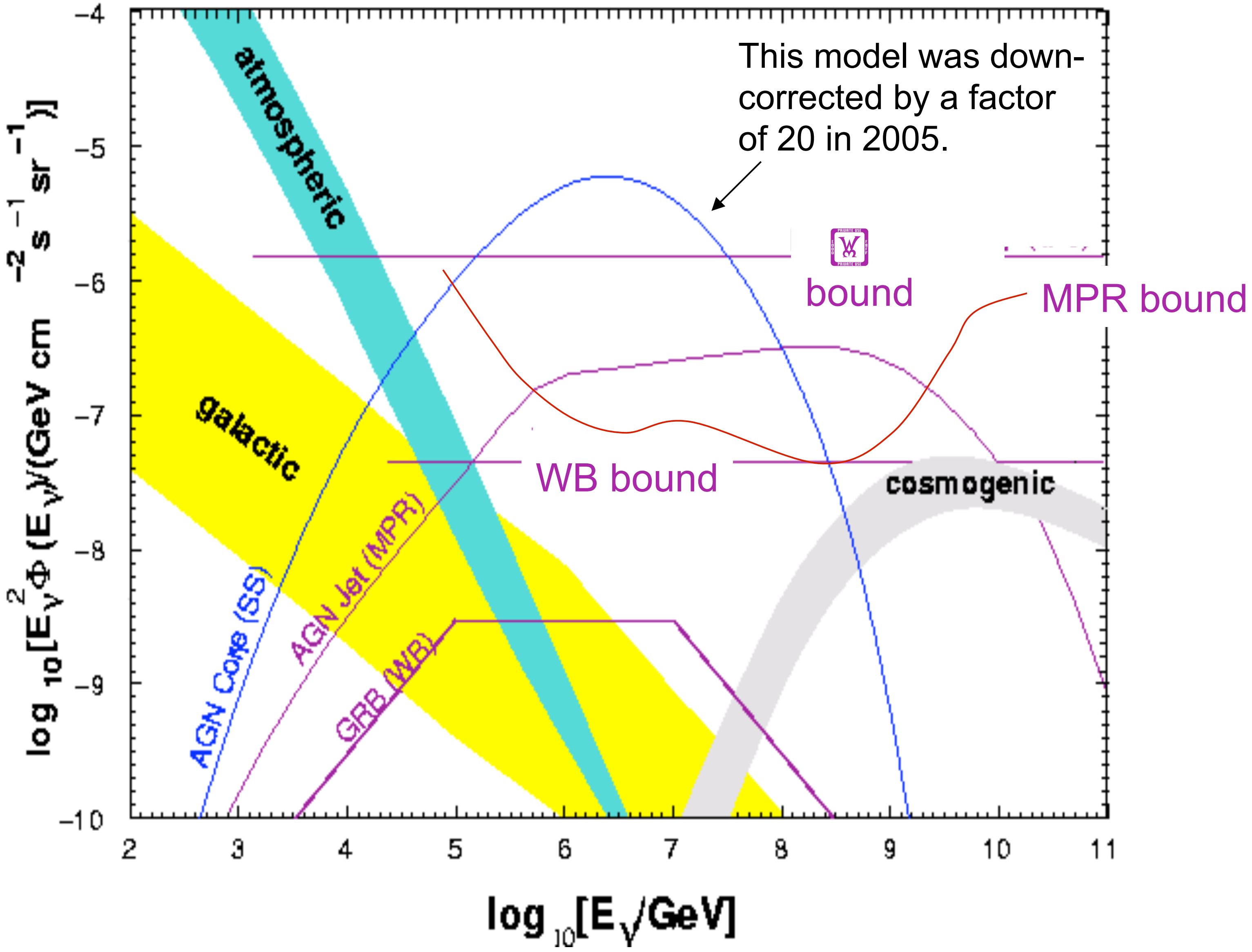


Since 2003: km3 initiative **KM3NeT**

1990-2000: revisiting the expectations

- Underground detectors, 1000 m², only for young Supernovae in our Galaxy (Berezinsky)
- New estimates on neutrinos from Supernova remnants and other galactic sources based on observations with Whipple and HEGRA
- For supernova remnants, microquasars, extragalactic sources: need detector of order 1 km³.
- The Waxman-Bahcall bound
- The Mannheim-Protheroe bound
- GRB as sources of cosmic rays and neutrinos

Diffuse Fluxes 2002

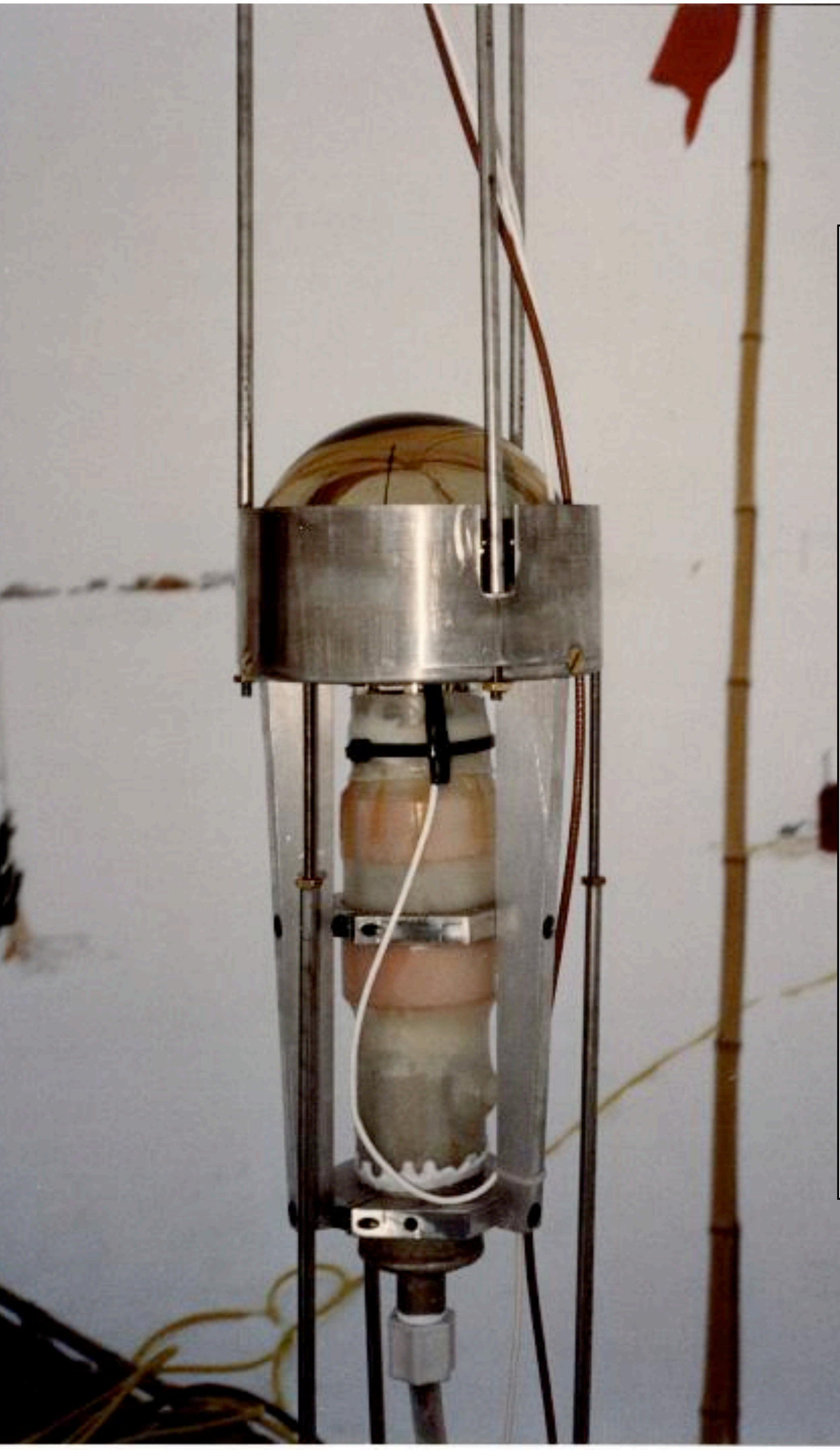


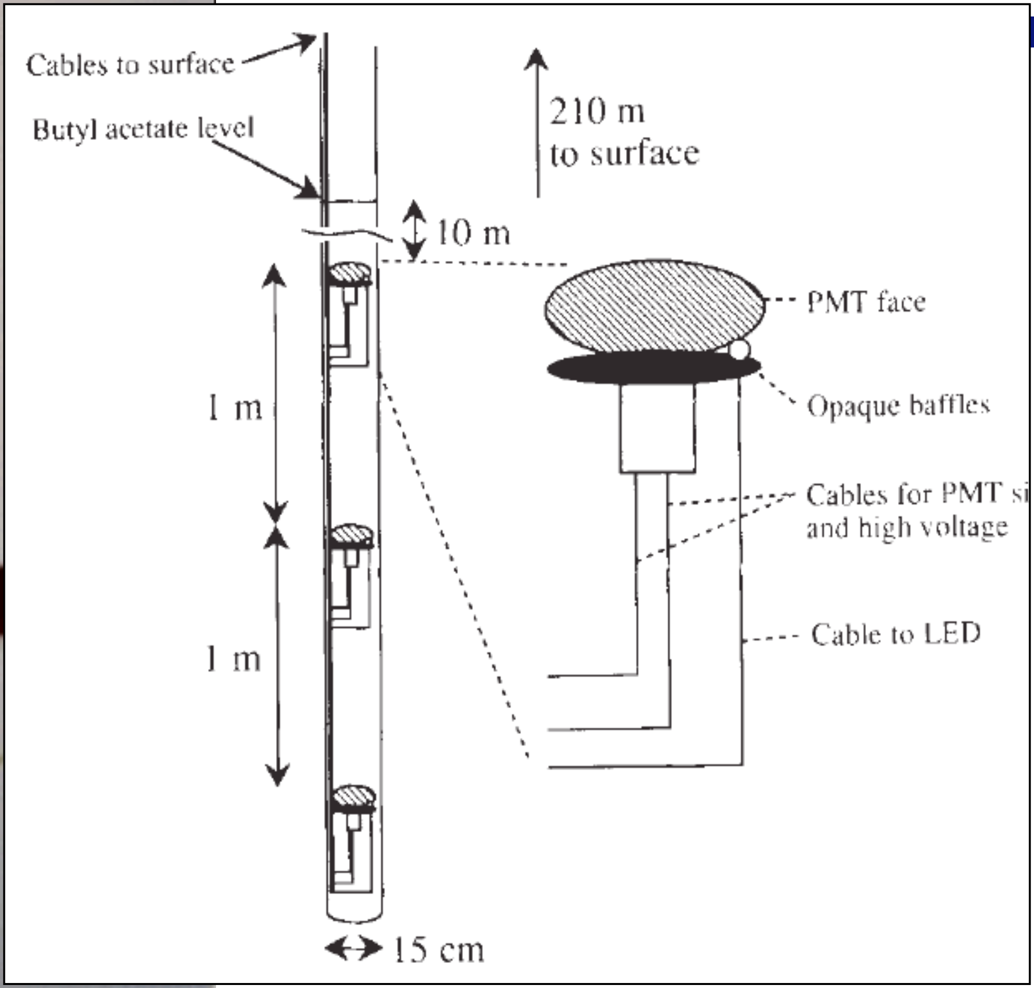
This model was down-corrected by a factor of 20 in 2005.

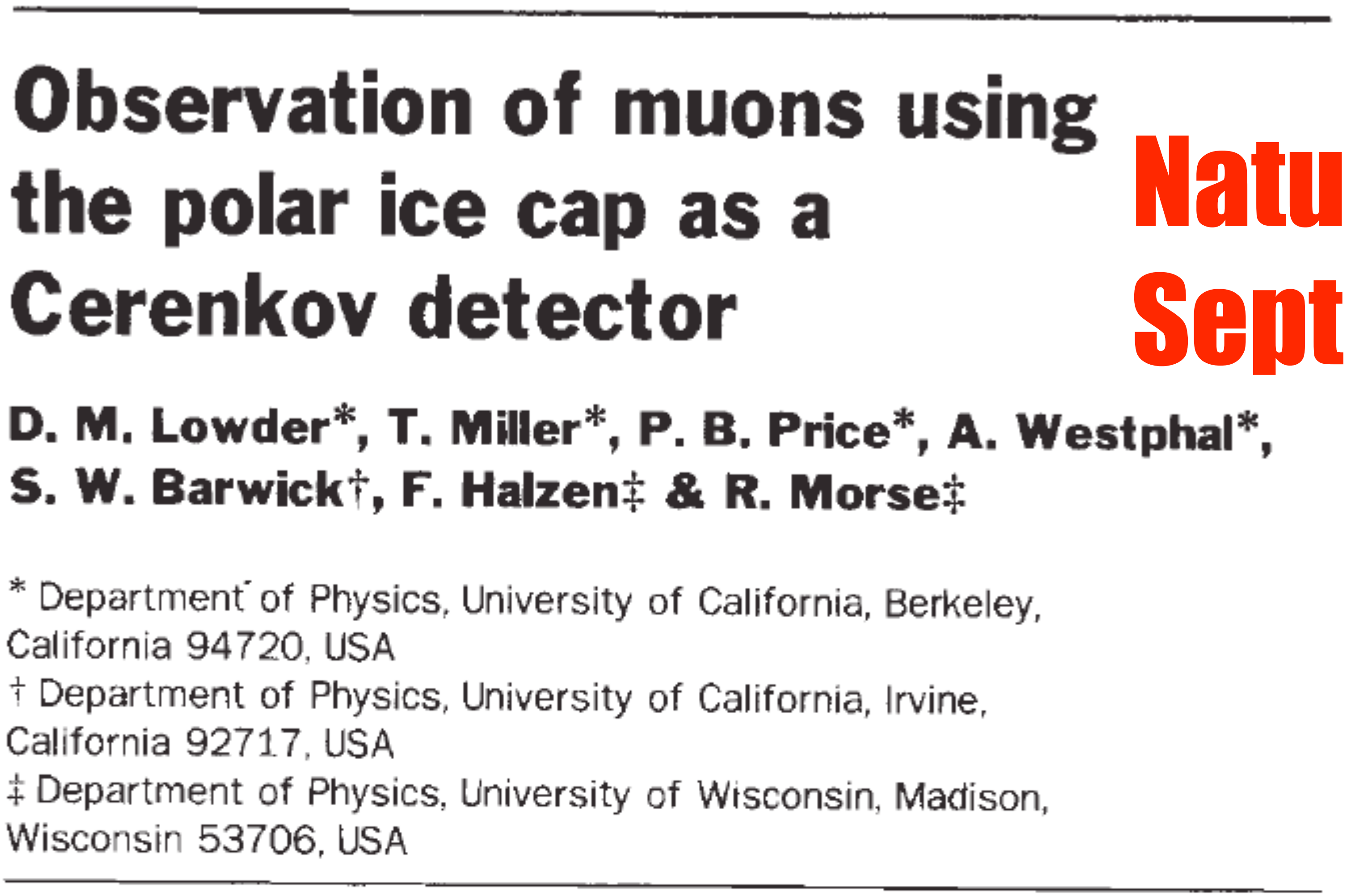
AMANDA

- 1988: Pomerantz workshop,
  NSF Science and Technology Center for the South Pole (A. Westphal, T.Miller, D. Lowder, B. Price)
- E. Zeller (Kansas) suggests to F. Halzen radiodetection of ▯ in Antarctic ice. Francis and John Learned discuss light detection of ▯ in Antartcica

- 1989: attempt of Westphal and Lowder to measure ice transparency in existing boreholes
- Jan. 89, ICRC, Adelaide: Decide to propose Amanda (B. Price, D. Lowder, S. Barwick, B. Morse, F. Halzen, A. Watson)
- 1990: Morse et al. deploy PMTs in Greenland ice




Cables to surface
Butyl acetate level
210 m
to surface
10 m
1 m
1 m
15 cm
PMT face
Opaque baffles
Cables for PMT si
and high voltage
Cable to LED

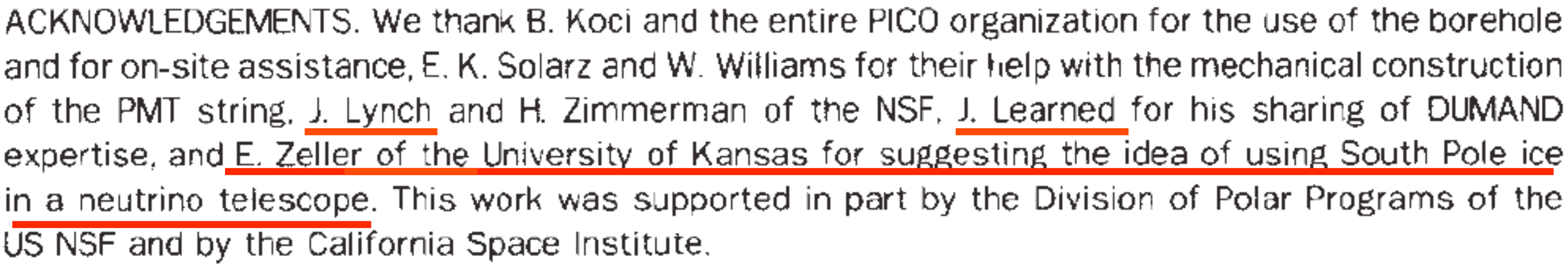


Observation of muons using the polar ice cap as a Cerenkov detector

D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

* Department of Physics, University of California, Berkeley,
California 94720, USA
† Department of Physics, University of California, Irvine,
California 92717, USA
‡ Department of Physics, University of Wisconsin, Madison,
Wisconsin 53706, USA

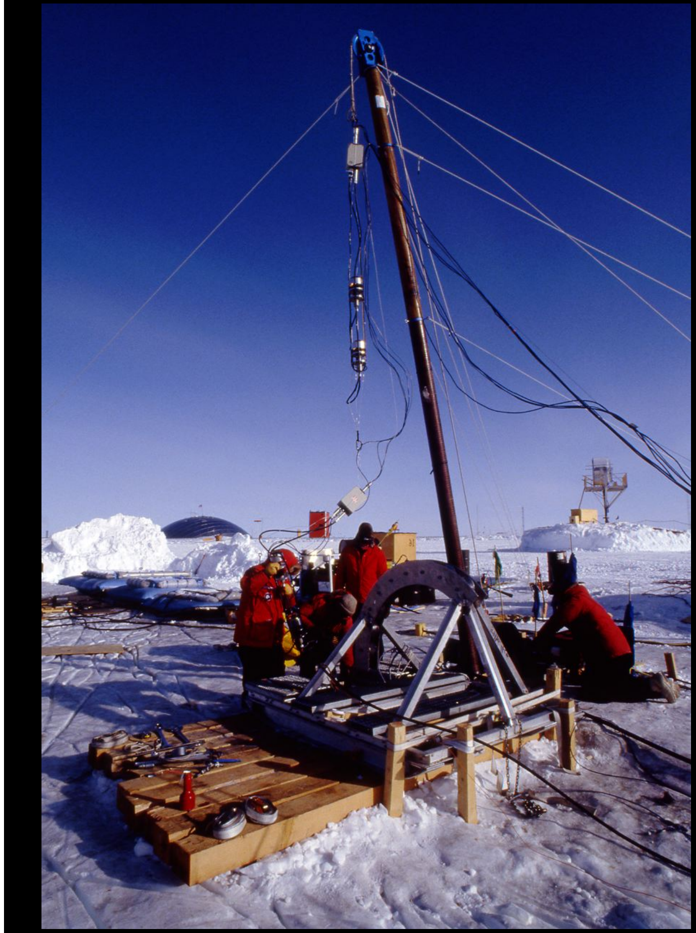
Nature Sept 91



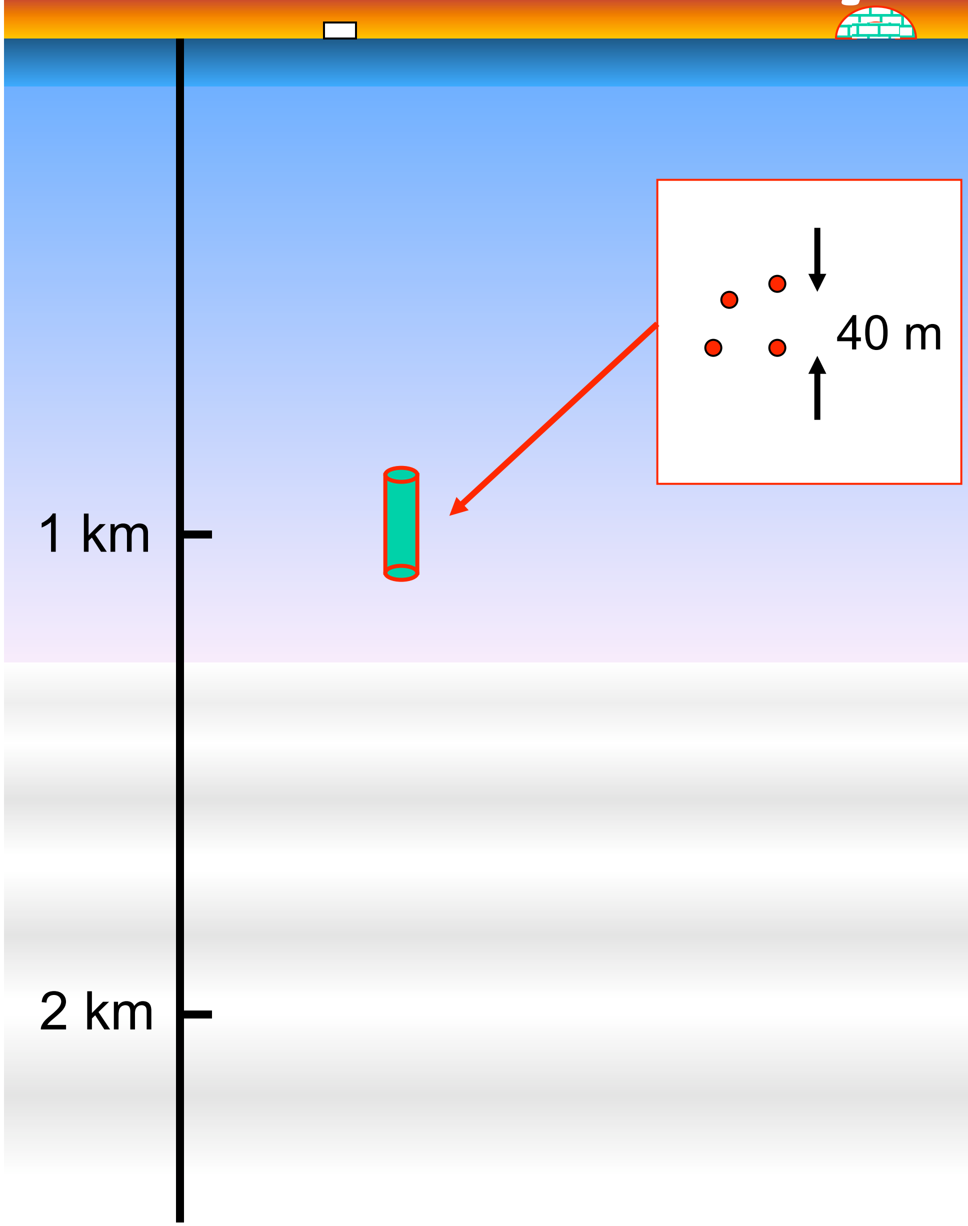
ACKNOWLEDGEMENTS. We thank B. Koci and the entire PICO organization for the use of the borehole and for on-site assistance, E. K. Solarz and W. Williams for their help with the mechanical construction of the PMT string, J. Lynch and H. Zimmerman of the NSF, J. Learned for his sharing of DUMAND expertise, and E. Zeller of the University of Kansas for suggesting the idea of using South Pole ice in a neutrino telescope. This work was supported in part by the Division of Polar Programs of the US NSF and by the California Space Institute.

DETECTION of the small flux of extraterrestrial neutrinos expected at energies above 1 TeV, and identification of their astrophysical point sources, will require neutrino telescopes with effective areas measured in square kilometres—much larger than detectors now existing[1–3]. Such a device can be built only by using some naturally occurring detecting medium of enormous extent: deep Antarctic ice is a strong candidate. A neutrino telescope could be constructed by drilling holes in the ice with hot water into which photomultiplier tubes could be placed to a depth of 1 km. Neutrinos would be recorded, as in underground neutrino detectors using water as the medium, by the observation of Cerenkov radiation from secondary muons. We have begun the AMANDA (Antarctic Muon and Neutrino Detector Array) project to test this idea, and here we describe a pilot experiment using photomultiplier tubes placed into Arctic ice in Greenland. Cerenkov radiation from muons was detected, and a comparison of count rate with the expected muon flux indicates that the ice is very transparent, with an absorption length greater than 18 m. Our results suggest that a full-scale Antarctic ice detector is technically quite feasible.

- South Pole 1991/92 first small PMTs deployed
- Results consistent with 25 m absorption length

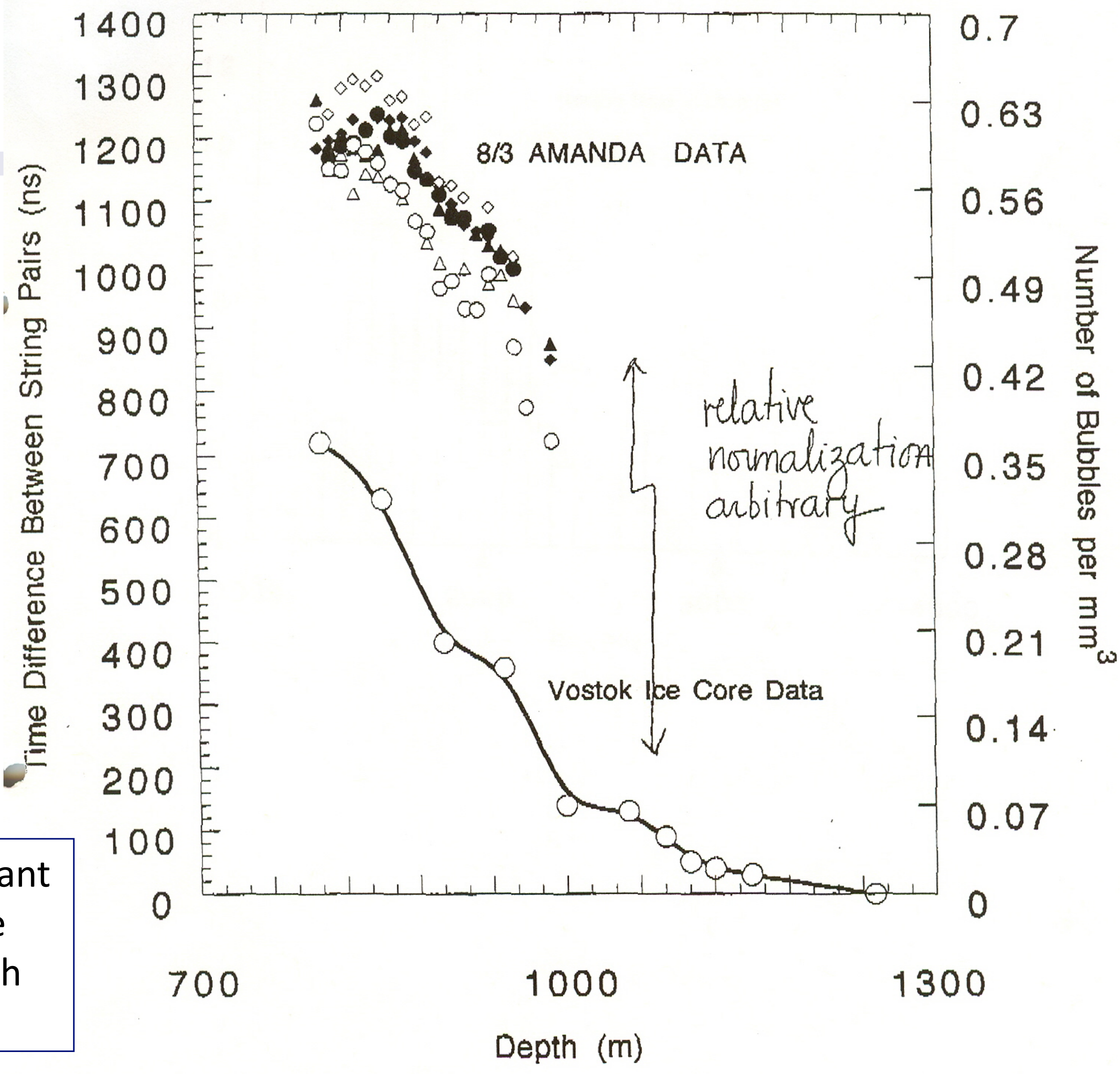


1993/94: AMANDA-A



Catastrophal delay of light between strings 20 m away!

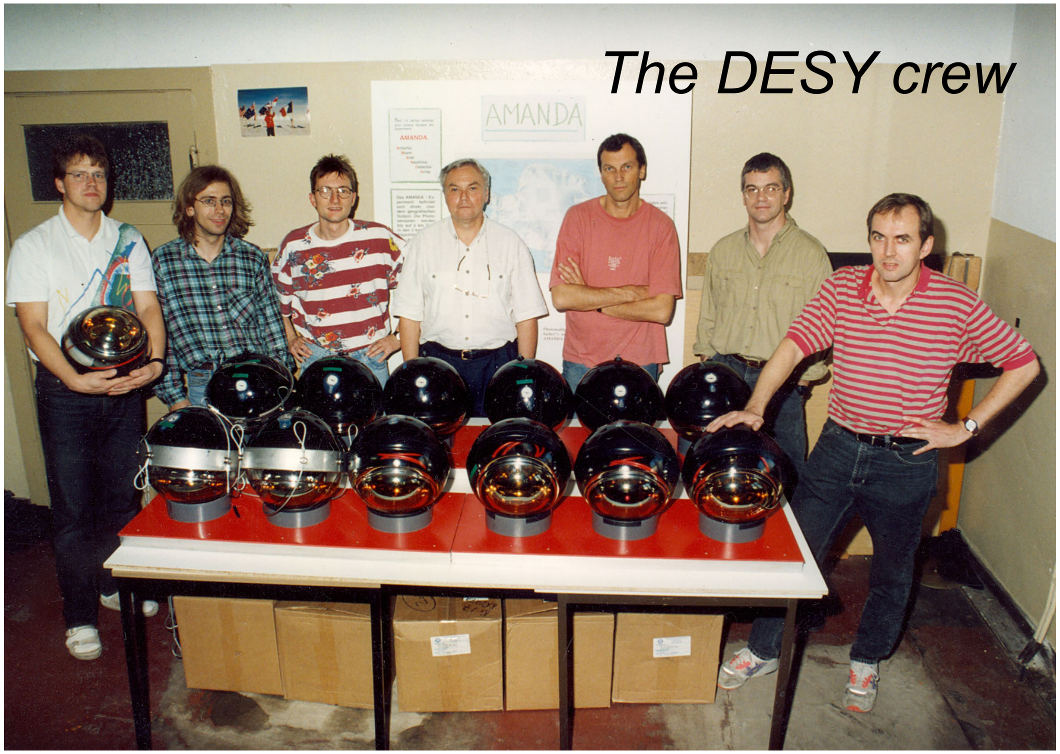
(µsec instead of 100 nsec)



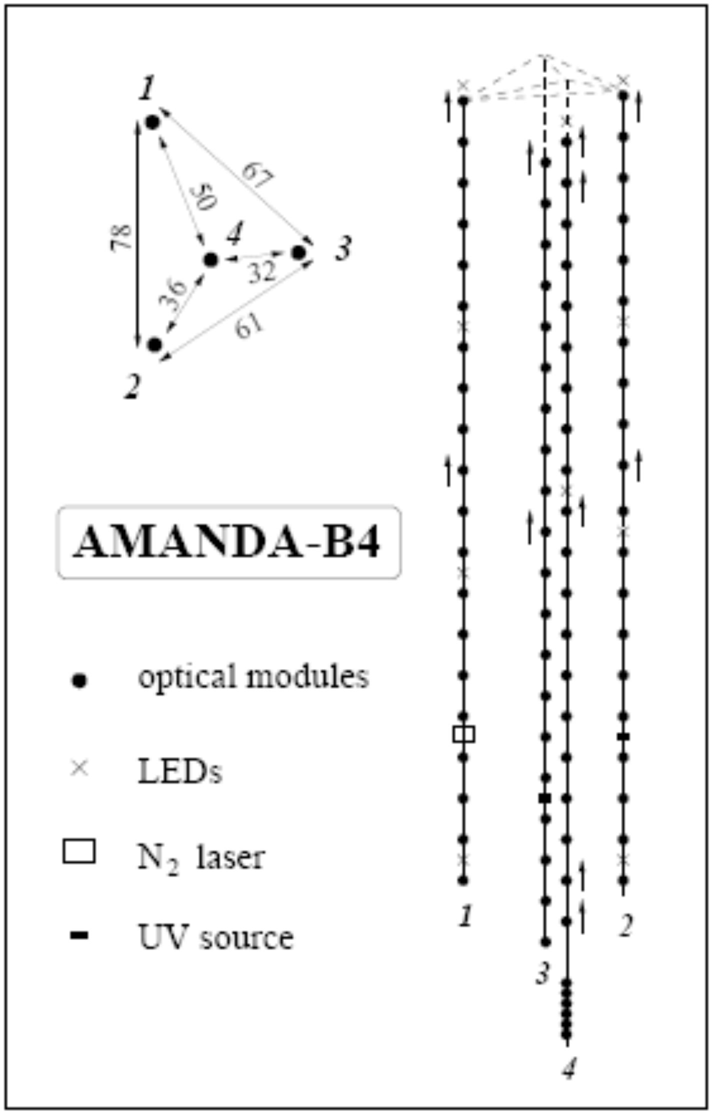
Explanation remnant bubbles which are disapppearing with increasing depth.

Amanda B4

1995: DESY and Stockholm build
~ 100 modules, 86 deployed in
the season 95/96 at 1450-1950 m depth

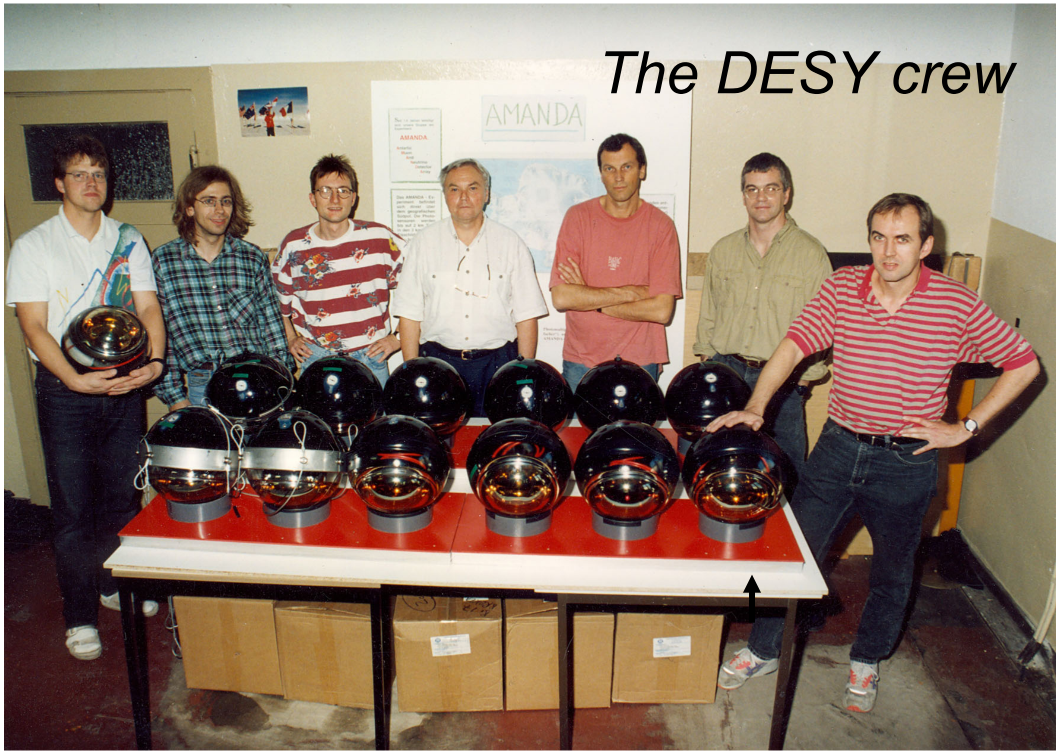


The DESY crew



Amanda B4

1995: DESY and Stockholm build
~ 100 modules, 86 deployed in
the season 95/96 at 1450-1950 m depth



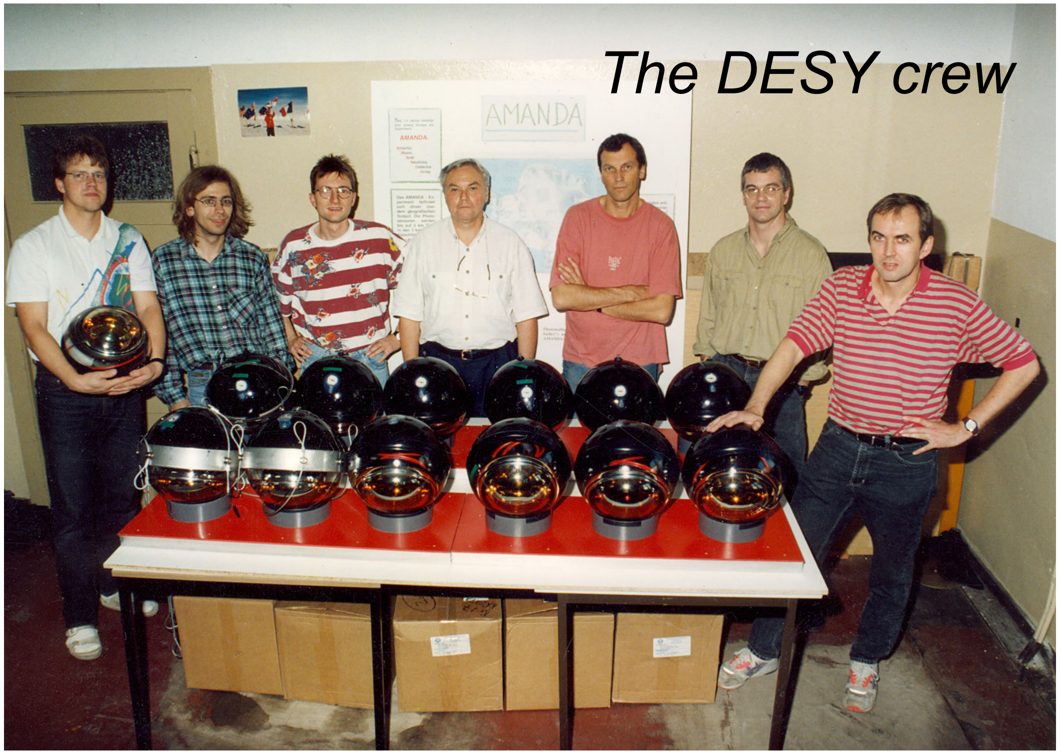
The DESY crew

- no bubbles left
- scattering now dominated by dust
- average scattering length ~ 25 m
- average absorption length >100 m

  down to wavelength of 337 nm !

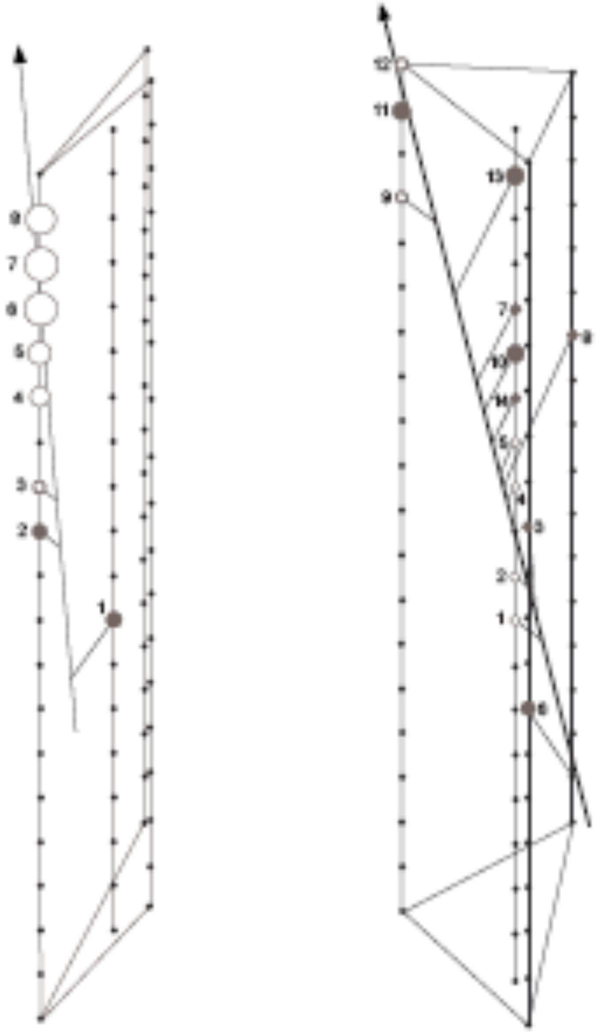
Amanda B4

1995: DESY and Stockholm build
~ 100 modules, 86 deployed in
the season 95/96 at 1450-1950 m depth

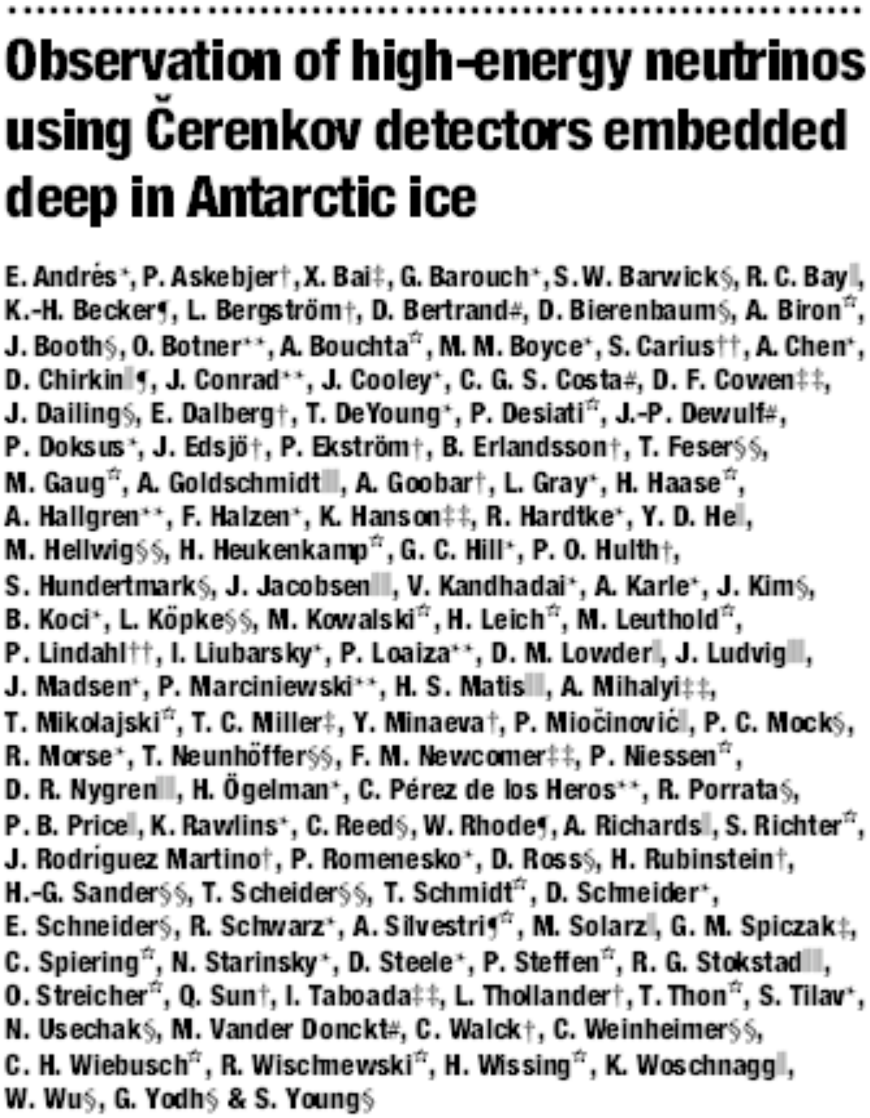


The DESY crew

The first 2 neutrinos



AMANDA B10 (1996/97)
IceCube will work !



Observation of high-energy neutrinos using Čerenkov detectors embedded deep in Antarctic ice

E. Andrés[*], P. Askebjer[†], X. Bai[‡], G. Barouch[*], S.W. Barwick[§], R. C. Bay[‖],
K.-H. Becker[¶], L. Bergström[†], D. Bertrand[#], D. Bierenbaum[§], A. Biron[☆],
J. Booth[§], O. Botner[**], A. Bouchta[☆], M. M. Boyce[*], S. Carius[††], A. Chen[*],
D. Chirkin[‖¶], J. Conrad[**], J. Cooley[*], C. G. S. Costa[#], D. F. Cowen[‡‡],
J. Dailing[§], E. Dalberg[†], T. DeYoung[*], P. Desiati[☆], J.-P. Dewulf[#],
P. Doksus[*], J. Edsjö[†], P. Ekström[†], B. Erlandsson[†], T. Feser[§§],
M. Gaug[☆], A. Goldschmidt[‖‖], A. Goobar[†], L. Gray[*], H. Haase[☆],
A. Hallgren[**], F. Halzen[*], K. Hanson[‡‡], R. Hardtke[*], Y. D. He[‖],
M. Hellwig[§§], H. Heukenkamp[☆], G. C. Hill[*], P. O. Hulth[†],
S. Hundertmark[§], J. Jacobsen[‖‖], V. Kandhadai[*], A. Karle[*], J. Kim[§],
B. Koci[*], L. Köpke[§§], M. Kowalski[☆], H. Leich[☆], M. Leuthold[☆],
P. Lindahl[††], I. Liubarsky[*], P. Loaiza[**], D. M. Lowder[‖], J. Ludvig[‖‖],
J. Madsen[*], P. Marciniewski[**], H. S. Matis[‖‖], A. Mihalyi[‡‡],
T. Mikolajski[☆], T. C. Miller[‡], Y. Minaeva[†], P. Miočinović[‖], P. C. Mock[§],
R. Morse[*], T. Neunhöffer[§§], F. M. Newcomer[‡‡], P. Niessen[☆],
D. R. Nygren[‖‖], H. Ögelman[*], C. Pérez de los Heros[**], R. Porrata[§],
P. B. Price[‖], K. Rawlins[*], C. Reed[§], W. Rhode[¶], A. Richards[‖], S. Richter[☆],
J. Rodríguez Martino[†], P. Romenesko[*], D. Ross[§], H. Rubinstein[†],
H.-G. Sander[§§], T. Scheider[§§], T. Schmidt[☆], D. Schneider[*],
E. Schneider[§], R. Schwarz[*], A. Silvestri[¶☆], M. Solarz[‖], G. M. Spiczak[‡],
C. Spiering[☆], N. Starinsky[*], D. Steele[*], P. Steffen[☆], R. G. Stokstad[‖‖],
O. Streicher[☆], Q. Sun[†], I. Taboada[‡‡], L. Thollander[†], T. Thon[☆], S. Tilav[*],
N. Usechak[§], M. Vander Donckt[#], C. Walck[†], C. Weinheimer[§§],
C. H. Wiebusch[☆], R. Wischnewski[☆], H. Wissing[☆], K. Woschnagg[‖],
W. Wu[§], G. Yodh[§] & S. Young[§]

NATURE 2001

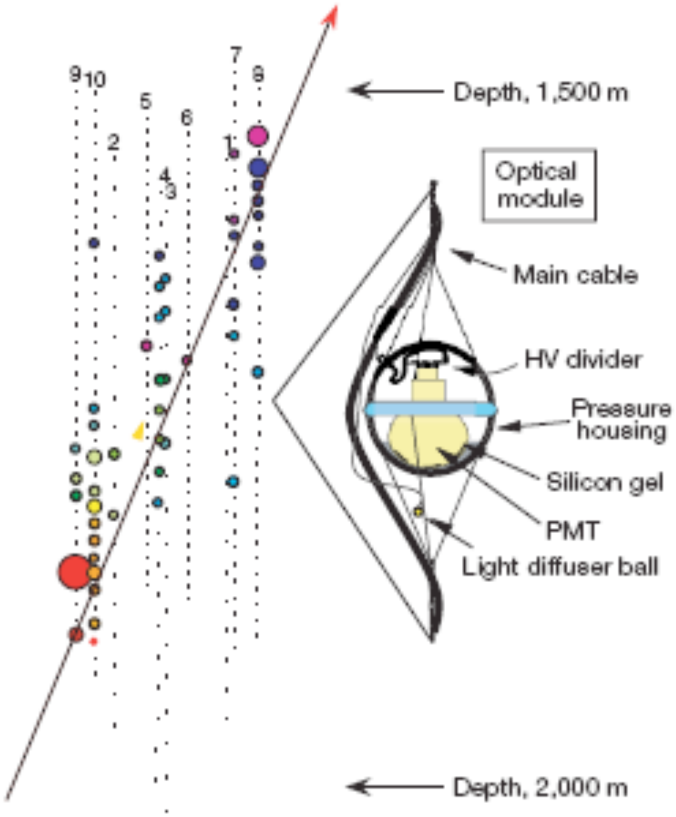


Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular event; the sizes of the circles indicate the amplitudes of the pulses and the colours correspond to the time of a photon's arrival. Earlier times are in red and later ones in blue. The arrow indicates the reconstructed track of the upwardly propagating muon.

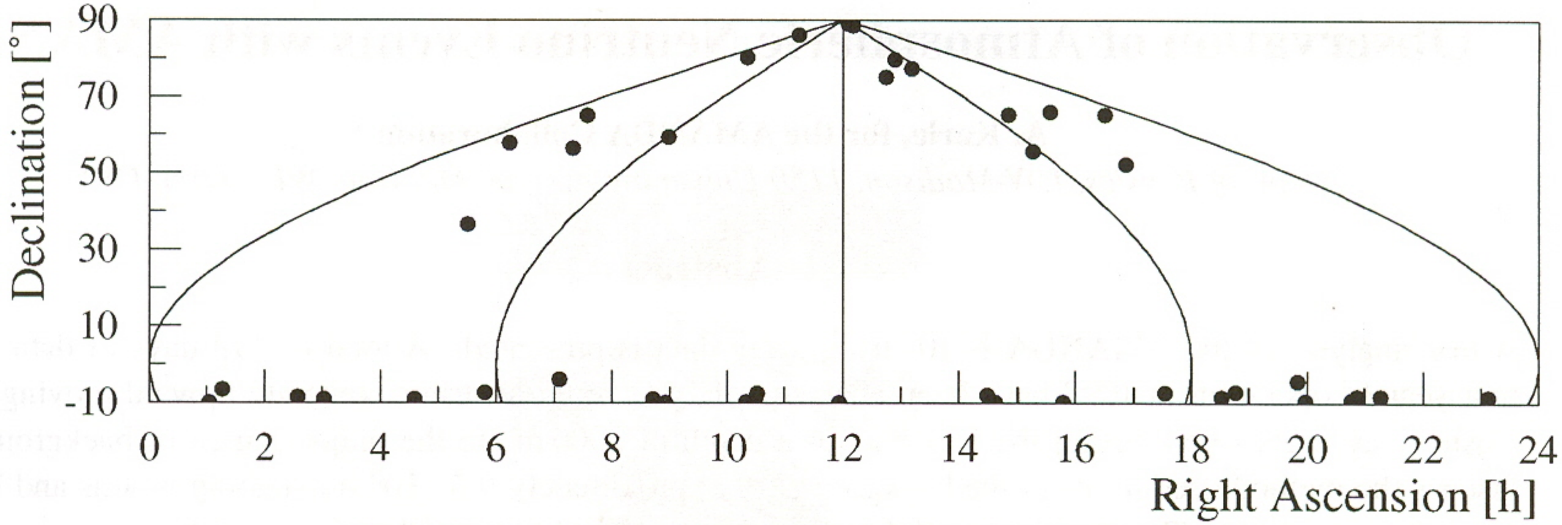


Figure 2: Sky plot of all events that pass level 4 quality cuts.

Skyplot of the very first 17 Nu candidates in B10

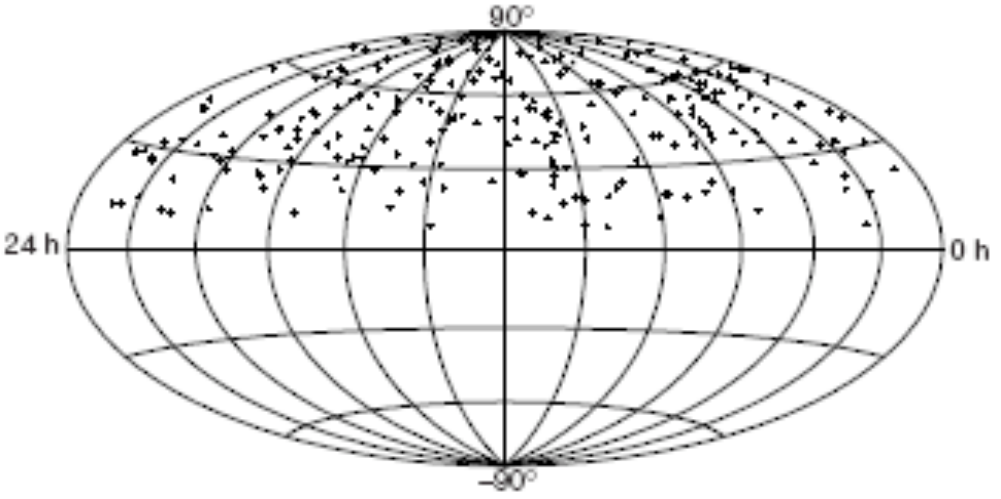
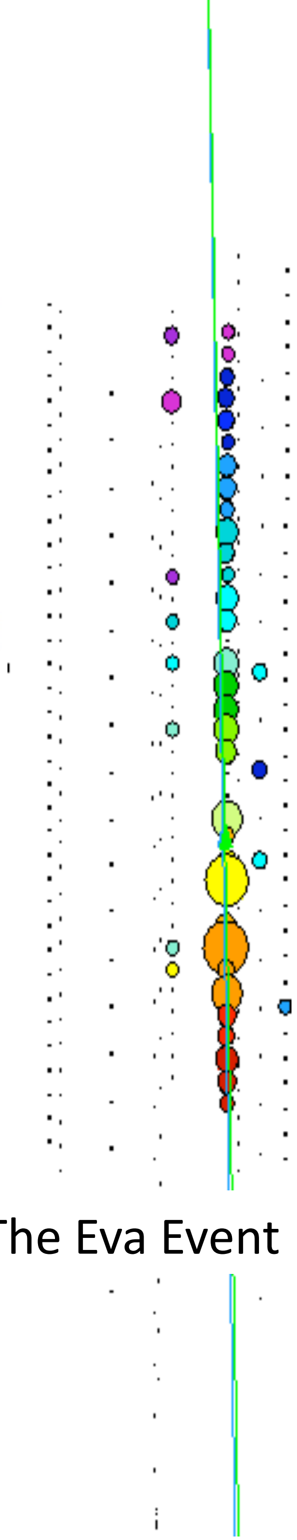


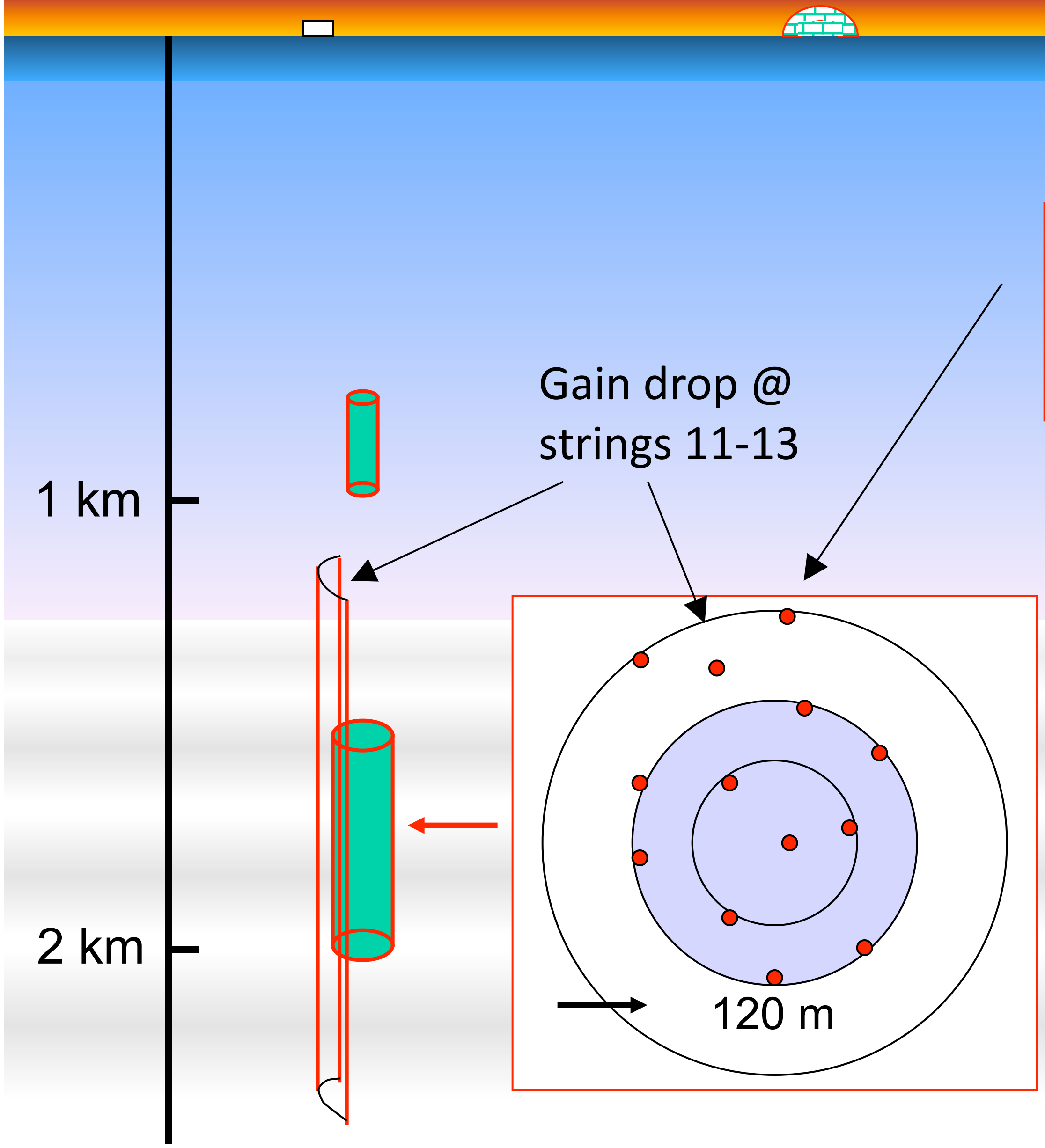
Figure 4 Distribution in declination and right ascension of the upwardly propagating events on the sky. The 263 events shown here are taken from the upward muons contained in both analysis A and analysis B. The median difference between the true and the reconstructed muon angles is about 3 to 4 degrees.

B10 skyplot published in Nature 2001



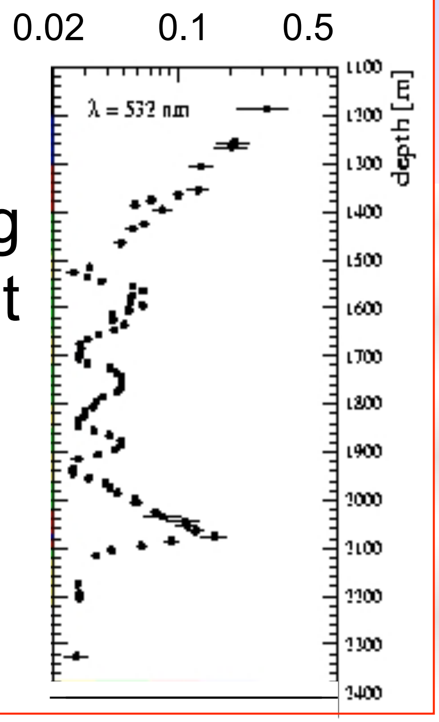
The Eva Event

1997/98

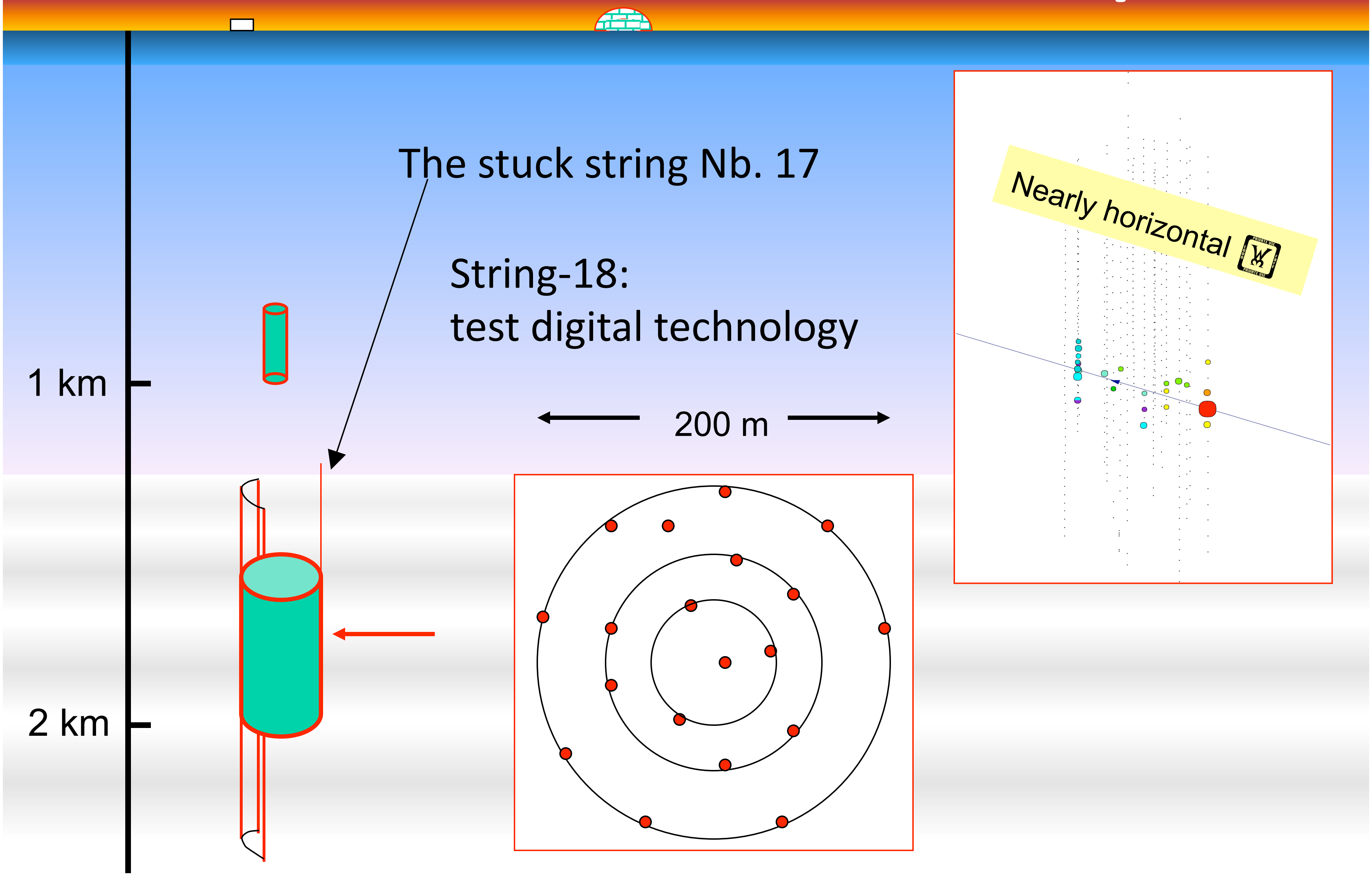


- 3 long strings
- study deep and shallow ice for future IceCube

Scattering coefficient (1/m) vs. depth



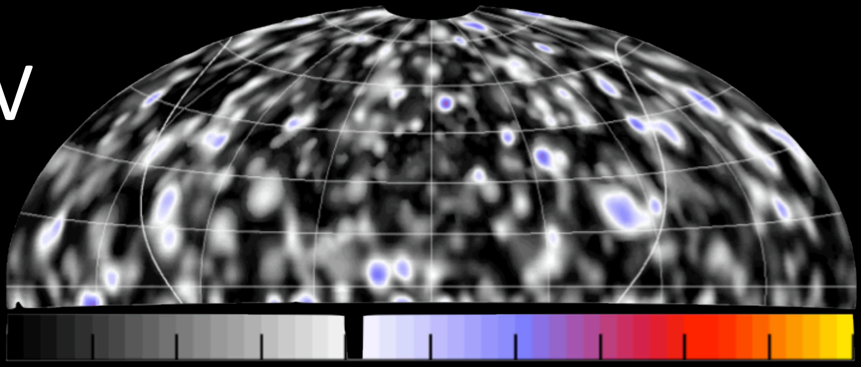
AMANDA-II 1999/2000



The stuck string Nb. 17

String-18:
test digital technology

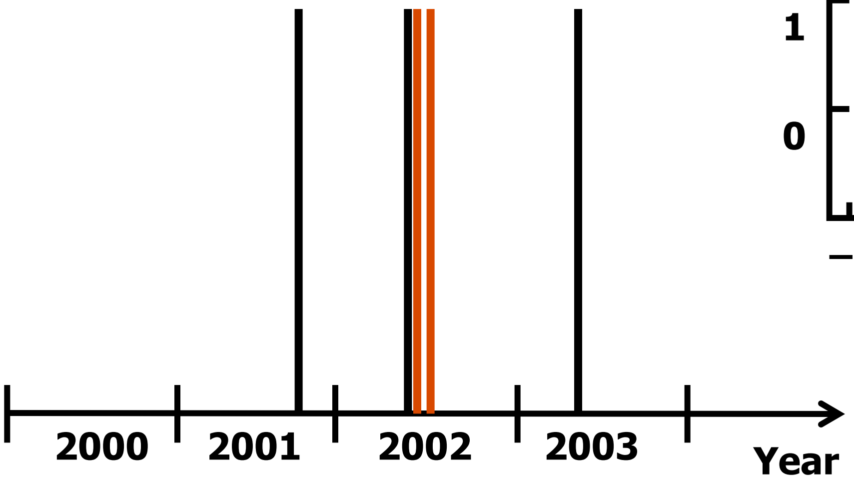
AMANDA 7 years: The results

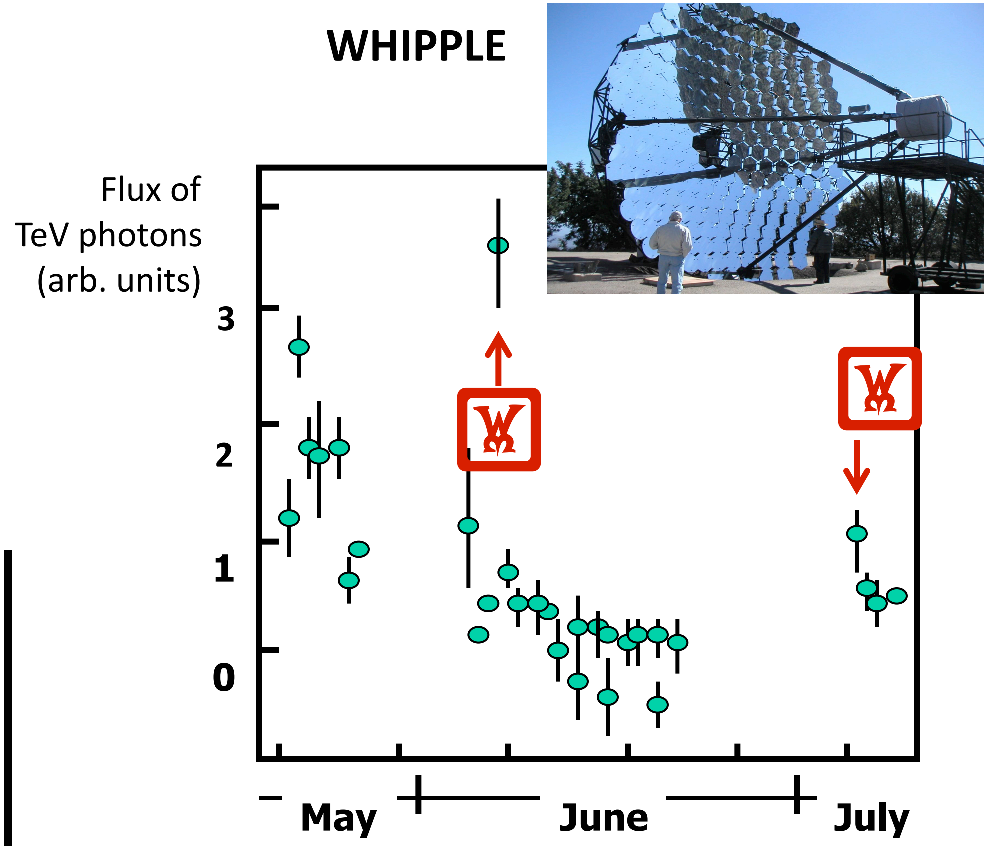


- 6595 neutrinos up to record energy of 200 TeV
- Record limits on fluxes for cosmic neutrinos (diffuse, point sources, GRB)
- Record limits on indirect dark matter search, magnetic monopoles, tests of Lorentz invariance
- Monitoring the galaxy for supernova bursts
- Spectrum and compositon of cosmic rays

The one intriguing coincidence …

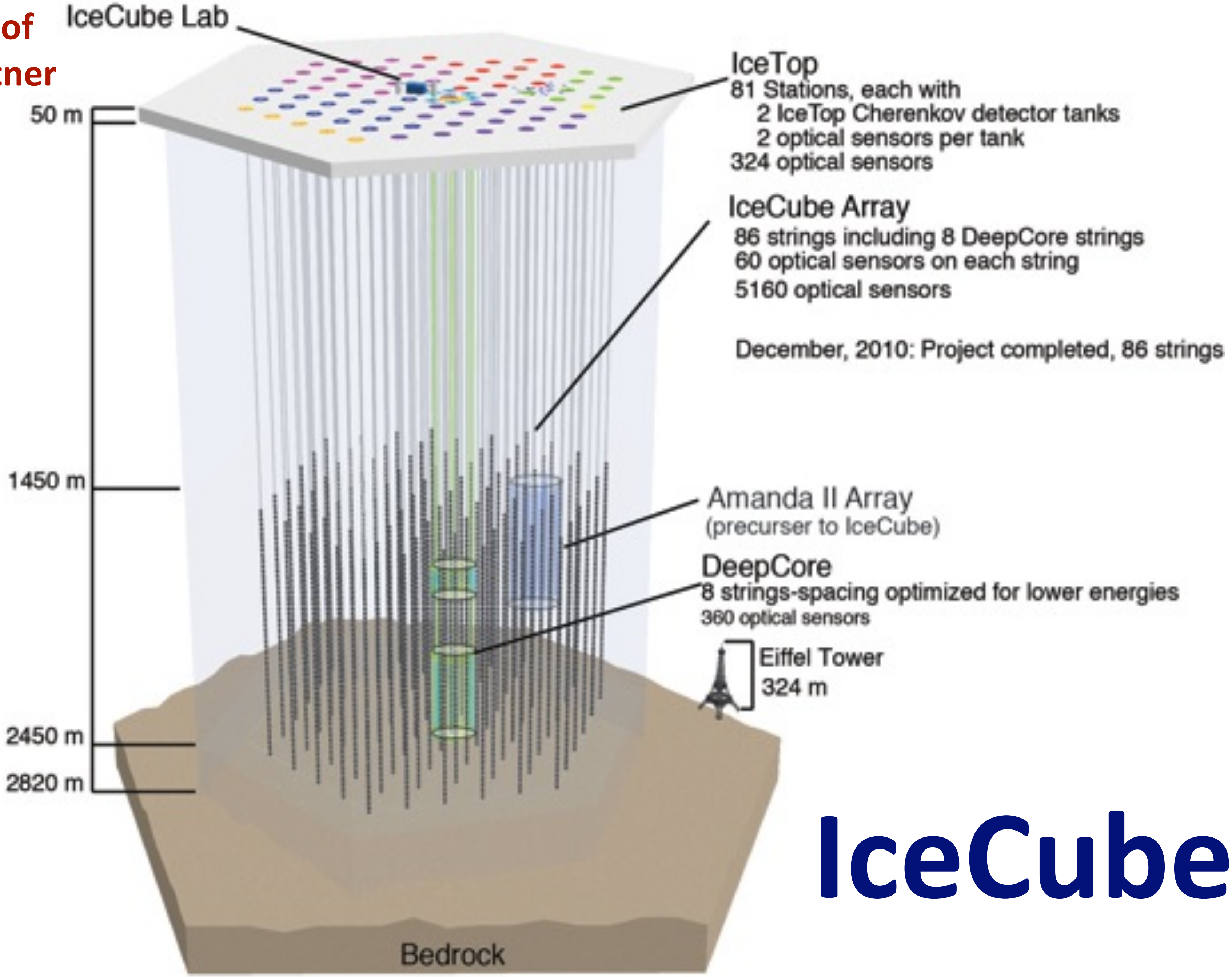
Arrival time of neutrinos from the direction of the AGN ES1959+650





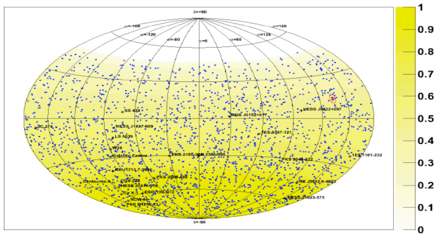
IceCube

See talk of Olga Botner



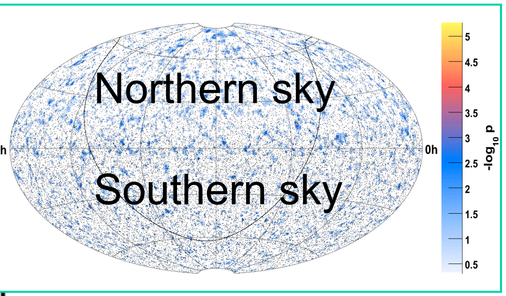
December, 2010: Project completed, 86 strings

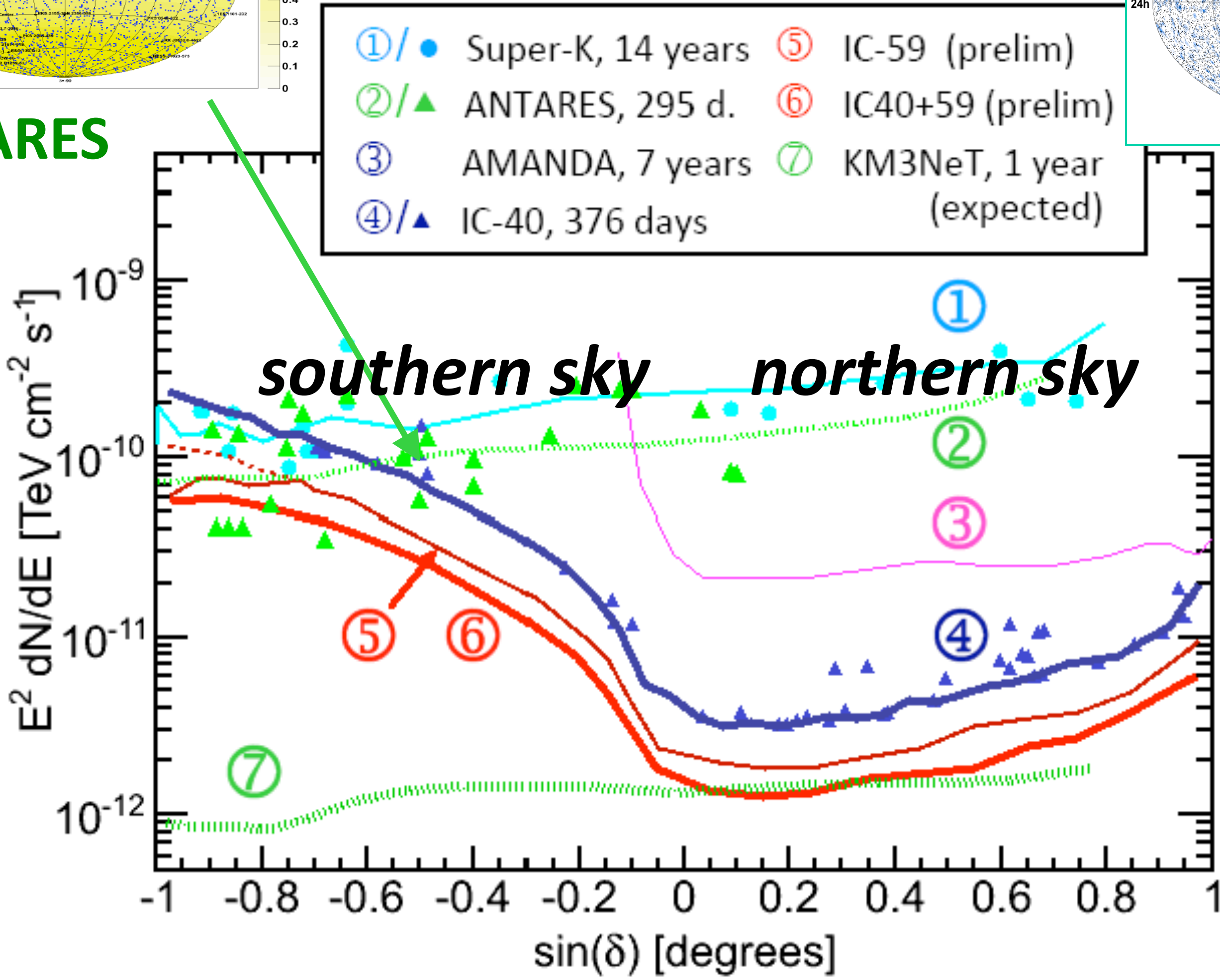
A factor 1000 in 12 years!

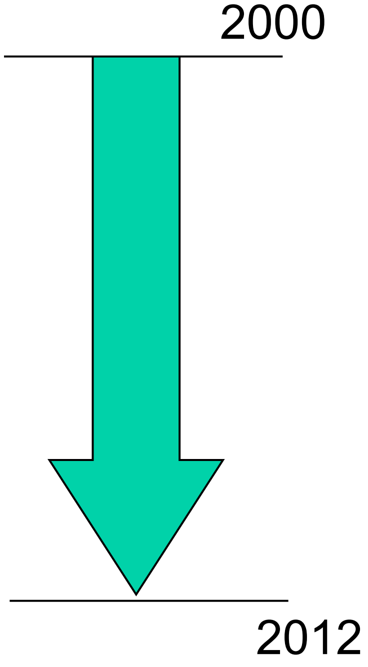


ANTARES

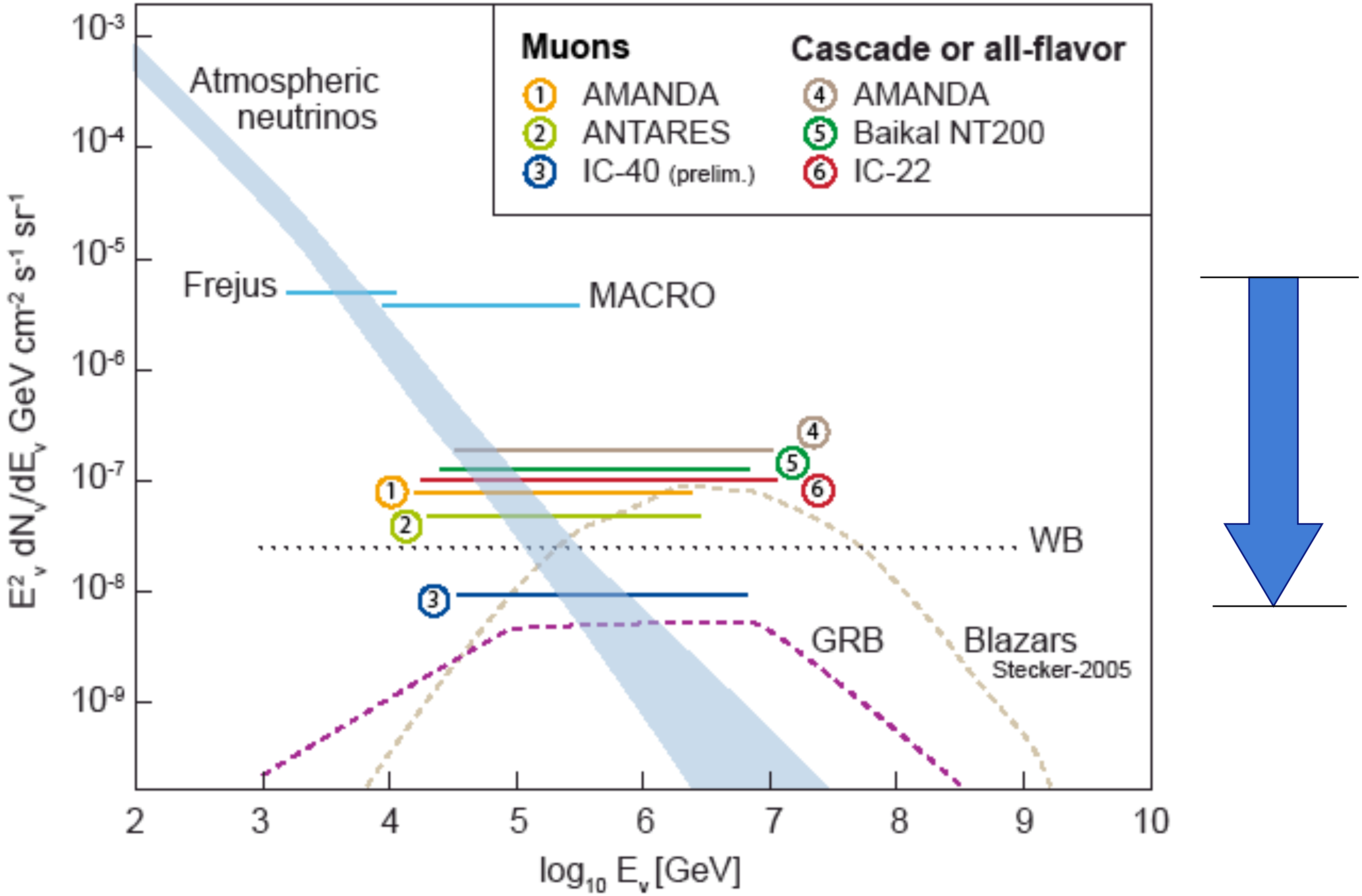
IceCube-40



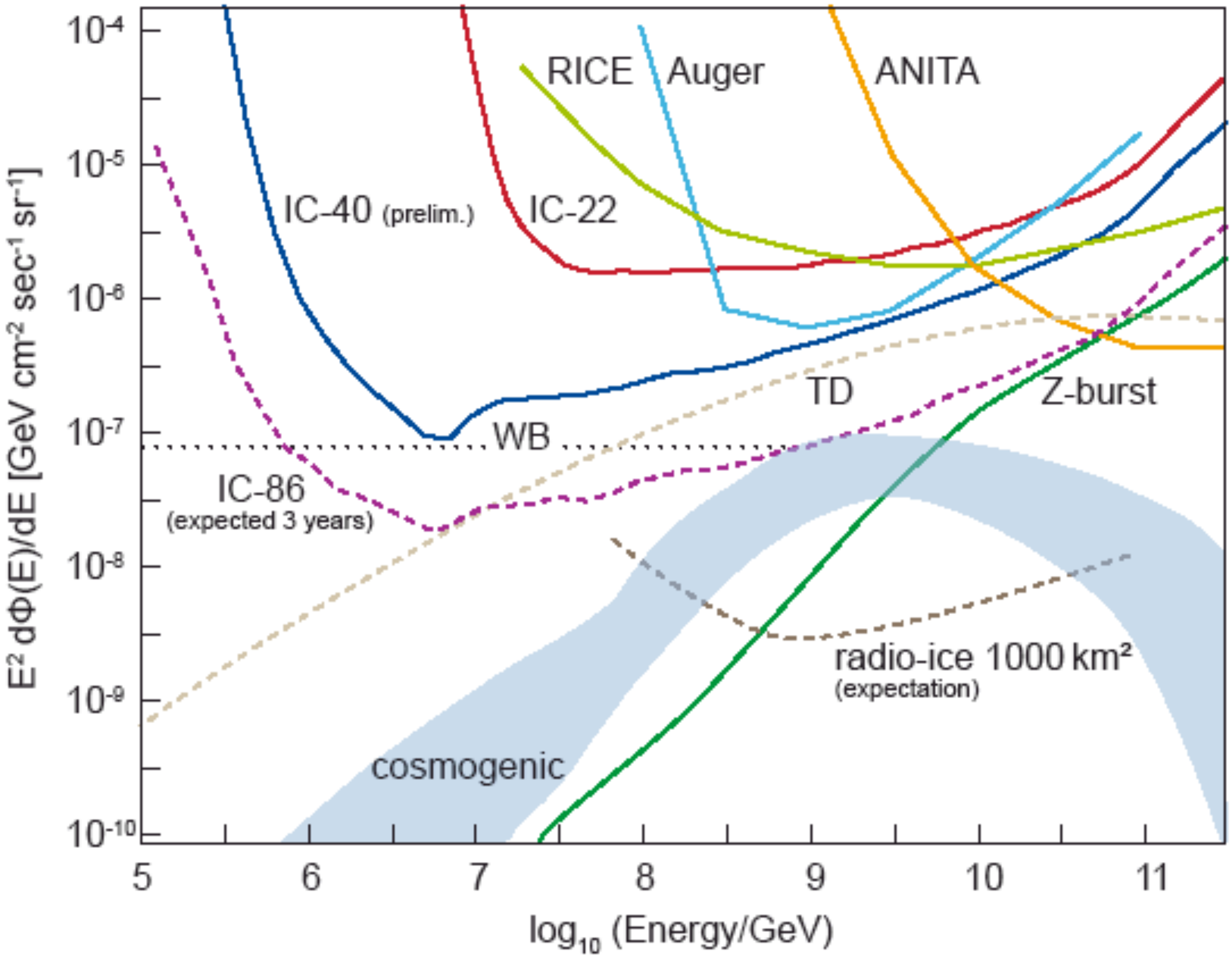




Diffuse Fluxes: a factor 1000 w.r.t. underground detectors



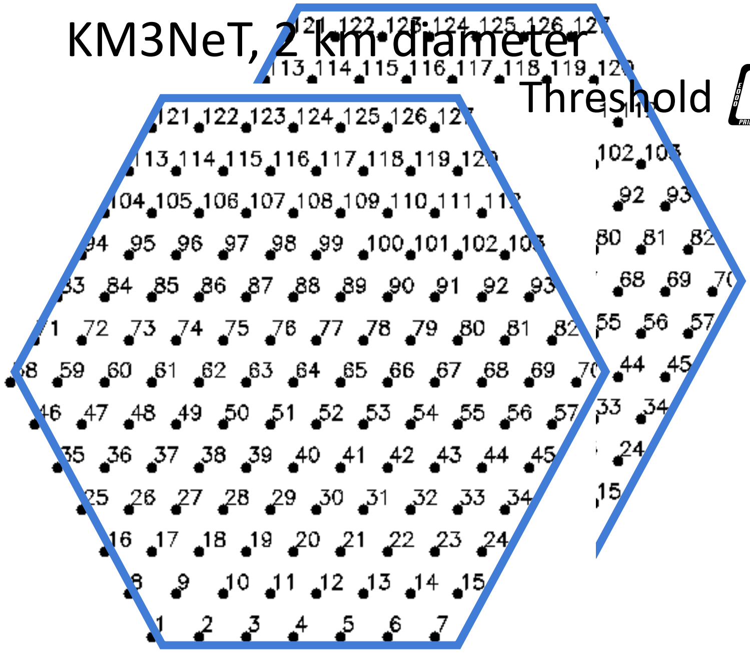
Peering into the EeV region



The Future ?

KM3NeT, GVD, IceCube++

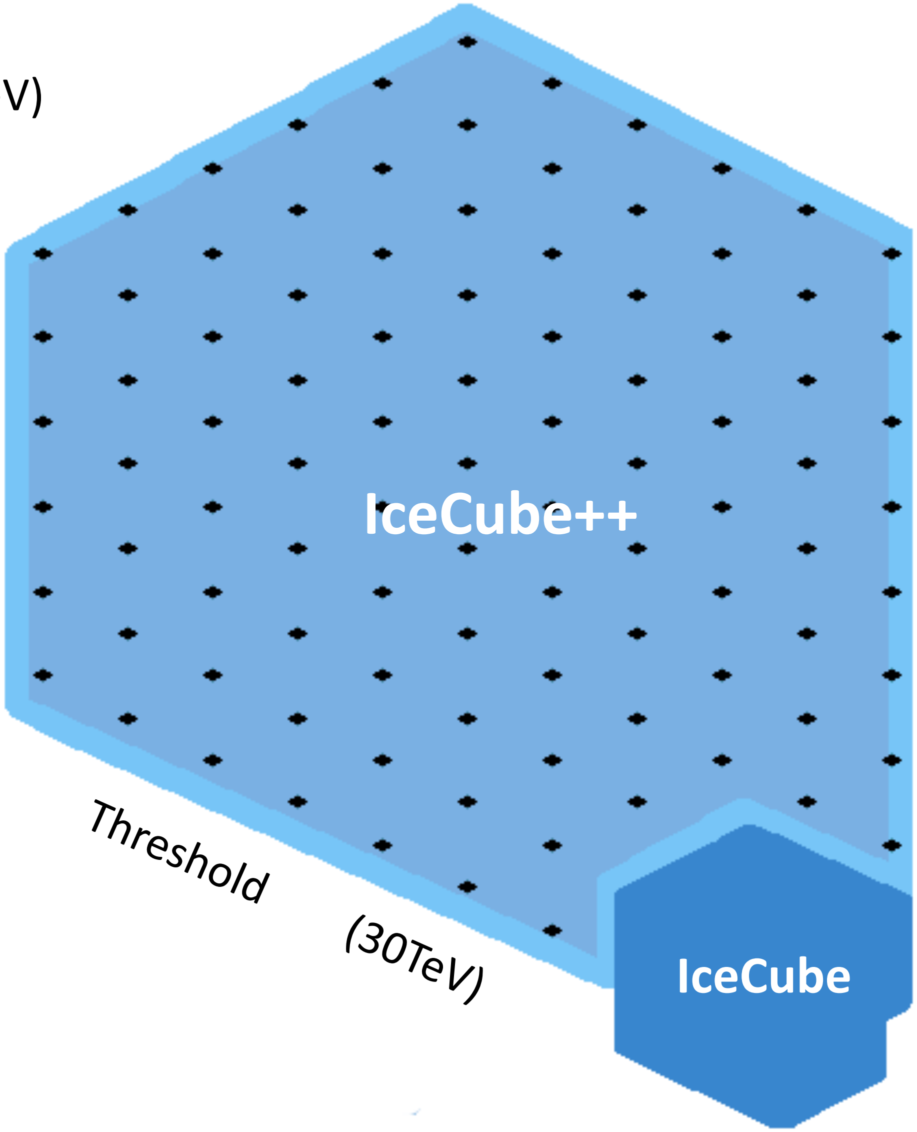
KM3NeT, 2 km diameter



Threshold ν_μ (1TeV)

Threshold

ν_μ (30TeV)

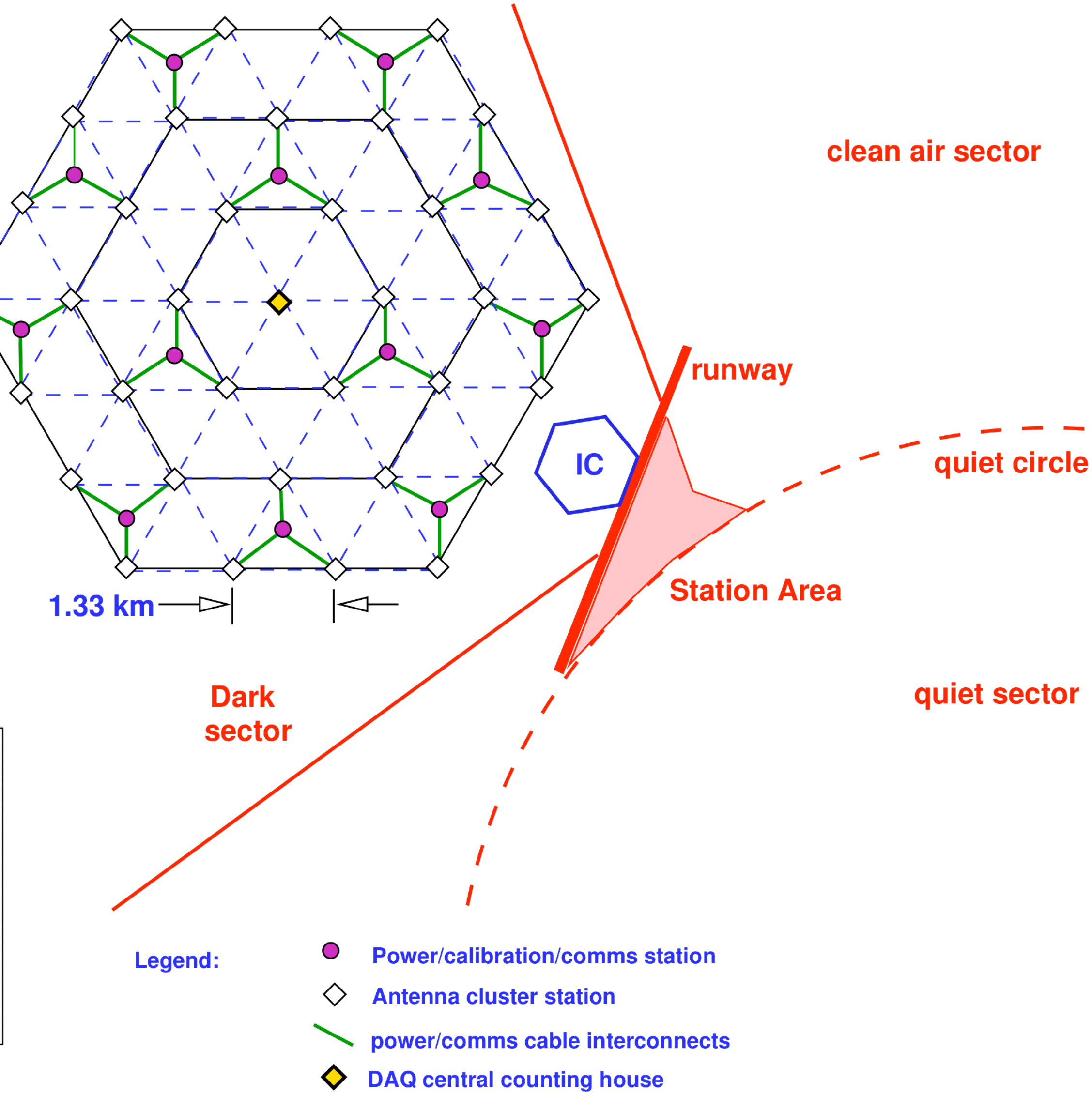


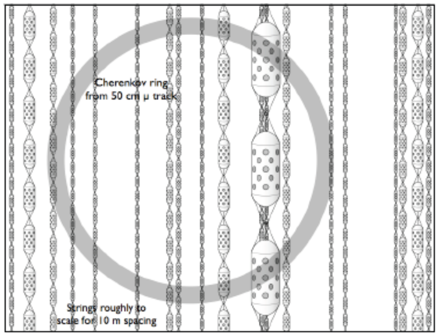
Threshold (30TeV)

South Pole ARA, PINGU

- ARA
  for > 30 PeV ?

- PINGU
  for < 10 GeV ?





The long March

The journey continues ...

Deep is the fountain of the past – couldn‘t we call it bottomless?

Thomas Mann, Joseph and his brothers

Cross sections, W-mass

… one of the main motivations for **Reines‘ South Africa detector**, the **Kolar Gold Field Detector** (India) and the **Baksan scintillation detector**(Russia).
Early sixties: does the neutrino cross section saturate beyond 1 GeV (i.e. one would never measure atm. neutrinos with energies higher than a few GeV).

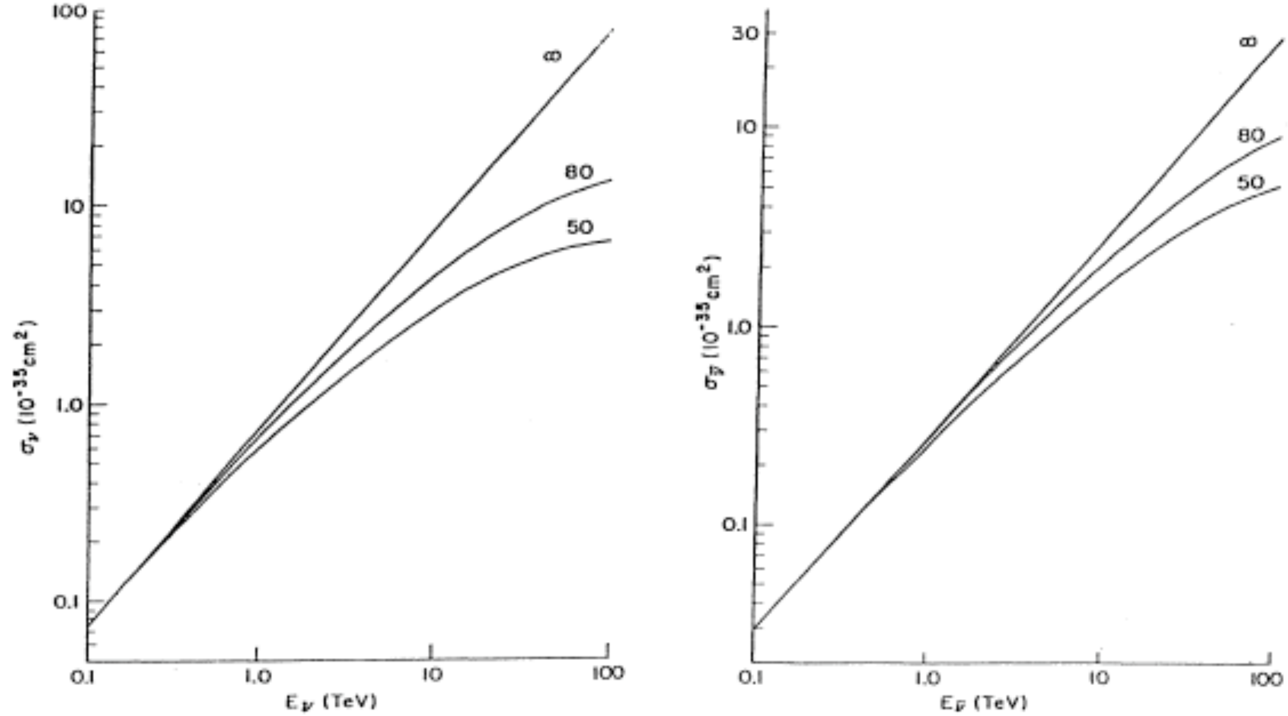


FIG. 7. Theoretical predictions (Halprin and Oakes, 1978) from the *W*-propagator model, of the muon neutrino and antineutrino cross sections for interaction with a proton, for three different assumed *W* masses (in GeV/c^2).