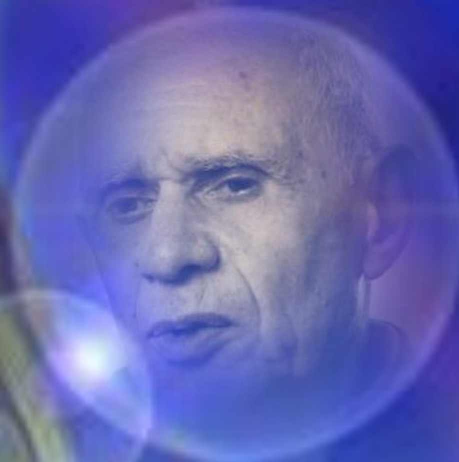
Early History

of Neutrino Astronomy and Neutrino Telescopes



Conference
in Memory
of V.S Berezinsky
GSSI, Oct .2024

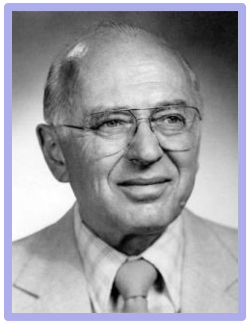
Christian Spiering, DESY

- Focus on optical detection underwater/ice
- (almost) nothing about
  - underground detectors
  - radio detection
  - acoustic detection
  - surface detection

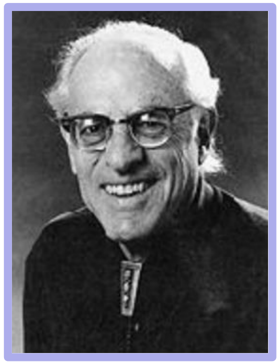
The Seeds: 1960, Rochester Conference

Three important talks address the detection of cosmic neutrinos

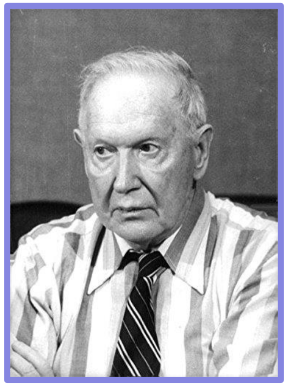
Kenneth Greisen



Fred Reines



Moisej Markov

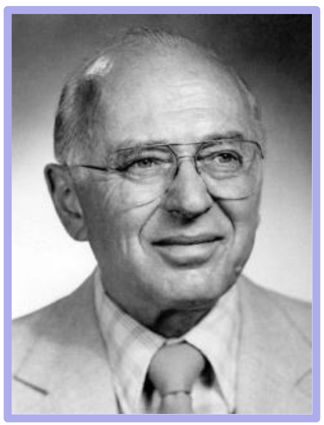


Ann.Rev.Nucl.Sci
10 (1960) 63

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



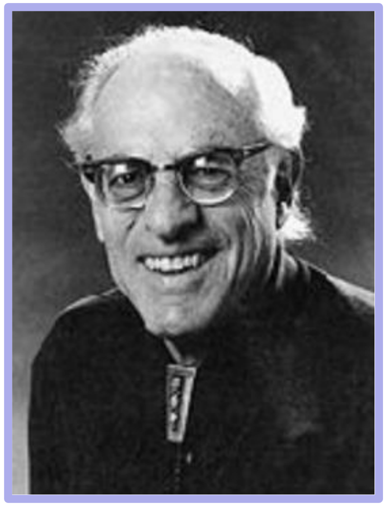
For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6\cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with 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]



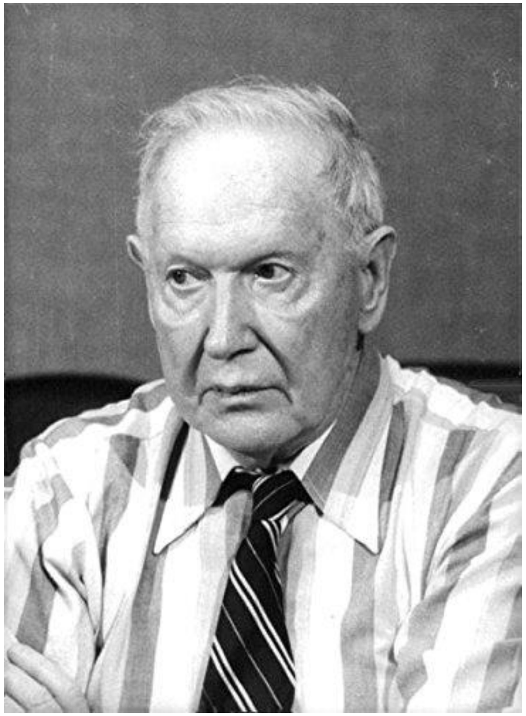
IV. COSMIC AND COSMIC RAY NEUTRINOS

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

Neutrino detection underwater

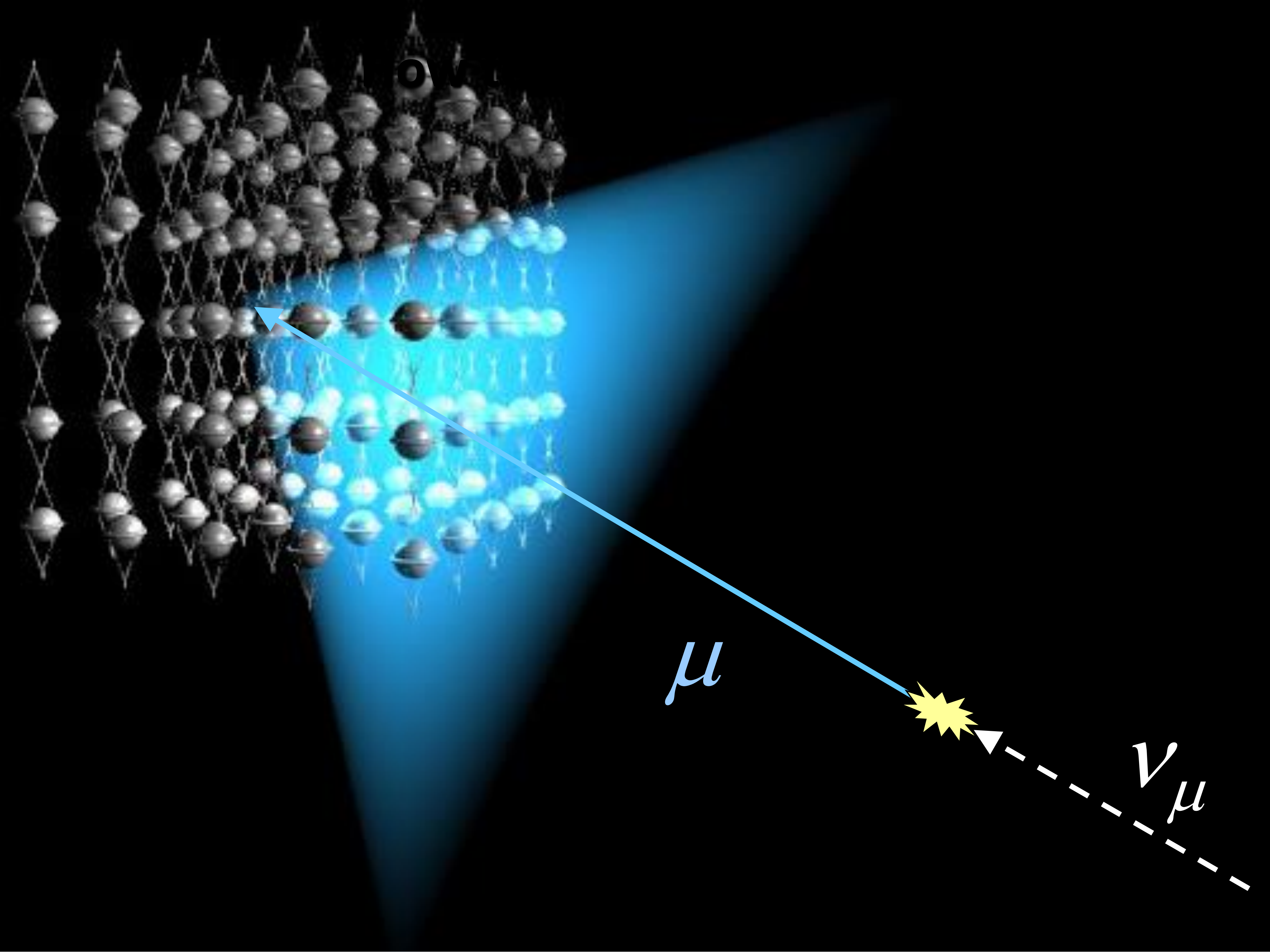
Moisej Markov



We propose setting up detectors deep in a lake or in the ocean to determine the direction of charged particles with the help of Cherenkov radiation.

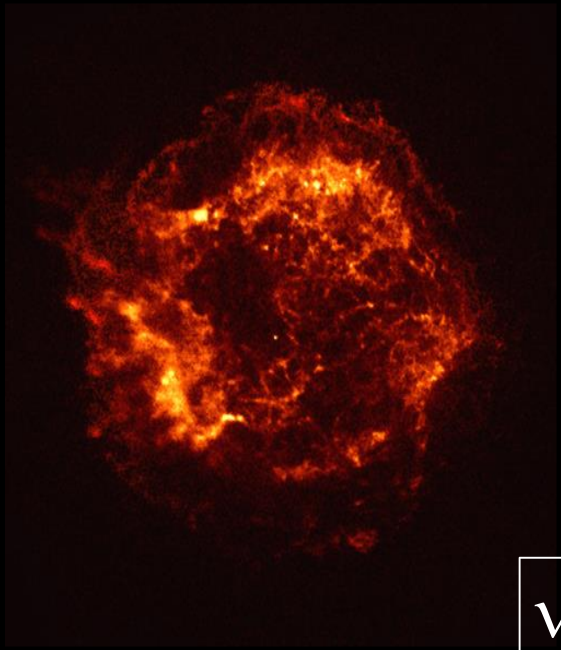
We consider μ mesons produced in the ground layers under the detector“

Proc. 1960 ICHEP, Rochester, p. 578.


μ
ν μ

Neutrino Generation in Cosmic Ray Sources

$$p + \text{target} \rightarrow \pi^+ + \ldots\ldots$$



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

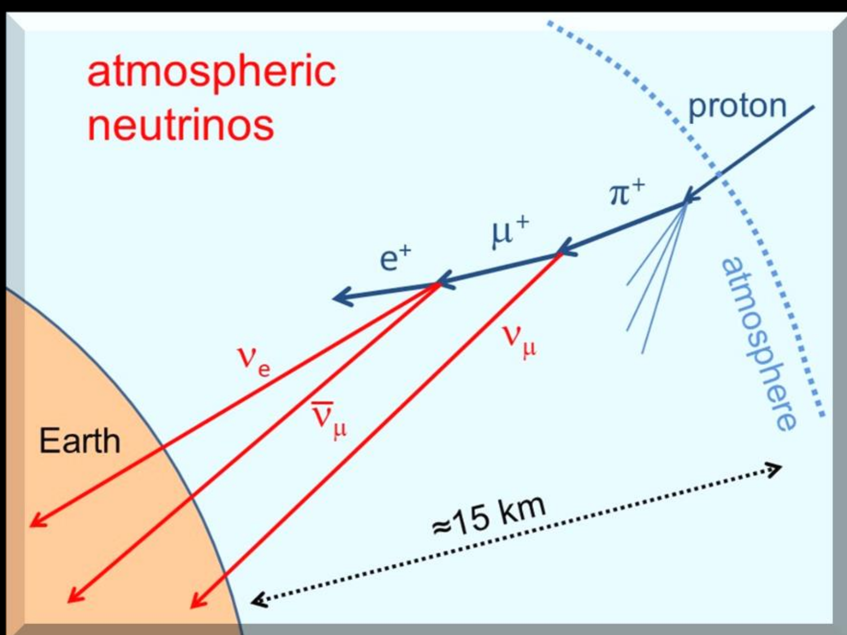
$$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$$

Only from the 1990s on: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Neutrino Generation in the Atmosphere

$$p + \text{target} \rightarrow \pi^{+} + \ldots..$$
$$\rightarrow \mu^{+} + \nu_{\mu}$$
$$\rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$



Atmospheric Neutrinos

- Flux calculations
  - Zhelesnykh 1958
  - Markov and Zhelesnykh 1961
  - Zatsepin & Kuzmin 1961
  - Coswik 1963
  - Osborne 1965
  - Volkova & Zatsepin 1965

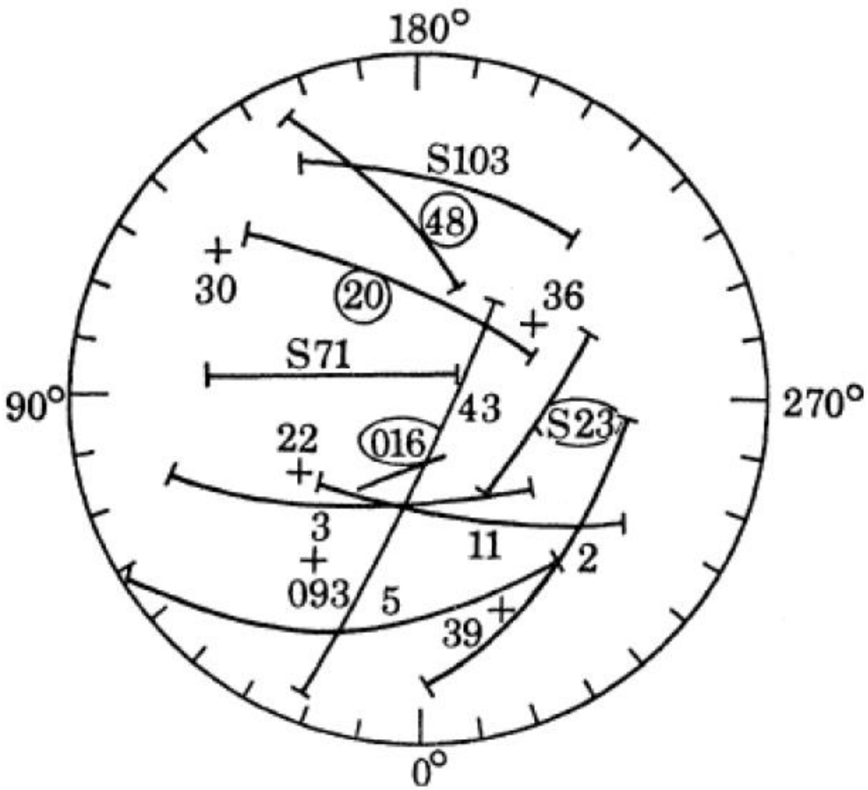
First event recorded

- Detection 1965
  - Case-Witwatersrand: February 23 (submitted July 26)
  - Kolar Gold Field: April 20 (submitted July 12)

The first neutrino skymap

The first neutrino sky map with the celestial coordinates of 18 KGF neutrino events

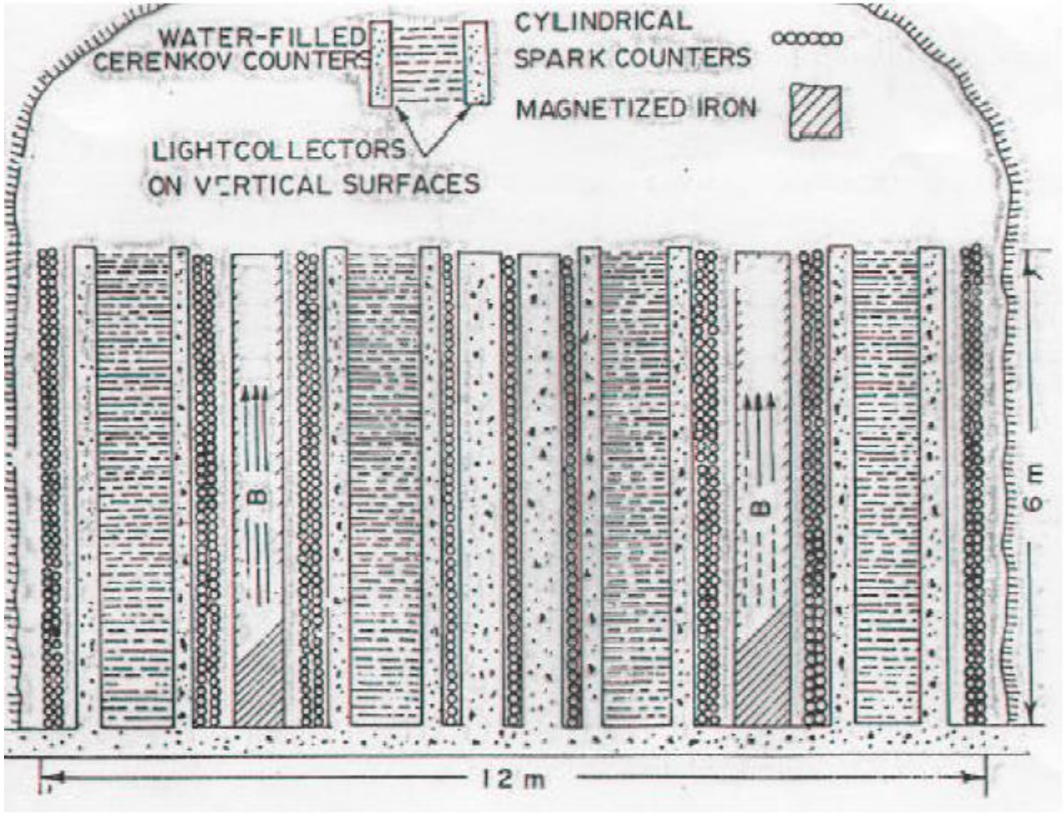
(Krishnaswamy et al. 1971)



Due to uncertainties in the azimuth, the coordinates for some events are arcs rather than points. The labels reflect the numbers and registration mode of the events (e.g. "S" for spectrograph). Only for the ringed events the sense of the direction of the registered muon is known.

Utah Salt Mine Detector and the Keuffel effect

- Utah detector plus KGF: W-mass must be >> a few GeV



- Utah: downgoing muon flux behaves strange („Keuffel effect") $\rightarrow$ one of the motivations for 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.

DUMAND

- 1973 ICRC, Reines, Learned, Shapiro, Zatsepin, Miyake: a deep water detector to clarify puzzles in muon depth-intensity curves („Keuffel effect“)
- 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.Roberts

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 !

V.S. Berezinsky to C.S. 2016

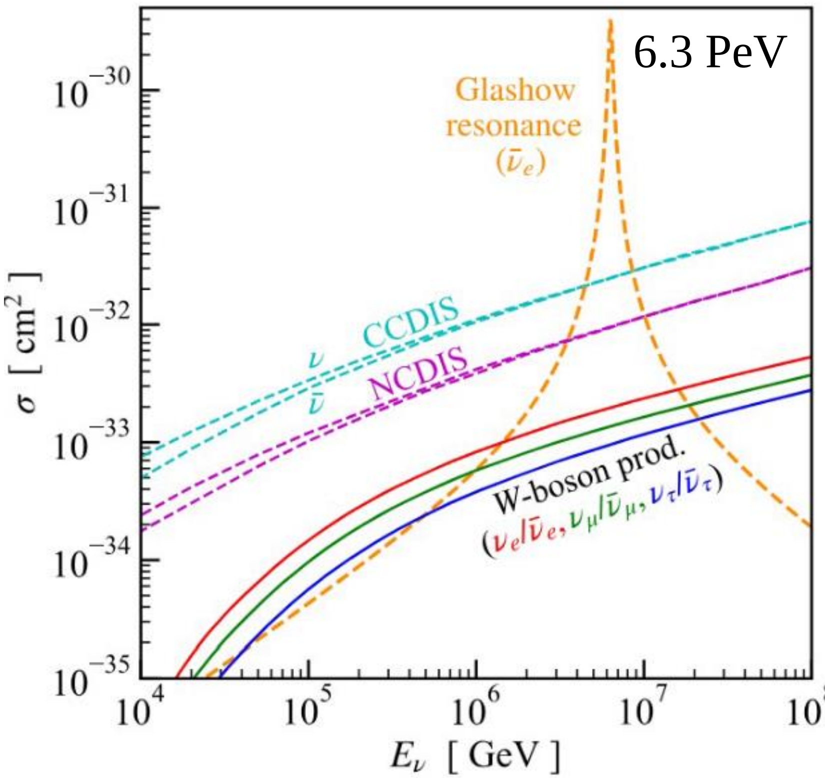
"In 1976 I was at Neutrino conference in Aachen, the first time in my life abroad and I probably given there a talk about extraterrestrial neutrinos (may be it was part of my talk, I do not remember exactly). Fred Reines was interested, he found me and several times was speaking with me. Once John Learned was present and he was interested, too. DUMAND was designed for atmospheric neutrinos, in particular for search for W boson, and I was … convincing them that DUMAND can see extraterrestrial neutrinos. My ideas and calculations are described in DUMAND 1976 proceedings, in Uspekhi 1977 and in Neutrino 1977."

V.S. Berezinsky to C.S. 2016

“In the end Reines and Learned asked me to come to DUMAND 1976. I said this is absolutely impossible, because one from USSR cannot come twice a year to the West and because the time to go through formalities is not enough. Fred told me: ‘You do not know me and do not know my connections with Soviet Academy of Sciences”. To my great surprise it was true, and very soon I received a phone call from Academy and I started to go through formalities which went surprisingly fast. The delegation (to visit Western countries alone was forbidden) was formed from 3 persons (Dolgoshein and Petrukhin).“

V.S. Berezinsky to C.S. 2016

“By the way, at DUMAND 76 David Cline gave a talk how W boson can be searched for in DUMAND. I was very skeptical about his suggestion, but thinking about it I came to idea of resonance \nu_e e production



V.S. Berezinsky to C.S. 2016

"By the way, at DUMAND 76 David Cline gave a talk how W boson can be searched for in DUMAND. I was very sceptical about his suggestion, but thinking about it I came to idea of resonance \nu_e e production, and soon I made the calculations and then I invited Askhat who was my student
to this work"

Cosmic neutrino and the possibility of searching for *W* bosons with masses 30–100 GeV in underwater experiments

V. S. Berezinskiĭ and A. Z. Gazizov

Institute of Nuclear Reseach, USSR Academy of Sciences

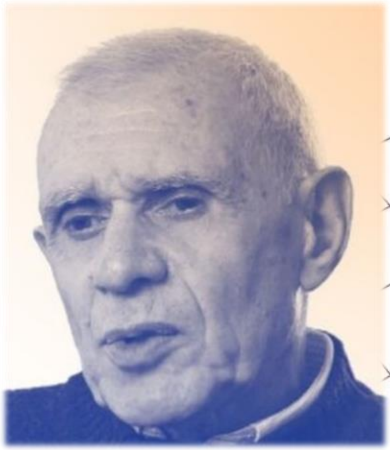
(Submitted February 3, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 5, 276–278 (5 March 1977)

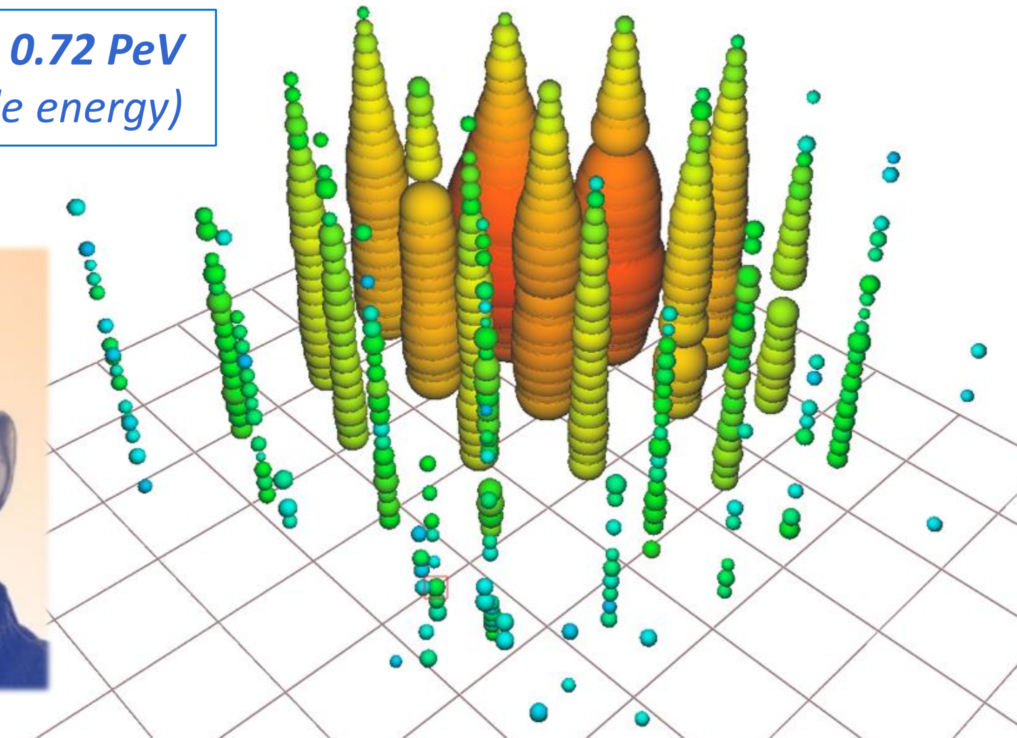
The possibility is discussed for searching for W bosons in underwater experiments with the aid of the resonant reaction $\bar{\nu}_e + e^- \to W^- \to$ hadrons. The resonance production of W bosons manifests itself as a narrow peak in the energy spectrum of the underwater nuclear-electromagnetic cascades. For W-boson masses 30–100 GeV (resonant antineutrino energies $9\times10^{14} - 1\times10^{16}$ eV) the resonant effect should exceed by more than one order of magnitude the background due to the nonresonant neutrino events.

IceCube 2021

"By the way, at DUMAND 76 David Cline gave a talk how W boson can be searched for in DUMAND. I was very sceptical about his suggestion, but thinking about it I came to idea of resonance \nu_e e production, and soon I made the calculations and then I invited Askhat who was my student
to this work"

6.05 ± 0.72 PeV
(visible energy)





Potential neutrino sources considered in the late 1970s – early 1980s

- AGN:  Berezinksy, Ginzburg, Eichler
- Radio Galaxies: Silberberg & Shapiro
- Pulsars in SN shells:  Silberberg & Shapiro, Berezinsky
- Binary systems: Eichler, Begelman
- Galactic Center:  Berezinsky & Zatsepin
- Cocooned sources:  Schramm, Berezinsky & Priludsky
- Neutrinos from GZK processes:  Berezinsky & Zatsepin

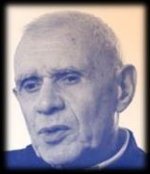
Neutrino Generation along the Way of Cosmic Rays through Space

$$p + \gamma_{3K} \rightarrow \pi^{+} + \ldots..$$

$$\rightarrow \mu^{+} + \nu_{\mu}$$

$$\rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

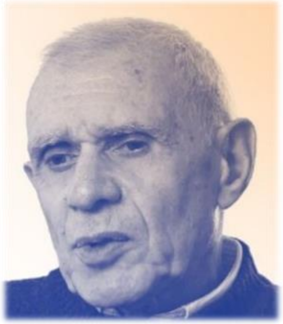
Greisen, Zatsepin, & Kusmin 1966

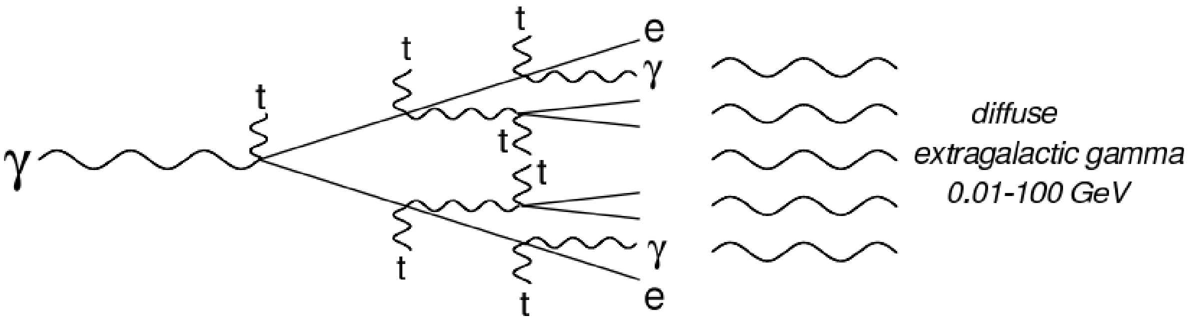
Neutrino flux: Berezinsky & Zatsepin 1970 

Expect O(1 event) per cubic kilometer

The cascade limit

- 1975: V. Berezinsky and A. Smirnov calculate the relation between diffusive high-energy neutrino fluxes and gamma-ray fluxes (a few 100 ν events per year and km³)





- Further developed with O. Kalashev and other co-authors: strongest and most general limits on extragalactic neutrino fluxes.

1978: 1.26 km^3

22,698 OMs

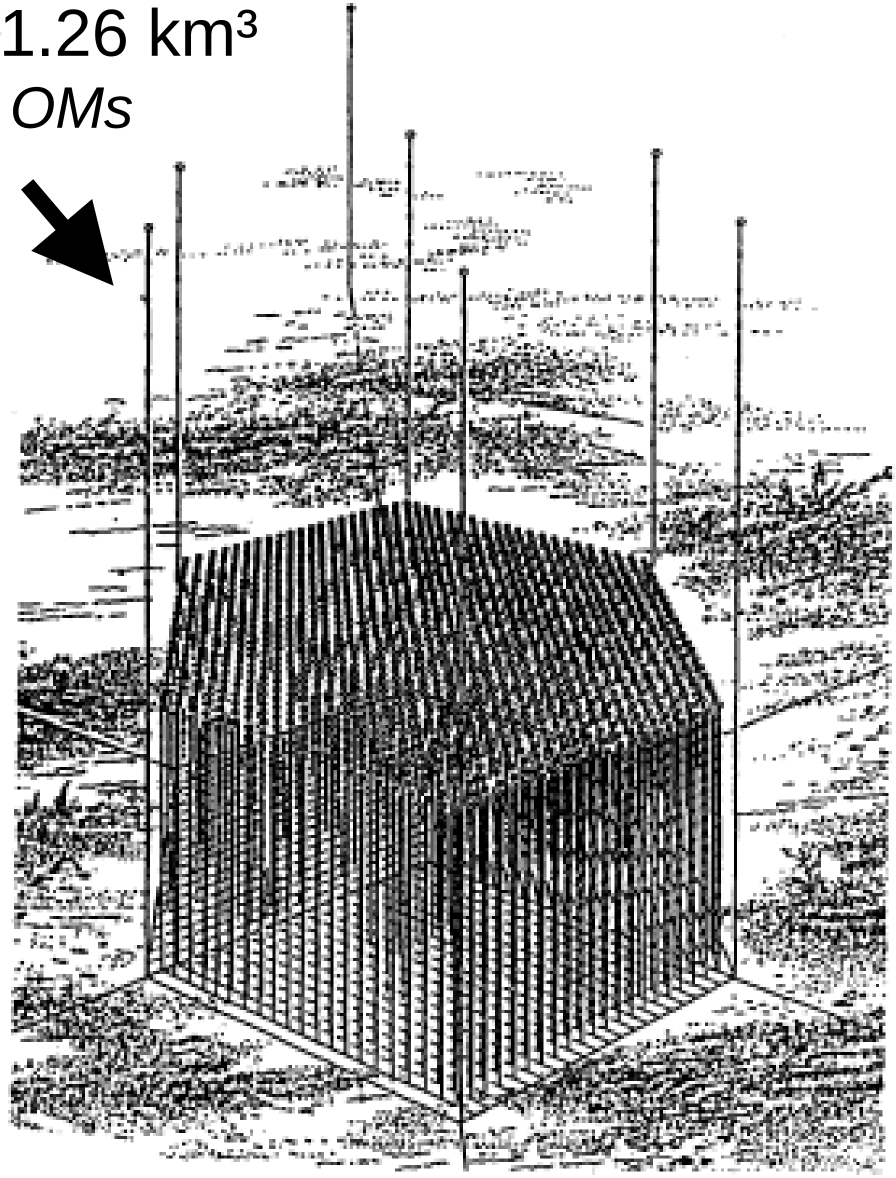


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

back to DUMAND !

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.

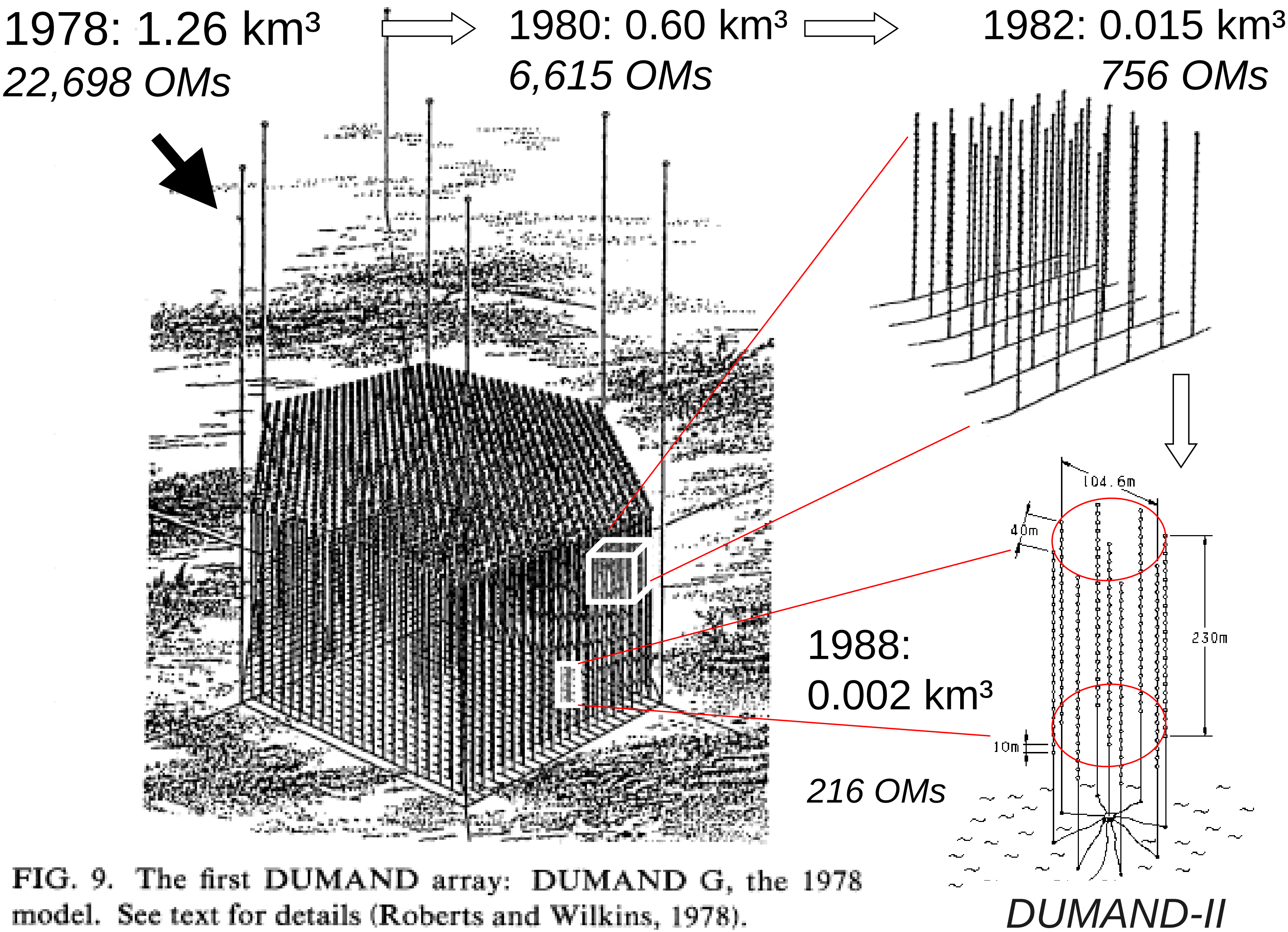
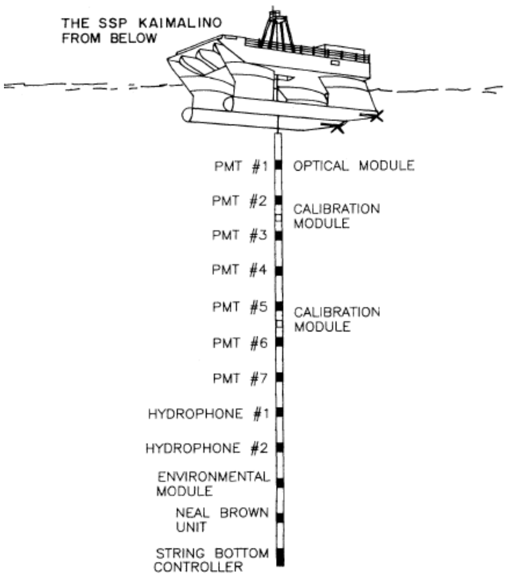


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

From first successes to termination

- 1987: Operation of a short prototype string from a ship
- 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

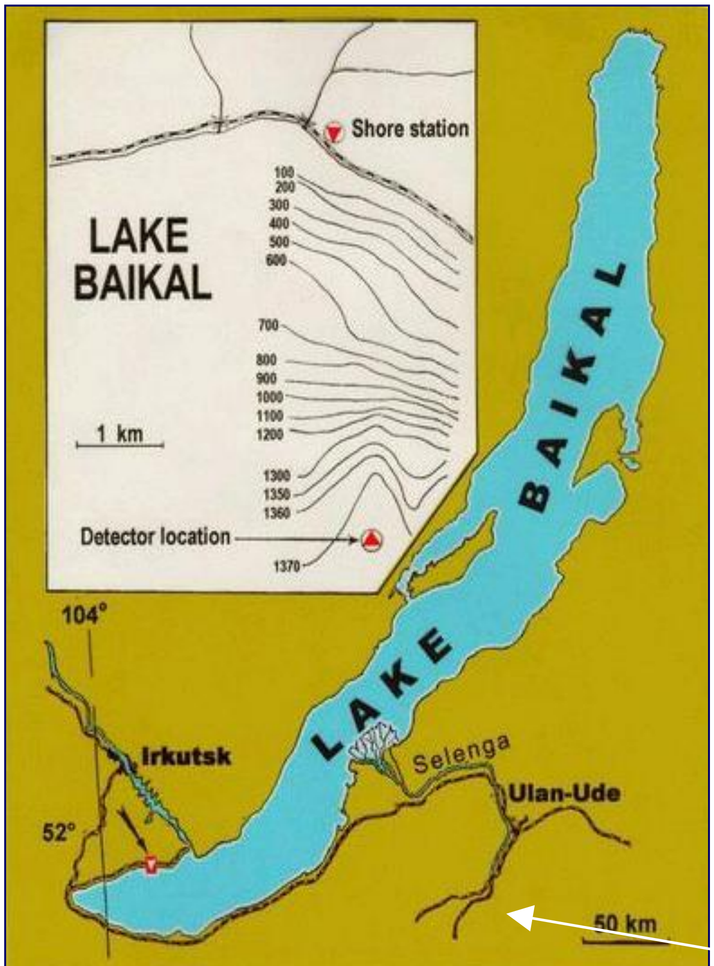
Russia

- Very active during early DUMAND workshops
- Kicked out after Russian Afghanistan invasion
- 1980: Chudakov proposes exploration of Lake Baikal as possible site for a neutrino telescope

- 1981: start of site investigations at Lake Baikal (Domogatsky, Bezrukov)
- Exploration of Atlantic, Black Sea, Indian Ocean, Pacific and Mediterranean sites (Zheleznyk, Petrukhin)

The Lake BAIKAL experiment

Bezrukov, Domogatsky, Berezinsky, Zatsepin



- Largest & deepest fresh water reservoir in the world
- Choosen site 3.6 km from shore, 1.3 km depth
- **Deployment in winter from ice cover**

Lake Baikal: the eighties

- 1984: first stationary string

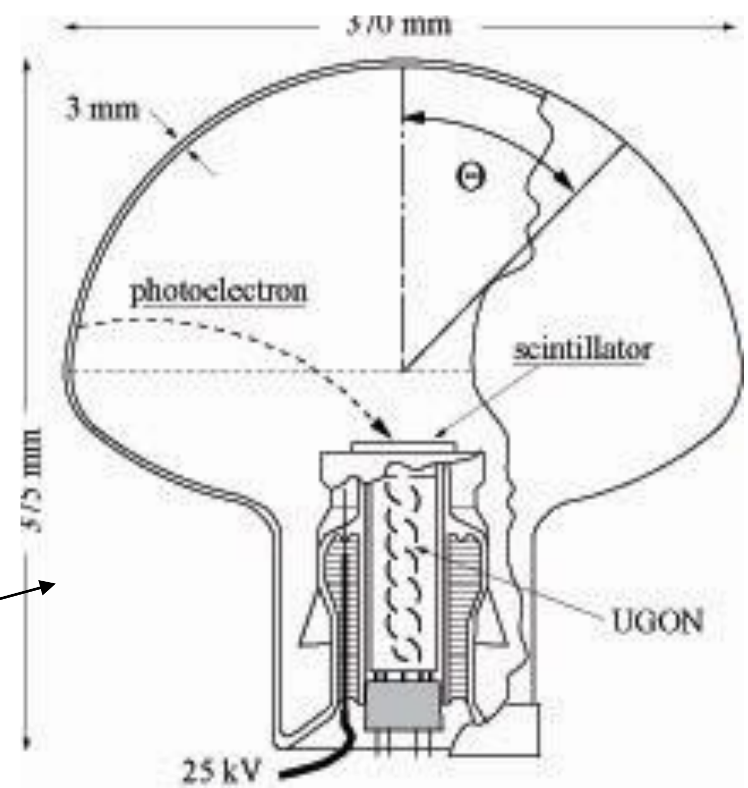
  Muon flux measurement

- 1986: second stationary string

  Limits on GUT magnetic monopoles

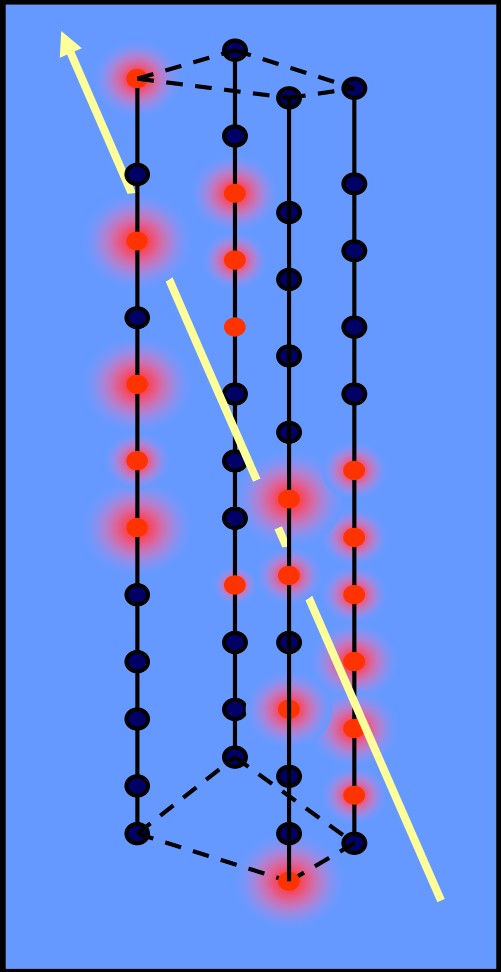
- All that with a 15-cm flat-window PMT

- Development of a Russian smart phototube (Quasar)



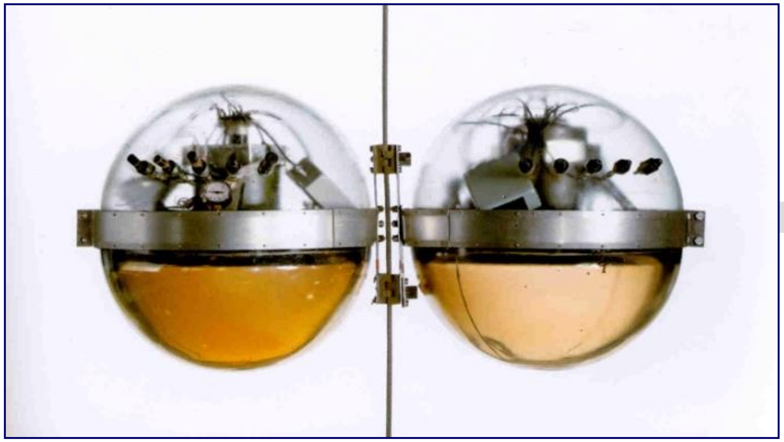
Towards NT-200

- 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

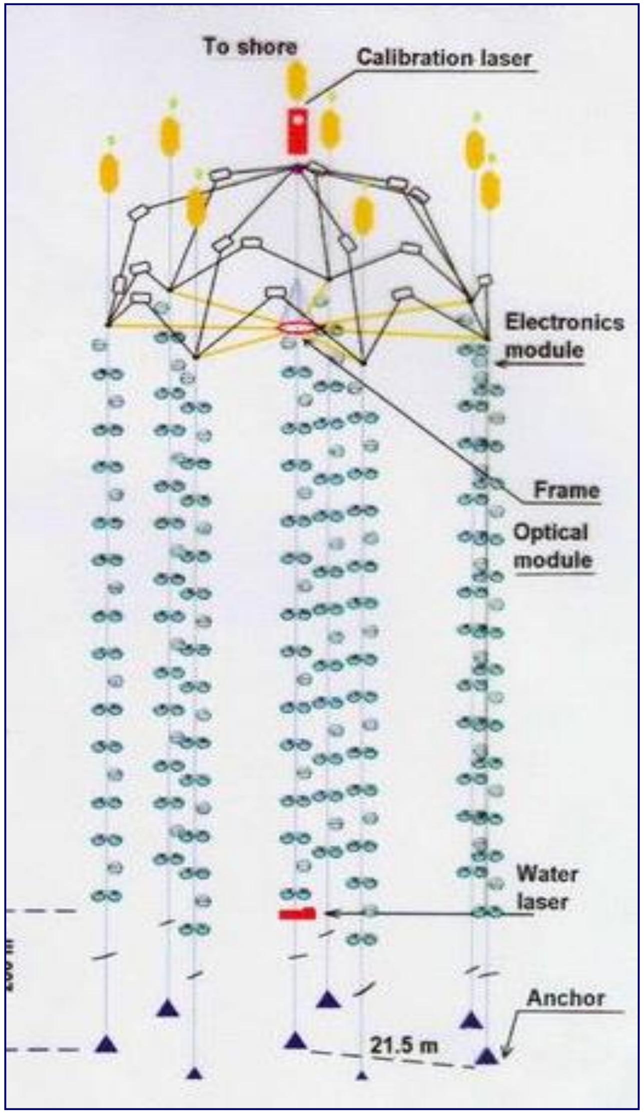


4-string stage (1996)

NT-200



- **Pioneering detector**
  - First 3-string array underwater
  - First detection of neutrinos with Markov's method
- **But:**
  - Small (~ twice Super-K)
  - Poor reliability, high failure rates
  - → low statistics (only 396 ν_μ events)
- **Still:**
  - Competitive with early AMANDA in searching diffuse flux (looking beyond the detector)



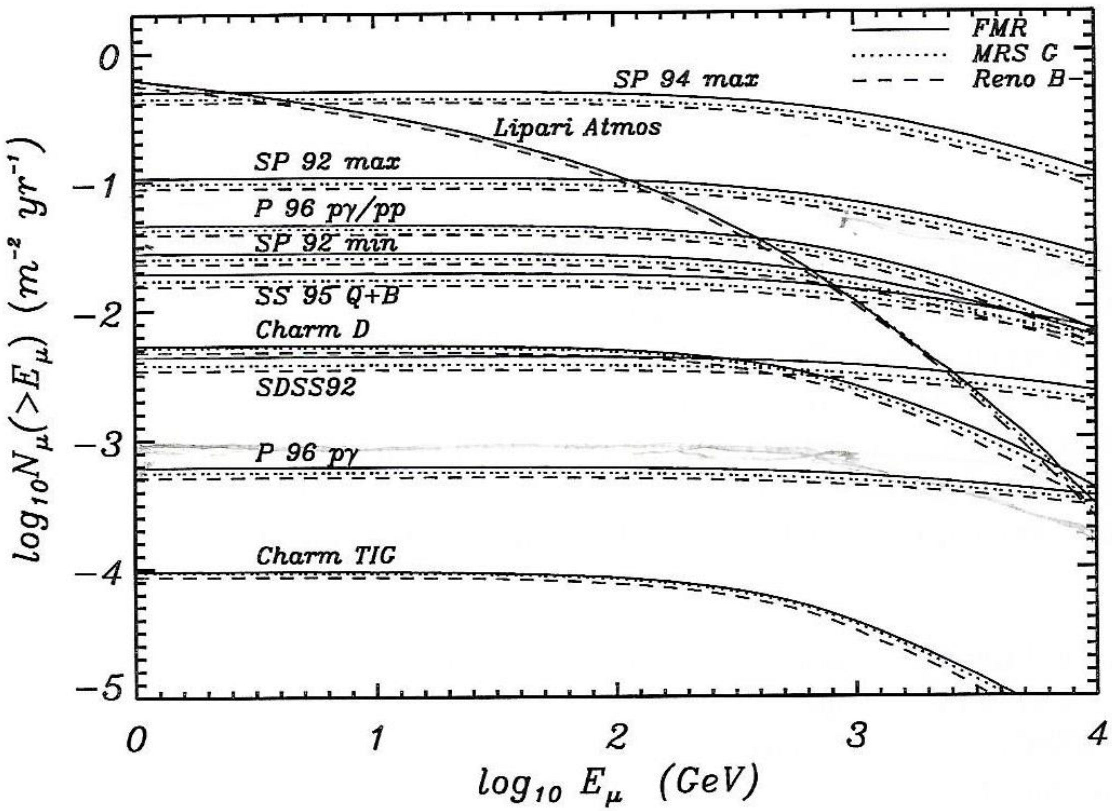
Point sources, DUMAND-II (0.002 km³)
Expectations in the early 1990s

Source name	γ-ray Energy (TeV)	γ flux at Earth ($cm^{-2}s^{-1}$)	Luminosity ($erg\ s^{-1}$)	μ/yr DUM II $\epsilon_{\nu/\gamma}=1$ Min γ	$\epsilon_{\nu/\gamma}=30$ Max γ
Vela PSR	5	1.8×10^{-12}	3×10^{32}	0.1	1506
Vela X-1	1	2×10^{-11}	2×10^{34}	0.2	126
Crab SNR	2	1.1×10^{-11}	2×10^{34}	0.2	438
Crab PSR	1	7.9×10^{-12}	6×10^{33}	0.06	38
Geminga	6	9.5×10^{-12}	3×10^{33}	0.49	1506
4U 0115	1	7.0×10^{-11}	6×10^{35}	0.47	273
Her X-1	1	3×10^{-11}	3×10^{35}	0.24	141
SS433	1	$<10^{-10}$	$<4\times10^{35}$	<0.88	<510
Cen X-3	1	$<5.2\times10^{-12}$	$<2\times10^{34}$	<0.08	<48
Cyg X-3	1	5.0×10^{-11}	3×10^{36}	0.4	234
LMC X-4	10^4	5×10^{-15}	1×10^{38}	8.2×10^{-5}	4.8×10^{-2}
M 31	1	2.2×10^{-10}	2×10^{40}	1.8	1050
Cen A	0.3	4.4×10^{-11}	3×10^{40}	0.14	6
3C 273	5	$<9\times10^{-12}$	$<3\times10^{45}$	<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^2) expectations in the early/mid 1990s

From G. Hill 1996



Models

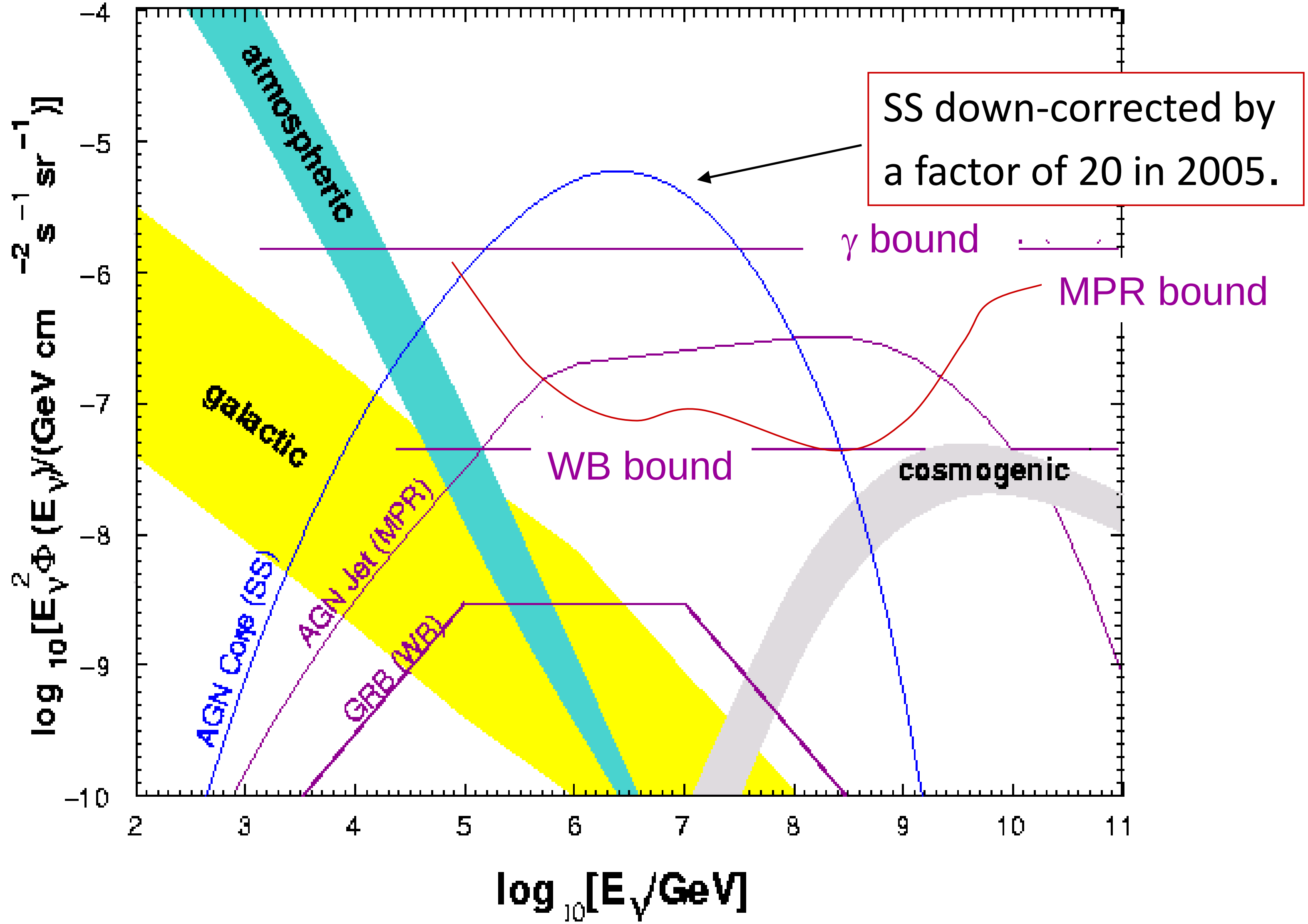
SDDS Stecker, Done,
Salomon, Sommers 1992
SP Szabo and Protheroe 1994
SS Stecker and Salomon 1992
P Protheroe 1995

Others not shown, e.g. from Biermann 1992 and from Berezinsky 1992

1990-2000: revisiting the expectations

- Underground detectors, 1000 m^2, 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 km^3.
- F. Halzen & J. Learned, 1993:
  High Energy Neutrino Astronomy – towards a 1 km^3 detector
- The Waxman-Bahcall bound
- The Mannheim-Protheroe bound
- GRB as sources of cosmic rays and neutrinos (Waxmann Bahcall)

Diffuse Fluxes 2002



The ice option

- 1988: Halzen & Learned:
  "High Energy Neutrino Detection in Deep Polar Ice"
- 1989: attempt to measure ice transparency in existing boreholes at South Pole
- Jan. 89, ICRC, Adelaide: Decision to propose AMANDA
  (B. Price, D. Lowder, S. Barwick, B. Morse, F.Halzen, A. Watson)
- 1990: Morse et al. deploy PMTs in Greenland ice. Measured muons and derived attenuation length at ~200 m depth.

Nature Sept 1991

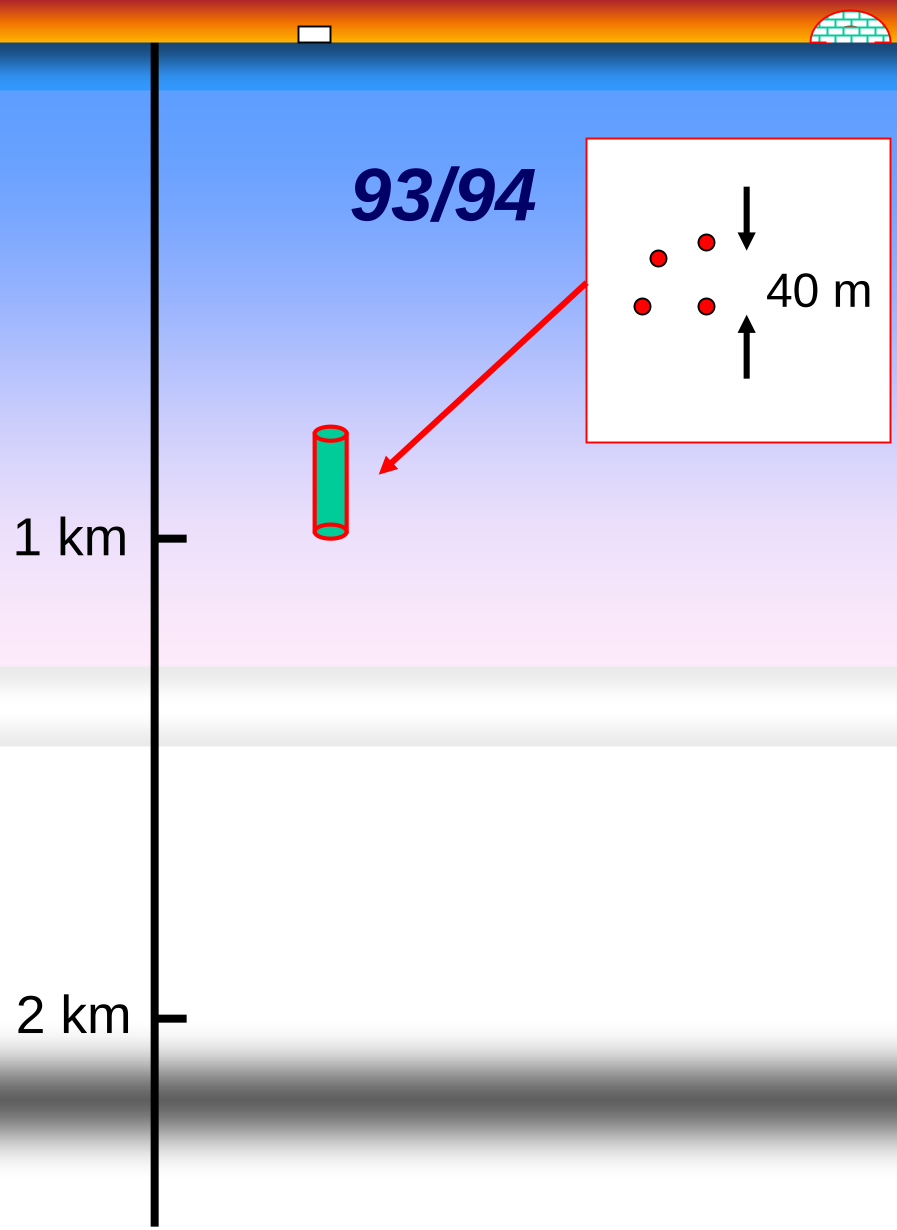
Observation of muons using the polar ice cap as a Cerenkov detector

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

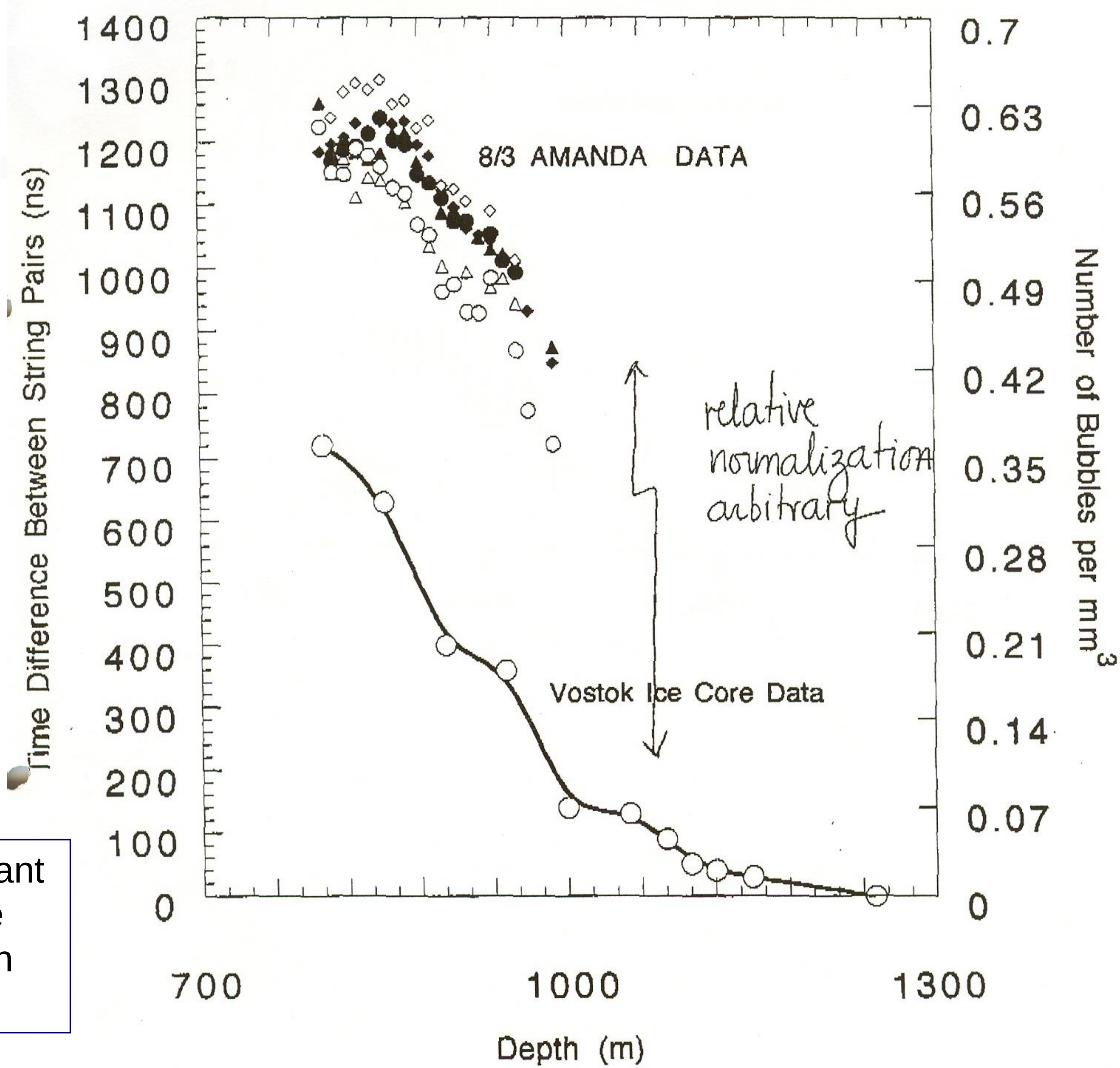
DETECTION of the small flux of extraterrestrial neutrinos expected at energies above 1 TeV, and identification of their astrophysical point sources, will require neutrino telescopes with effective areas measured in square kilometres—much larger than detectors now existing[1–3]. Such a device can be built 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: AMANDA-A

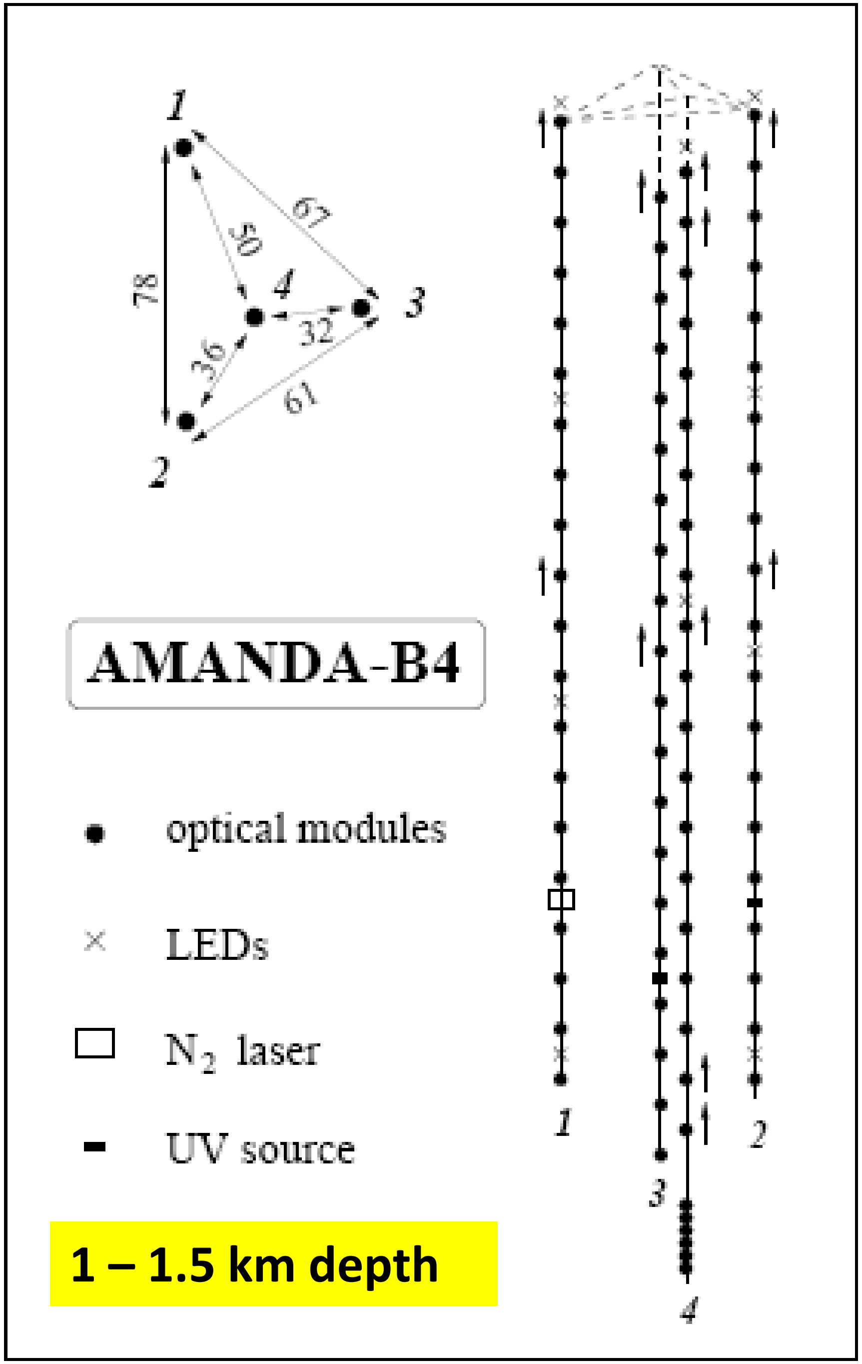


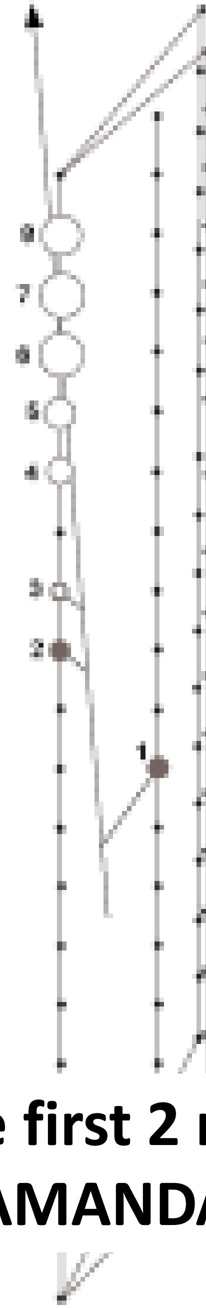
Catastrophal delay of light between strings 20 m away!

(µsec instead of 100 nsec)

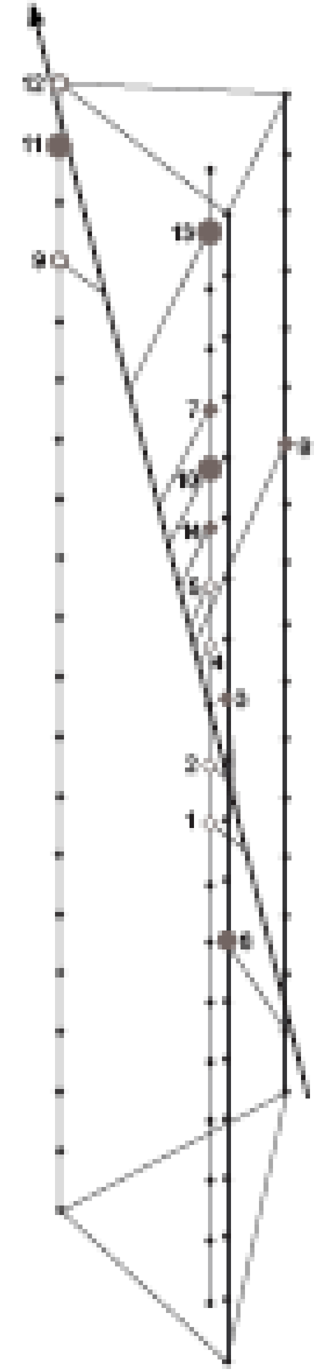


Explanation remnant bubbles which are disapppearing with increasing depth.

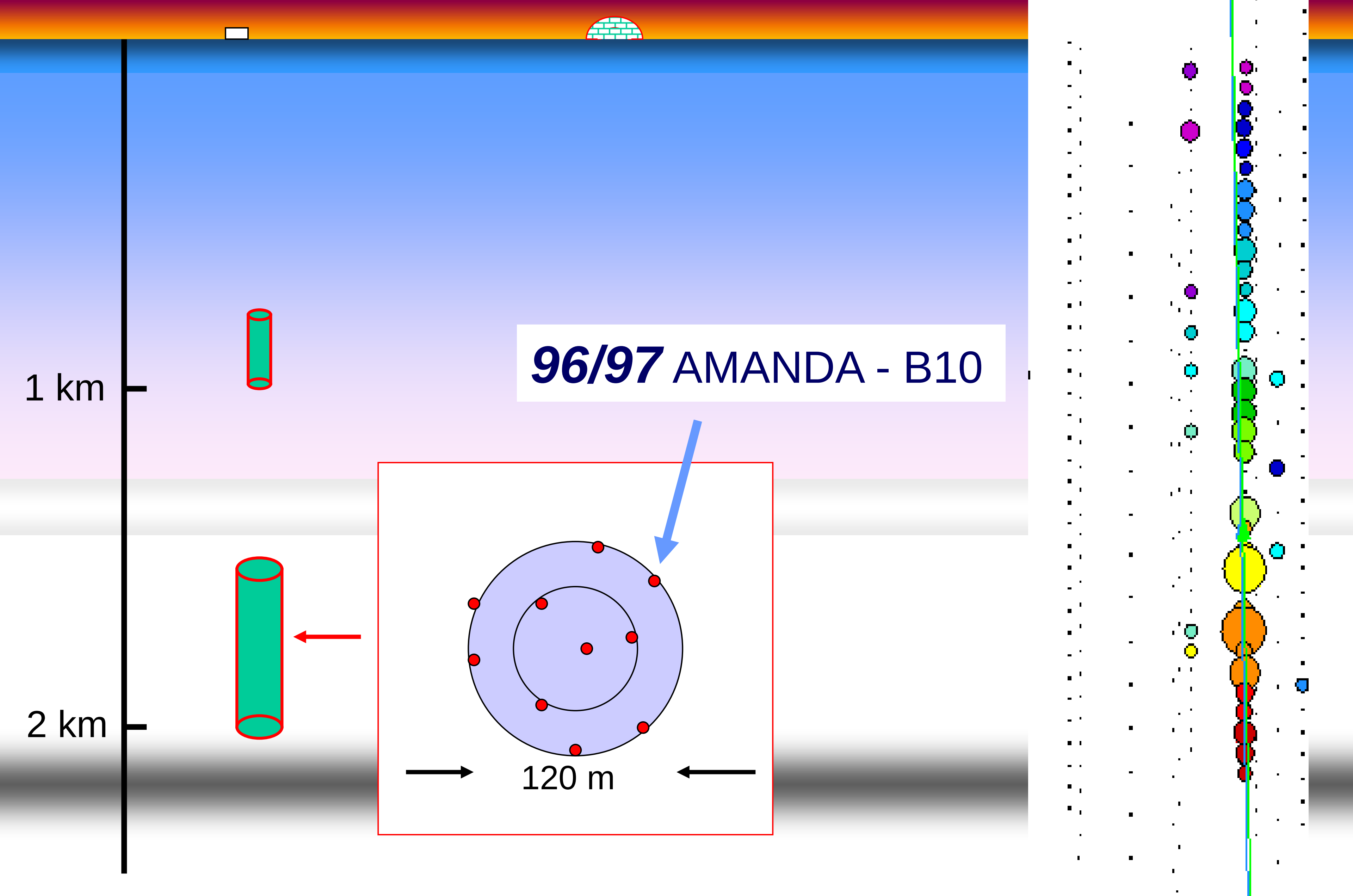




The first 2 neutrinos in AMANDA (1996)



AMANDA B10



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

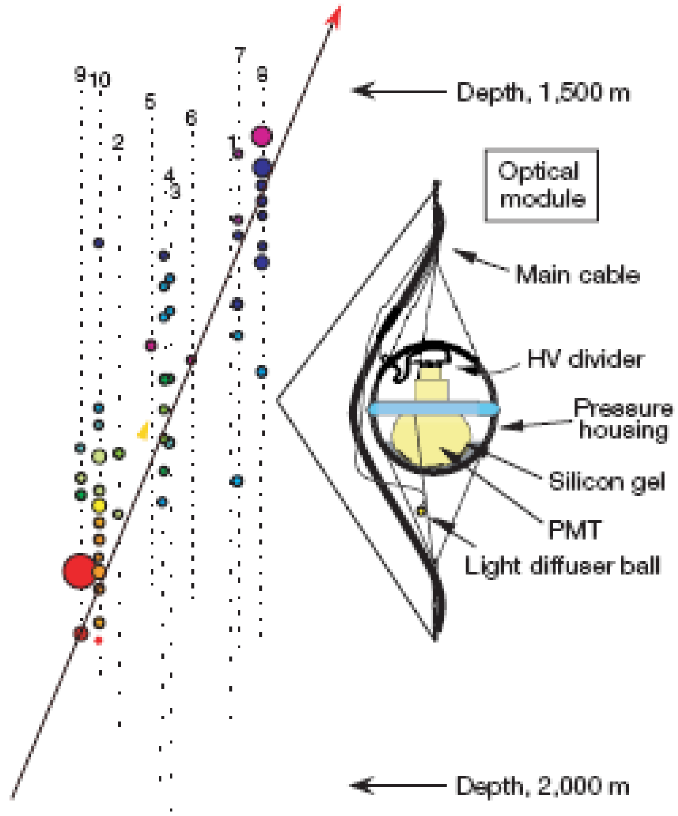
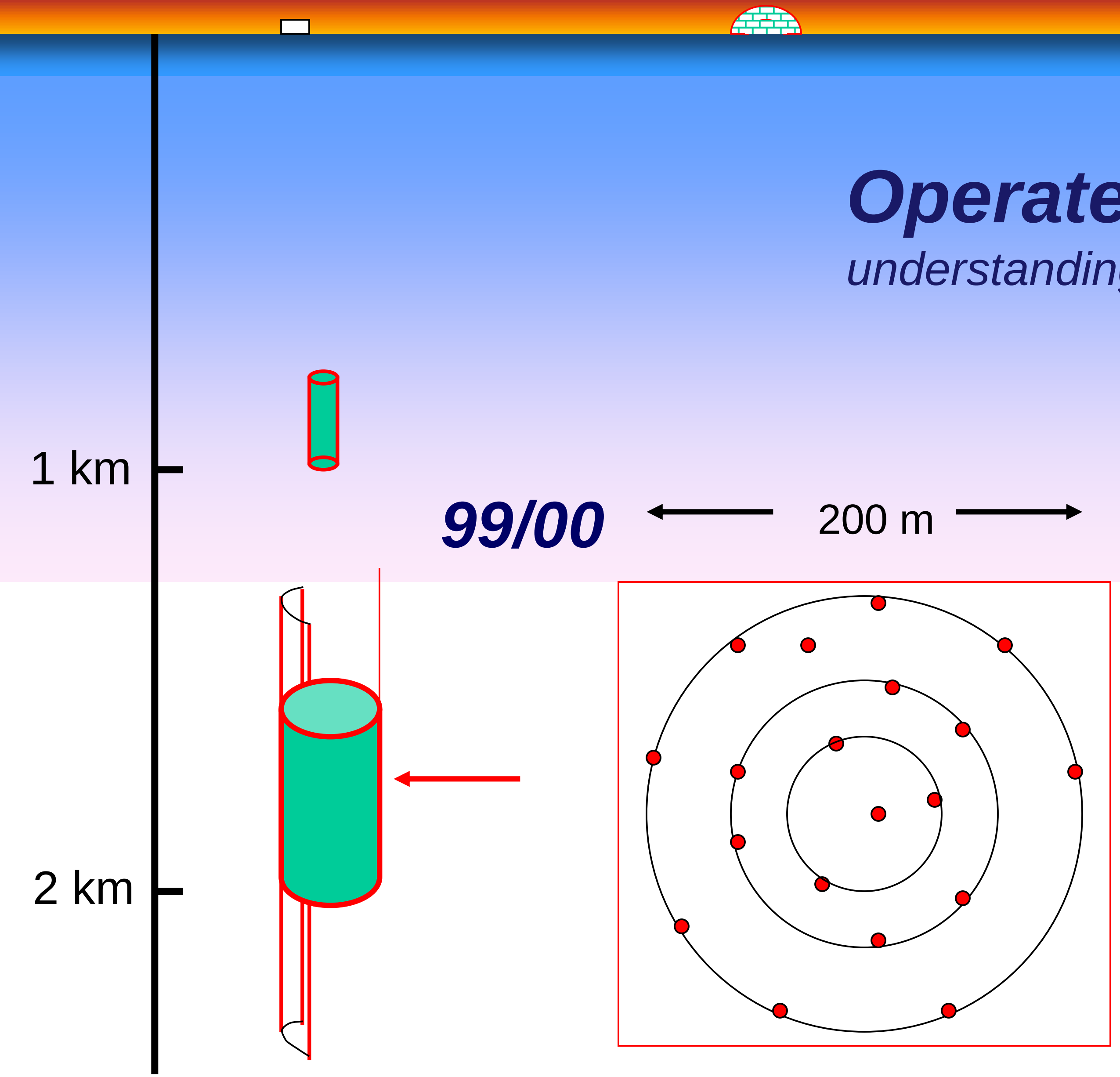


Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular 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.

AMANDA II

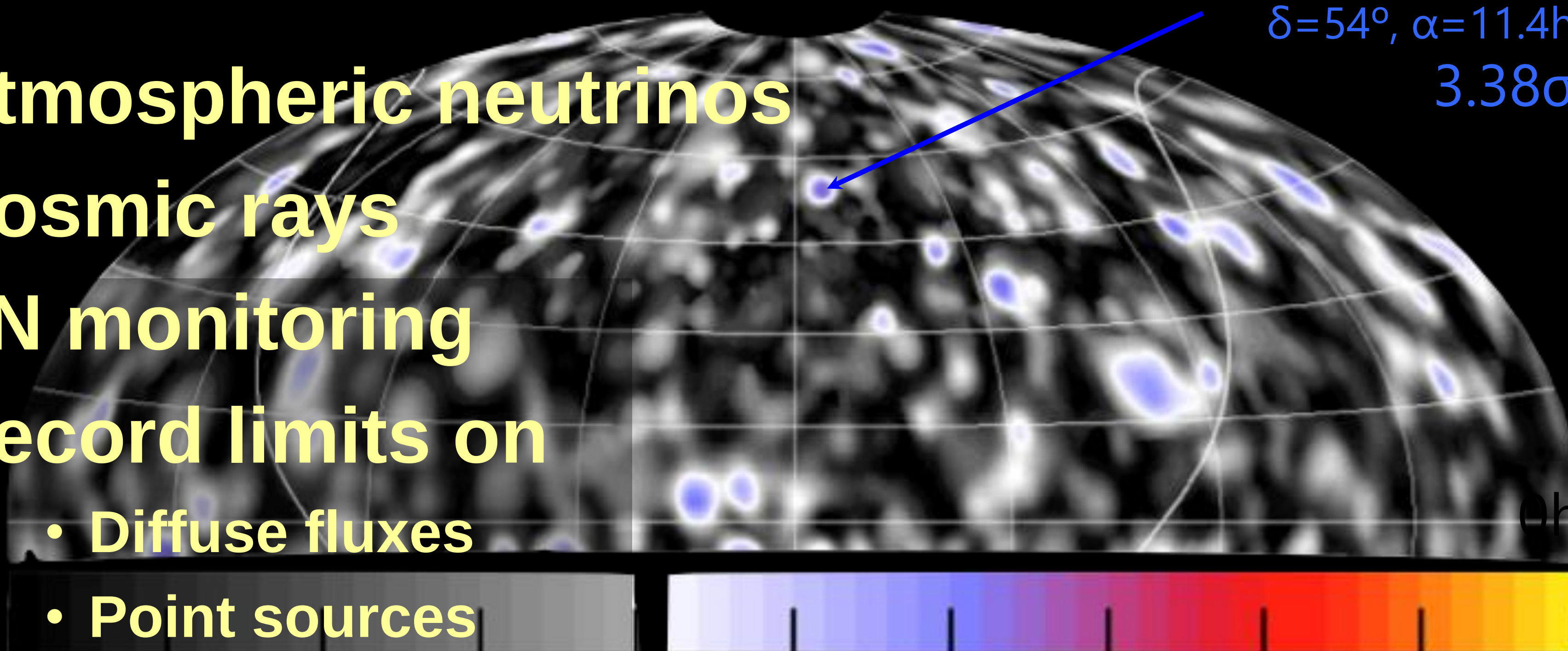
Operated until 2009

understanding ice properties!



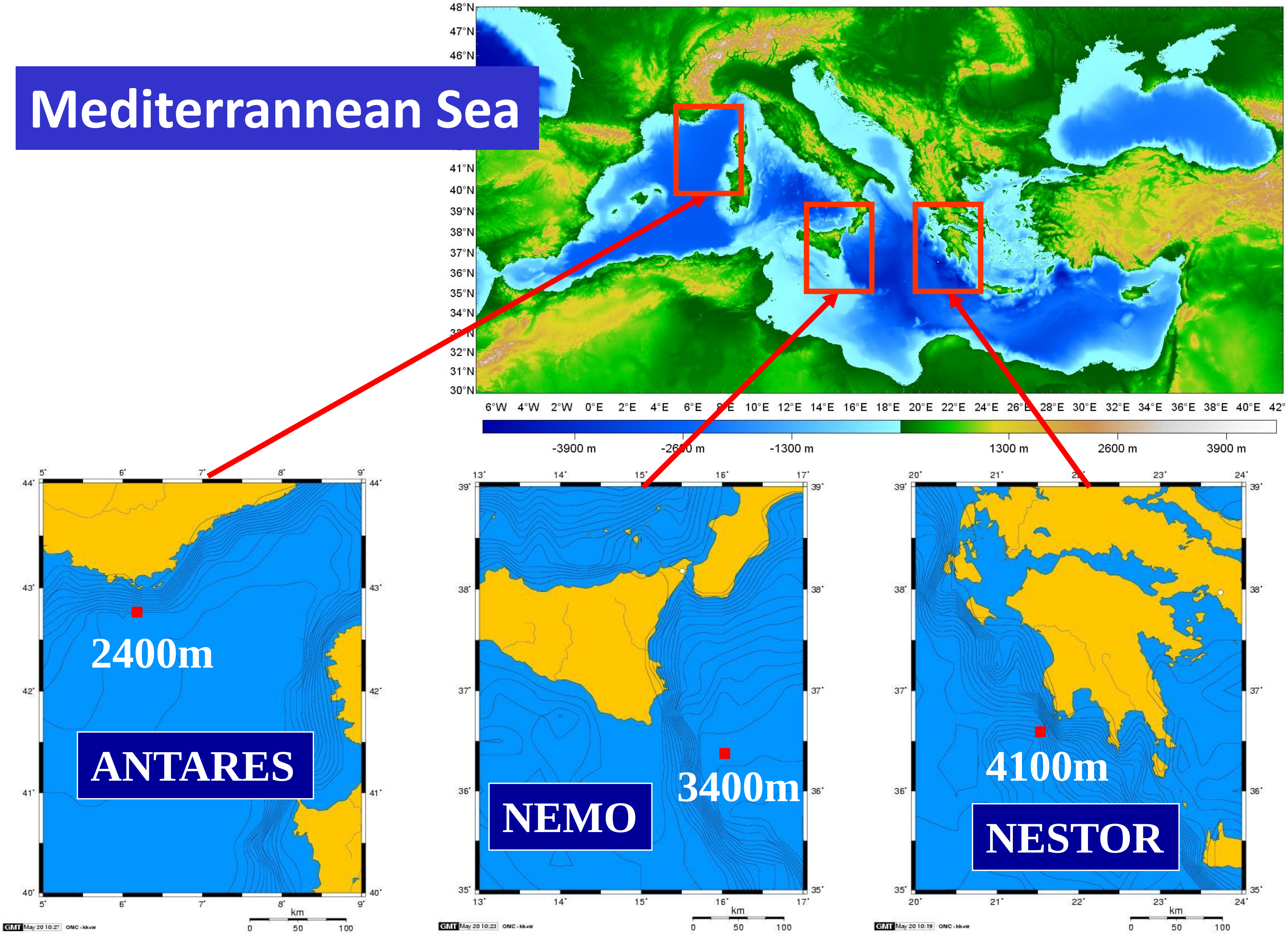
AMANDA results

- Atmospheric neutrinos
- Cosmic rays
- SN monitoring
- Record limits on
  - Diffuse fluxes
  - Point sources
  - Neutrinos from GRB
  - Neutrinos from WIMPs
  - Magnetic Monopole flux



Skymap from 7years AMANDA:
no significant excess (6595 ν_μ)

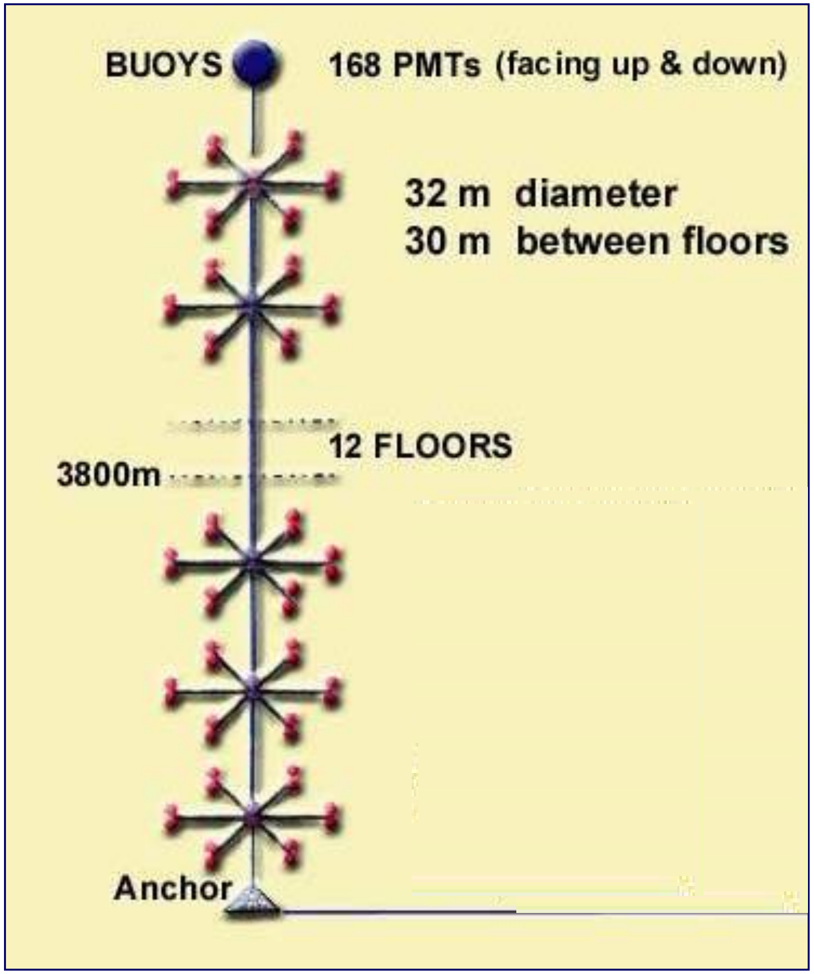
Mediterrannean Sea



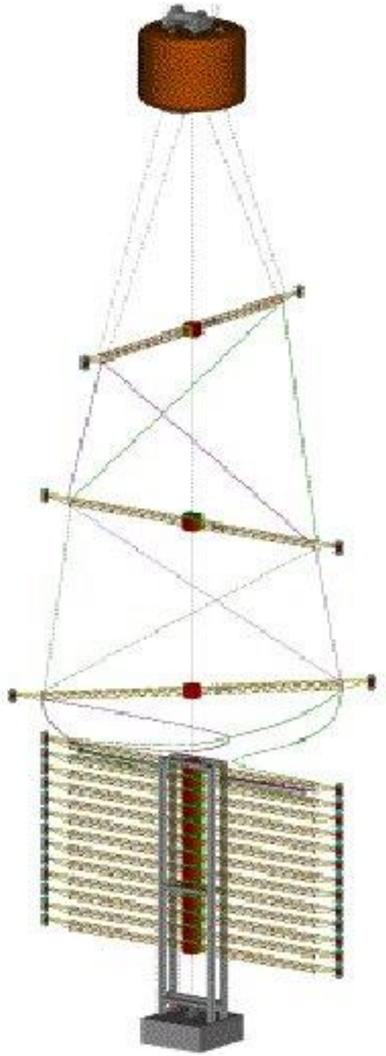
NESTOR

Deepest of all sites (up to 5200 m)

- **1989-91:**
  first site studies
  (Russians, L.Resvanis)
- **1991:** first muon count with hexagonal structure
- **1992-2001:** ocean tests, lab& infrastructure
- **2000:**
  cable to site
- **2004**:
  deploy first floor. Cable failure after a few weeks



NEMO R&D for KM3NeT



- A. Capone, E. Migneco
- Tower concept

- First campaign 1998
- 4-floor tower 2006
- full tower 2009

- Further deployments in the context of KM3NeT

ANTARES

Collab. Formation:

mid 1990s

JJ. Aubert, L. Moscoso, ..

Proposal: 1999

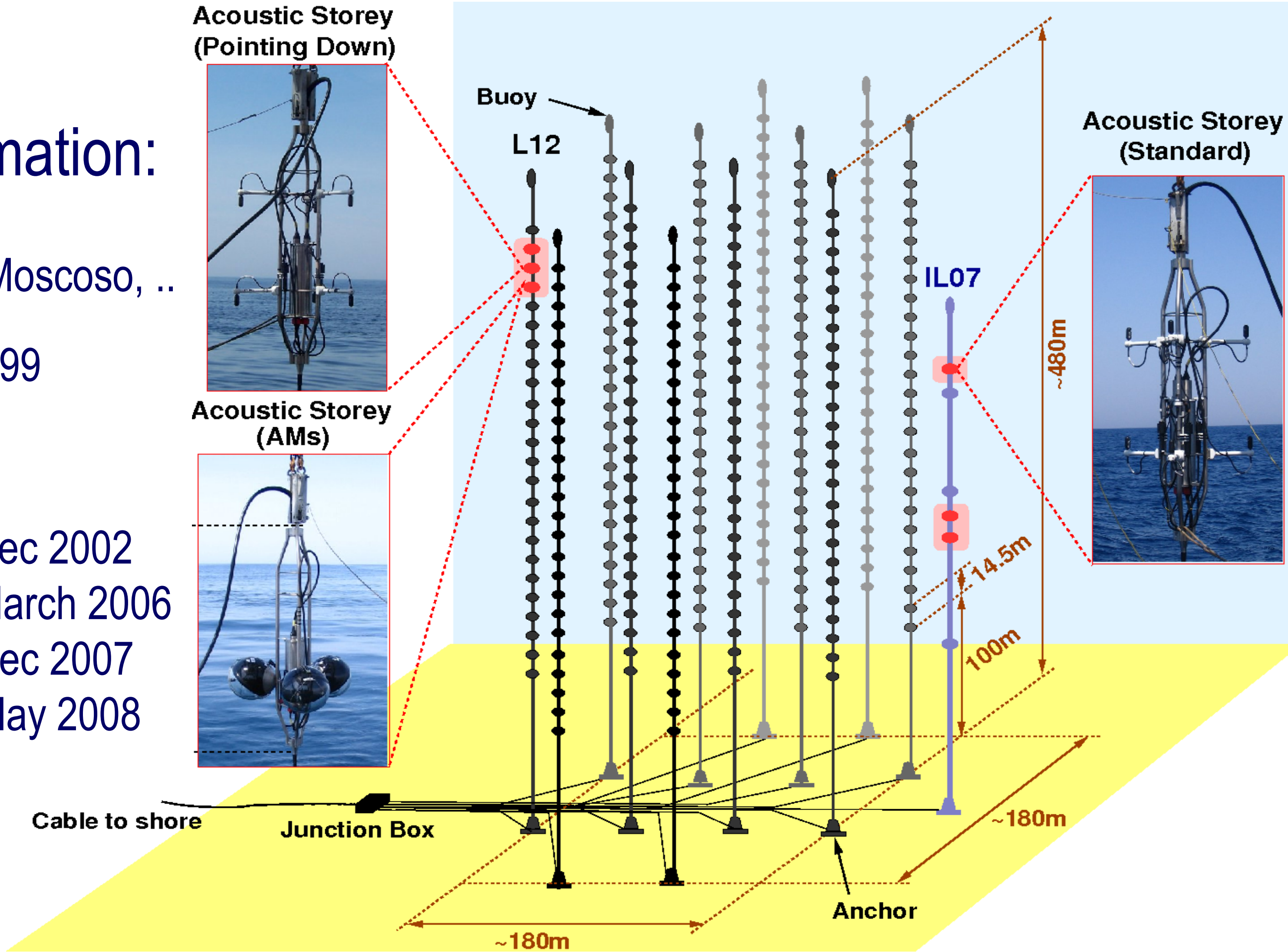
Installation:

Junction Box - Dec 2002

Line 1 - March 2006

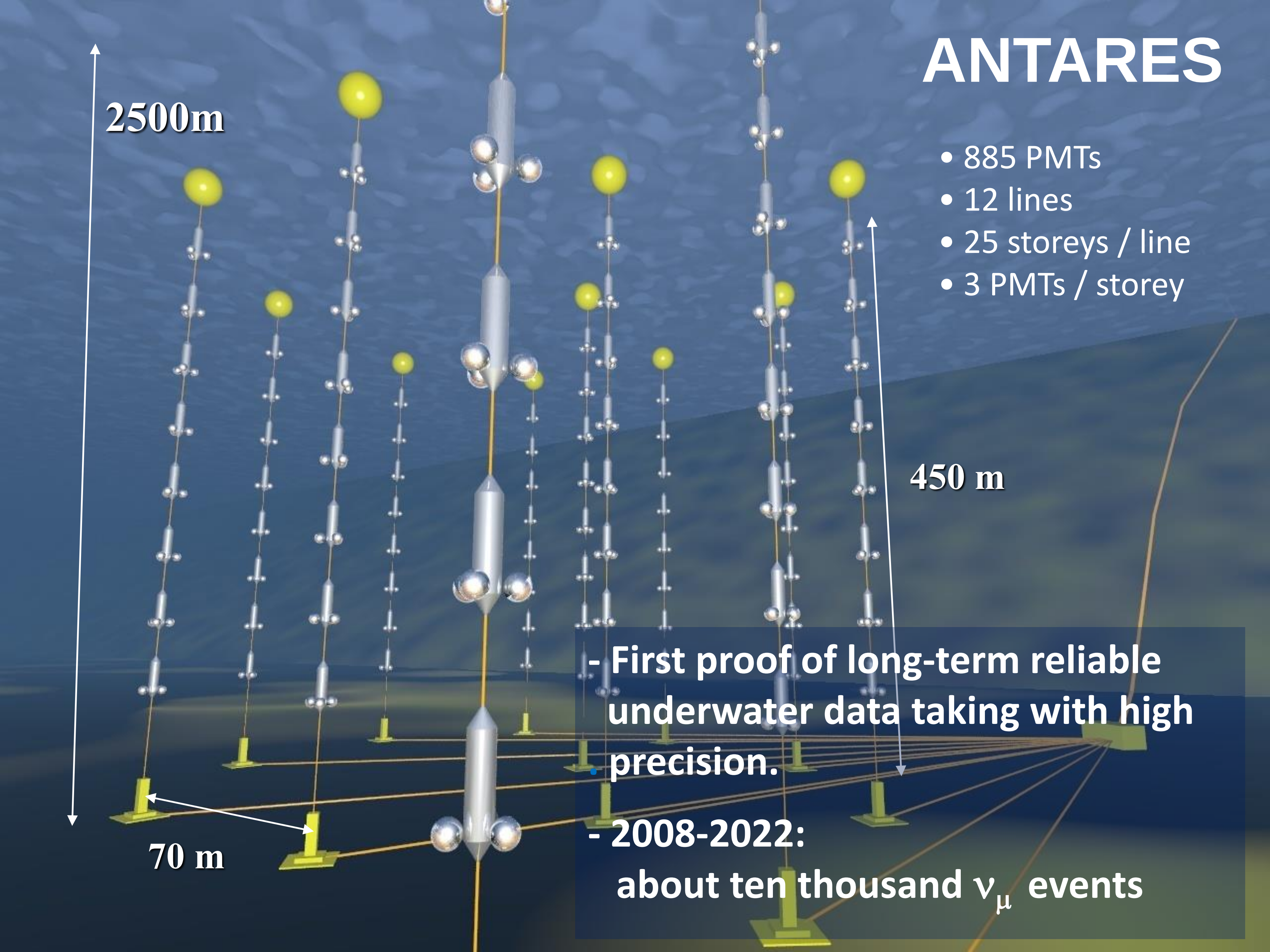
Line 5-1 - Dec 2007

Line 11-12 - May 2008



ANTARES

- 885 PMTs
- 12 lines
- 25 storeys / line
- 3 PMTs / storey



- First proof of long-term reliable underwater data taking with high precision.

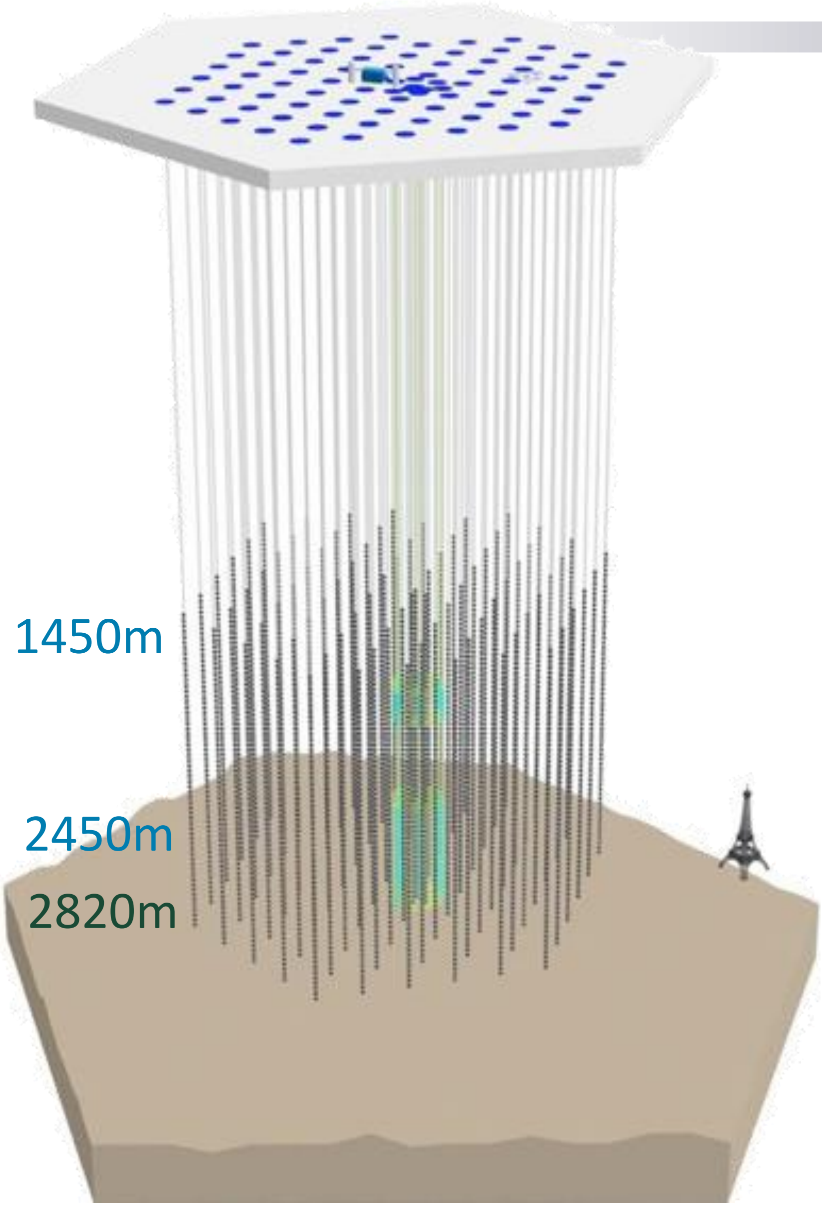
- 2008-2022: about ten thousand ν_μ events

Enter the cubic kilometer era

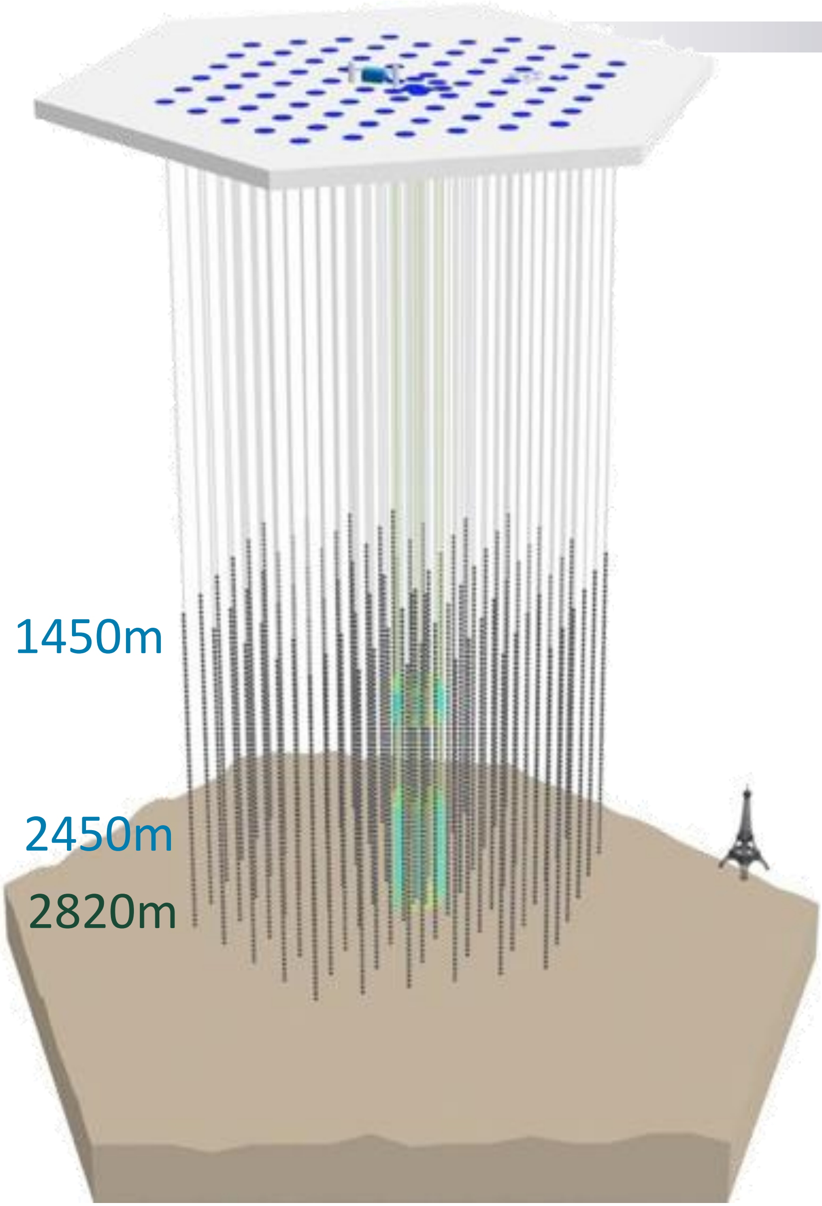
→ see the talks of Francis Halzen and Elisa Resconi

IceCube Neutrino Observatory

- 1999: First proposal
- 2004: Start construction
- 2010: Last (86th) string



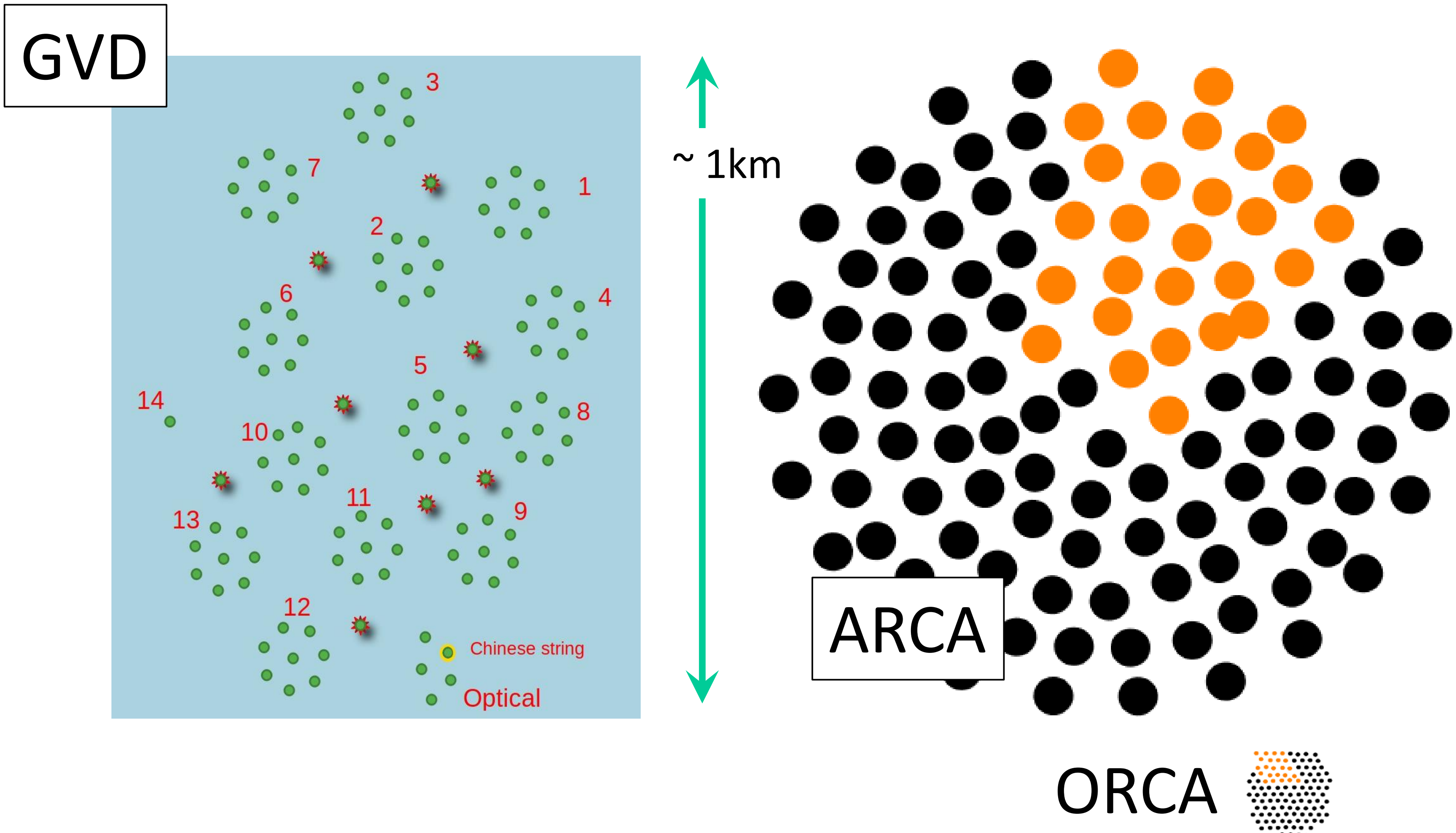
IceCube Neutrino Observatory



- 1999: First proposal
- 2004: Start construction
- 2010: Last (86th) string

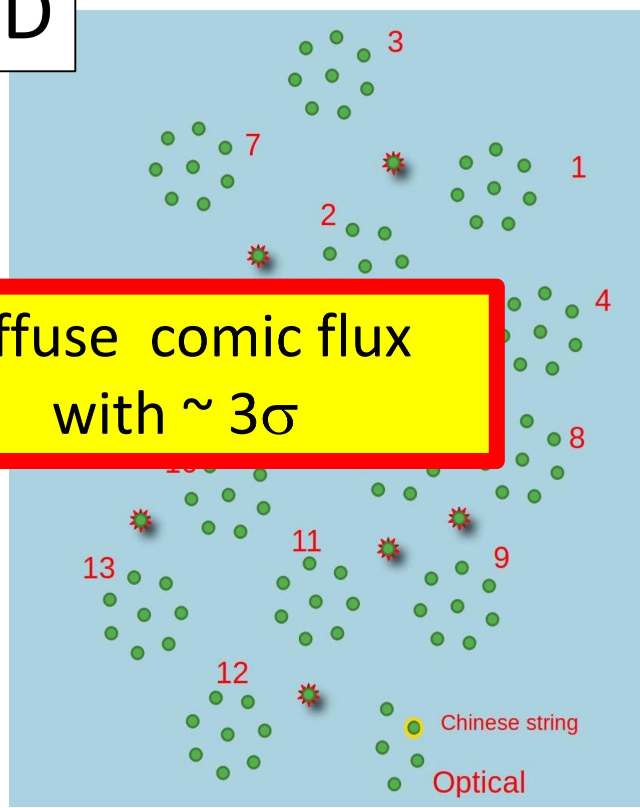
- 2013: diffuse extraterrestrial flux of neutrinos
- 2018: first transient individual source TXS 0506+056
- 2022: first steady individual source NGC 1068
- 2023: neutrinos from galatic plane

Operating partial configurations: Baikal GVD and KM3NeT 2024



Operating partial configurations: Baikal GVD and KM3NeT 2024

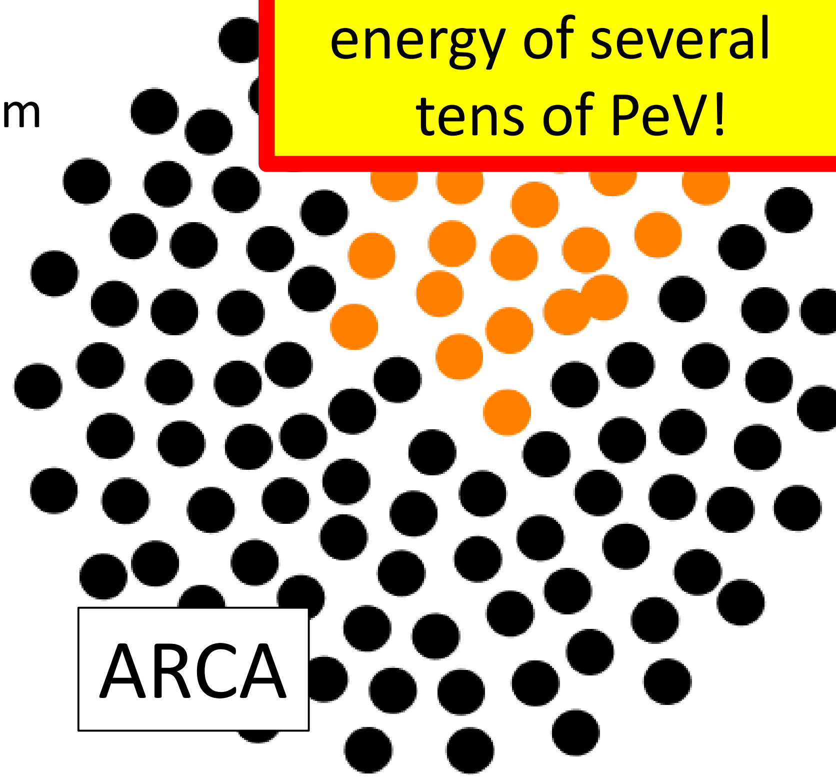
GVD



Diffuse comic flux with ~ 3σ

~ 1km

A single event with energy of several tens of PeV!



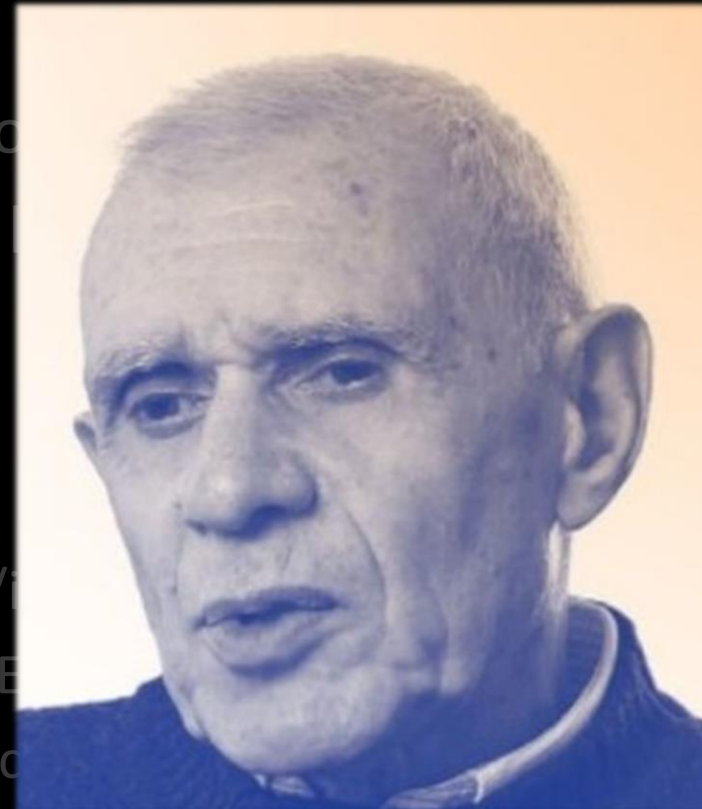
ORCA

Conclusions:

- Technological challenges: tremendous
- Flux predictions: from uncertain to low
- Long march:
  - 1960: method proposed
  - 1973 : first steps toward DUMAND
  - 1993/96: first neutrinos underwater /in ice (Baikal/AMANDA)
  - 2008: first deep sea detector - ANTARES
  - 2010: first cubic kilometer detector - IceCube
  - 2013: detection of a diffuse extraterrestrial flux of neutrinos (meanwhile also by Baikal-GVD)
  - 2018 - 2023: evidence of first individual sources and of neutrinos from the Galactic Plane in IceCube
  - First „tens-of-PeV“ event in KM3NeT

- Next steps: Baikal-GVD, KM3NeT, Chinese Project, P-ONE, Gen2

Conclusions:



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Thank you for your attention !