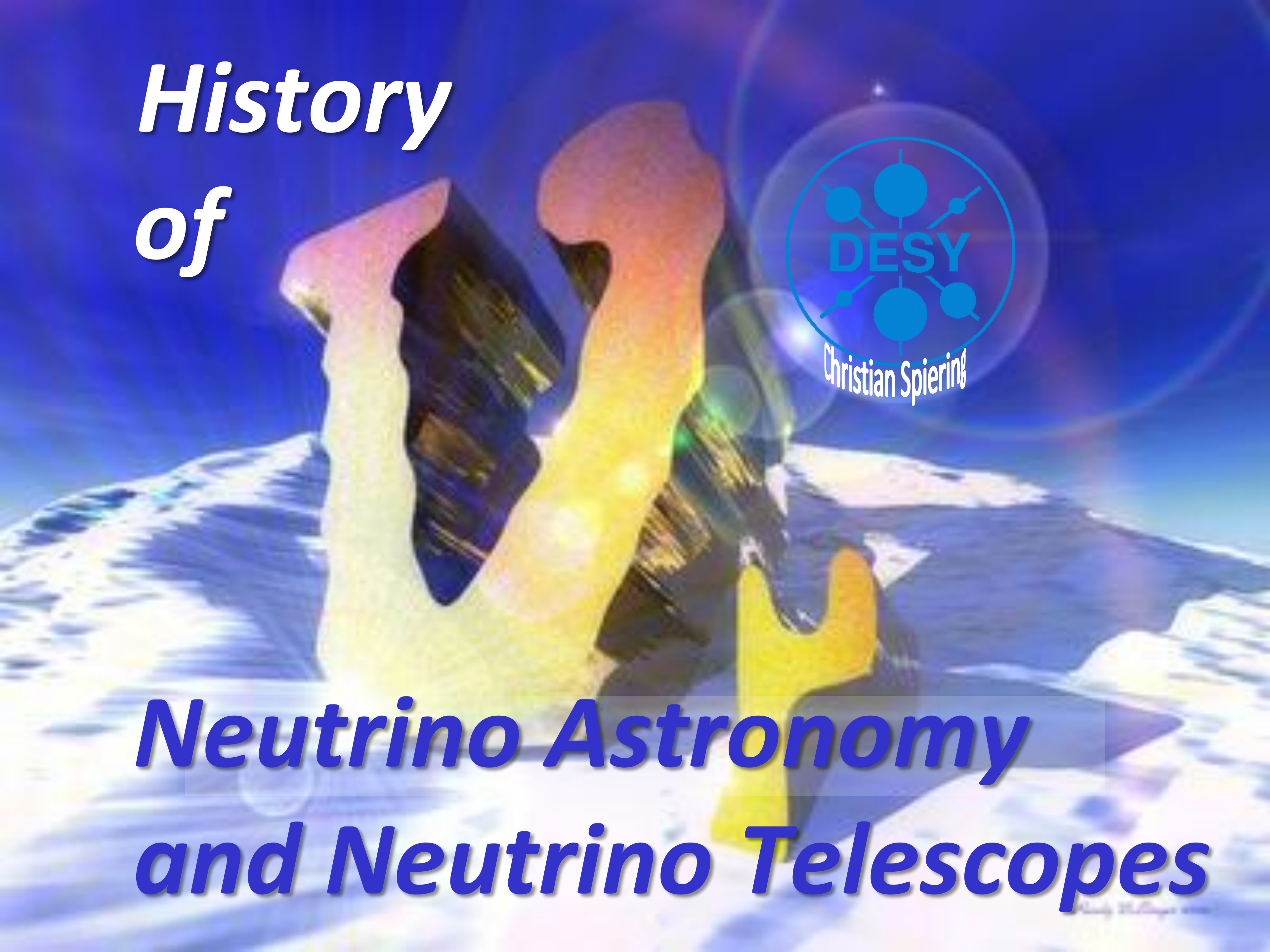
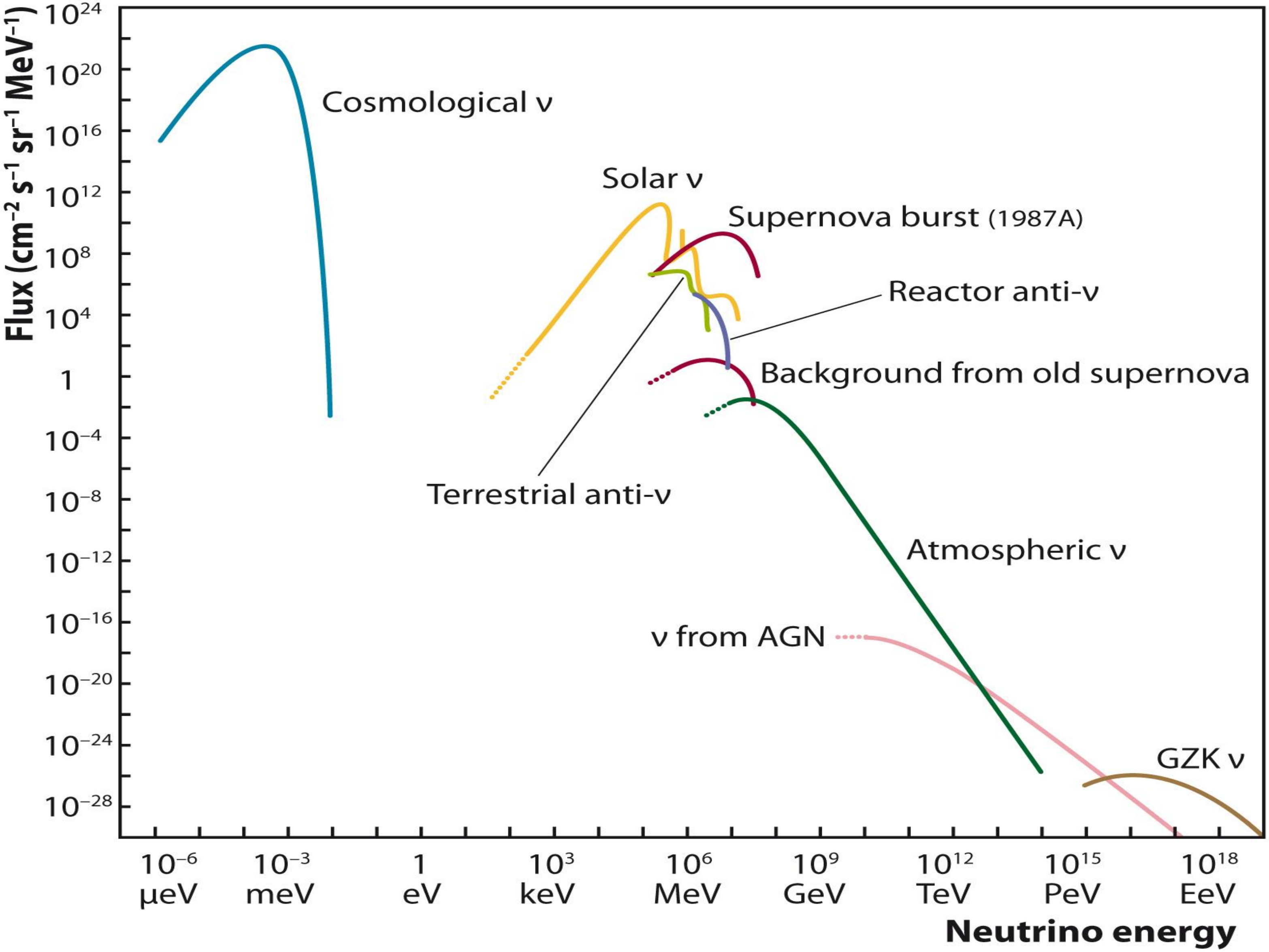
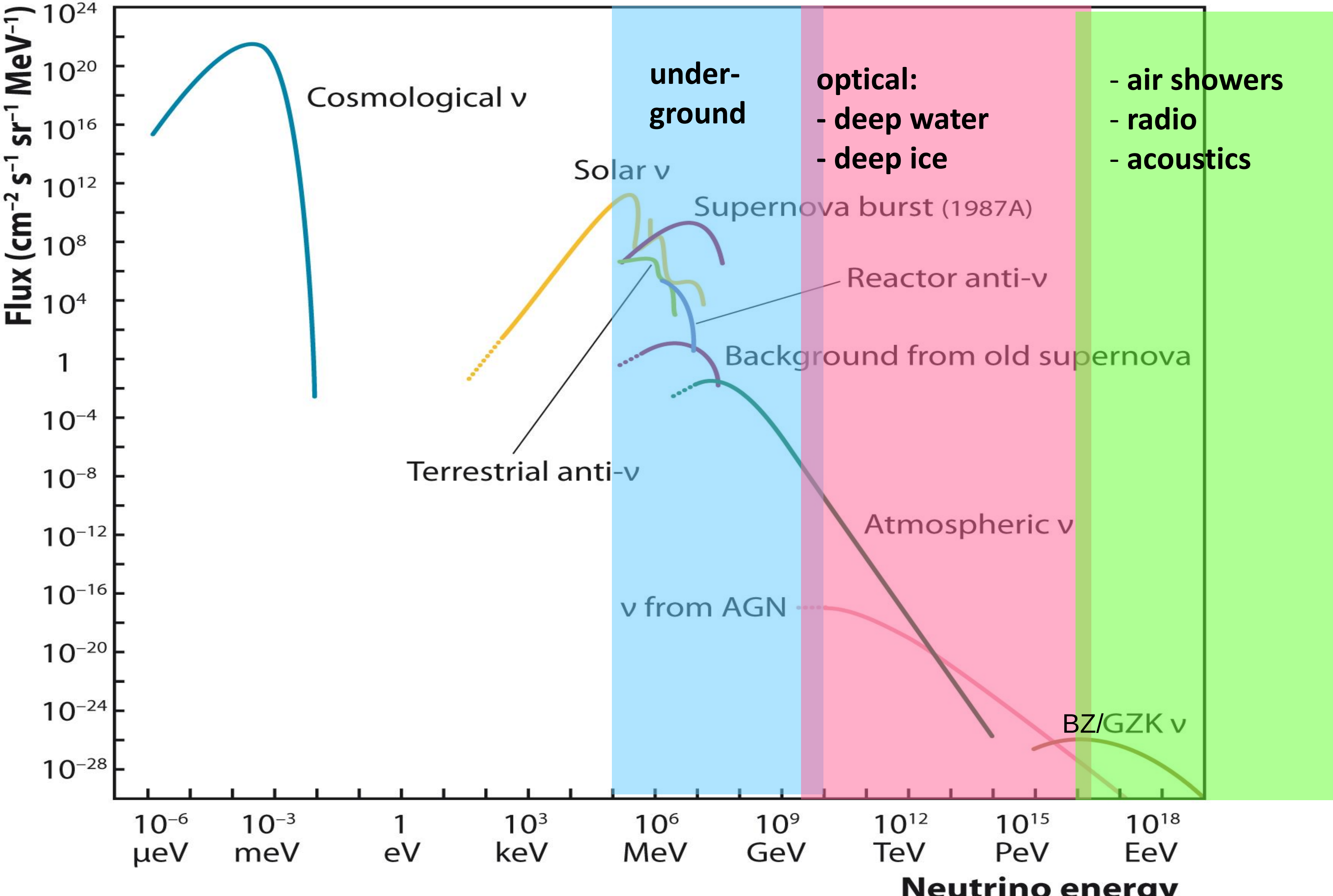


History of Neutrino Astronomy and Neutrino Telescopes

DESY
Christian Spiering



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
10^24
10^20
10^16
10^12
10^8
10^4
1
10^−4
10^−8
10^−12
10^−16
10^−20
10^−24
10^−28
10^−6 μeV
10^−3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy



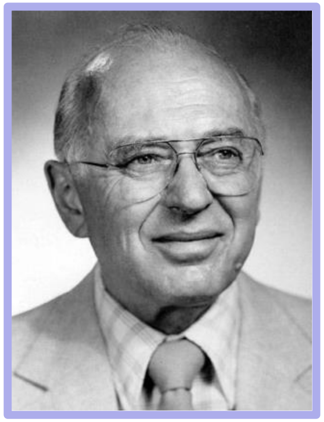
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
under-
ground
optical:
- deep water
- deep ice
- air showers
- radio
- acoustics
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
BZ/GZK ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

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



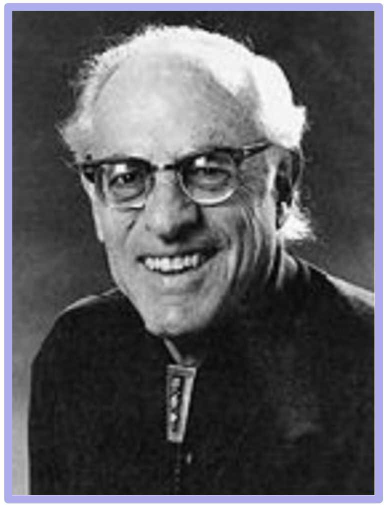
For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6 \cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with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

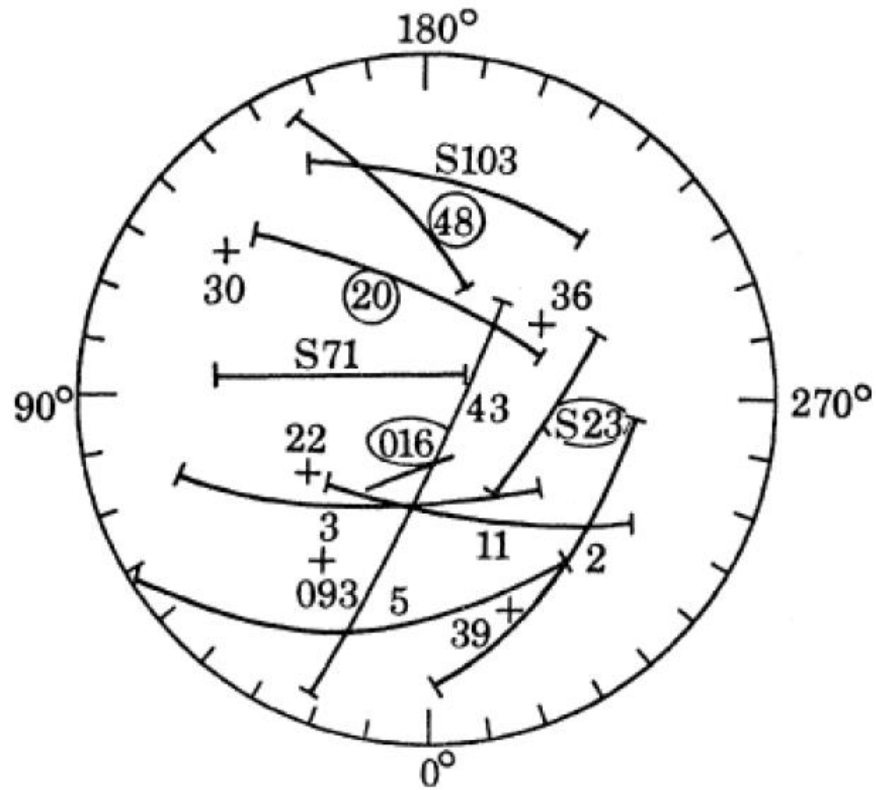
Atmospheric Neutrinos

- Flux calculations
  - Zhelesnykh 1958
  - Markov and Zhelesnykh 1961
  - Zatsepin & Kuzmin 1961
  - Coswik 1963
  - Osborne 1965
  - Volkova & Zatsepin 1965
- Detection
  - Case-Witwatersrand: 2/23/1965 (submitted 7/26)
  - Kolar Gold Field: 4/20/1965 (submitted 7/12)

The first neutrino skymap

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

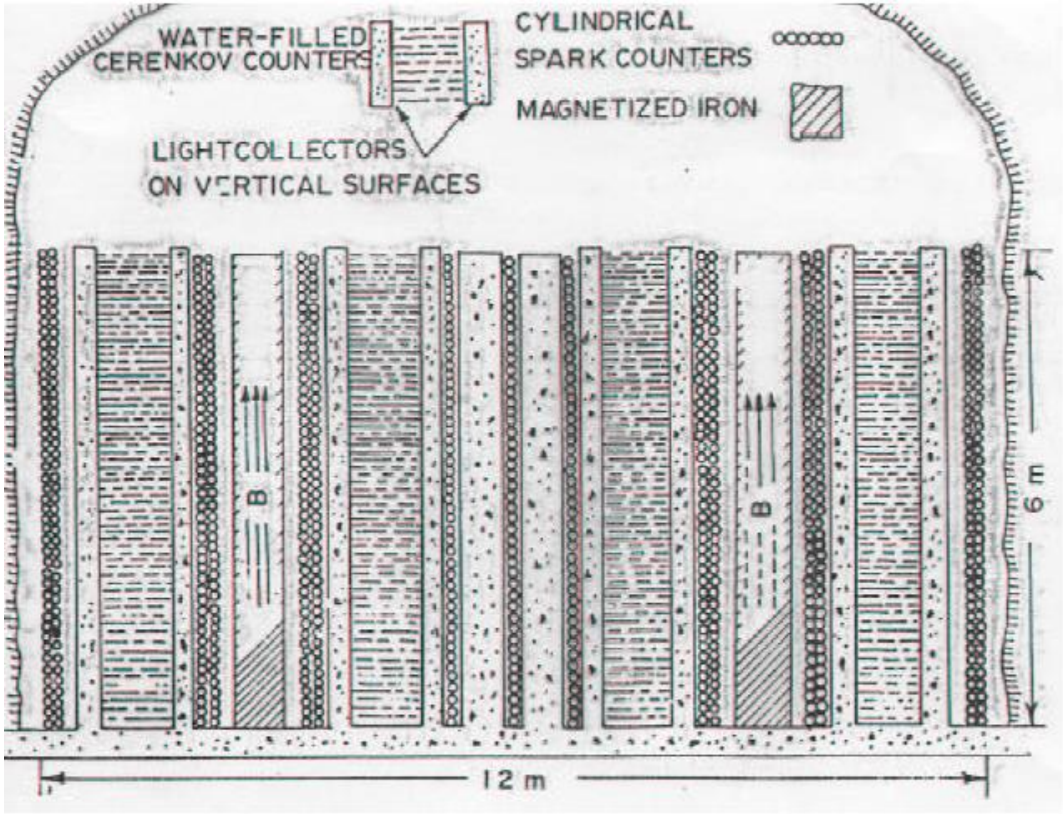
(Krishnaswamy et al. 1971)



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

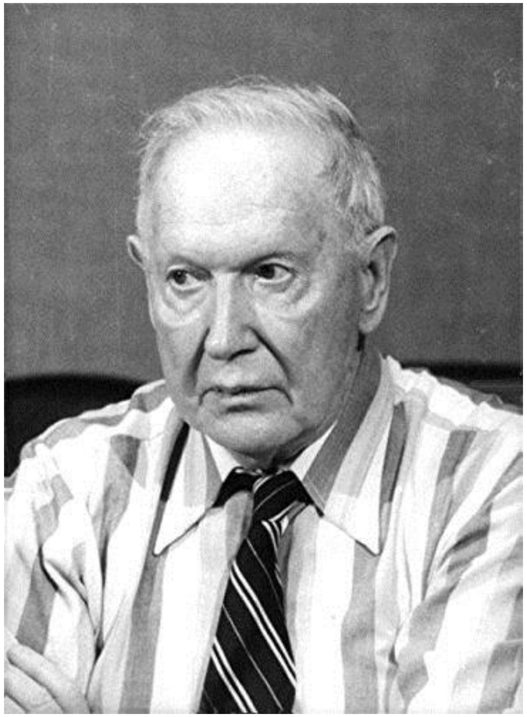
- Utah detector plus KGF: W-mass must be >> a few GeV



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

Neutrino detection underwater

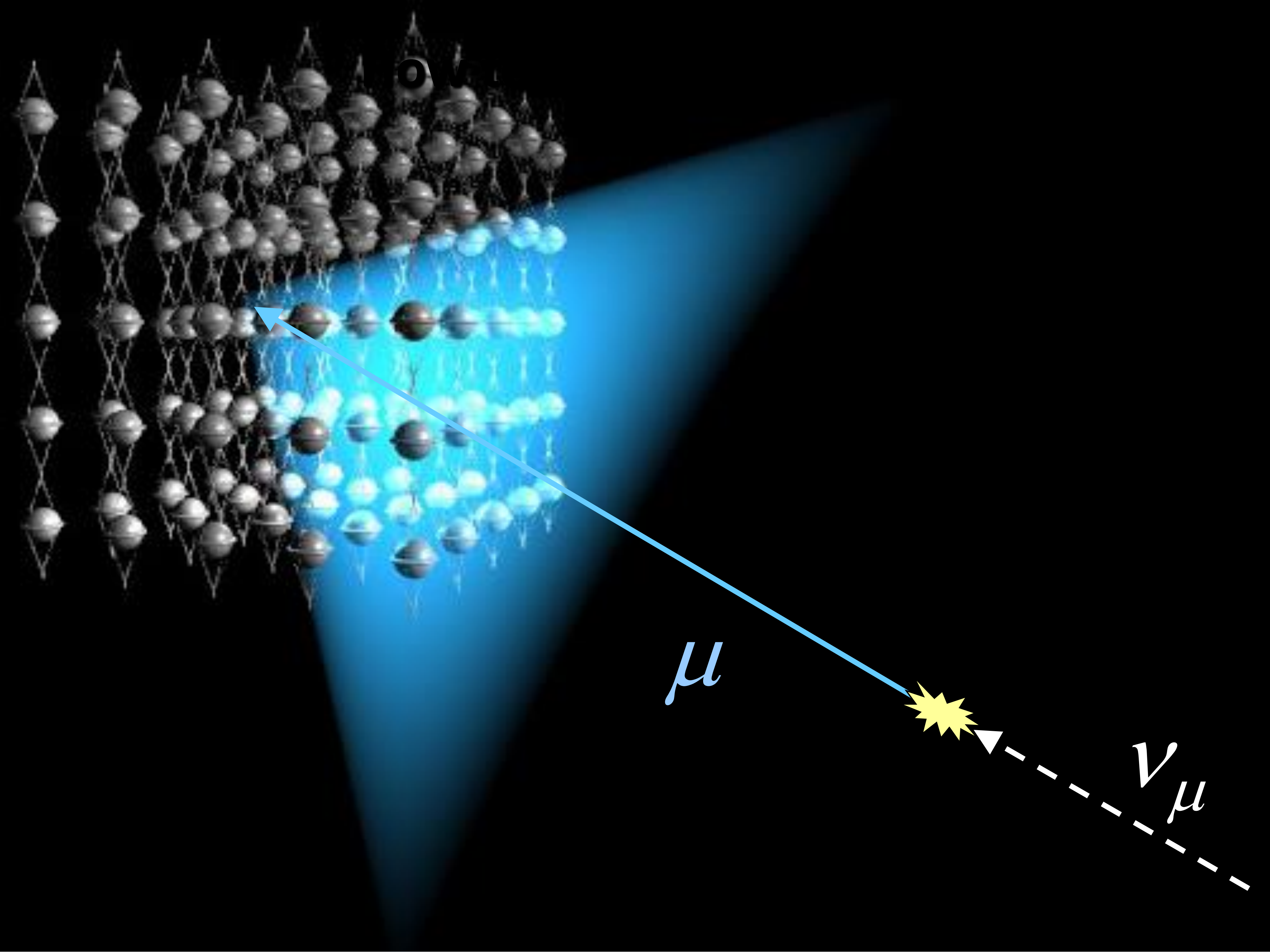
Moisej Markov



„We propose setting up detectors deep in a lake or in the ocean to 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

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“ from Utah detector)
- 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?

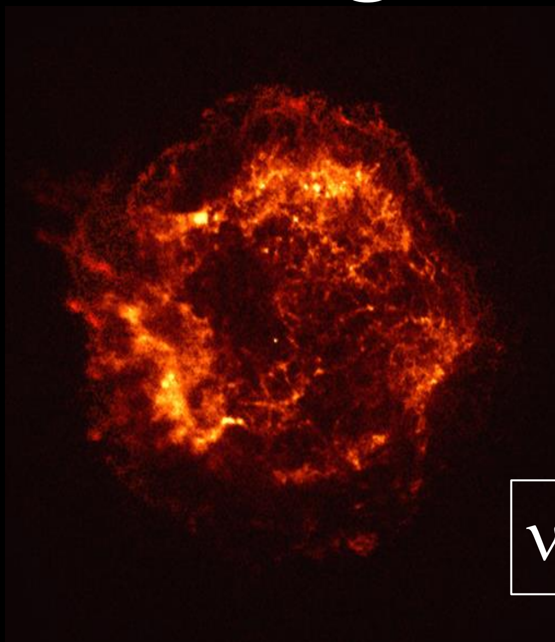
- UNDINE: UNderwater Detection of Interstellar Neutrino Emission
  - *i.e. Supernova → too rarely to optimize an ocean detector for it (→ IMB)*
- ATHENE: ATmospheric High-Energy Neutrino Experiment
  - *Better with underground experiments*
- UNICORN: UNderwater Interstellar COsmic Ray Neutrinos
  - The high energy option
  - Preferred option, but:
    how large are the fluxes ?
  - → think as big as possible!

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.

Neutrino Generation in Cosmic Ray Sources

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



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

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

$$\boxed{\nu_e : \nu_\mu : \nu_\tau = 1:2:0}$$

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

Neutrino Generation along the Way of Cosmic Rays through Space

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

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

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

Greisen, Zatsepin, & Kusmin 1966

Neutrino flux: Berezinky & Zatsepin 1970

Expect O(1 event) per cubic kilometer

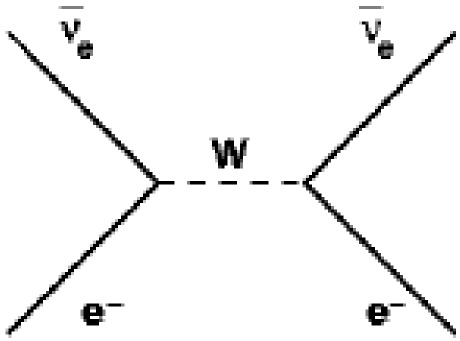
The DUMAND Workshops

- 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

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

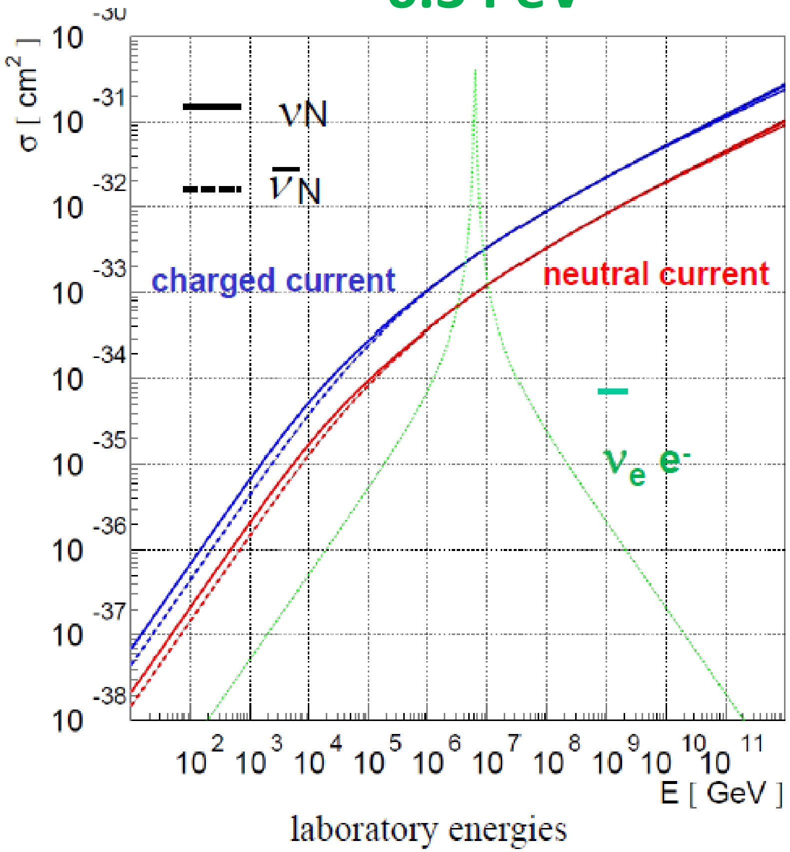
- Neutrinos from GZK processes: Berezinsky & Zatsepin

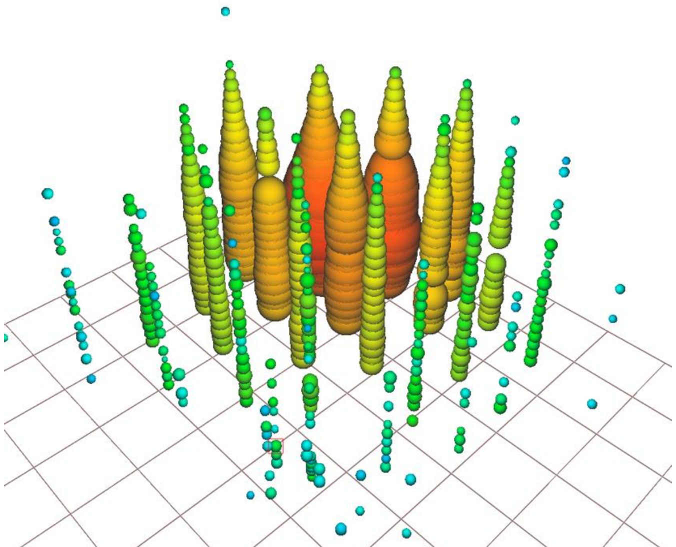


Glashow Resonance

- Glashow, 1960
  Berezinsky and Gazizov, 1977
- Only way to distinguish ν and anti-ν
- First IceCube candidate 2018

6.3 PeV





1978: 1.26 km³

22,698 OMs

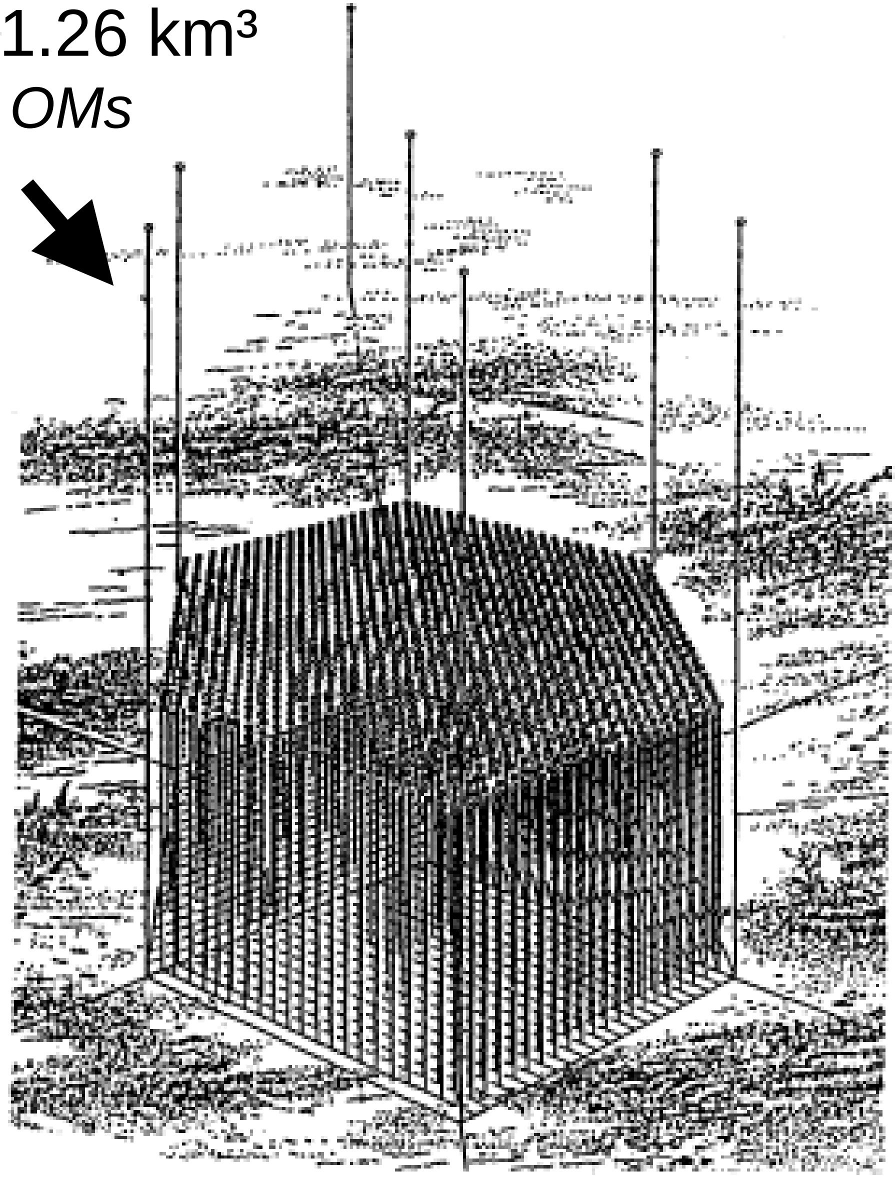


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

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.

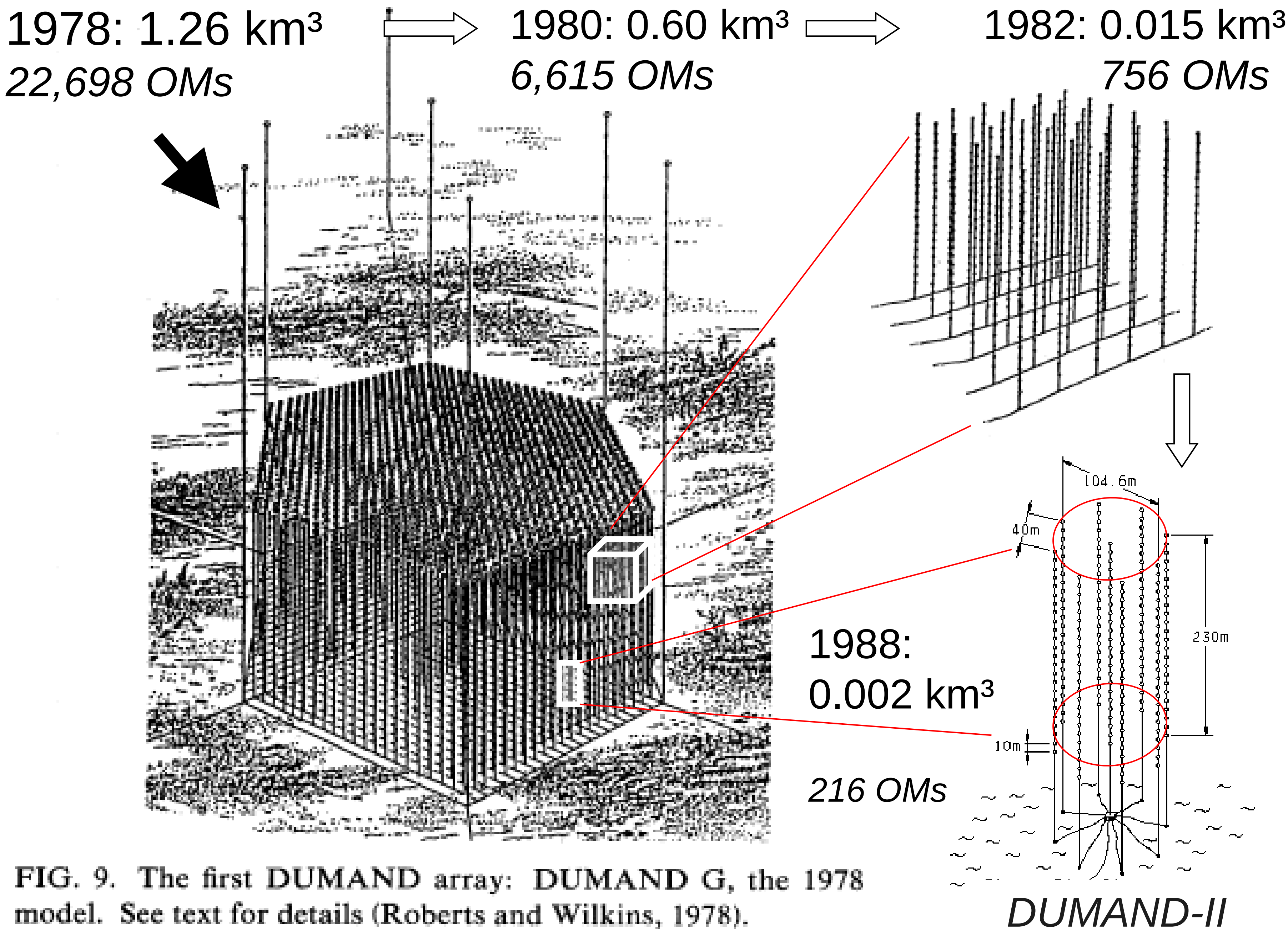
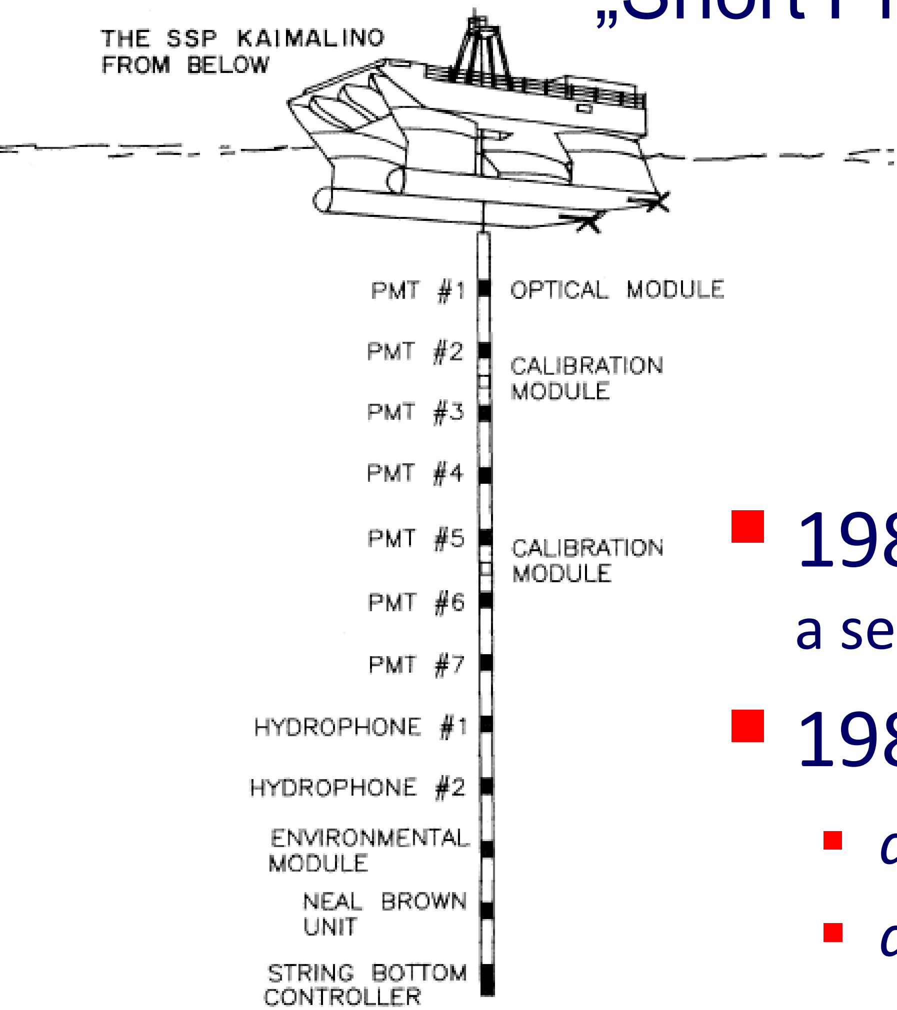


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

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)*

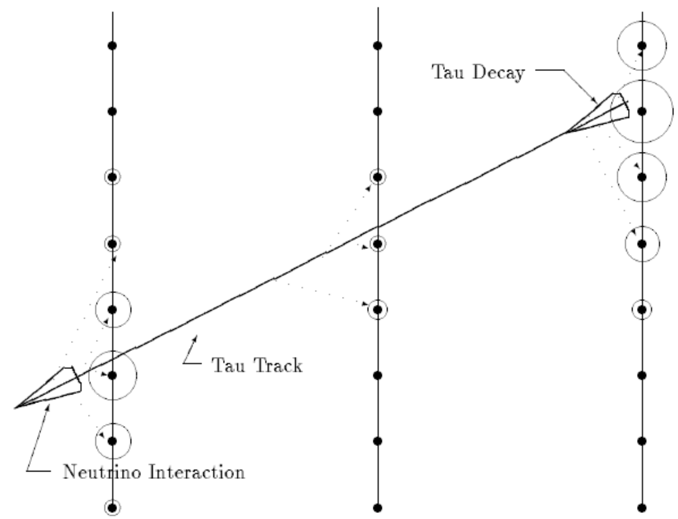
DUMAND after the SPS:

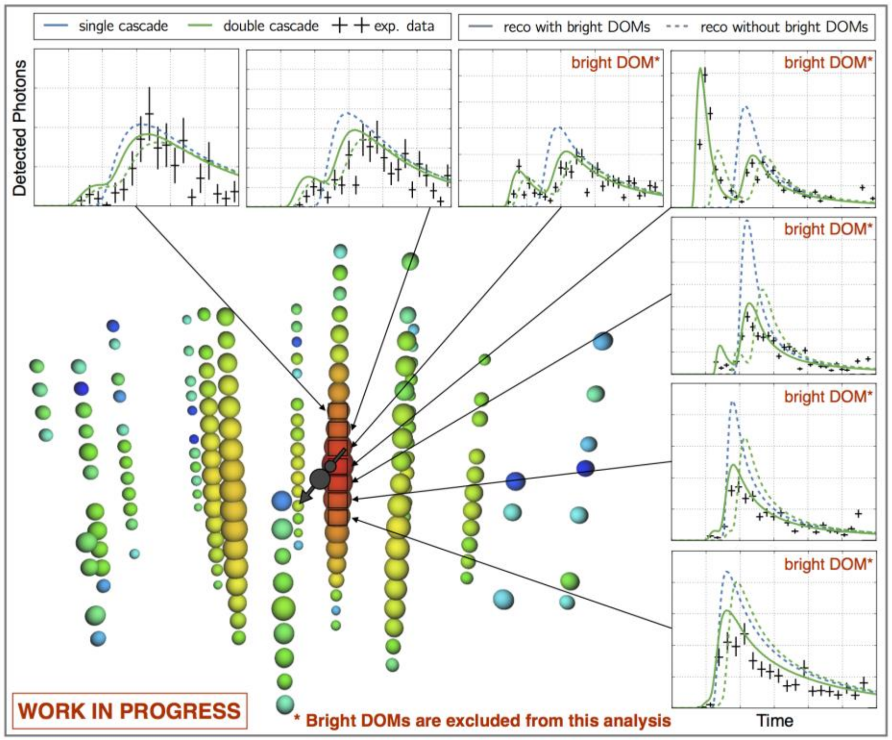
- 1989: HEPAP supports DUMAND-II
- 1990: DOE allocates funds for DUMAND-II
- Further financial cuts → TRIAD (3 strings)
- 1993: shore cable laid
- December 1993: deployment of first string and connection to junction box. Failure after several hours
- 1995: DUMAND project is terminated

Double Bang Events

Proposed 1994, J. Learned and S. Pakvasa

Clear signature for ν_τ

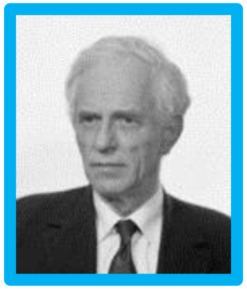




First double cascade candidate 2018, IceCube

Russia

- Very active during early DUMAND workshops
- Kicked out of DUMAND 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)

see the poster of Igor Zheleznykh

Russia

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

Arthur 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.

- Exploration of Atlantic, Black Sea, Indian Ocean, Pacific and Mediterranean sites (Zheleznyk, Petrukhin)

see the poster of Igor Zheleznykh

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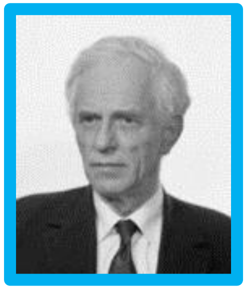

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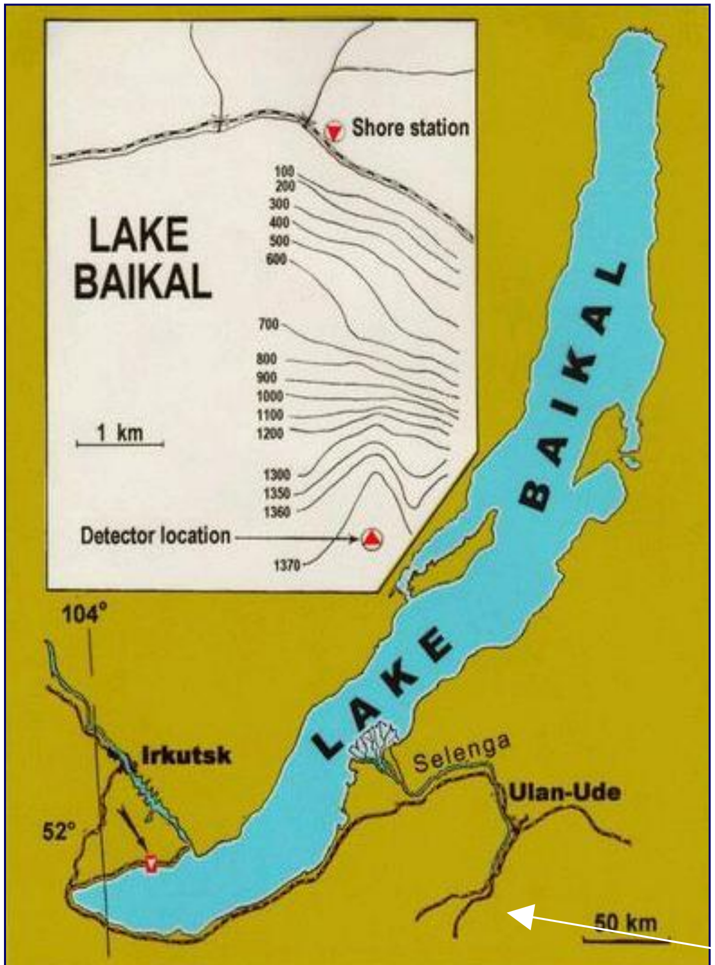
- Exploration of Atlantic, Black Sea, Indian Ocean, Pacific and Mediterranean sites (Zheleznyk, Petrukhin)

see the poster of Igor Zheleznykh

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**

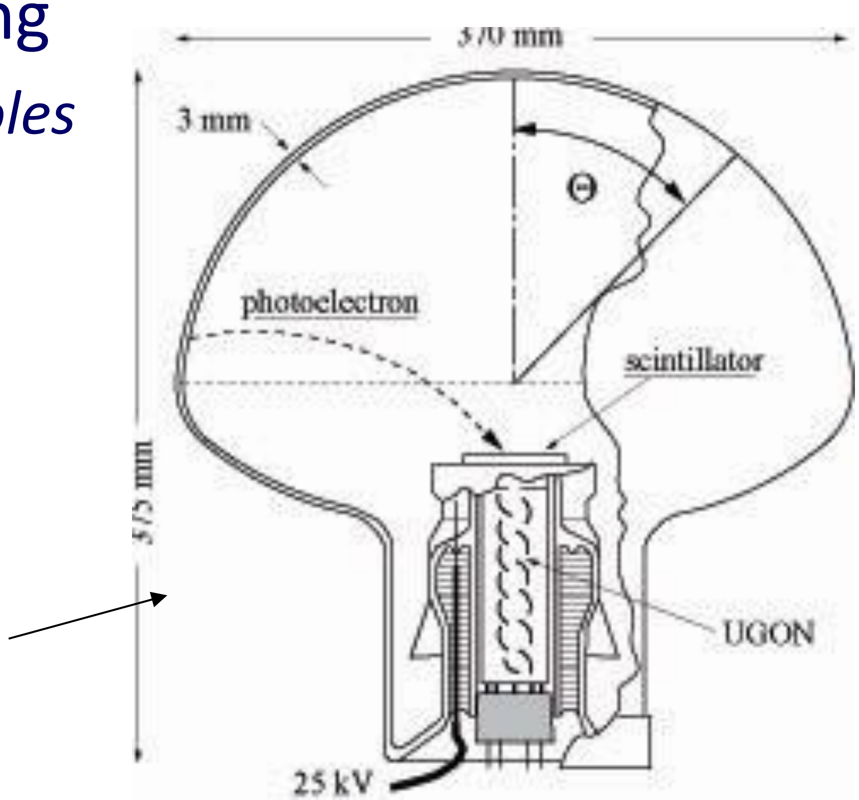
Lake Baikal: the eighties

- 1984: first stationary string
  Muon flux measurement

- 1986: second stationary string
  Limits on GUT magnetic monopoles

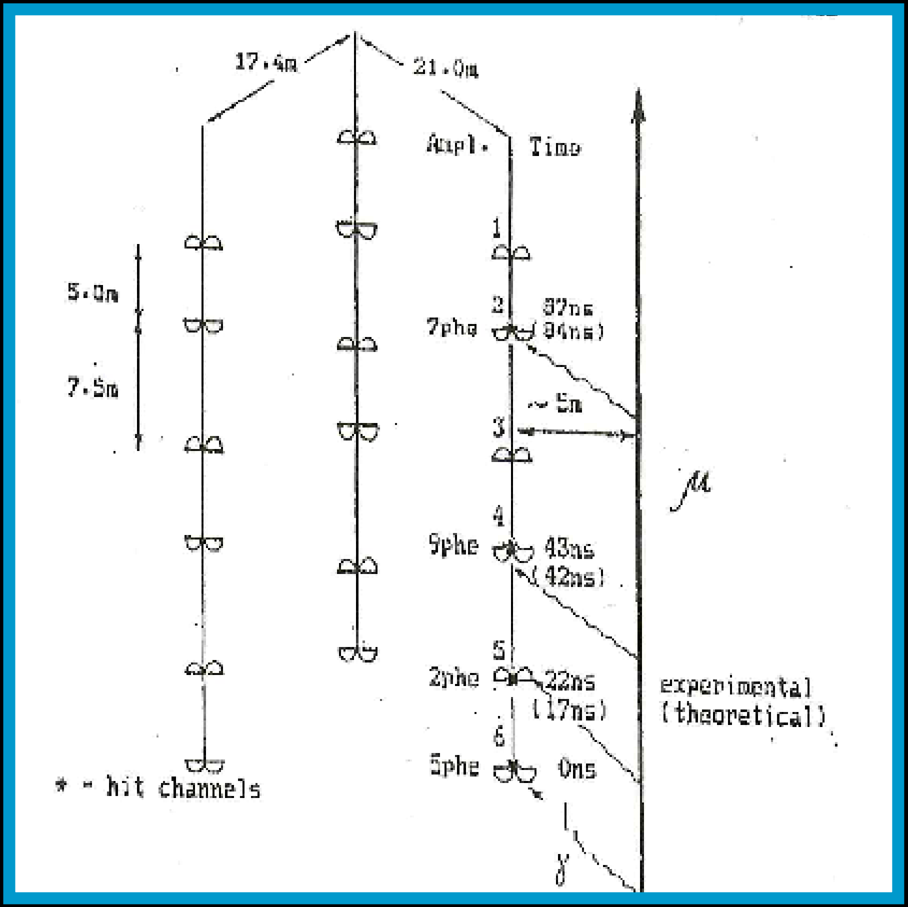
- All that with a 15-cm flat-window PMT

- Development of a Russian smart phototube (Quasar)



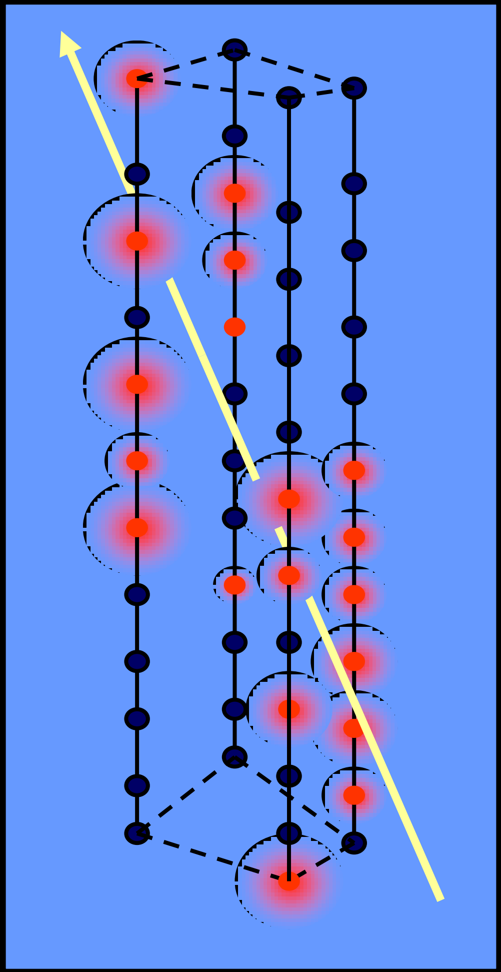
Towards NT-200

- 1989/90: design of NT-200
- 1993 + 1994: NT-36
  - 18 channels at 3 strings
  - first underwater array
  - first 2 neutrino candidates
  - (identified 1996)



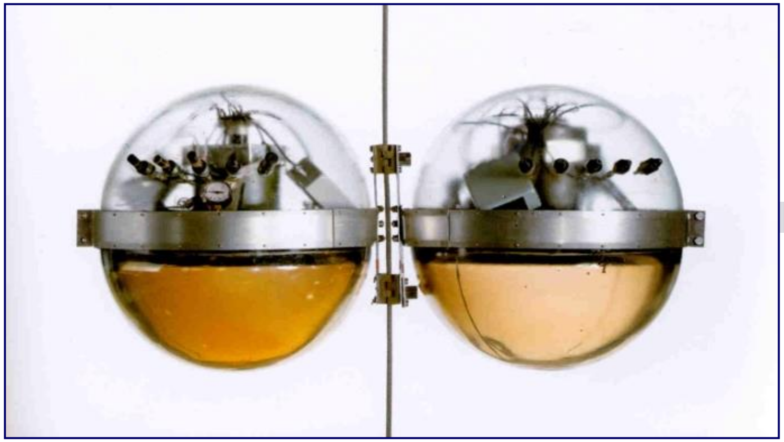
Towards NT-200

- 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

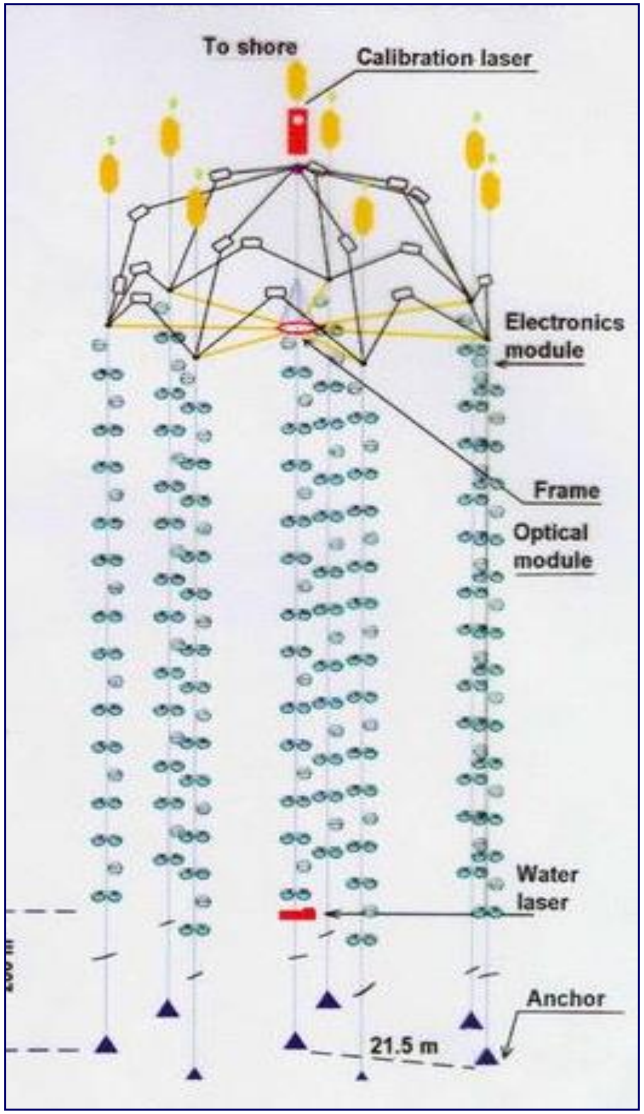


4-string stage (1996)

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)



FLUX PREDICTIONS

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

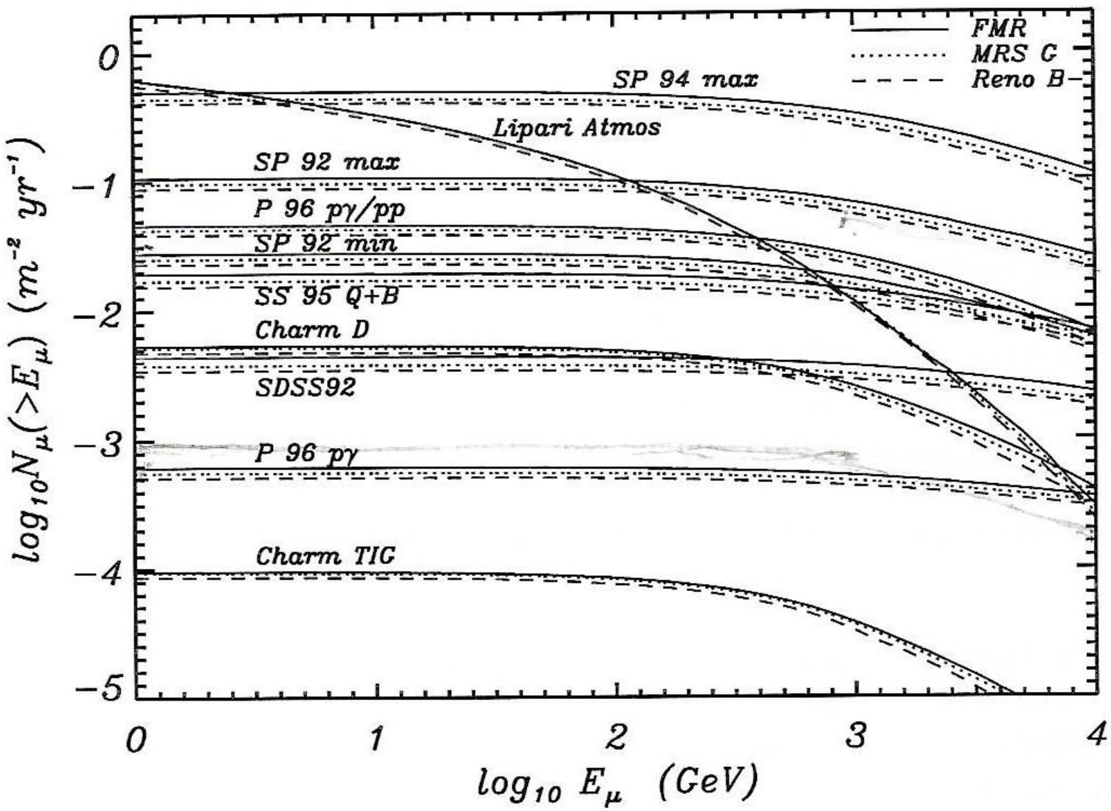
Source name	γ-ray Energy (TeV)	γ flux at Earth ($cm^{-2}s^{-1}$)	Luminosity ($erg\ s^{-1}$)	μ/yr DUM II $\epsilon_{\nu/\gamma}=1$ Min γ	$\epsilon_{\nu/\gamma}=30$ Max γ
Vela PSR	5	1.8×10^{-12}	3×10^{32}	0.1	1506
Vela X-1	1	2×10^{-11}	2×10^{34}	0.2	126
Crab SNR	2	1.1×10^{-11}	2×10^{34}	0.2	438
Crab PSR	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

100 events/DUMAND-II
(before trigger/cuts)



Models

SDDS Stecker, Done, Salomon, Sommers 1992

SP Szabo and Protheroe 1994

SS Stecker and Salomon 1992

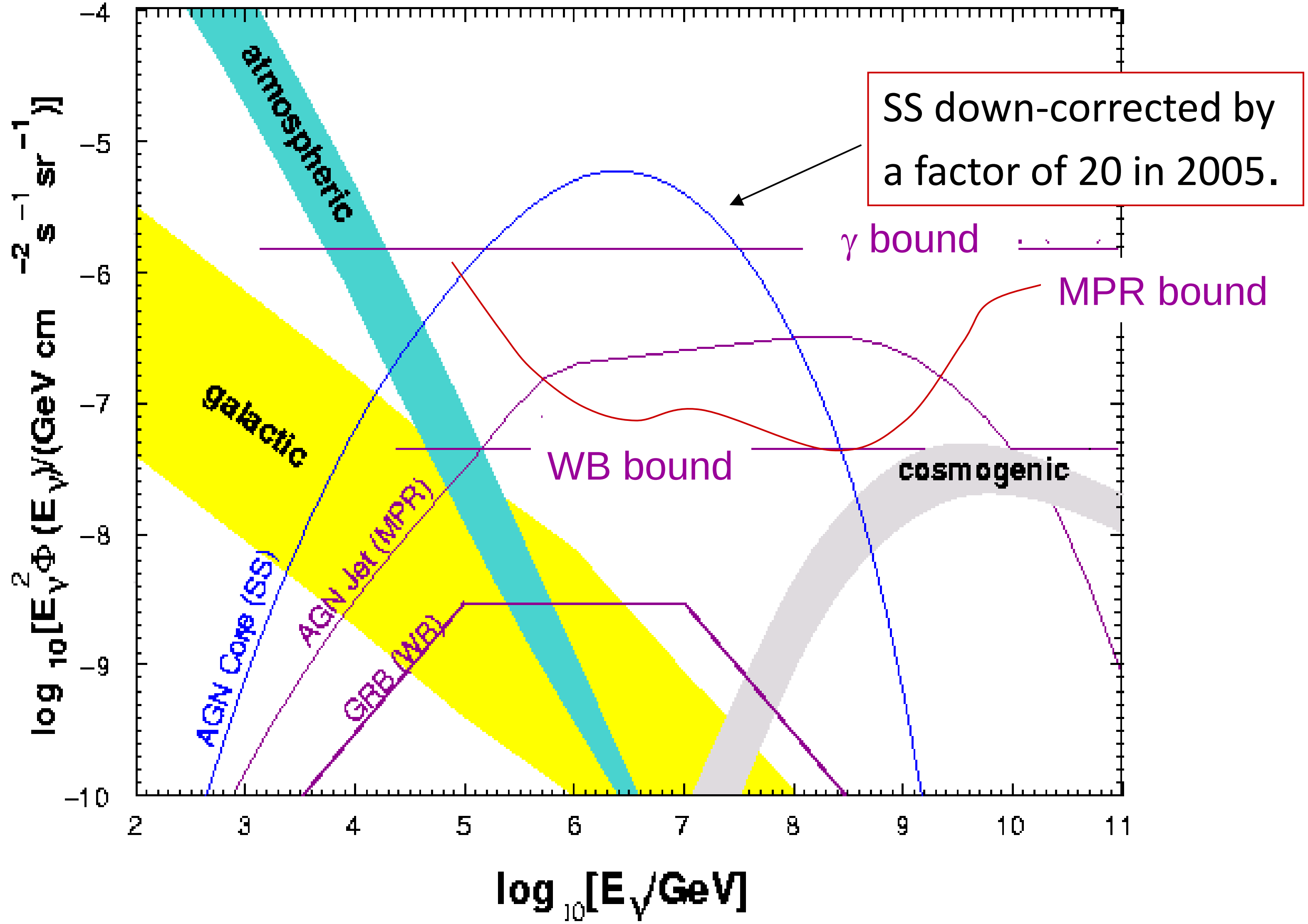
P Protheroe 1995

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 (months!) 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



Shallow detector projects (late 1980s)

Advantages: easy access, less challenging environment

Disadvantages: huge background, not expandable

- GRANDE Shallow Lake, Arkansas
- LENA Artificial water pool, Japan
- NET Artificial water pool, Italy
- SINGAO Resistive Plate Chambers, Italy
- Swedish lakes (explored before Sweden joined Amanda)

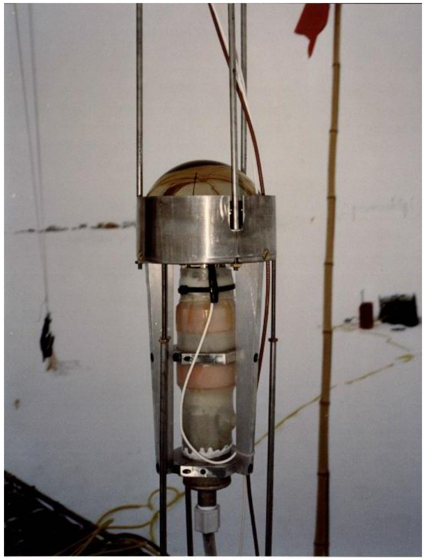
- NEVOD
  - Moscow, MEPhI, Large water tank. Working since the early 1990s
  - Cosmic ray physics with muons

AMANDA

Antartic Muon and Neutrino Detection Array

The ice option

- 1988: E. Zeller (Kansas) suggests to F. Halzen radiodetection of neutrinos in Antarctic ice
- Halzen: optical detection? ↔ J. Learned
- 1988: Halzen & Learned:
  “High Energy Neutrino Detection in Deep Polar Ice”
- 1989: attempt of 2 youngsters from UCB 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

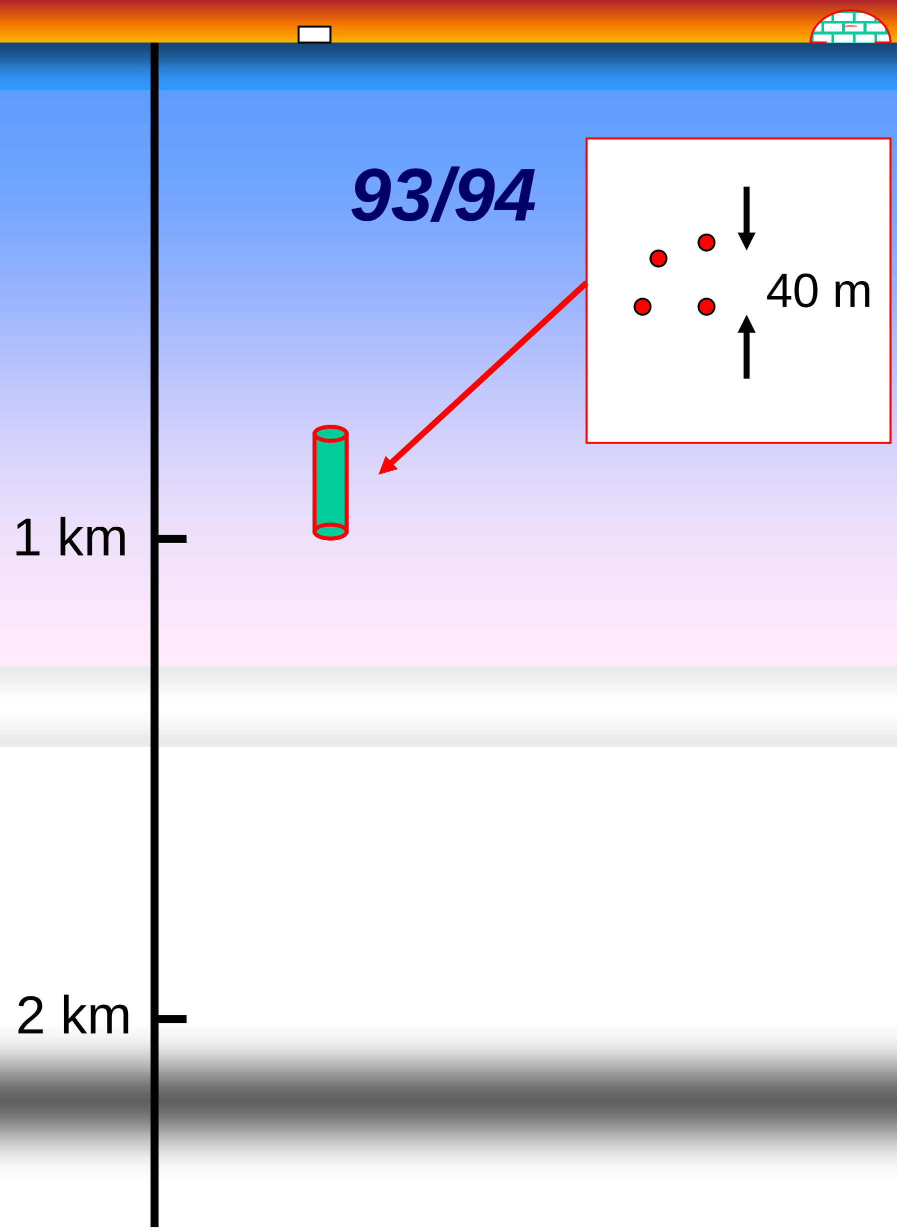
Observation of muons using the polar ice cap as a Cerenkov detector

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

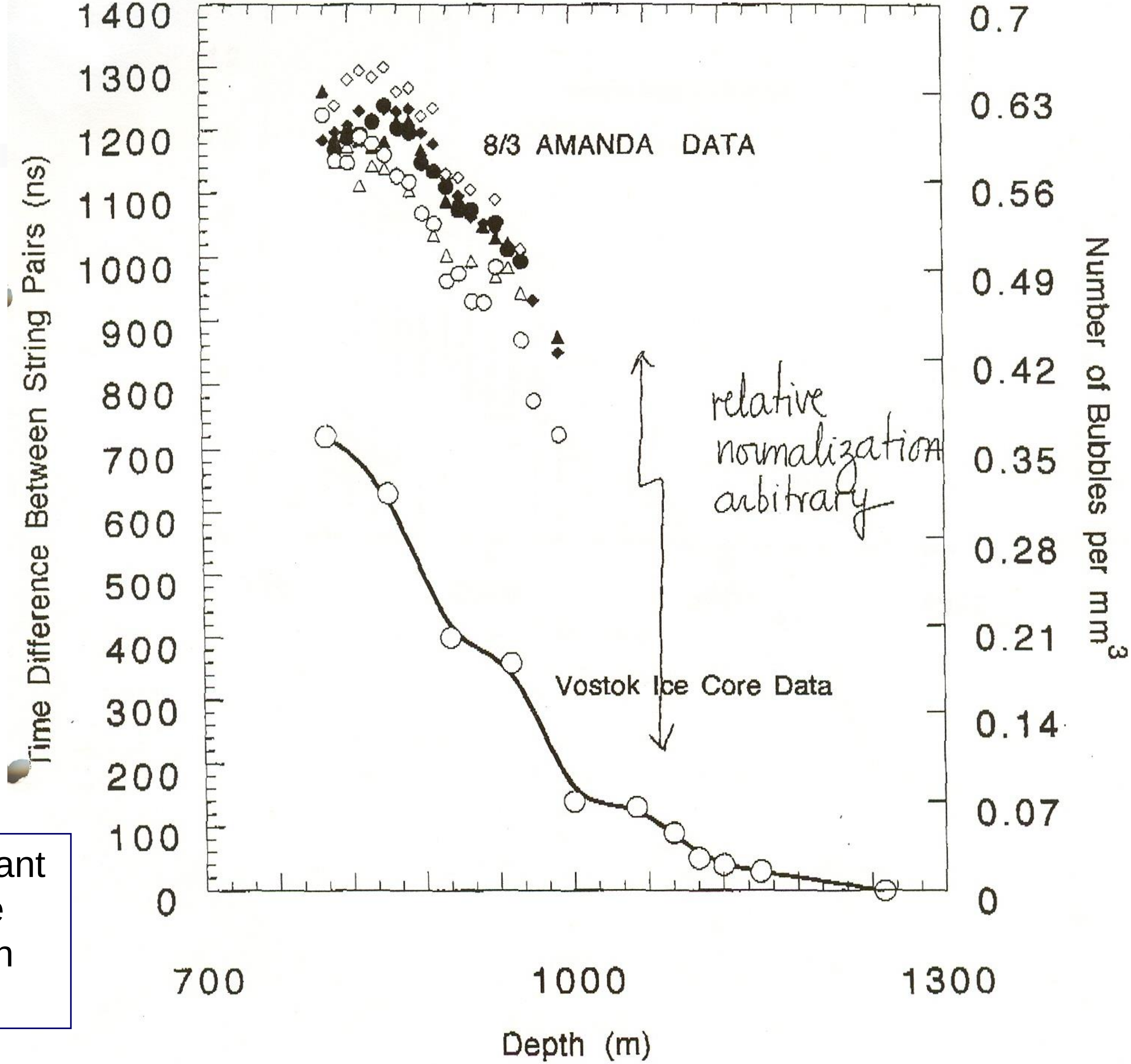
DETECTION of the small flux of extraterrestrial neutrinos expected at energies above 1 TeV, and identification of their astrophysical point sources, will require neutrino telescopes with effective areas measured in square kilometres—much larger than detectors now existing[1–3]. Such a device can be built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

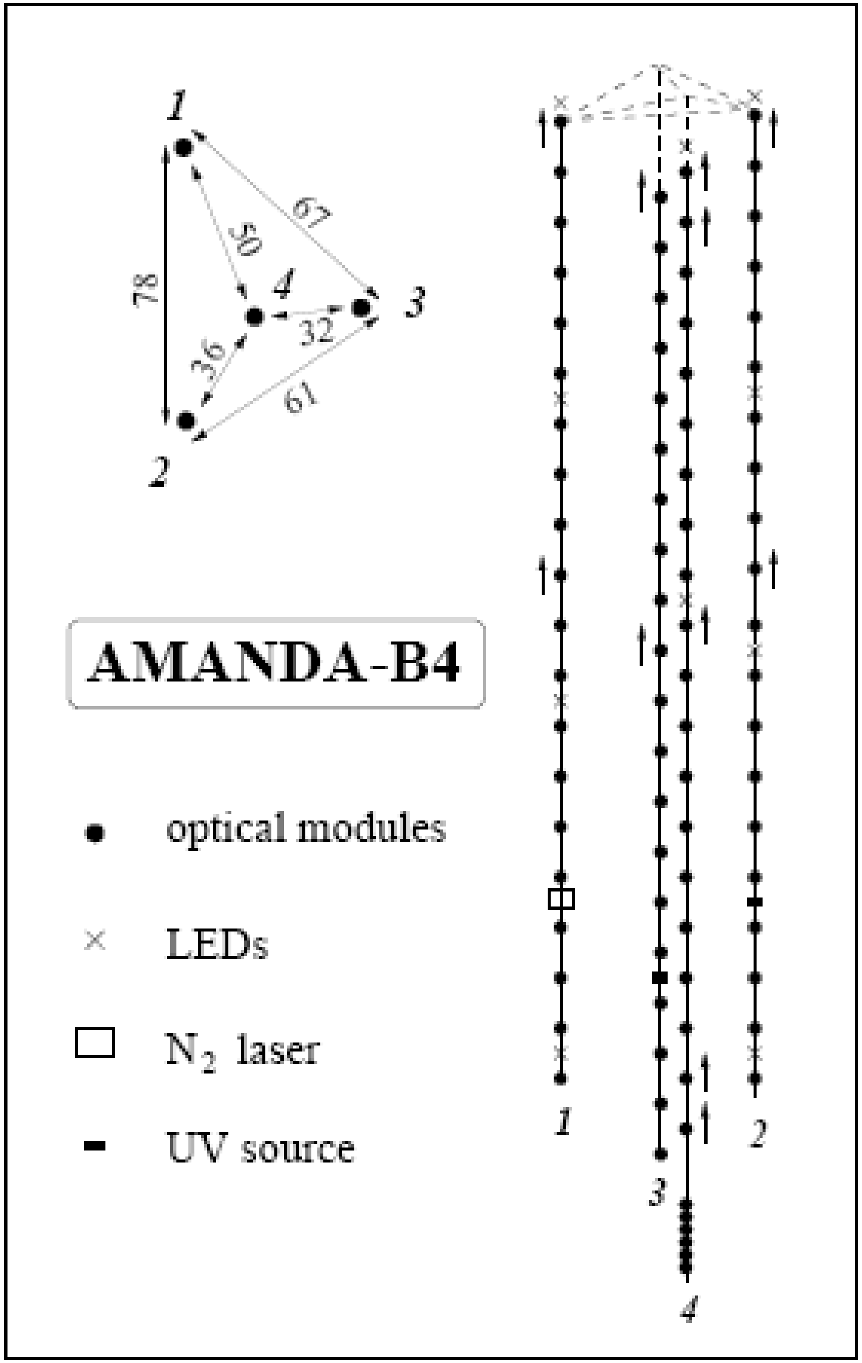


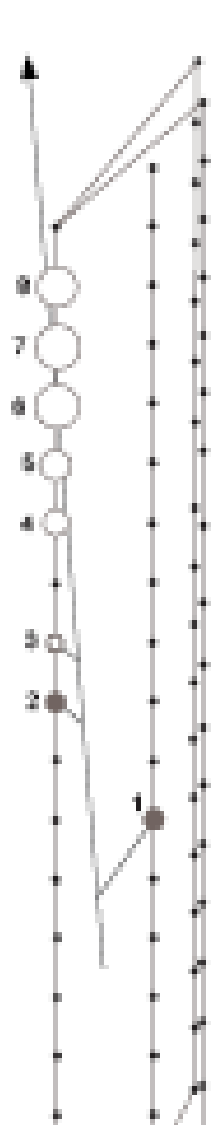
Catastrophal delay of light between strings 20 m away!

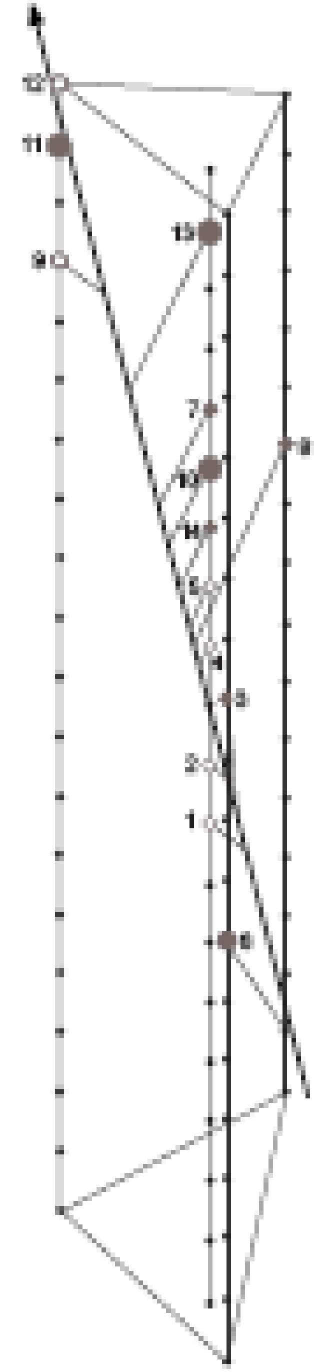
(µsec instead of 100 nsec)



Explanation remnant bubbles which are disapppearing with increasing depth.

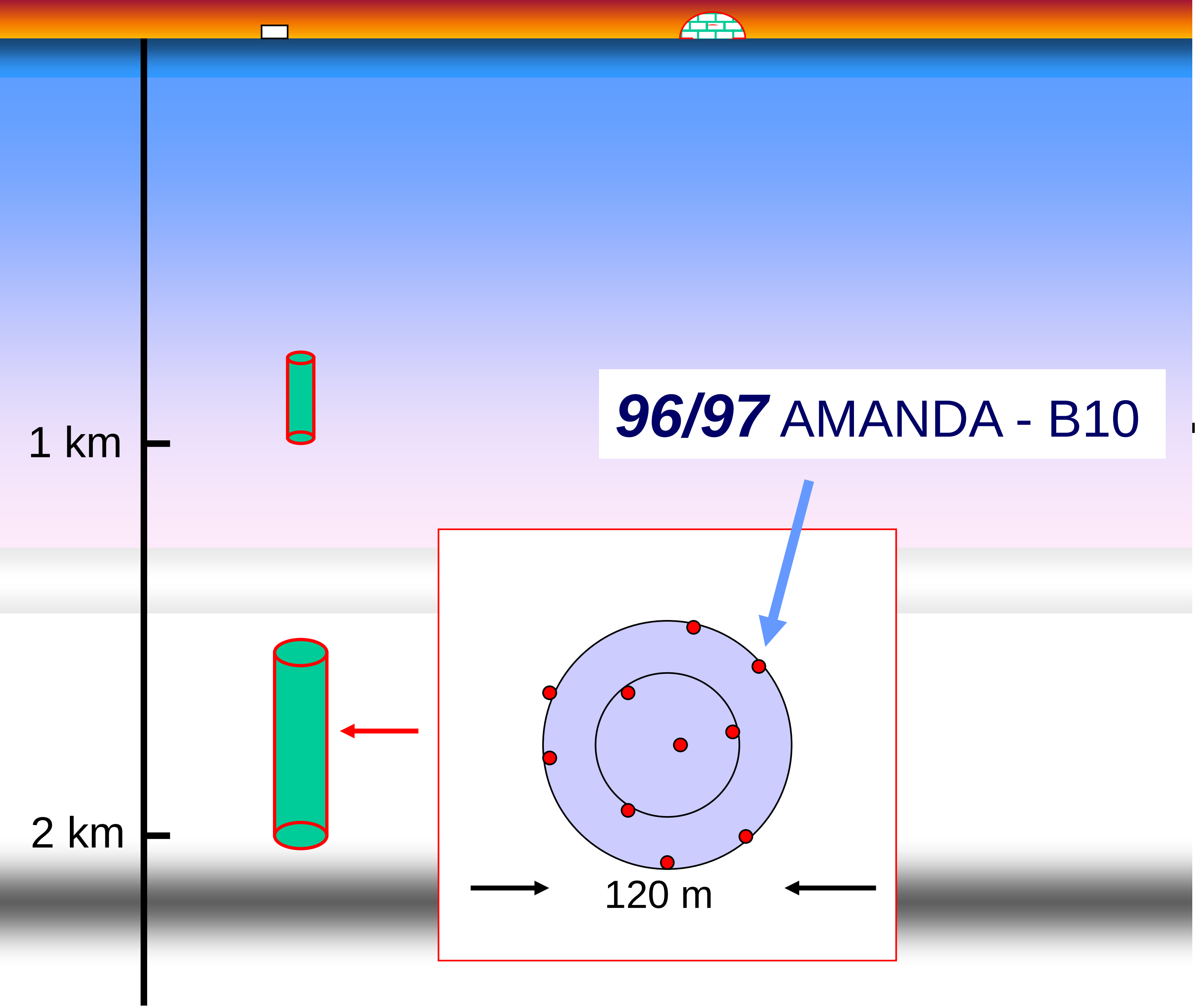


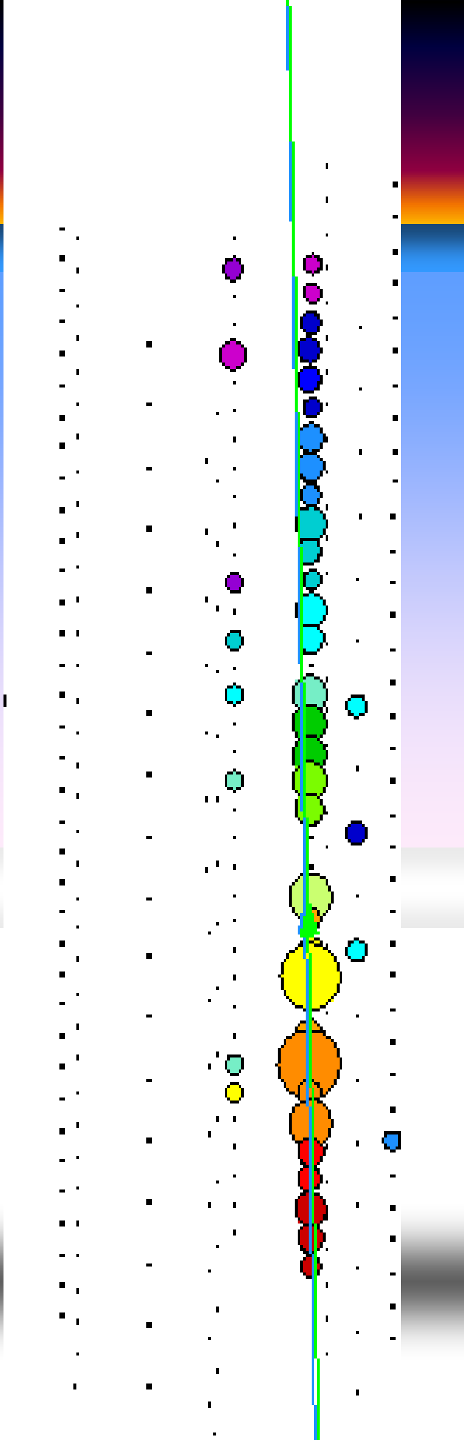




The first 2 neutrinos in AMANDA (1996)

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

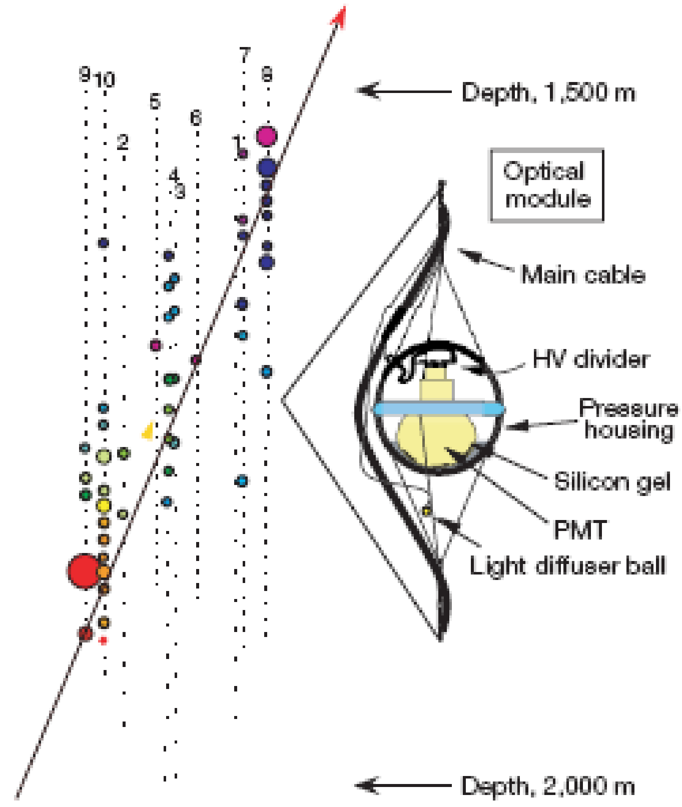
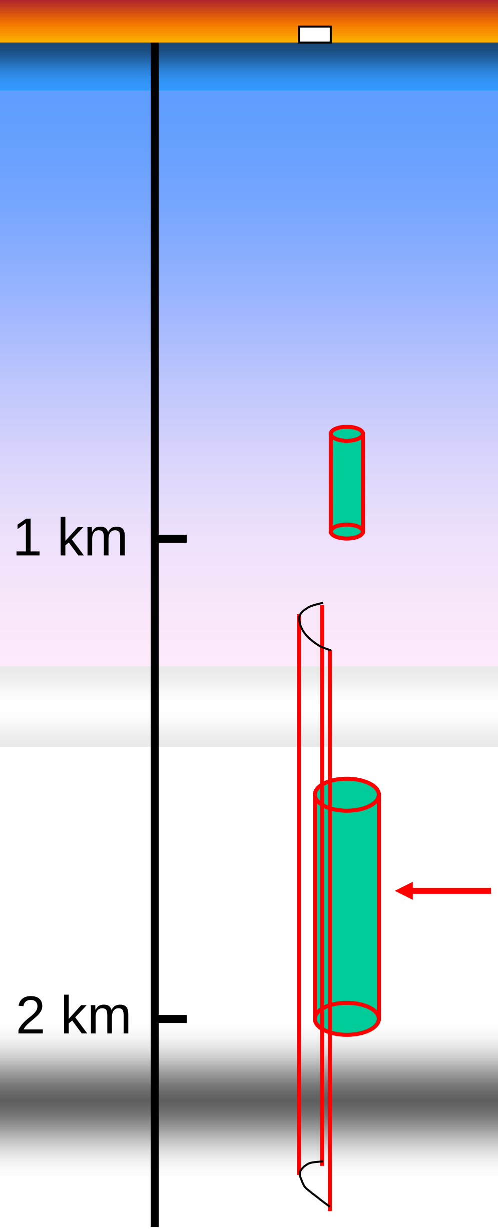
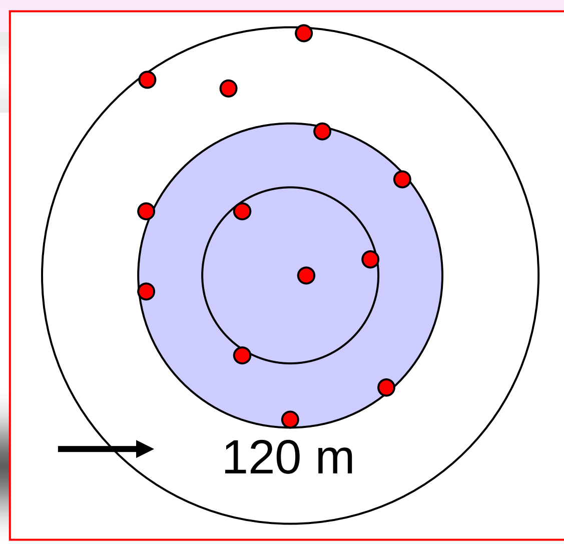


Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular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

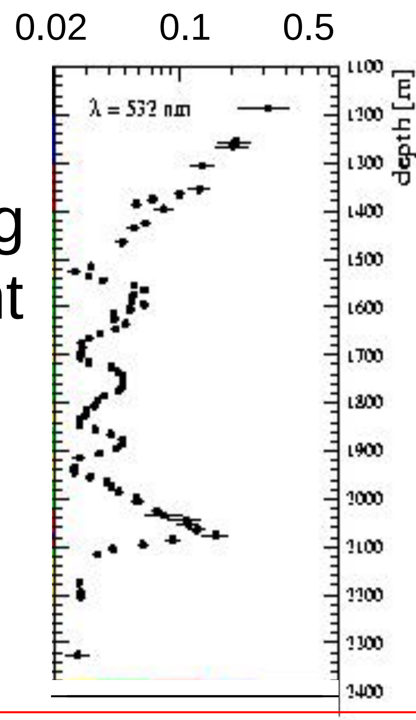
97/98

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



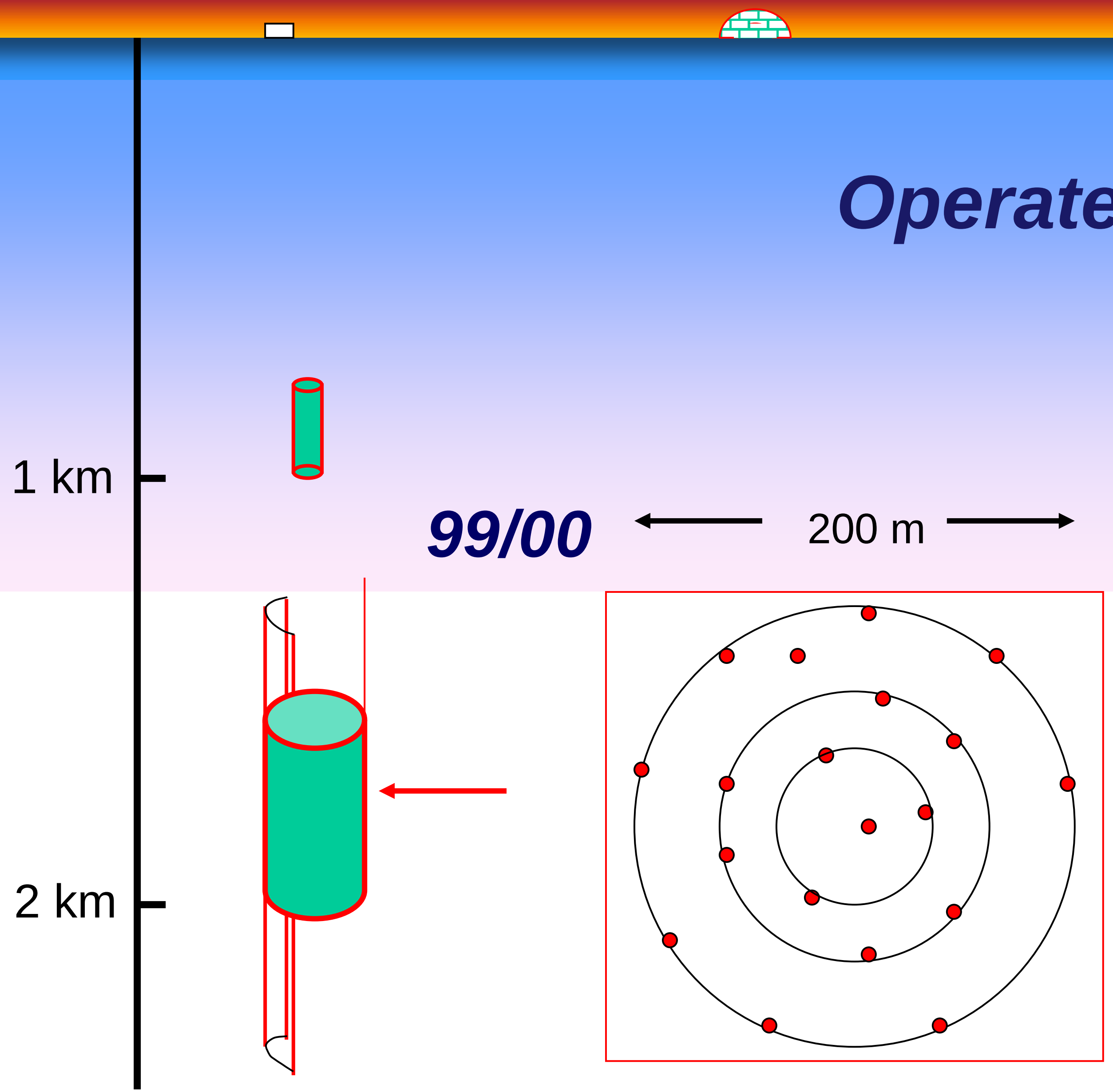


Scattering coefficient (1/m) vs. depth

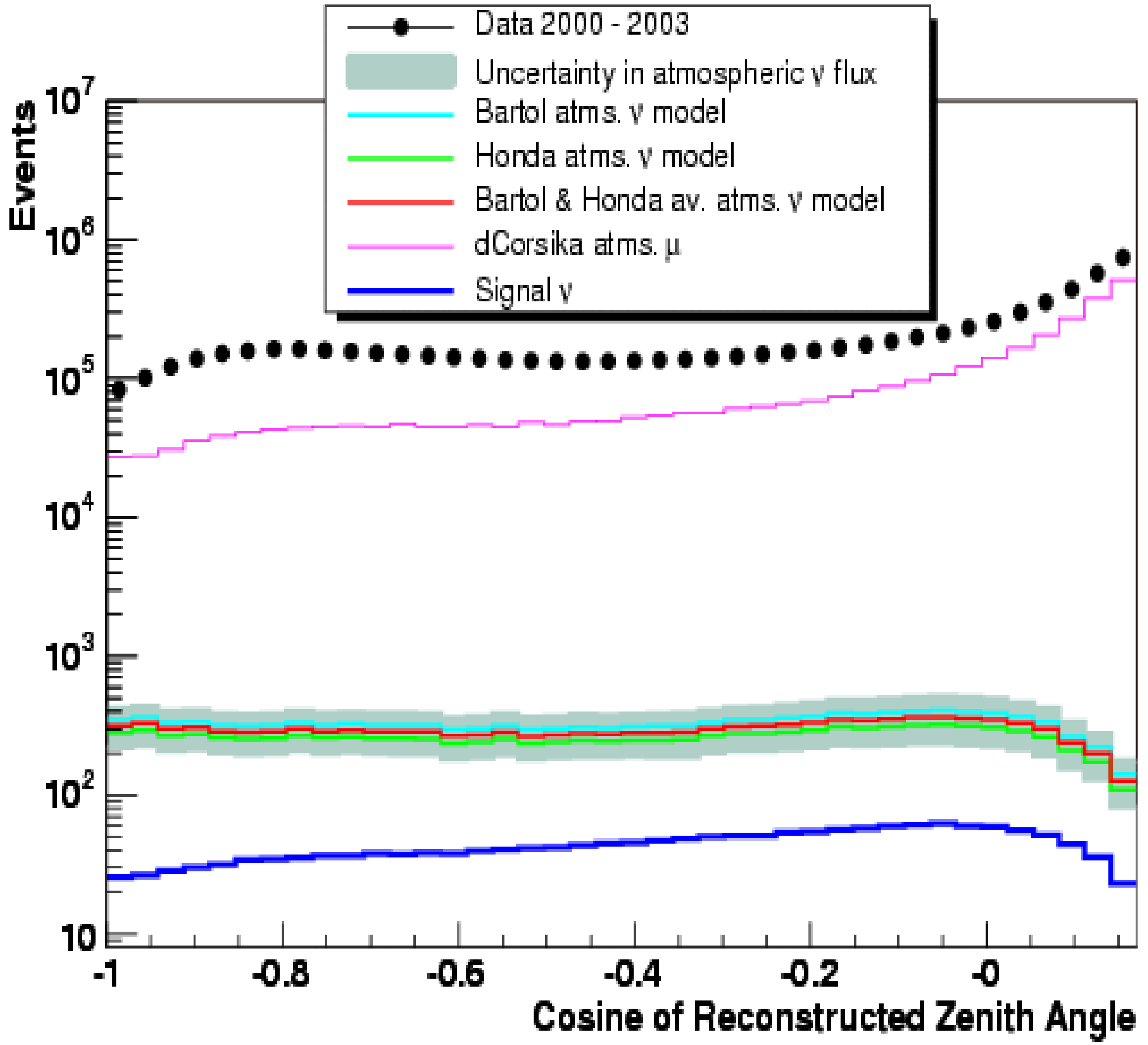


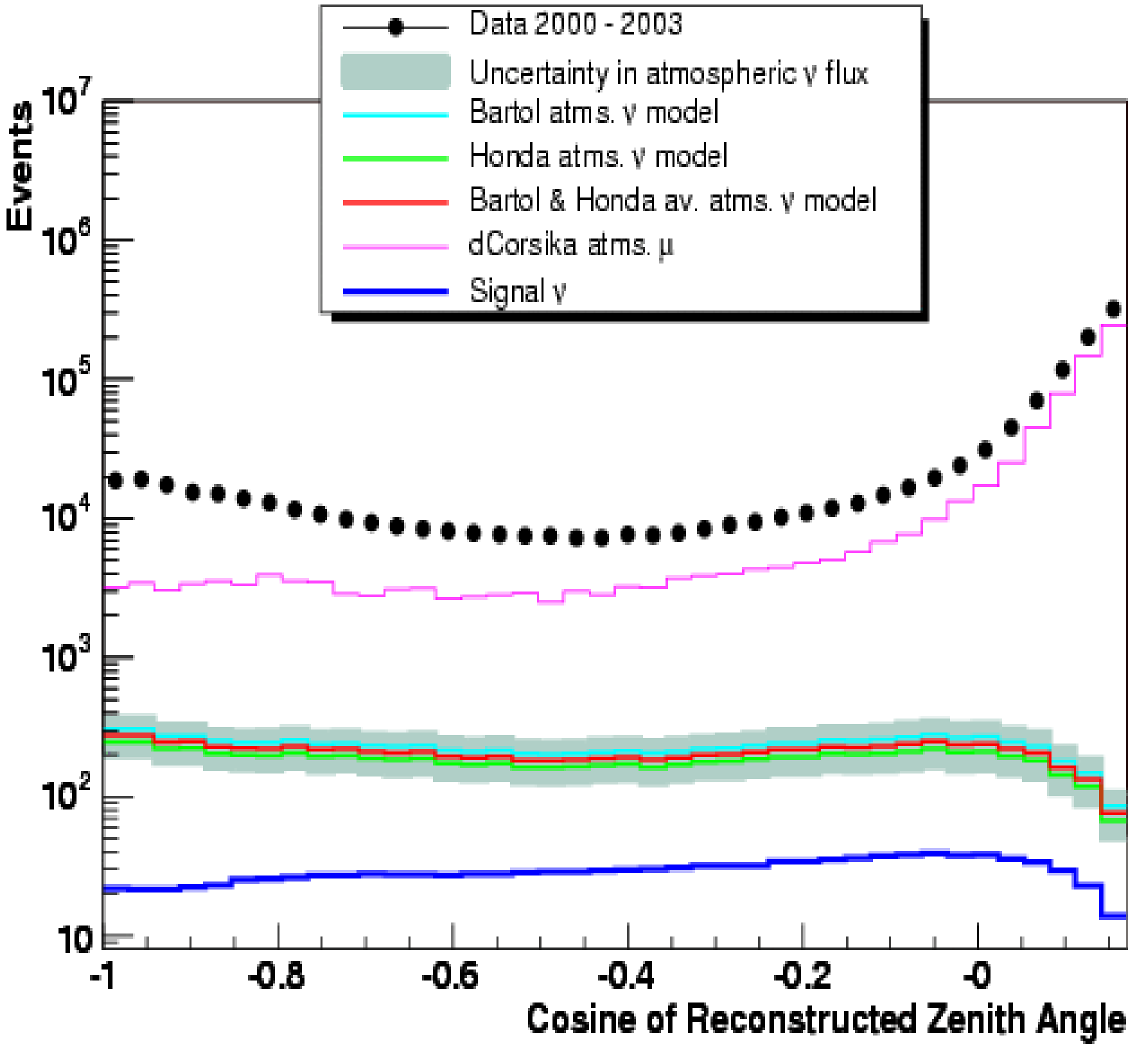
AMANDA II

Operated until 2009

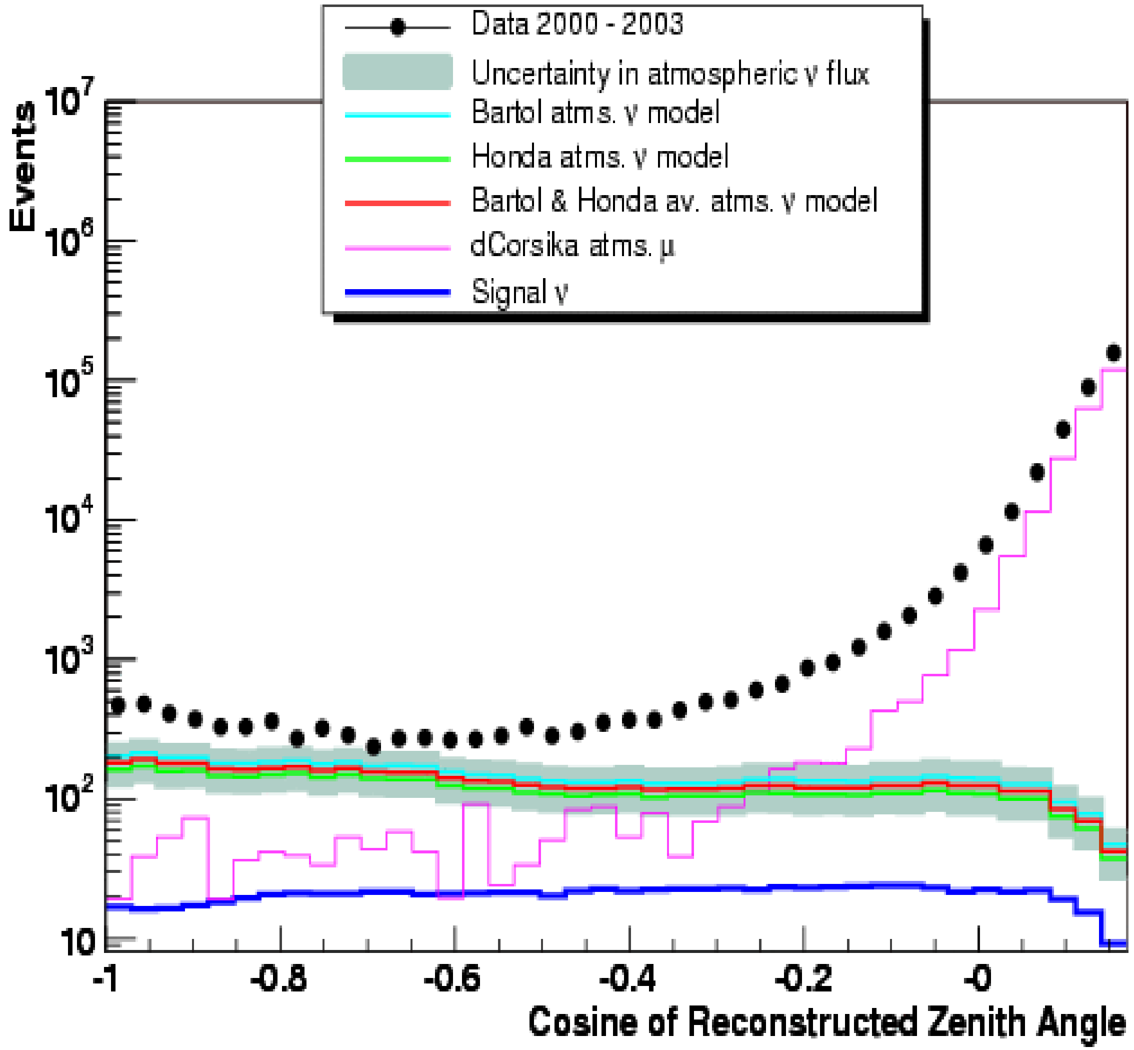


Removal of misreconstructed atmospheric muons by tightening event selection criteria (AMANDA-II)

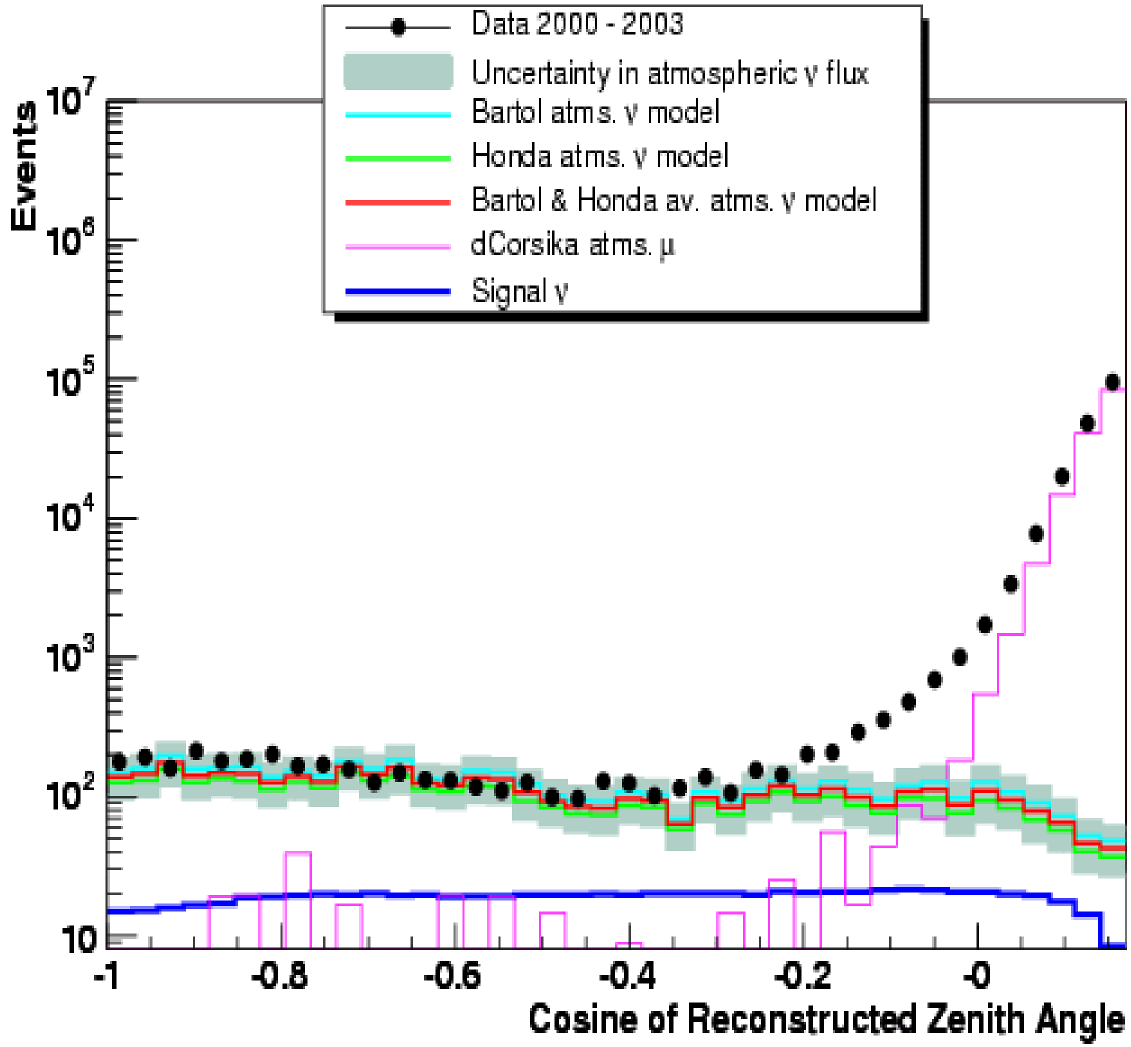




Data 2000 - 2003
Uncertainty in atmospheric ν flux
Bartol atms. ν model
Honda atms. ν model
Bartol & Honda av. atms. ν model
dCorsika atms. μ
Signal ν
Events
10^7
10^6
10^5
10^4
10^3
10^2
10
-1
-0.8
-0.6
-0.4
-0.2
-0
Cosine of Reconstructed Zenith Angle



Data 2000 - 2003
Uncertainty in atmospheric ν flux
Bartol atms. ν model
Honda atms. ν model
Bartol & Honda av. atms. ν model
dCorsika atms. μ
Signal ν
Events
10
10²
10³
10⁴
10⁵
10⁶
10⁷
-1
-0.8
-0.6
-0.4
-0.2
-0
Cosine of Reconstructed Zenith Angle



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Signal ν
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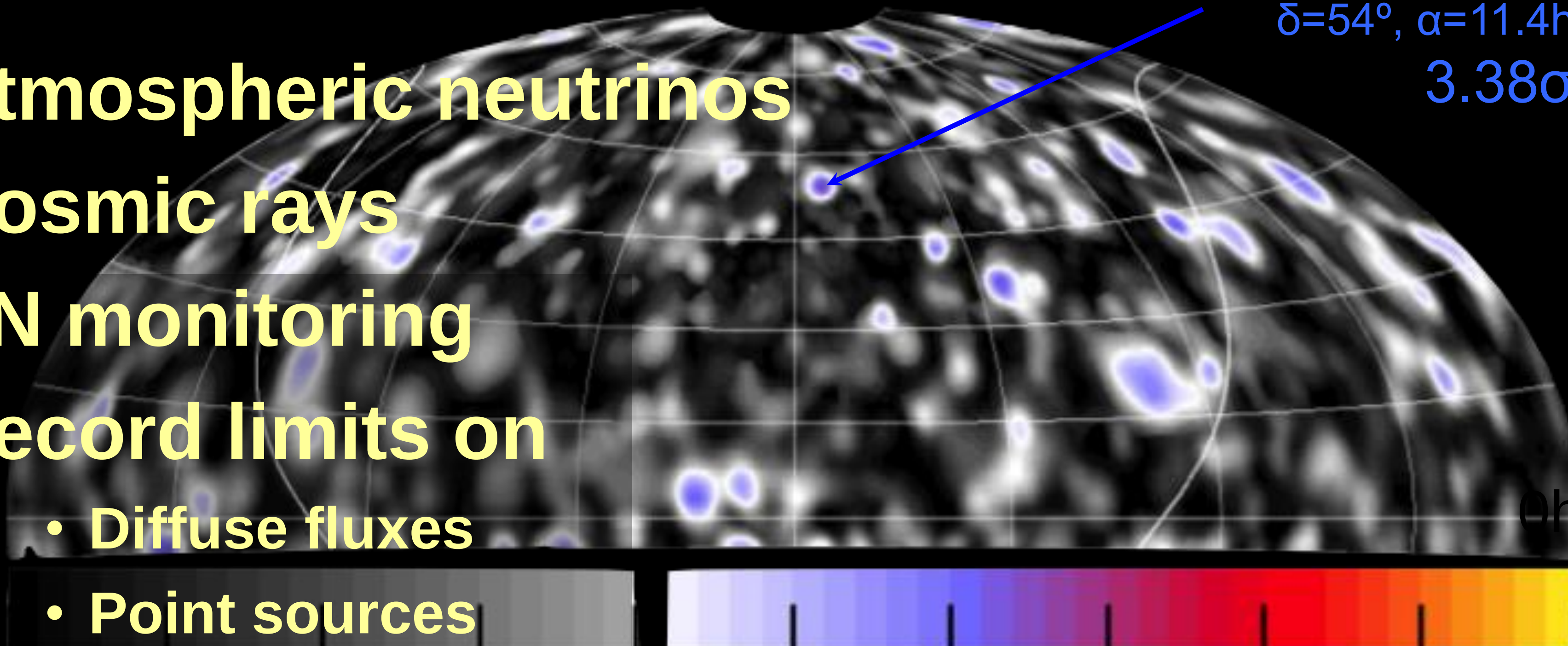
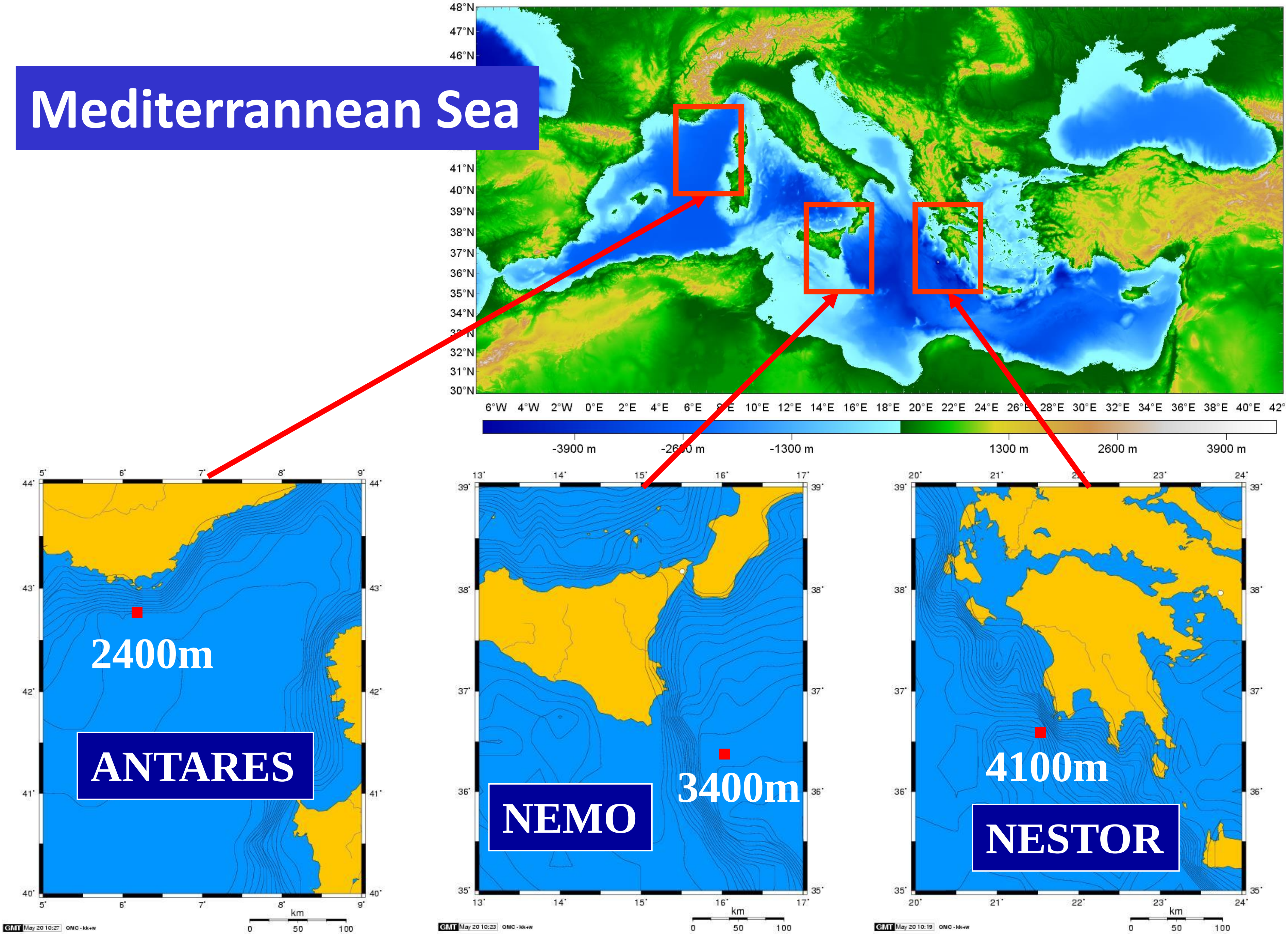
10⁶
10⁷
-1
-0.8
-0.6
-0.4
-0.2
-0
Cosine of Reconstructed Zenith Angle

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)



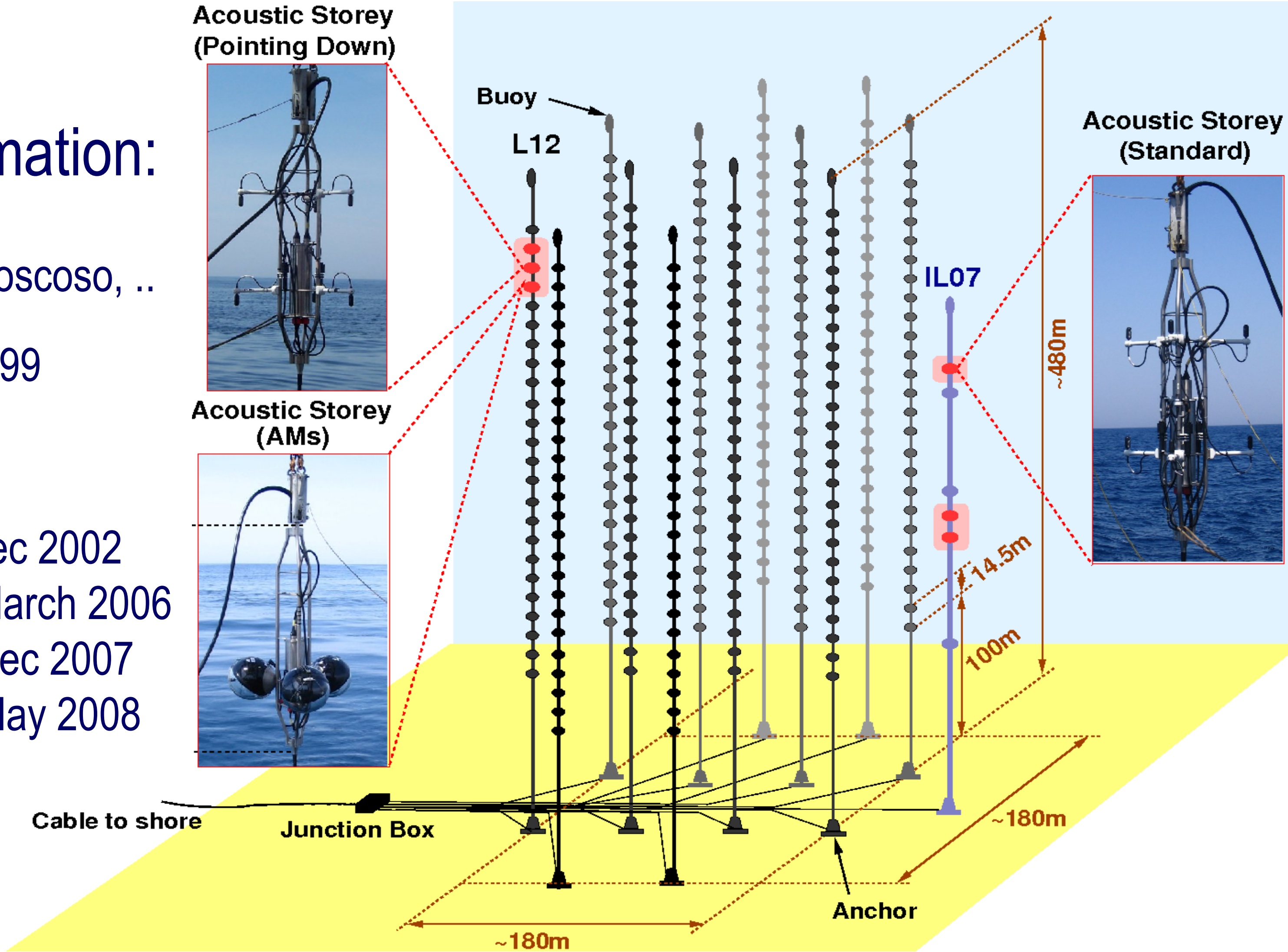
Mediterrannean Sea
-3900 m
-2600 m
-1300 m
1300 m
2600 m
3900 m
2400m
ANTARES
NEMO
3400m
4100m
NESTOR

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:** many ocean tests, lab& infrastructure
- **2000:**
  cable to site
- **2004**:
  deploy first floor. Cable failure after a few weeks

ANTARES



Collab. Formation:

mid 1990s

JJ. Aubert, L.Moscoso, ..

Proposal: 1999

Installation:

Junction Box - Dec 2002

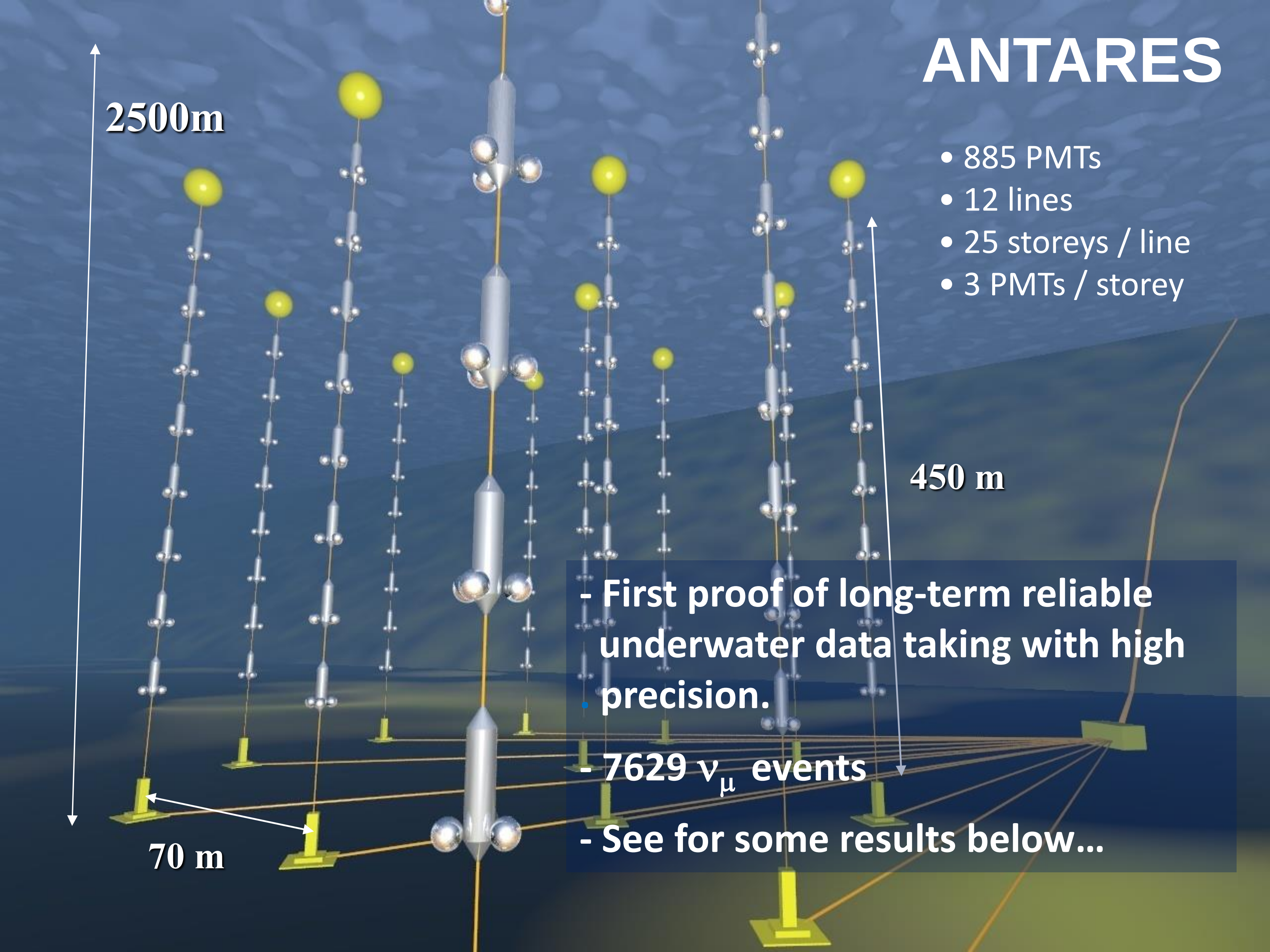
Line 1 - March 2006

Line 5-1 - Dec 2007

Line 11-12 - May 2008

ANTARES

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

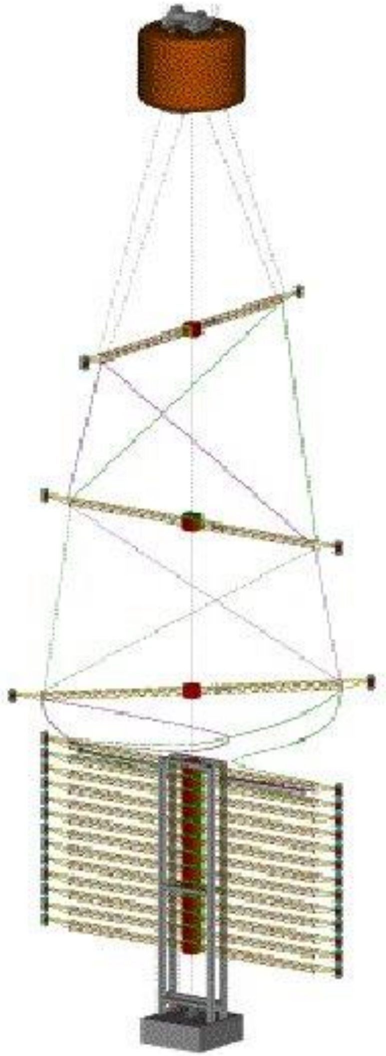


- First proof of long-term reliable underwater data taking with high precision.

- 7629 ν_μ events

- See for some results below…

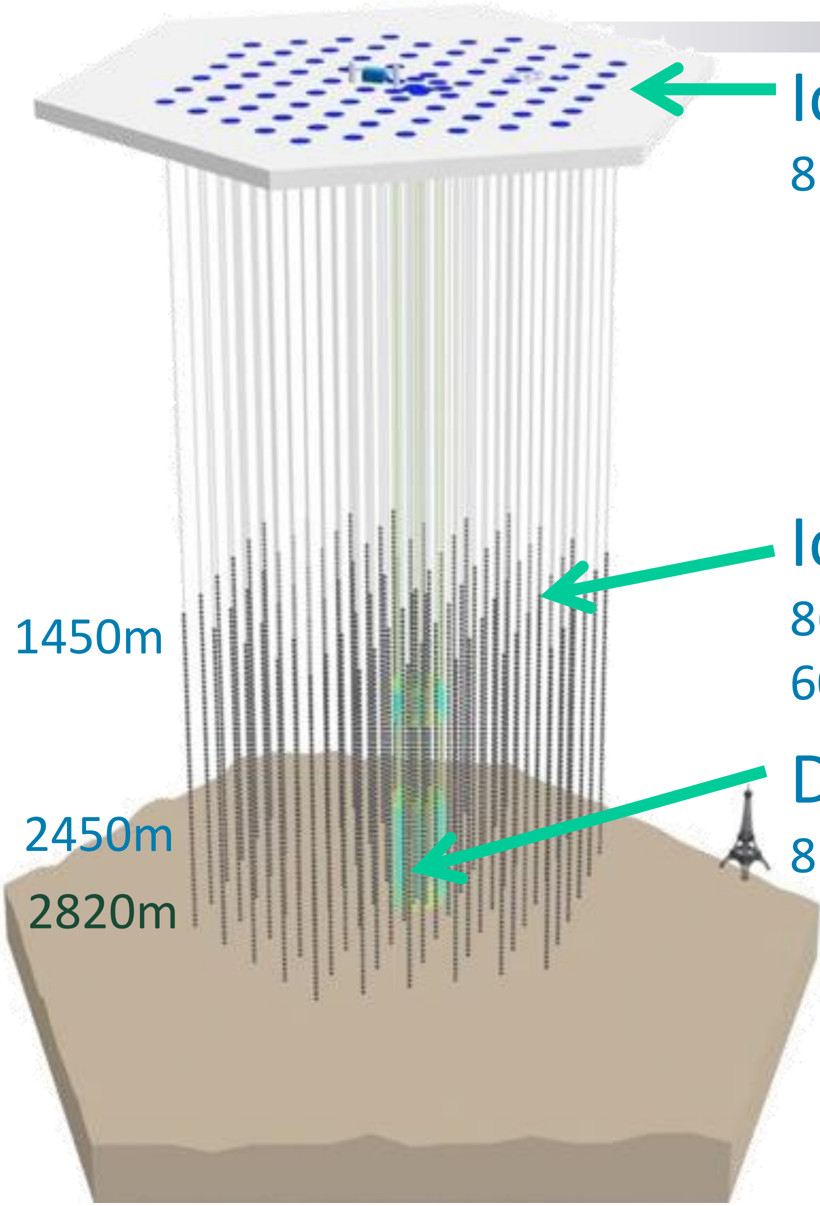
NEMO R&D for KM3NeT



- A. Capone, E. Migneco,
- Tower concept
- First campaign 1998

- 4-floor tower 2006
- full tower end 2009
- Further deployments in the context of KM3NeT

IceCube Neutrino Observatory

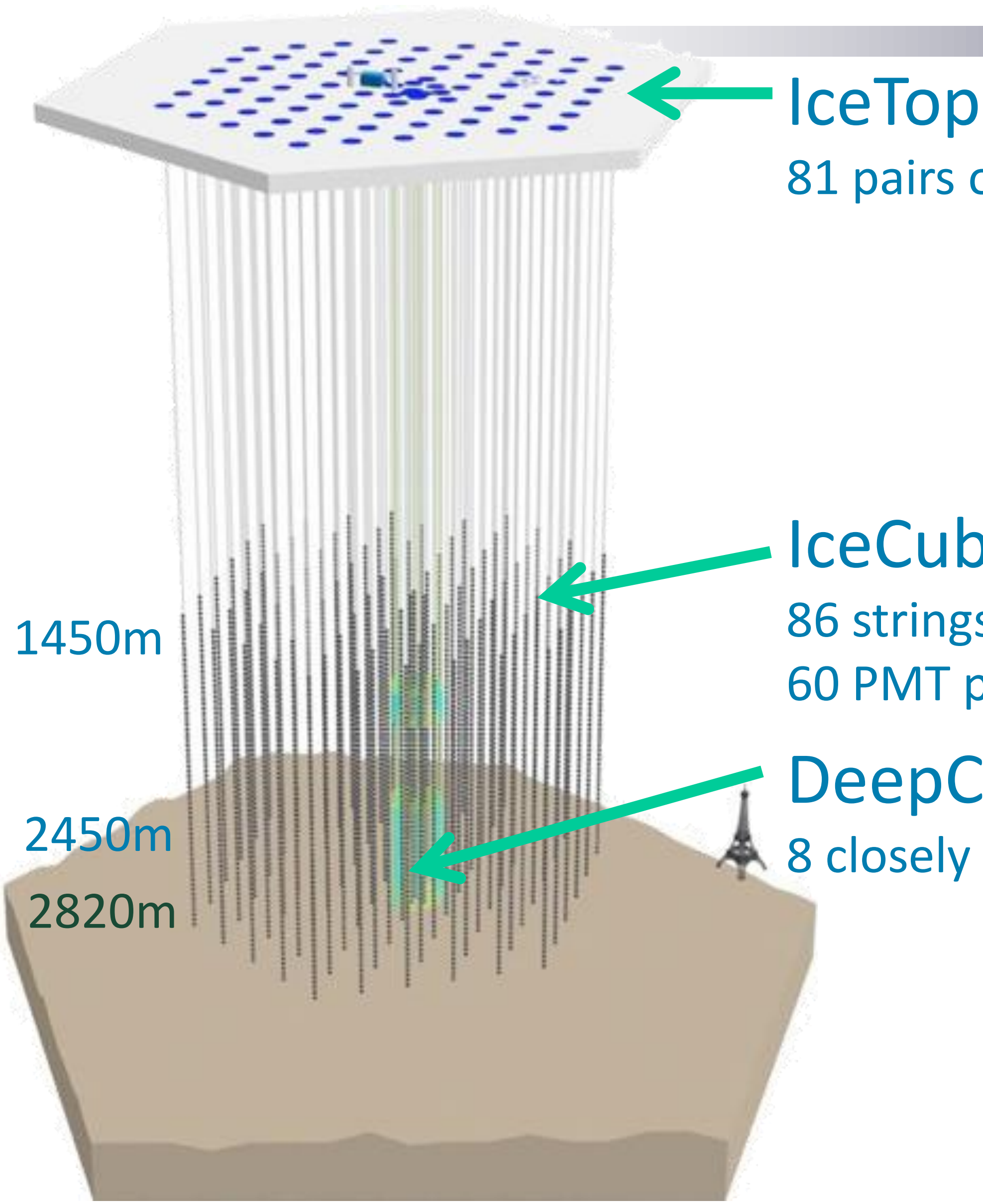


IceTop air shower detector
81 pairs of water Cherenkov tanks

IceCube
86 strings including 8 Deep Core strings
60 PMT per string

DeepCore
8 closely spaced strings

IceCube Neutrino Observatory



- First proposal 1999
- Start construction 2004
- Last (86^{th}) string 2010

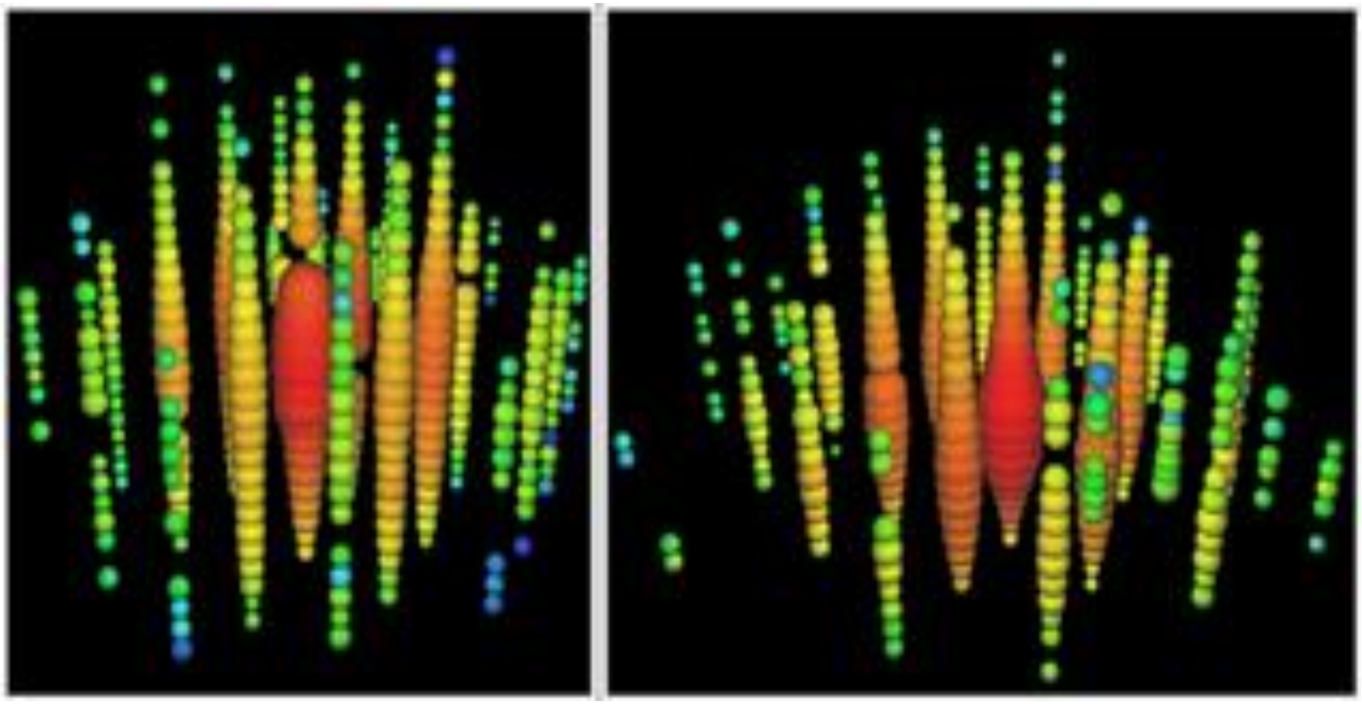
Uptime ~ 99.5%

DOM failure ~ 1/year

~10^5 Neutrinos/year

PHYSICS WITH ICECUBE AND ANTARES: WHERE DO WE STAND?

Ernie and Bert

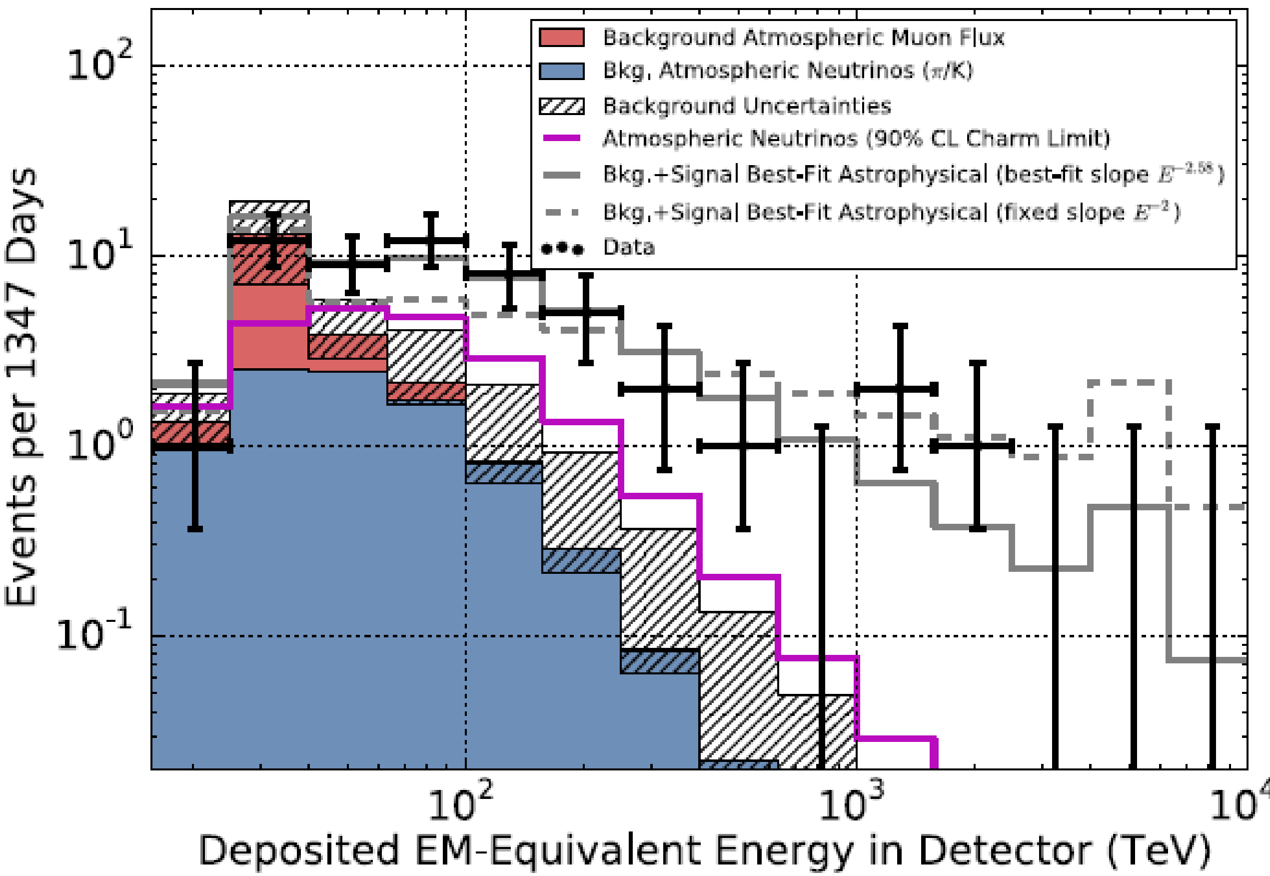


"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

From Ernie & Bert to HESE (High Energy Starting Event)

First evidence for an extra-terrestrial h.e. neutrino flux

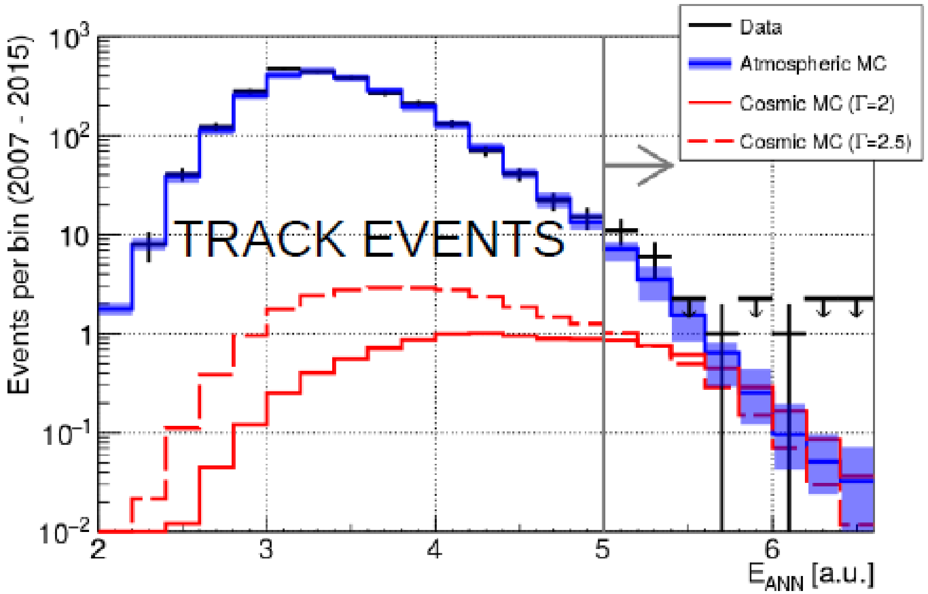


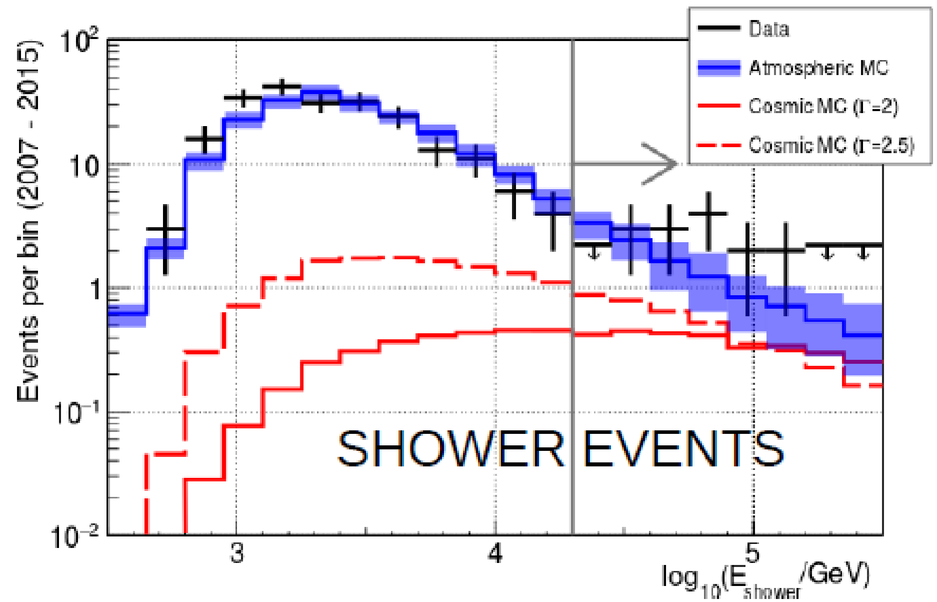
2 yrs data, 28 evts 4.1σ
Science 342 (2013)

3 yrs data, 37 evts 5.9σ
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts 6.7σ

Diffuse flux in ANTARES, 2018



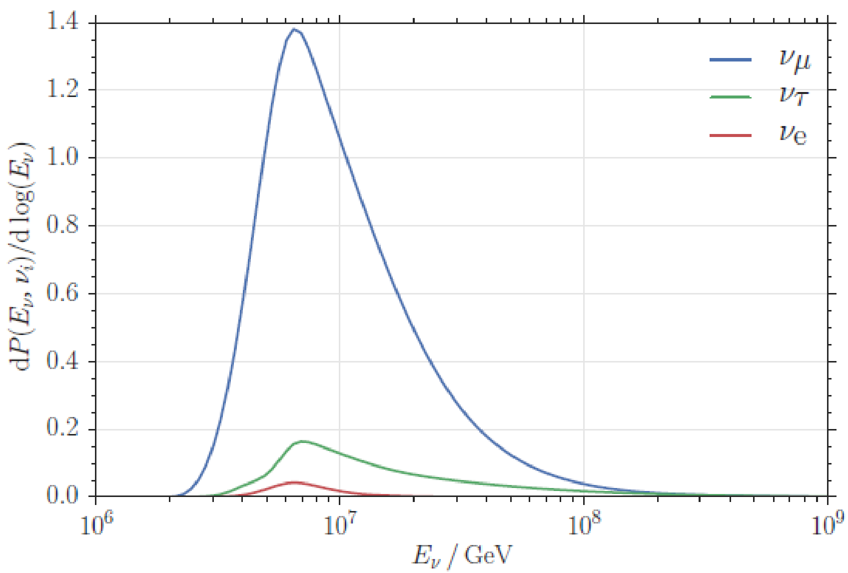


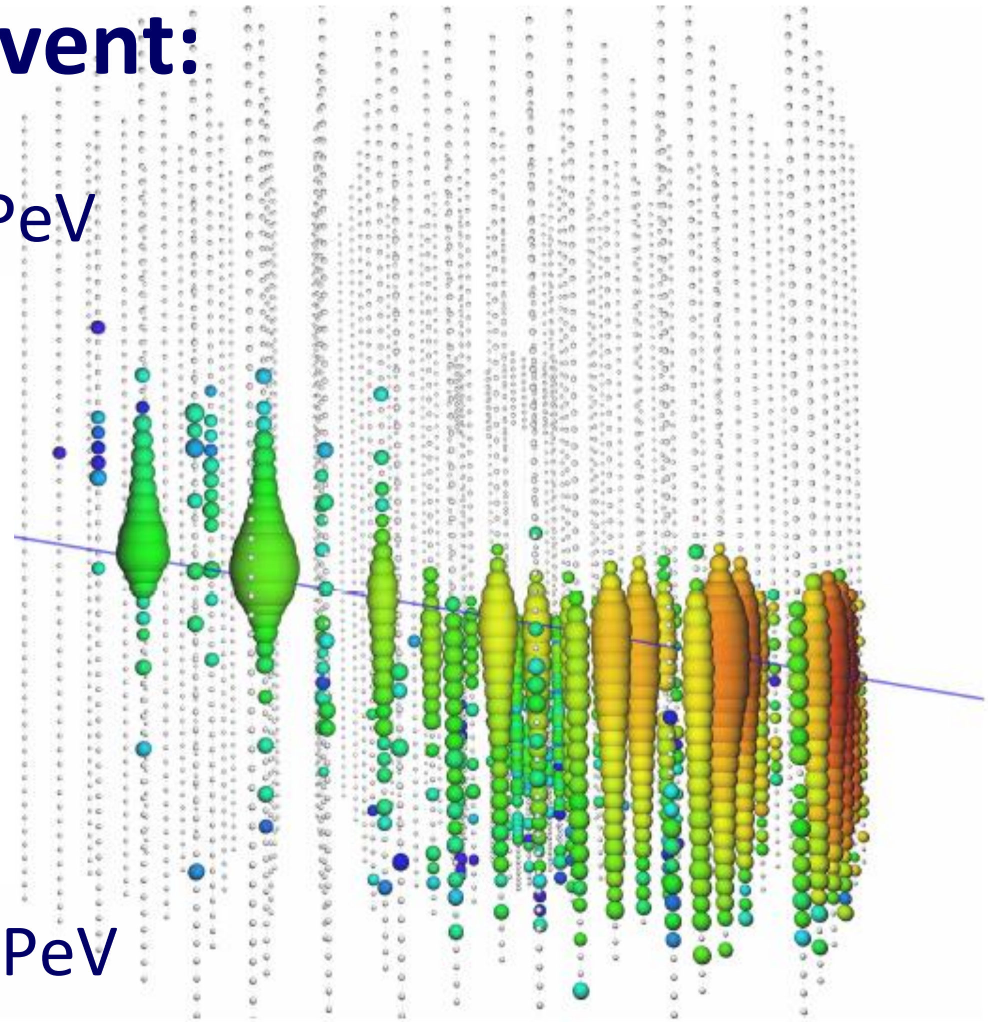
1.6σ excess **(in agreement with IceCube flux)**

Through-going muons

The highest-energy event:

Deposited energy 2.6±0.3 PeV

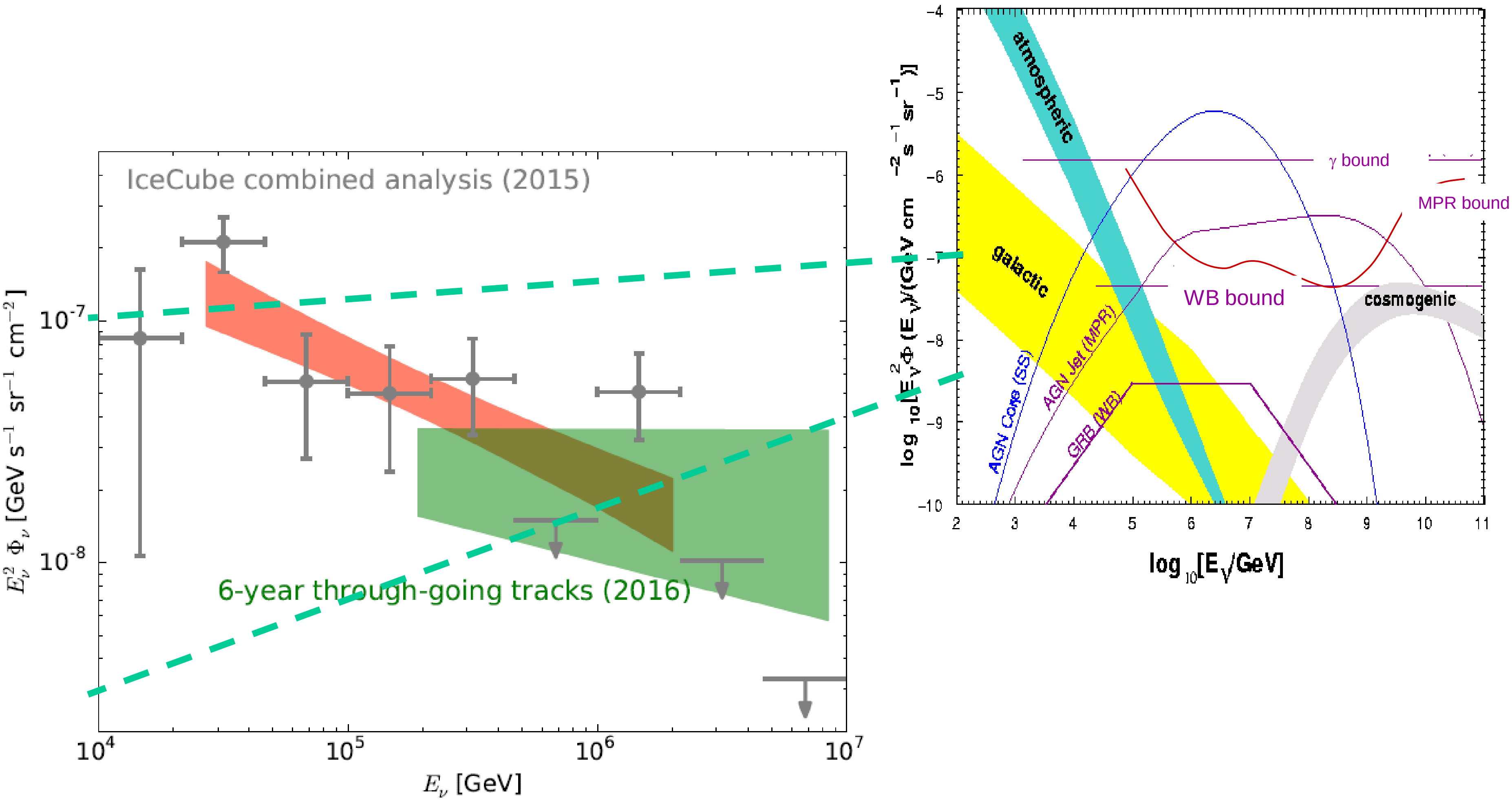




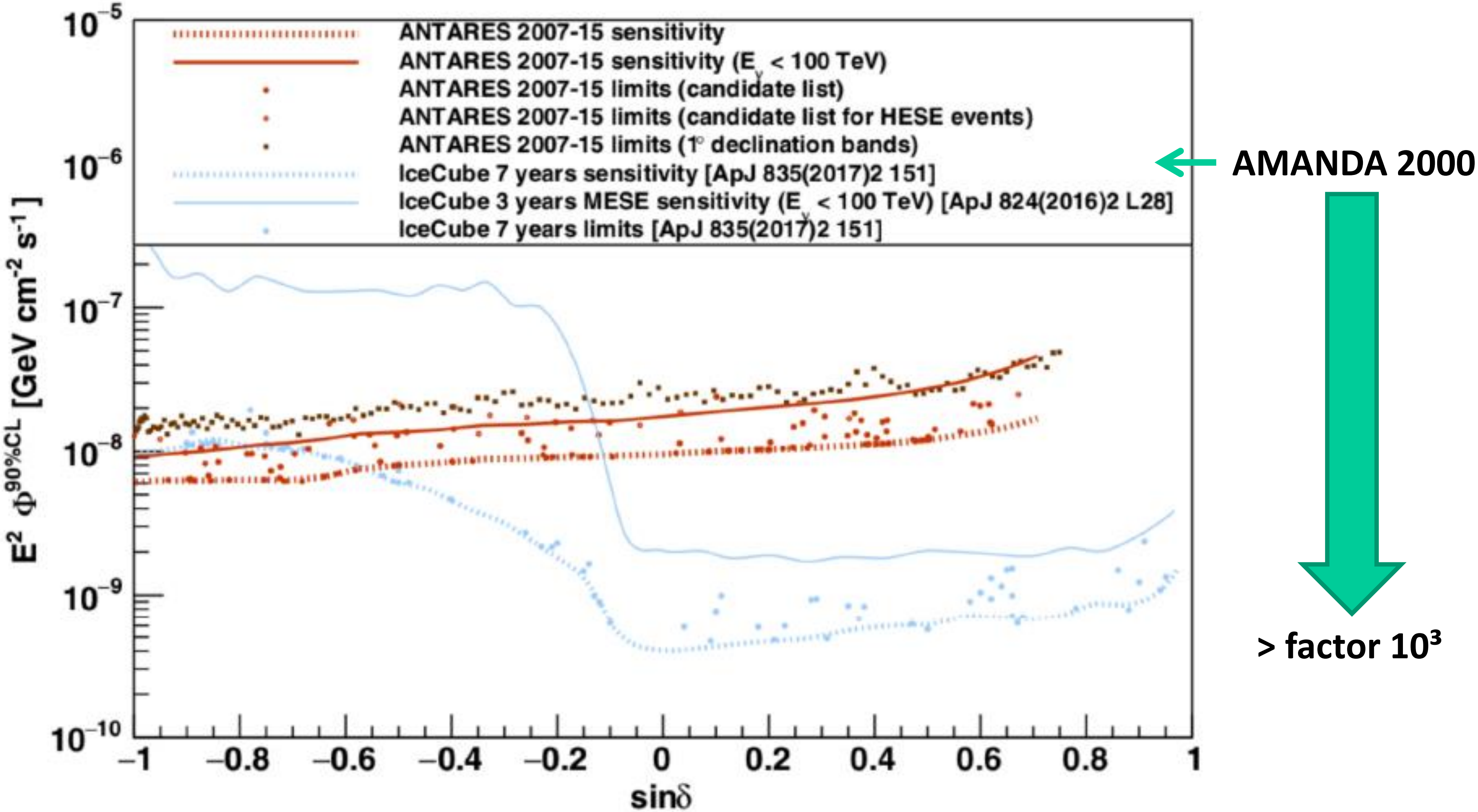
Most probable ν energy ~7 PeV

(for E^{-2} assumption)

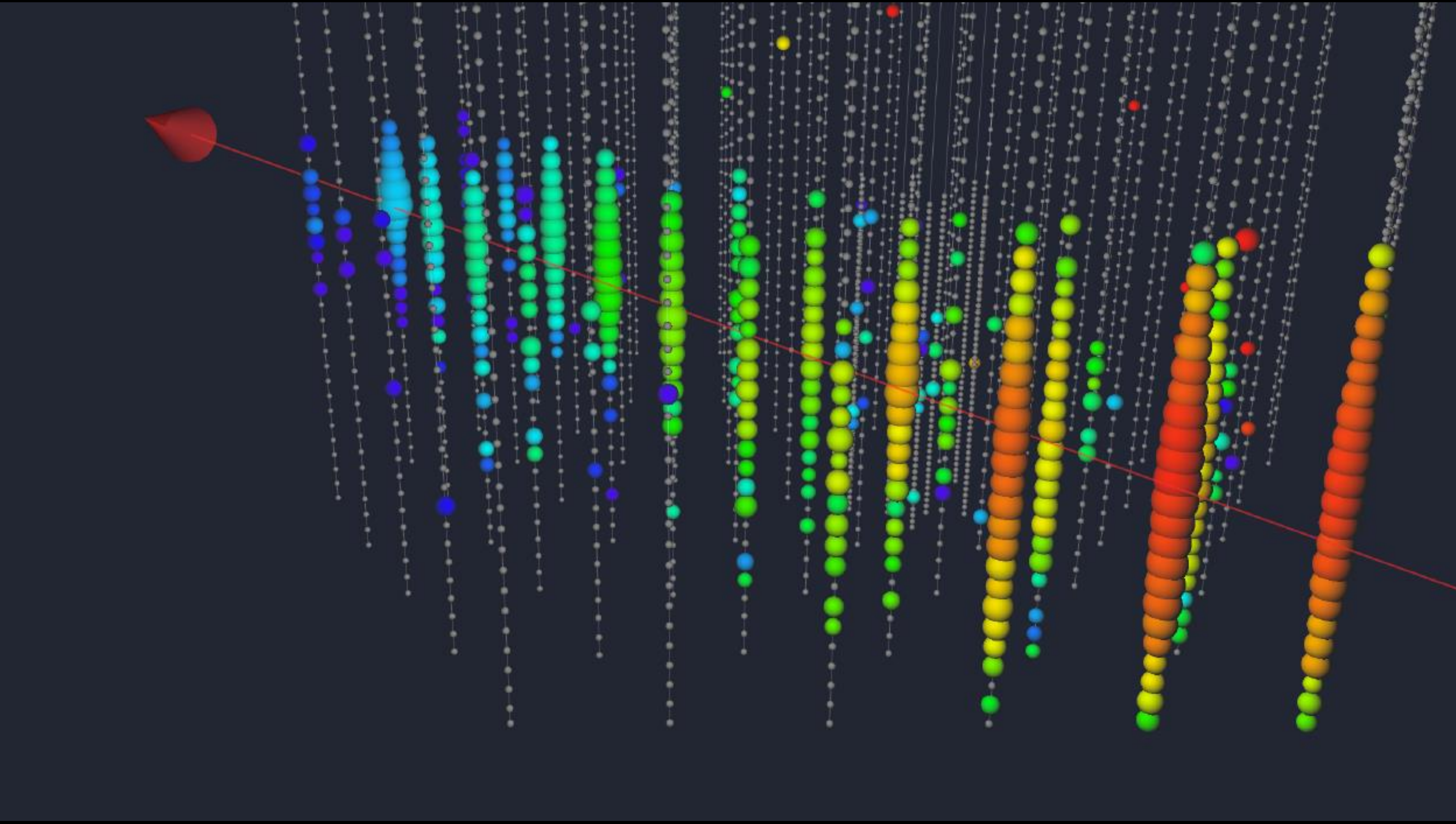
Measured fluxes compared to bounds

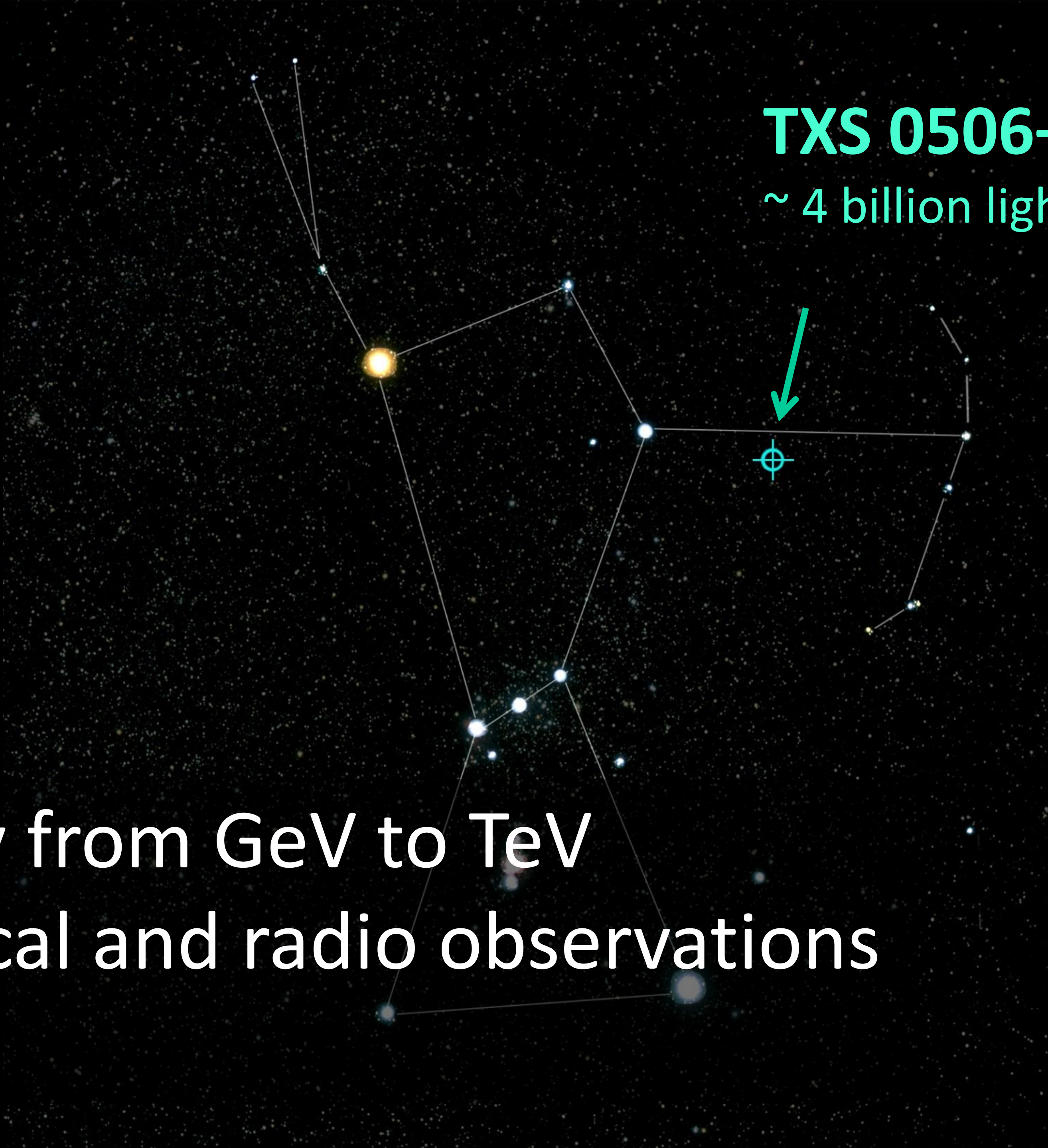


Search for steady point sources (2017)



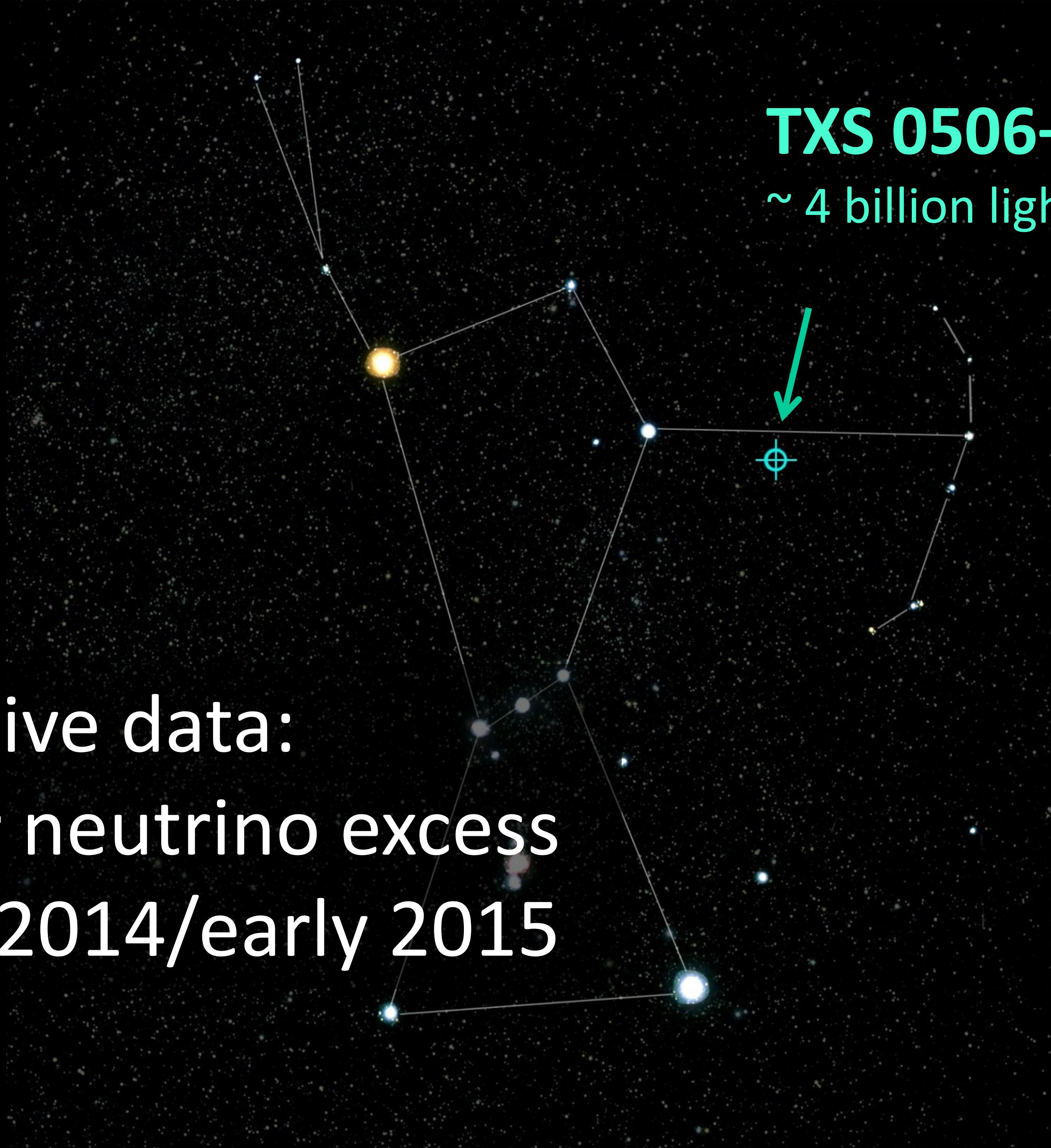
22. September 2017, 20:54 UTC





γ-ray from GeV to TeV

optical and radio observations



Archive data:
3.5σ neutrino excess
end 2014/early 2015

Conclusions:

- Technological challenges: tremendous
- Flux predictions: from uncertain to low
- Long and thorny march (not without fun)!
  - 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
  - > 2014: alert/multimessenger program of ANTARES and IceCube
  - 2018: evidence of a first individual transient source
- Next steps: Baikal-GVD, KM3NeT, IceCube-Gen2