

# THE BAIKAL NEUTRINO PROJECT: PRESENT AND PERSPECTIVE



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for the Baikal Collaboration  
Vienna, February 19, 2010

# Baikal Collaboration

- Institute for Nuclear Research RAS, Moscow,
- Irkutsk State University, Irkutsk
- Skobeltsyn Institute of Nuclear Physics MSU, Moscow,
- DESY – Zeuthen, Zeuthen
- Joint Institute for Nuclear Research, Dubna,
- Nizhny Novgorod State Technical University,
- St.Petersburg State Marine University,
- Kurchatov Institute, Moscow.

# **OUTLINE**

## **Introduction**

### **Present Neutrino telescope NT200 (NT200+)**

Design

Selected Physics Results

### **Future Gigaton-Volume Detector GVD in lake Baikal**

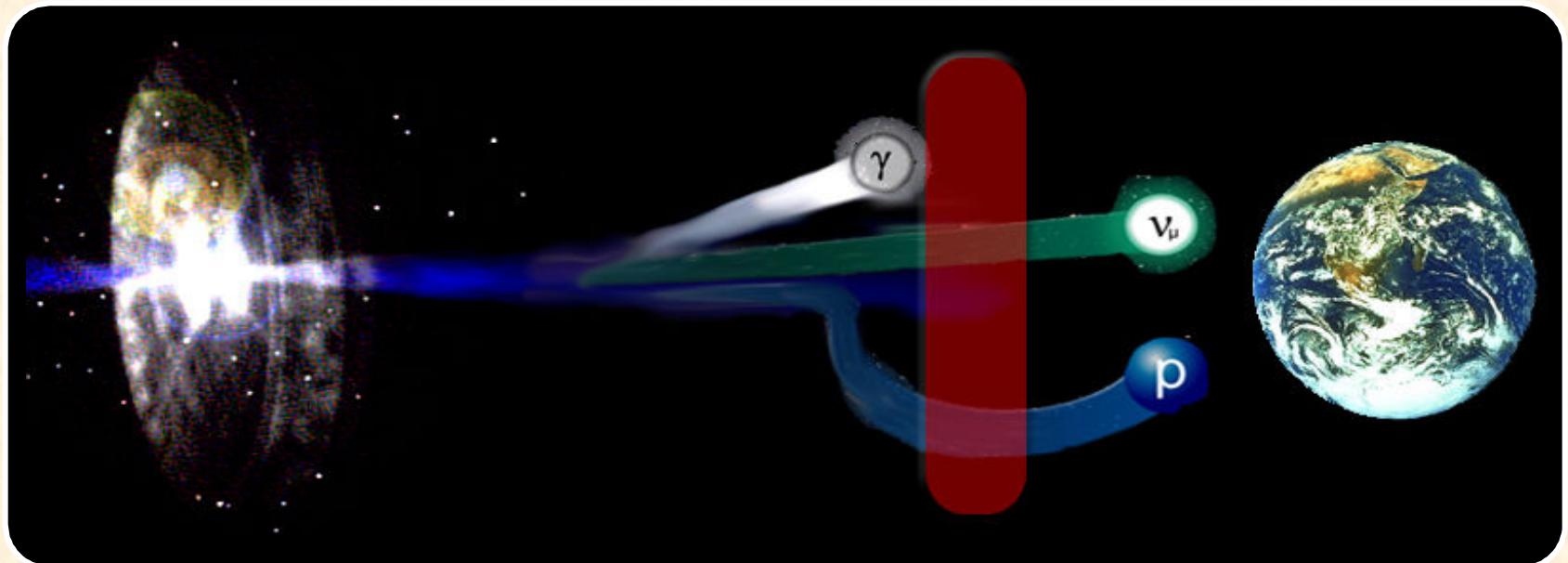
Preliminary Design

Prototype string for BAIKAL-GVD detector (2009)

## **Acoustic activity**

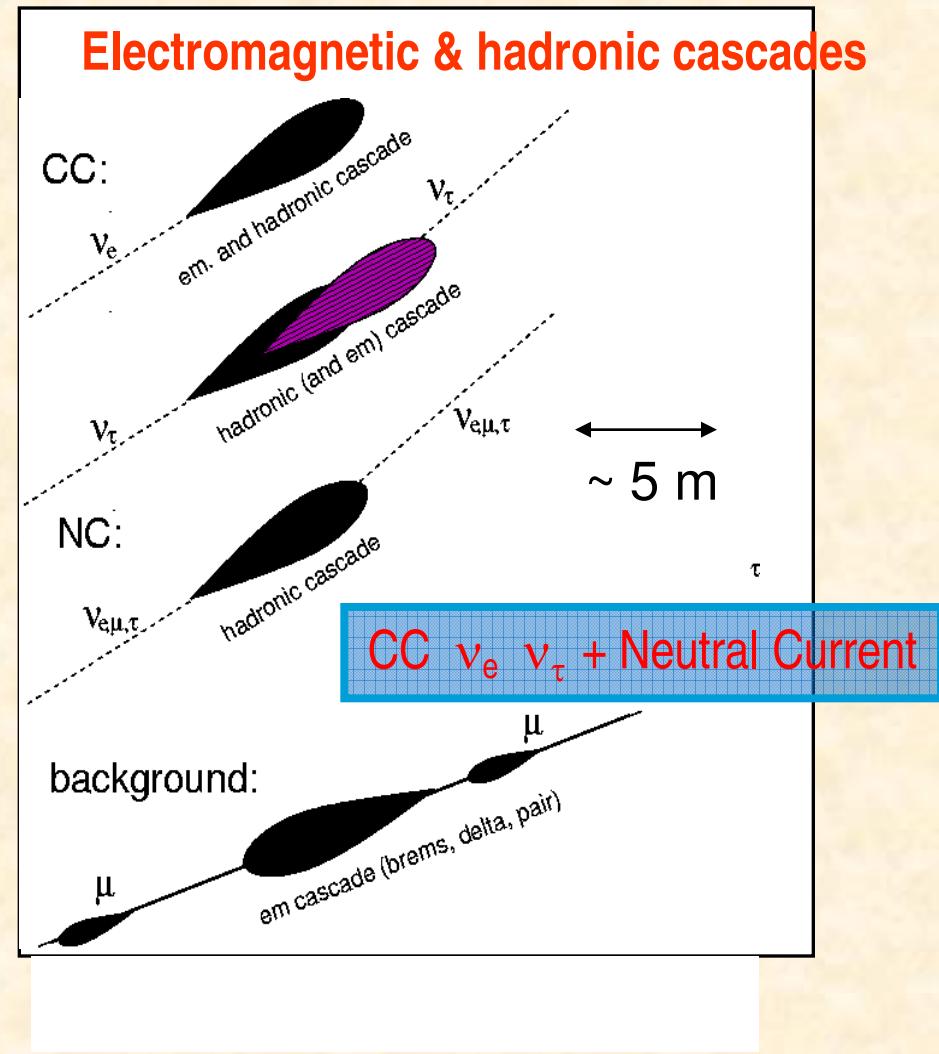
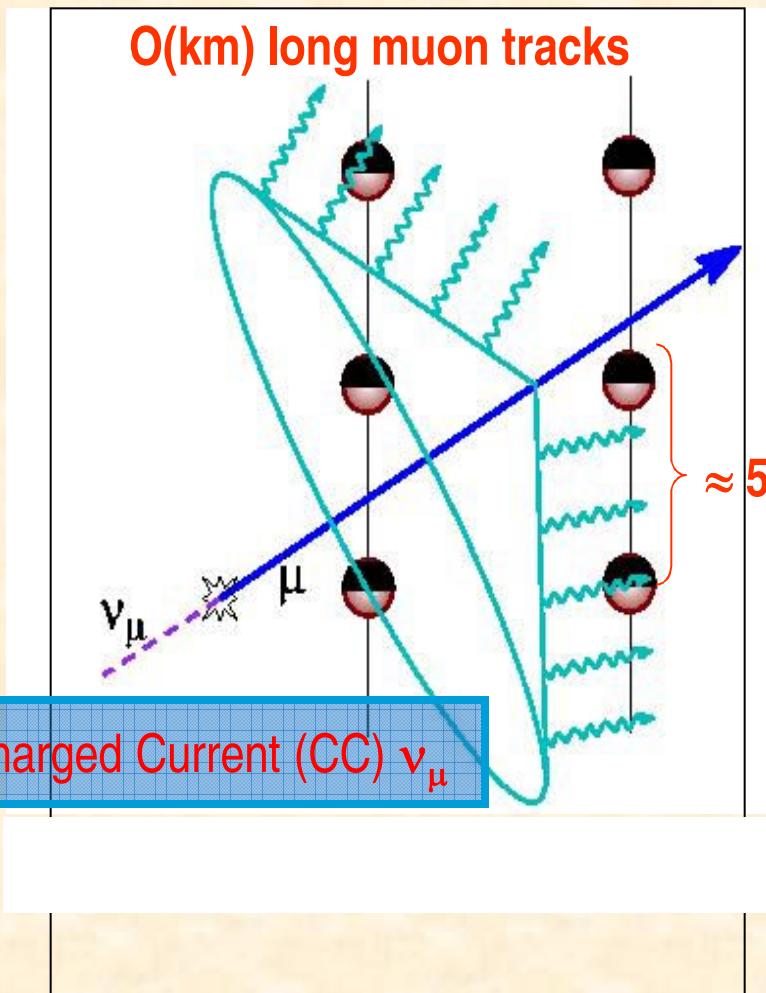
## **Summary**

# Neutrino – as messengers from the Universe



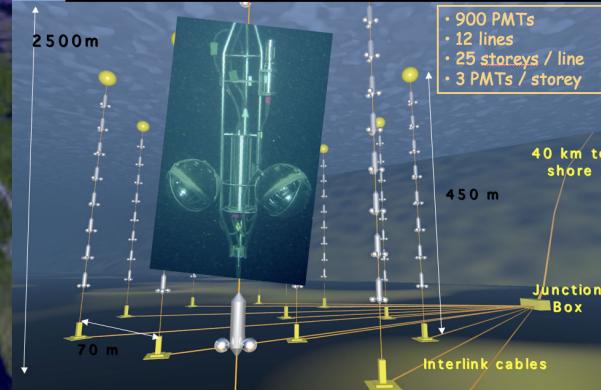
- Neutrinos open up a “new window on the Universe”
  - *Photons are absorbed in interactions with the interstellar medium*
  - Charged particles may be deviated in (extra-)galactic magnetic fields - loss of information on astrophysical source
- ***Neutrino form a powerful probe of the Universe even at large redshifts***

# 1960 - M. Markov: High Energy neutrino detection in natural transparent media (ocean water, ice):

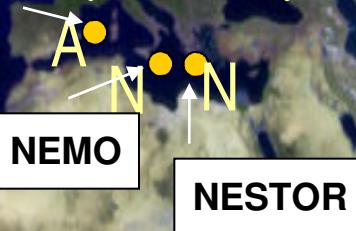




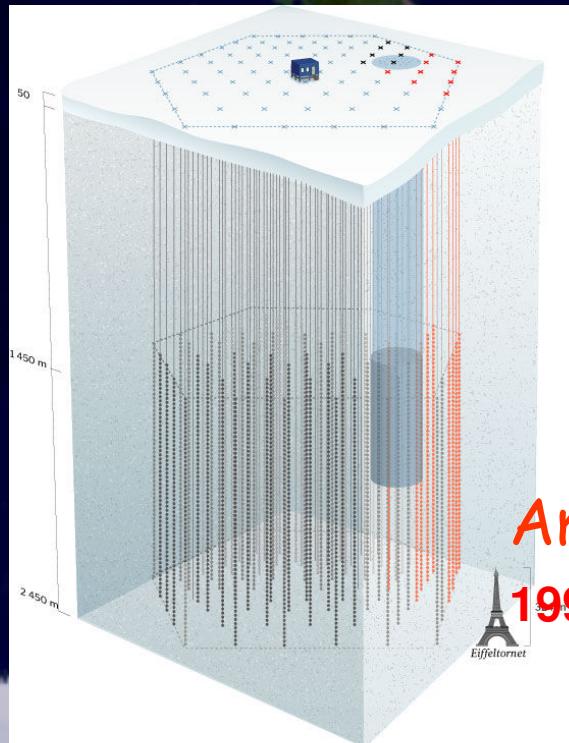
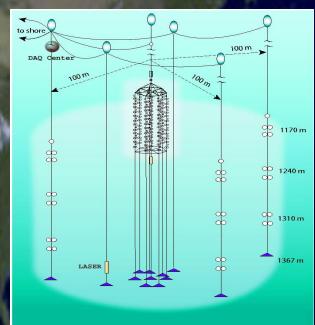
The ANTARES detector



KM3NeT  
(~2014)



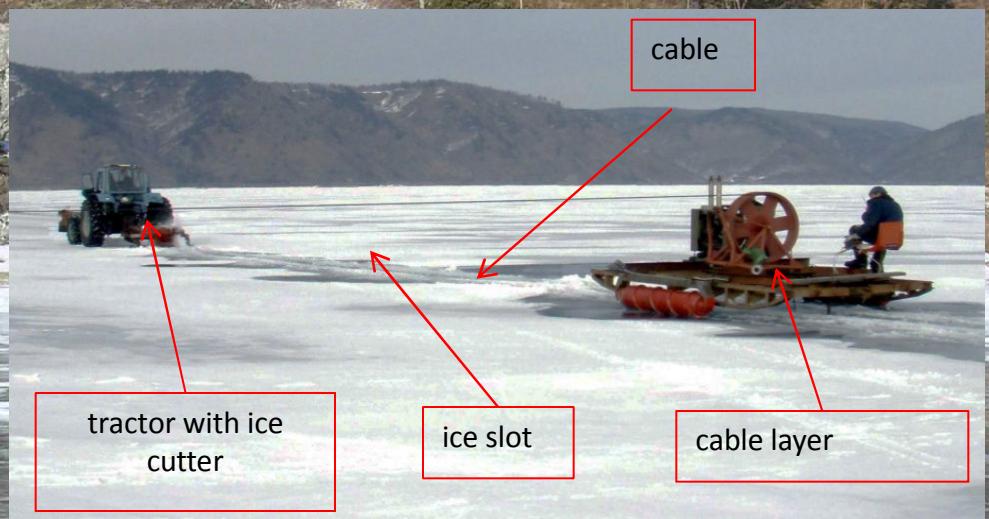
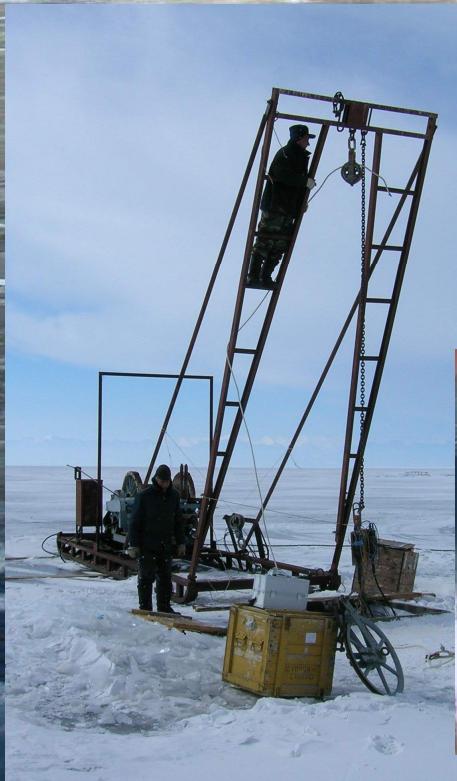
NT200+/Baikal-GVD  
1993-1998 (~2017)



Amanda/IceCube  
1996-2000 (~2011)

© 1990 Tom Van Sant, Inc. / The GeoSphere Project  
Santa Monica, California

# Ice as a natural deployment platform



*Shore cable mounting*

*Deployment with winches*

# Baikal - Milestones

**Since 1980** Site tests and early R&D started

**1990** Technical Design Report NT200

**1993** NT36 started:  
- the first underwater array  
- the first neutrino events.

**1998** NT200 commissioned: start full physics program.

**2005** NT200+ commissioned (NT200 & 3 outer strings).

**2006** Start R&D for Gigaton Volume Detector (GVD)

**2008** In-situ test GVD electronics: 6 new technology optical modules

**2009** Prototype string for GVD: 12 optical modules

**2011** GVD cluster (3 strings), Technical Design Report

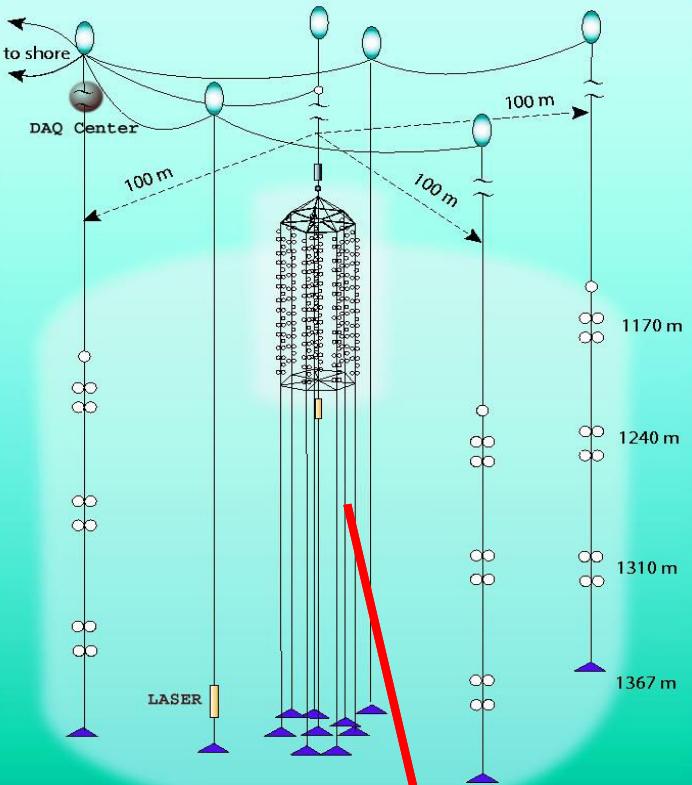


# Status of NT200+

NT200+ is operating now in Baikal lake

Quasar  
photodetector  
( $\varnothing=37\text{cm}$ )

LAKE BAIKAL



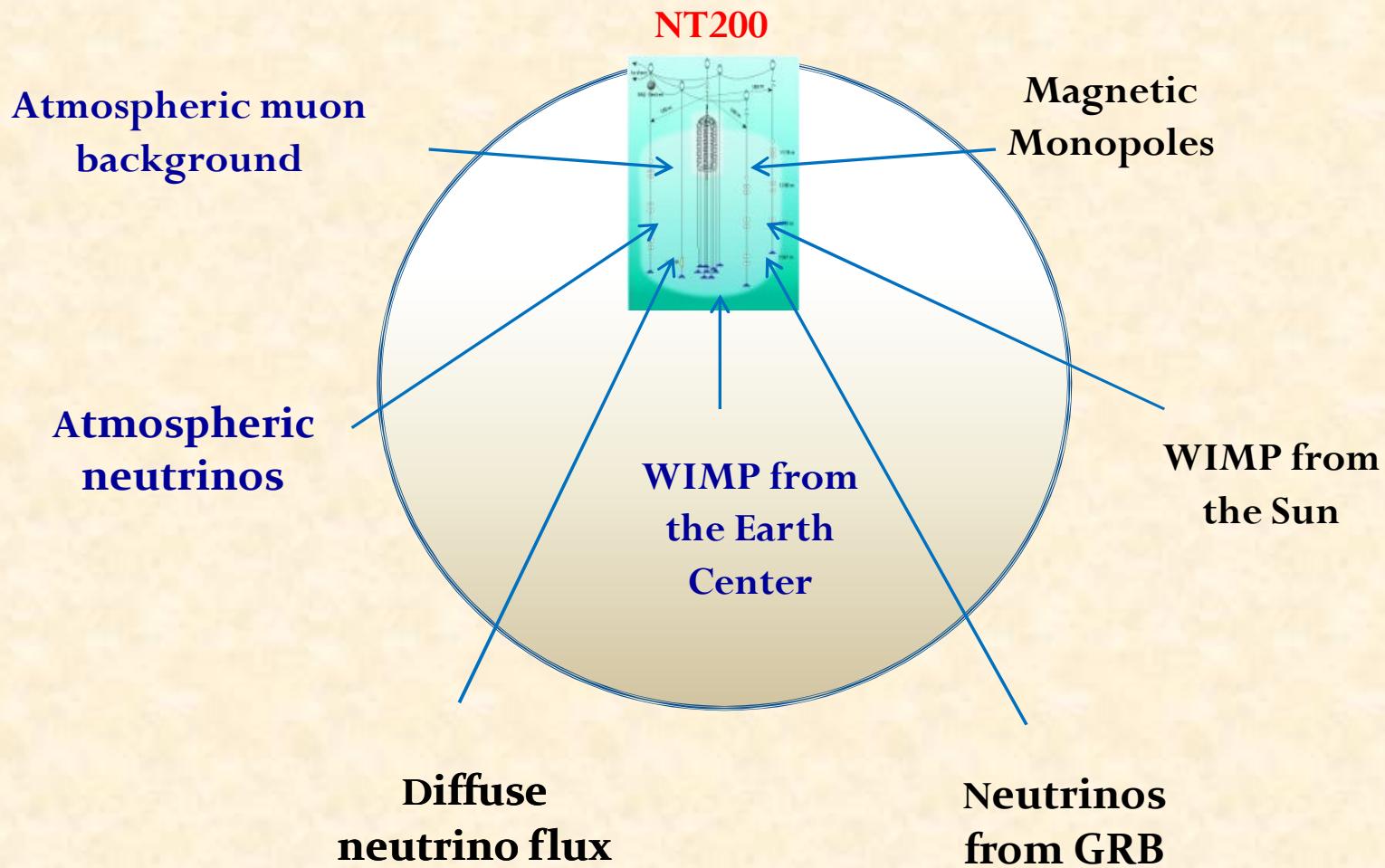
~ 3.6 km to shore,  
1070 m depth

NT200: 8 strings (192 optical modules)  
Height  $\times \varnothing = 70\text{m} \times 42\text{m}$ ,  $V_{\text{inst}} = 10^5\text{m}^3$   
Effective area:  $1\text{TeV} \sim 2000\text{m}^2$   
Eff. shower volume:  $10\text{TeV} \sim 0.2\text{ Mton}$

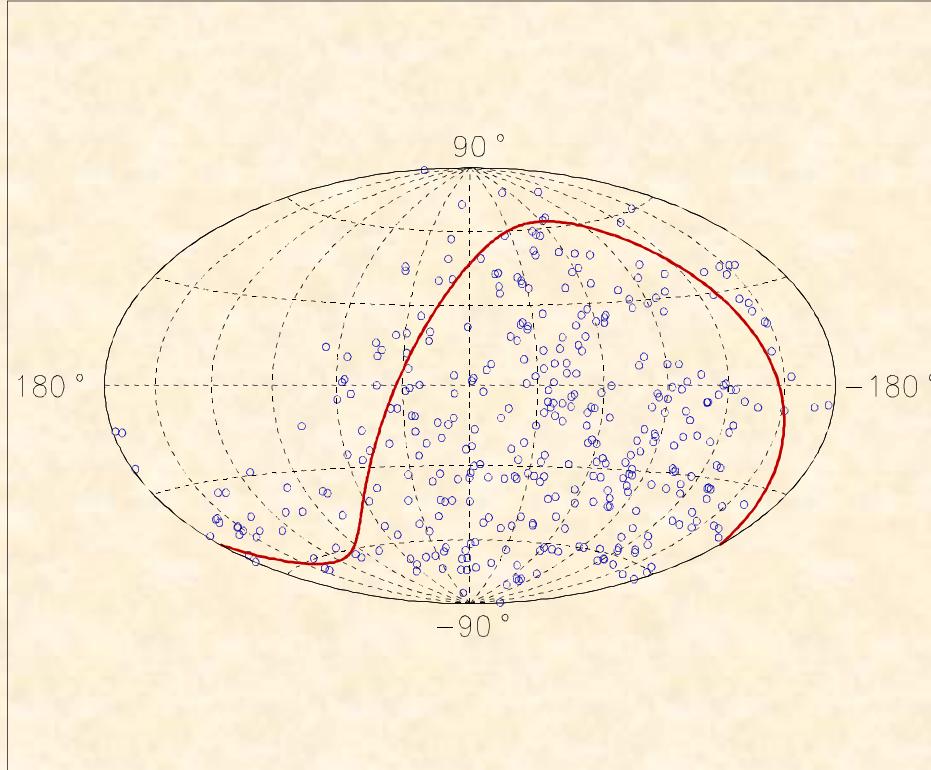
NT200+ = NT200 + 3 outer string (36 optical modules)  
Height  $\times \varnothing = 210\text{m} \times 200\text{m}$ ,  $V_{\text{inst}} = 4 \times 10^6\text{m}^3$   
Eff. shower volume:  $10^4\text{TeV} \sim 10\text{ Mton}$



# The items for NT200



# Atmospheric Muon-Neutrinos



Skyplot of NT200 neutrino events for 5 years  
(galactic coordinates)

**372 Neutrinos in 1038 Days (1998-2003)**

**385 events from Monte-Carlo**

# Diffuse Neutrino Flux Limits + Models

NT200 (1038 days)

no statistically significant excess above the background from atmospheric muons has been observed

The 90% C.L. "all flavour" limit

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

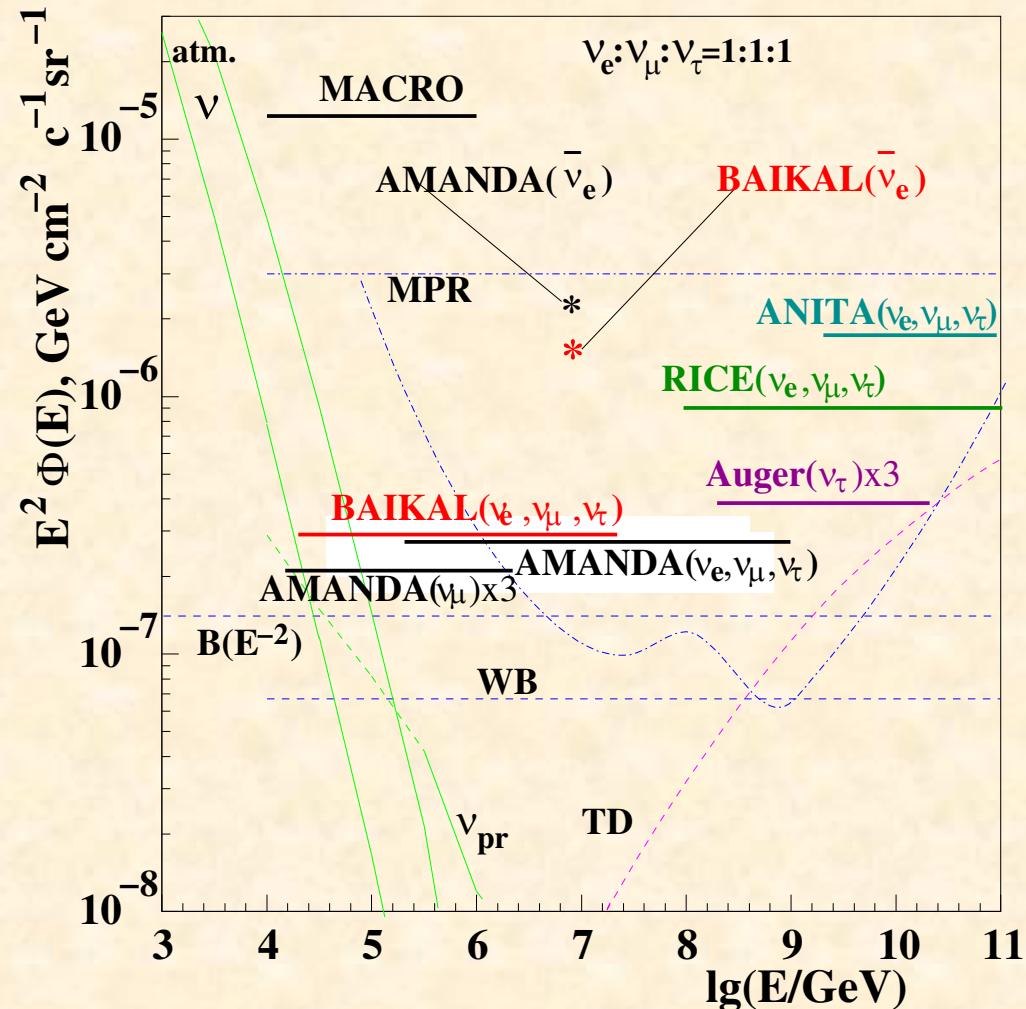
Cut  $E > 10$  TeV for up-going cascades

Cut  $E > 100$  TeV for down-going cascades

$E^2 \Phi_n < 2.9 \cdot 10^{-7}$  GeV cm $^{-2}$  s $^{-1}$  sr $^{-1}$   
(Cascades Baikal, 2008)

$E^2 \Phi_n < 2.2 \cdot 10^{-7}$  GeV cm $^{-2}$  s $^{-1}$  sr $^{-1}$   
(Muons AMANDA-II, 2007)

## Experimental limits + bounds/ predictions



# Search for neutrinos from Gamma-Ray Bursts

## Analysis of time and directional correlations between NT200 events and GRB

### Experimental data

NT200 data from April 1998 to May 2000

GRB data:

- basic BATSE catalog (triggered bursts): 155
- non-triggered GRB: 148

### Signal search:

Time window:  $T_{90} + 10\text{ s}$

Half angle of observation cone:  $\Psi = 5^\circ$

### Background:

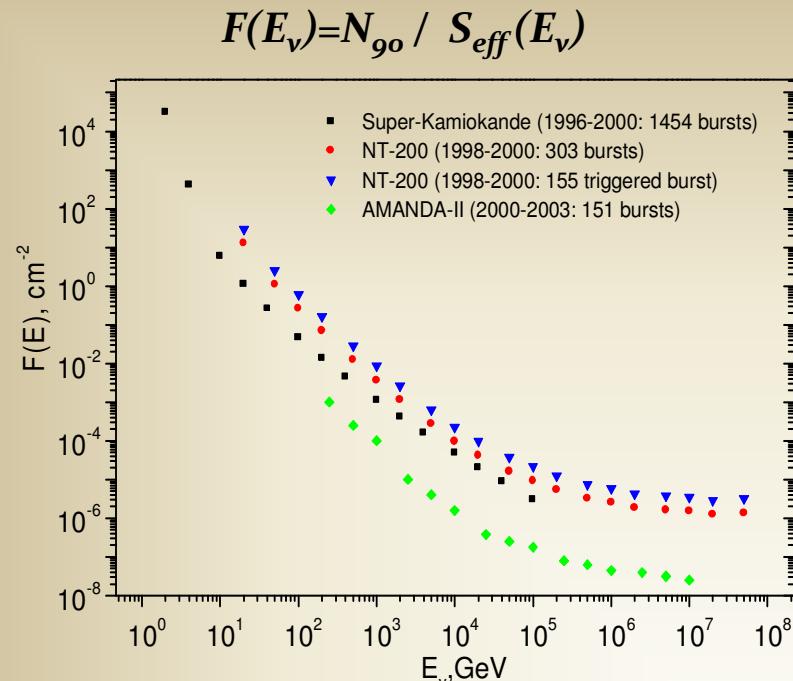
Time interval  $(t_{GRB} + 1000\text{ s}) - (t_{GRB} - 1000\text{ s})$

(excluding signal window);  $\Psi = 10^\circ$ .

GRB	Signal	Backgr.	$\mu_{90}$	$N_{90}$
All GRB	1	2.7	2.1	$1.0 \times 10^{-2}$
Ttrig. GRB	1	1.6	2.8	$2.3 \times 10^{-2}$

$\mu_{90}$  - event upper limit

$N_{90}$  - 90% C.L. upper limit on the number of events per GRB



90% C.L. upper limits on the GRB neutrino fluence Green's function for NT200, Super-Kamiokande and AMANDA

For Waxman – Bahcall spectrum and triggered GRB

$E_\nu^2 \Phi_\nu \leq 1.1 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, E_\nu > 100 \text{ TeV.}$

# WIMP Neutrinos from the Center of the Earth

1038 days livetime NT200 (1998 -2003)

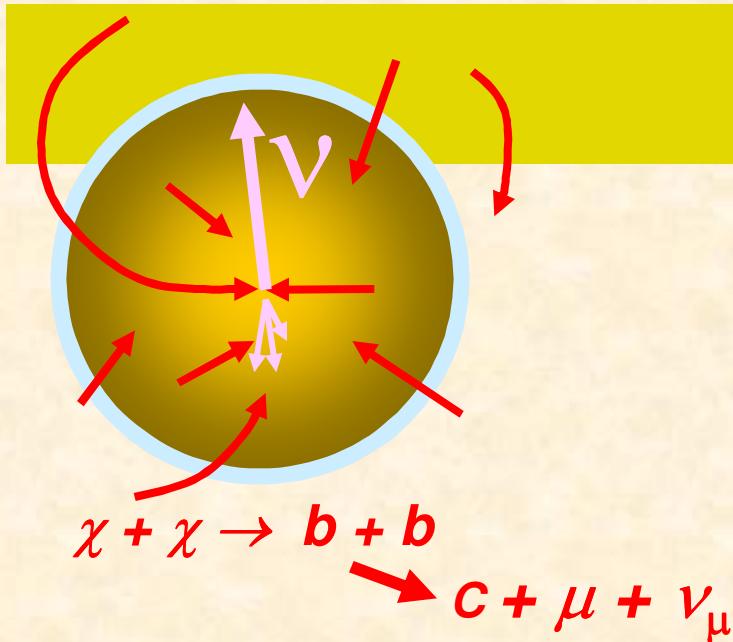
48 evts - experiment

73.1 evts - prediction without oscillations

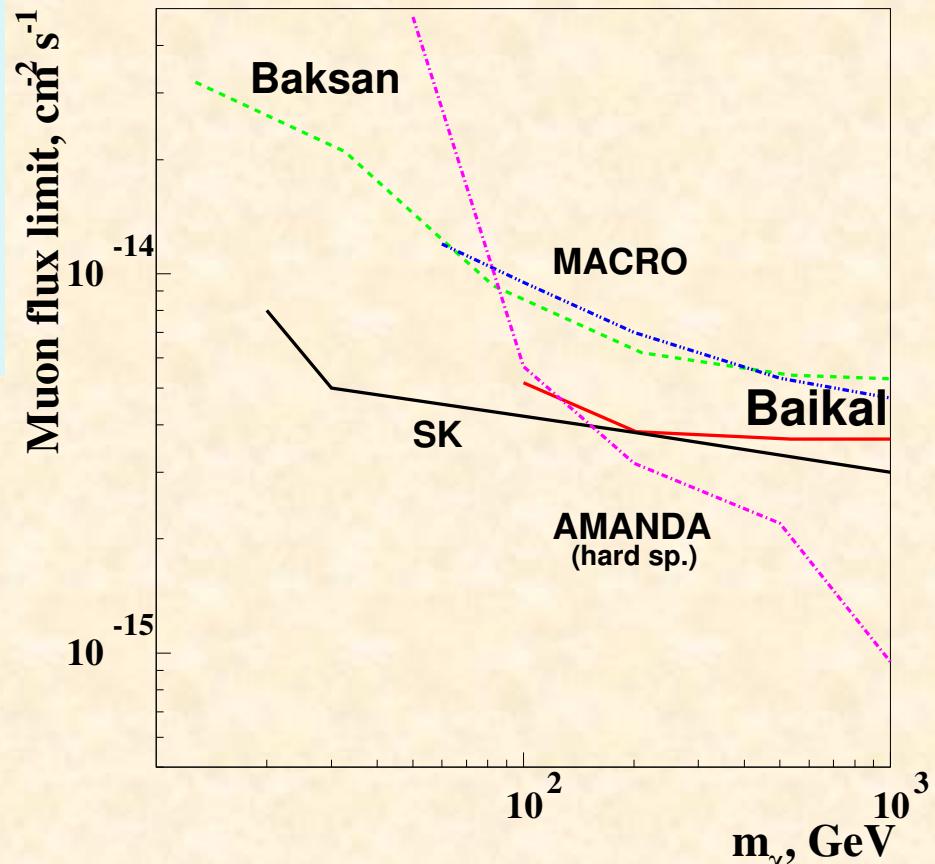
56.6 evts - prediction with oscillations

3.6 evts - atm. Muons (background)

Systematic uncertainties: 24%



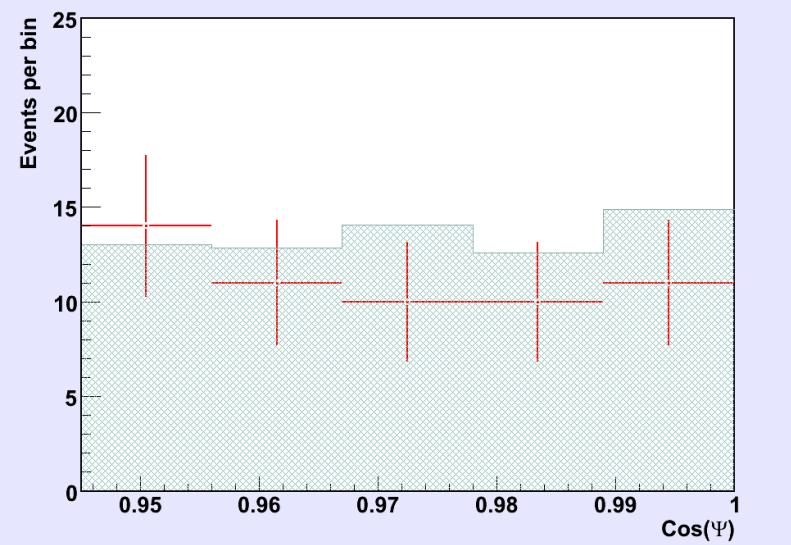
Limit on excess neutrino induced upward muon flux 90% c.l. limits from the Earth ( 1038 days NT200 livetime,  $E_\mu > 10$  GeV )



Preliminary

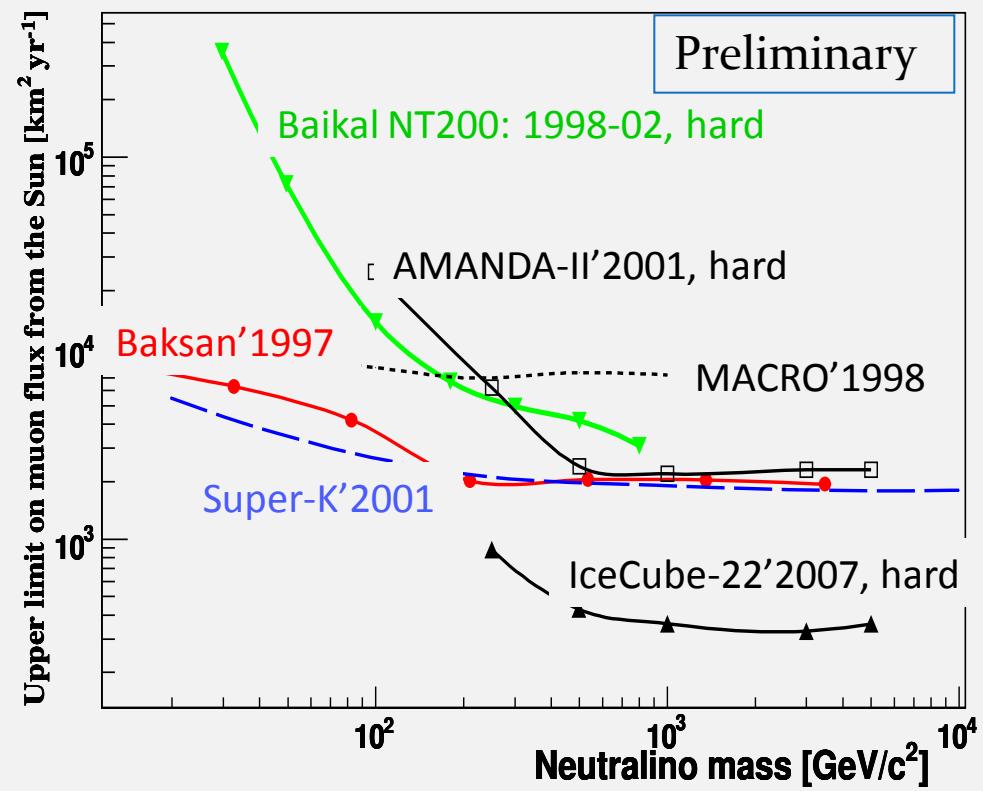
# WIMP Neutrinos from the Sun

- Neutralino (WIMP) as favored Dark Matter candidate
- Gravitationally trapped in the Sun (or Earth)
- the Sun would be a neutrino-source (annihilation) → “Indirect“ WIMP searches



**Sun-mismatch angle  $\Psi$   
(Muon/Sun):  
data and background (histogram)**

No excess of events above  
atm. BG → Flux Limits



# Search for fast monopoles

For a Dirac charge  $g = 68.5$  e, Cerenkov radiation emitted by monopoles **is 8300 times more than that of a muon.**

## Event selection criteria:

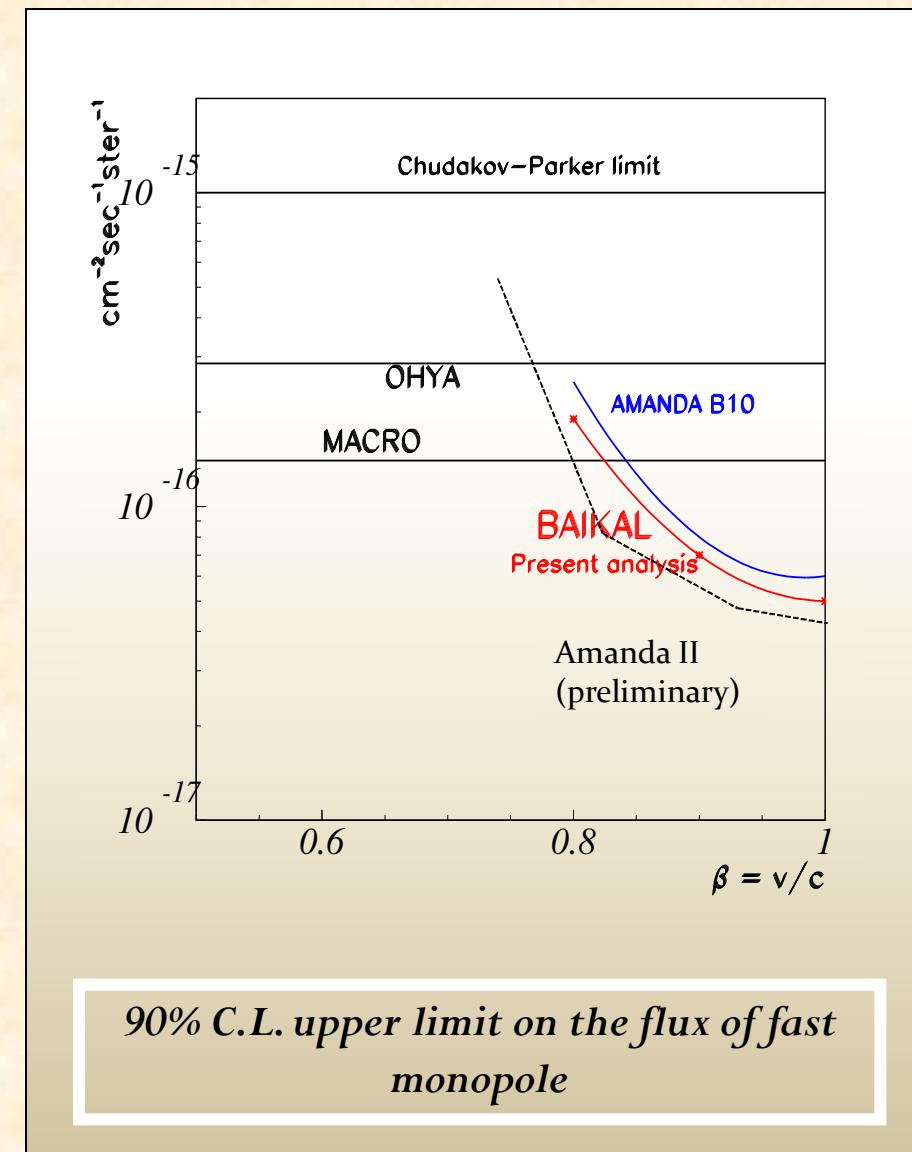
1. Hit channel multiplicity :  
 $>30$  pairs of PMTs hit.
2. Upward moving light patterns:  
time-vertical-coordinate correlation.

**Background** - atmospheric muons.

No excess over the expected background was found.

**Limit on a flux of relativistic magnetic monopoles (1003 days of live time):**

$$F < 4.6 \cdot 10^{-17} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$$



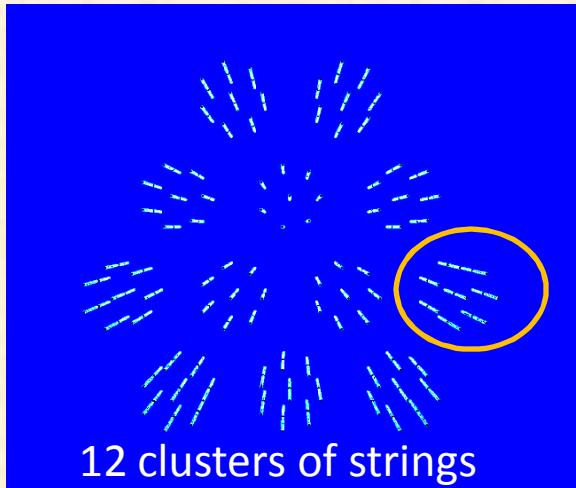
90% C.L. upper limit on the flux of fast monopole

# **Gigaton Volume Detector (GVD)**

## **in Lake Baikal**

**R&D status**

# Gigaton Volume Detector



NT1000: top view

## Layout:

~2300 Optical Modules at 96 Strings

String: 24 OM  $\rightarrow$  2 Sections with 12 OM

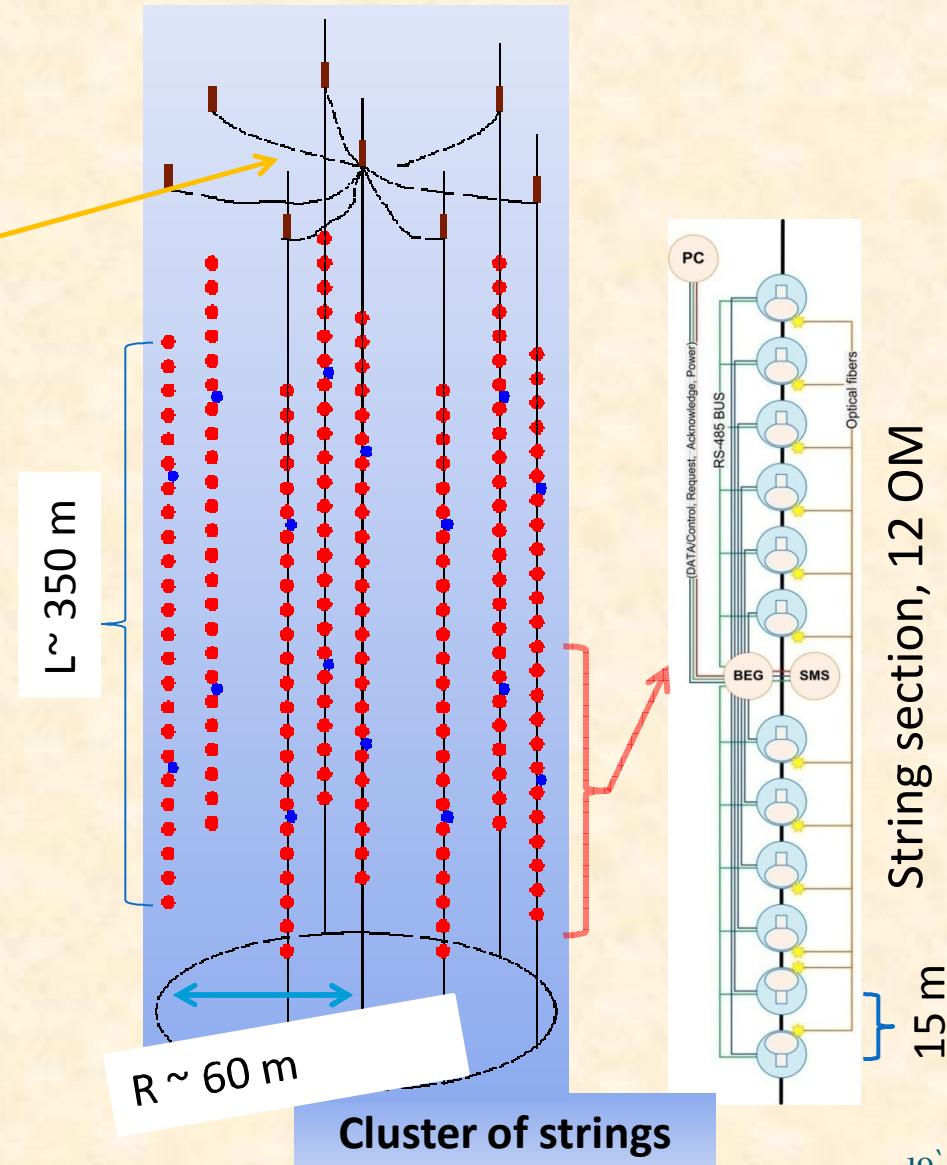
Strings are combined in Clusters  $\rightarrow$  8 strings

Cascades ( $E > 100 \text{ TeV}$ ):  $V_{\text{eff}} \sim 0.3 - 0.8 \text{ km}^3$

$$\delta(\lg E) \sim 0.1, \delta\theta_{\text{med}} \sim 2^\circ - 4^\circ$$

Muons ( $E > 10 \text{ TeV}$ ):  $S_{\text{eff}} \sim 0.2 - 0.5 \text{ km}^2$

$$\delta\theta_{\text{med}} \sim 0.5^\circ - 1^\circ$$



String section, 12 OM

15 m

# Optimisation of GVD configuration (preliminary)

## Parameters for optimization:

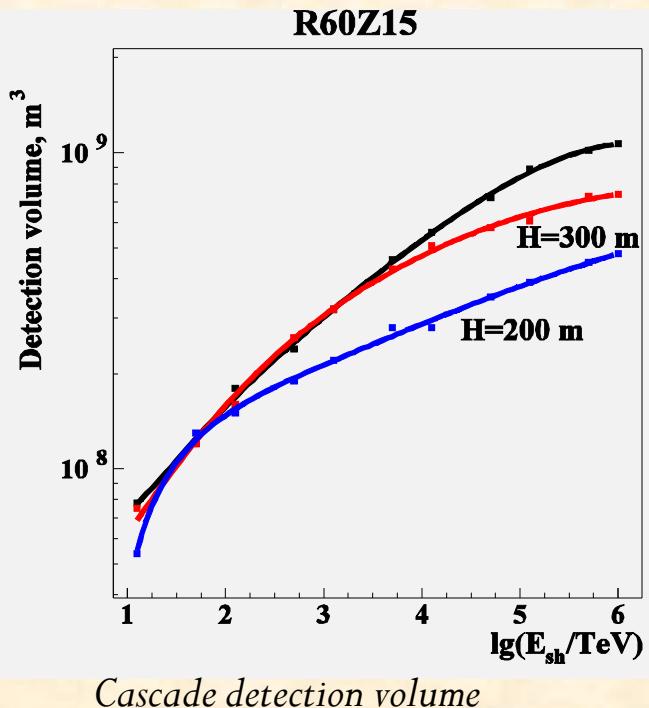
Z – vertical distance between OM

R – distance between string and cluster centre

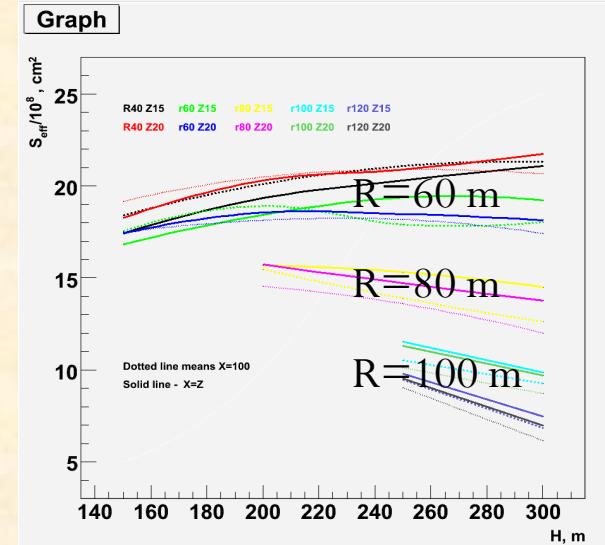
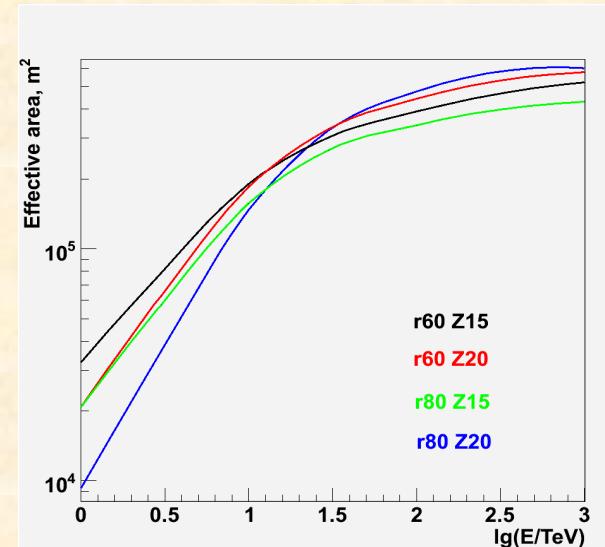
H – distance between cluster centres

**Trigger:** coincidences of any neighbouring OM  
on string (thresholds 0.5&3p.e.)

**PMT:** R7081HQE, 10", QE~0.35



The compromise between cascade detection volume and muon effective area:  
 $H = 300 \text{ m}$   
 $R = 60 \text{ m}$   
 $Z = 15 \text{ m}$



Muon effective area

# PM selection for the km3 prototype string

Basic criteria of PM selection is its effective sensitivity to Cherenkov light which depends on  
Photocathode area  $\times$  Quantum efficiency  $\times$  Collection efficiency

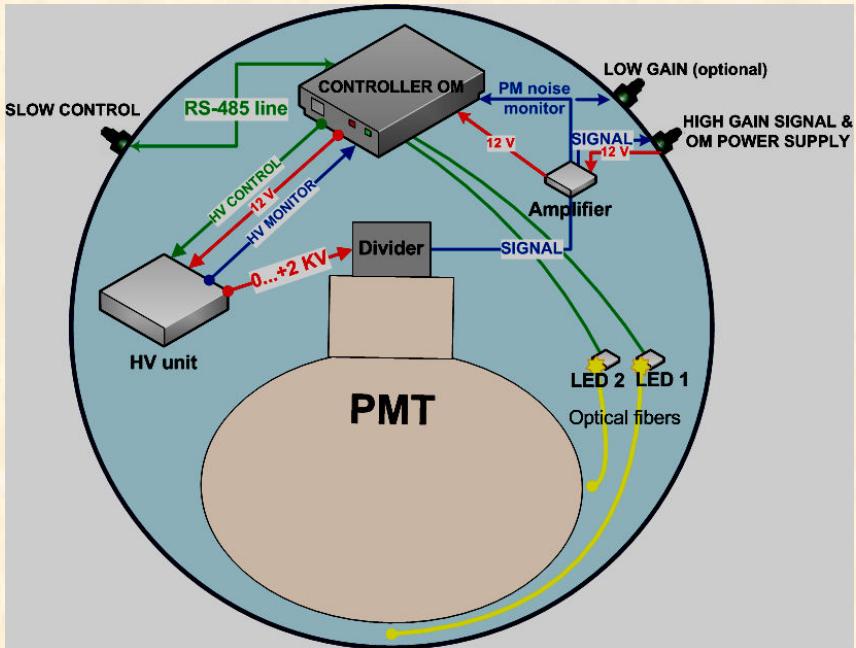


**Quasar-370**  
 $D \approx 14.6"$   
Quantum efficiency  $\approx 0.15$

**Hamamatsu R8055**  
 $D \approx 13"$   
Quantum efficiency  $\approx 0.20$

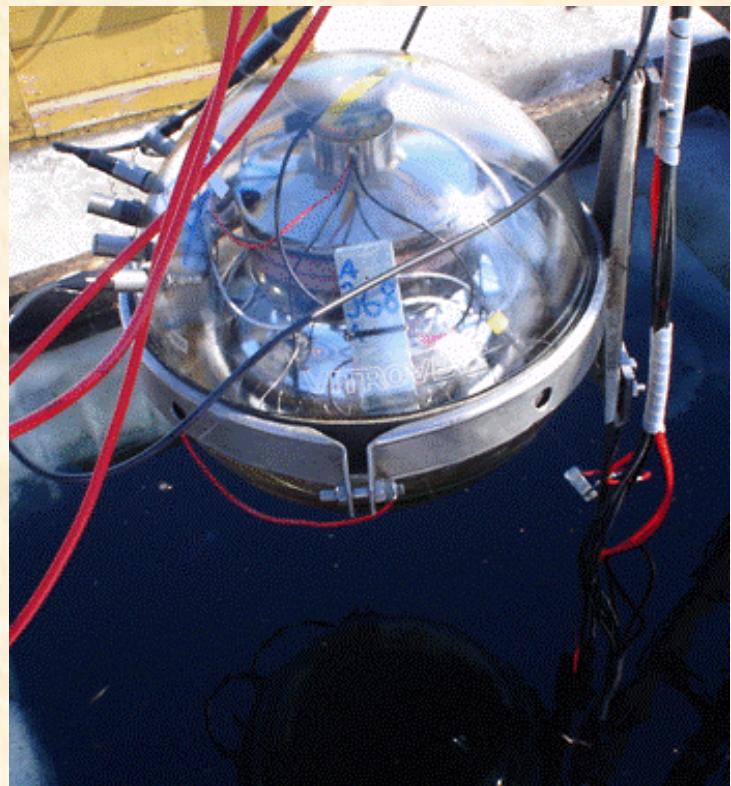
**Photonis XP1807**  
 $D \approx 12"$   
Quantum efficiency  $\approx 0.24$

# Optical Module (OM)

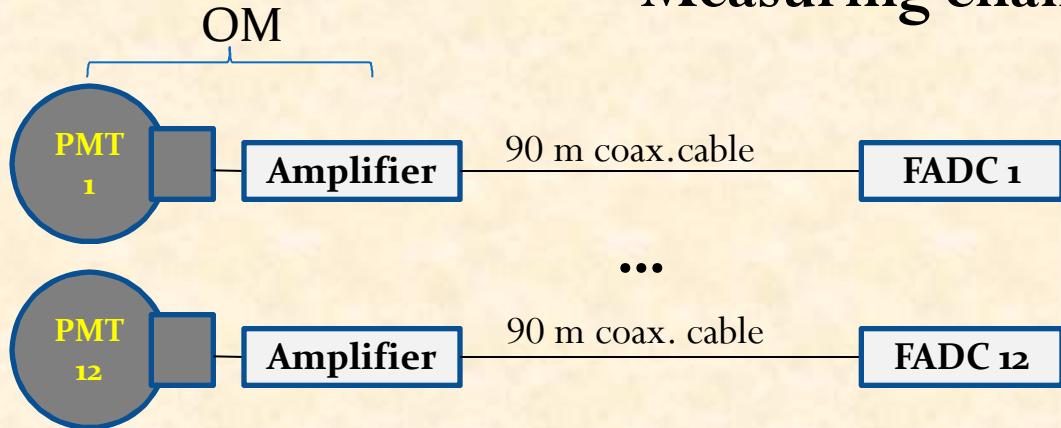


1. PMT: XP1807 (Photonis, ~12"), R8055 (Hamamatsu ~13")  
Divider 17 Mom  
Gain  $3...5 \times 10^7$
2. Preamplifier:  $K_a \sim 5$  for high gain ch.  
 $K_a \sim 1.5$  for low gain ch.
3. HV unit: PHV12-2.0K DC-DC converter  
VIP-2A converter

4. OM controller: microcontroller C8051F124
  - RS-485 interface
  - PM pulse counter with regulated threshold
  - HV monitor
  - 2-LED calibration system (LED amplitude and pulse delay regulation).



# Measuring channels



## The new generation Baikal Optical module

PM: XP1807(12"), R8055(13"), **R7081HQE(10")**

QE ~0.24

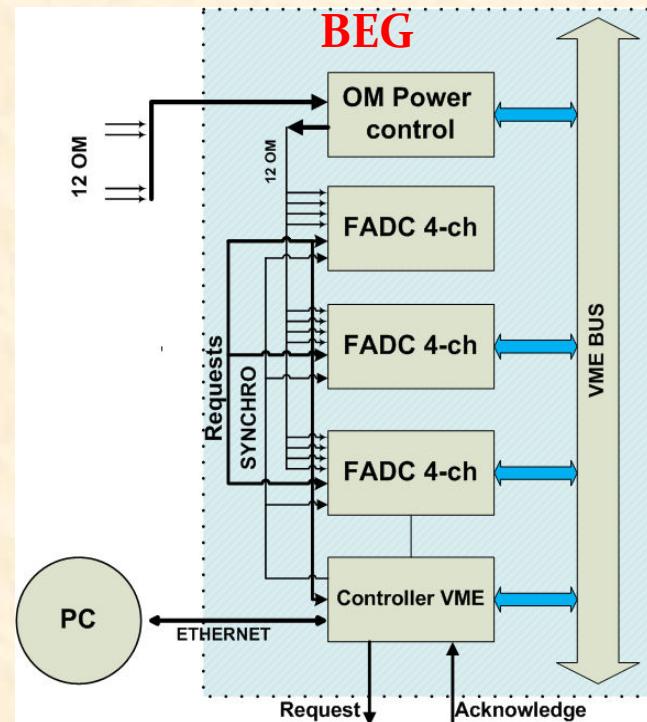
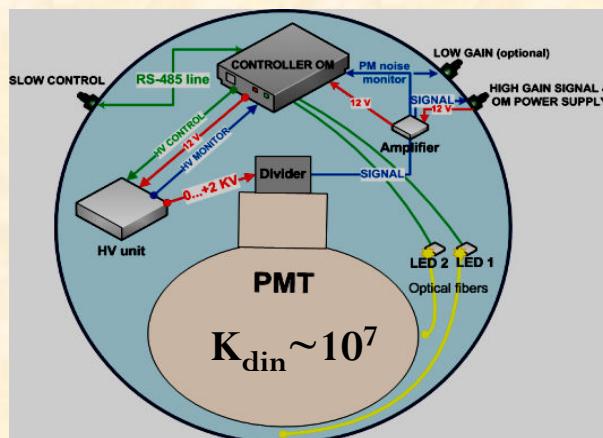
QE ~0.2

QE~0.35

HV unit: SHV12-2.0K, TracoPower

OM controller: monitoring, calibration, and PMT control;

Amplifier:  $K_{\text{amp}} = 10$



## BEG (FADC Unit):

- 3 FADC-board: 4-channel, 12 bit, 200 MHz;
- OM power controller ;
- VME controller: trigger logic, data readout from FADC, and connection via local Ethernet

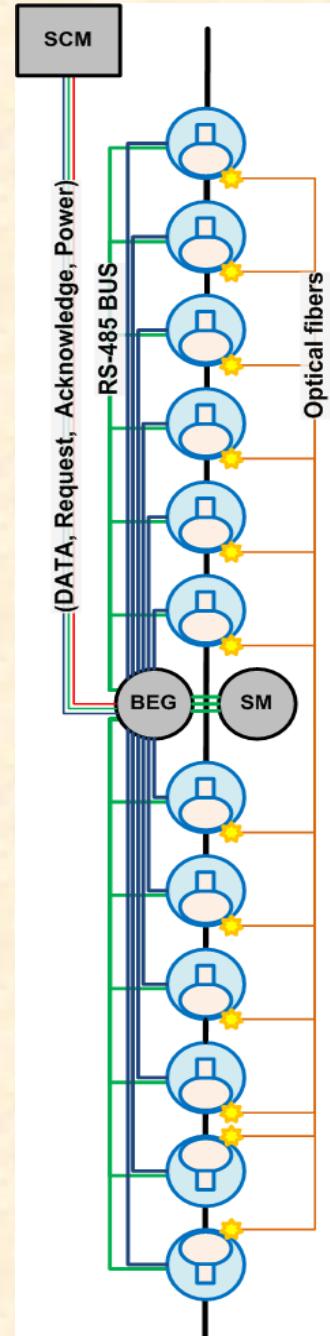
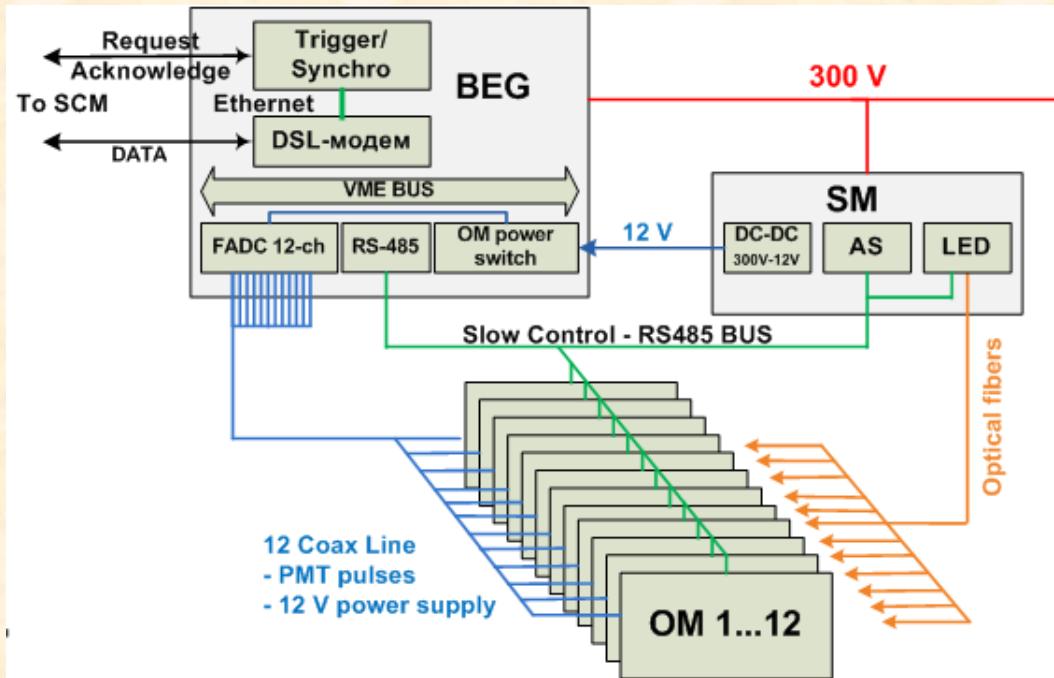
# String Section – basic cell of the Cluster

## Section consist of:

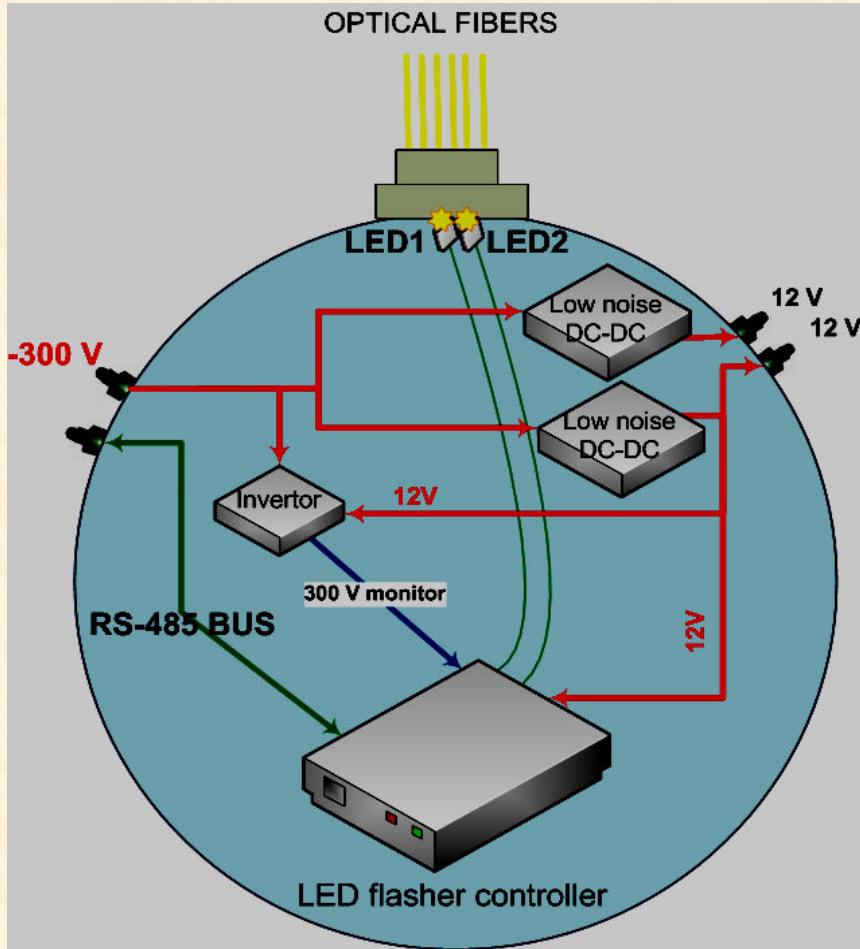
- 12 Optical Modules
- BEG with 12 FADC channels
- Service Module (SM) with LEDs for OM calibration, string power supply, and acoustic positioning system.

**Trigger:** coincidences of neighbouring OM (threch.  $\sim 0.5\&3$  p.e.)  
expected count rate  $\sim 100$  Hz

**Communication:** DSL-modem: expected dataflow  $\sim 0.5$ Mbit/s  
(only time intervals containing PMT pulses are transmitted)



# Service Module (LED Flasher)



Time and amplitude calibration is provided by string LED flasher.

Light pulses from flasher are transmitted to each OMs through optical fibers with calibrated length.

LED flasher allows obtaining time shifts of the channels, and provides the possibility of single electron spectrum monitoring for all PMs of the string.

LED flasher glass sphere contains low noise DC-DC converters for OM power supply .

DC-DC noise amplitude  $\sim 3 \text{ mV} \ll A_{1e}$

LED pulse parameters:

- FWHM  $\sim 5 \text{ ns}$
- Pulse delay range: 0...1000 ns, 10 points
- Pulse amplitude can be regulated in the range from 1 up to 200...1000 p. e. on PMs (after optical fibers) ,  $\sim 10^4$  points.

# In-situ test of the Prototype String 2009

The main goals:

**In-situ tests of basic elements of the GVD: new optical modules, DAQ system, new cable communications.**

**Studies of the Triggering approach for the GVD.  
Comparison of the classical TDC/ADC approach  
with a FADC-based full pulse shape readout.**

String length: **110 m**

Number of Optical Modules: **12**

Number of Sections: **2**

Number of FADC channels: **12**

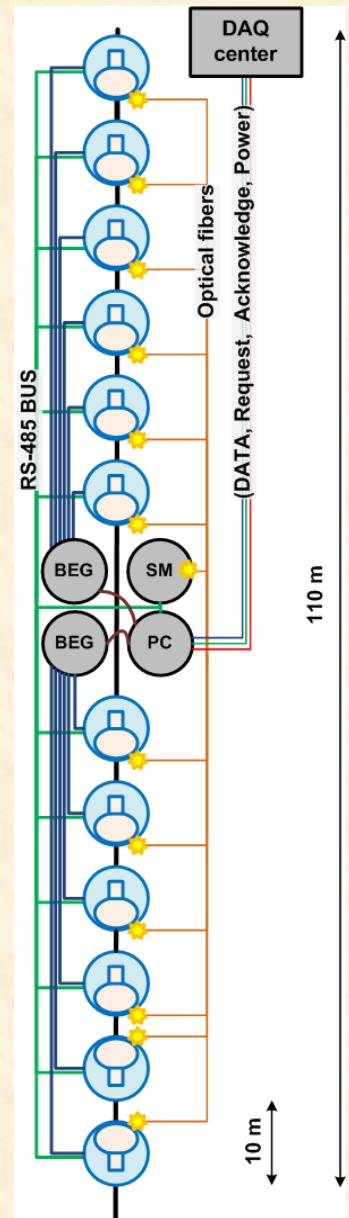
PMT: **Photonis XP1807 (12") : 6**

**Hamamatsu R8055(13") : 6**

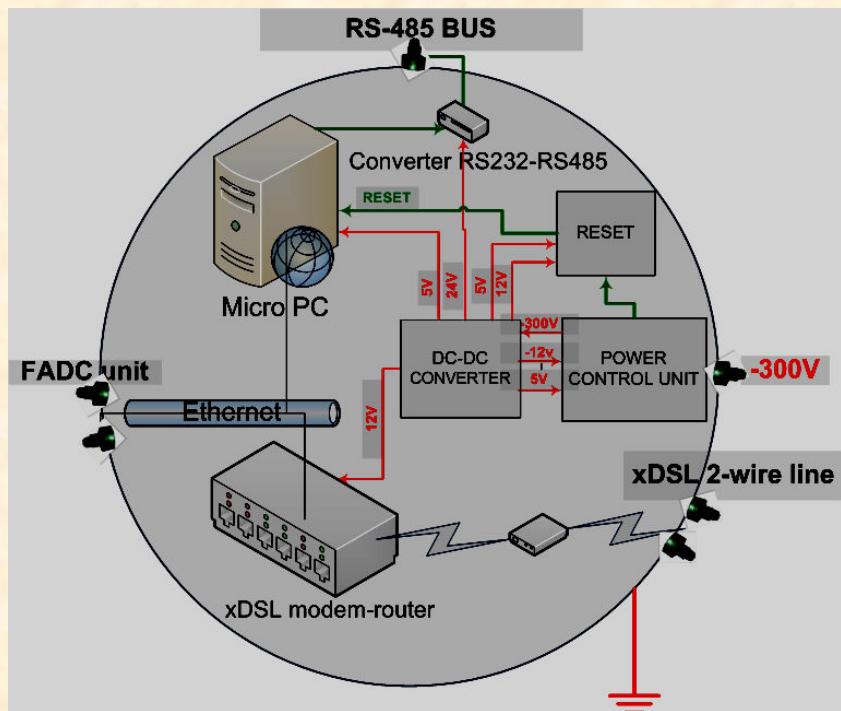
FADC Time Window: **5 mks**

FADC frequency: **200 MHz**

Dynamic range: **0.2 ... ~100 p.e**



# String PC unit



Data from the FADC are transmitted through an Ethernet line to an underwater micro-PC for on-line analysis and compressing.

Communication between PC-unit and underwater control center of NT200+ is provided by xDSL modems trough 2-wire line about 1 km length.

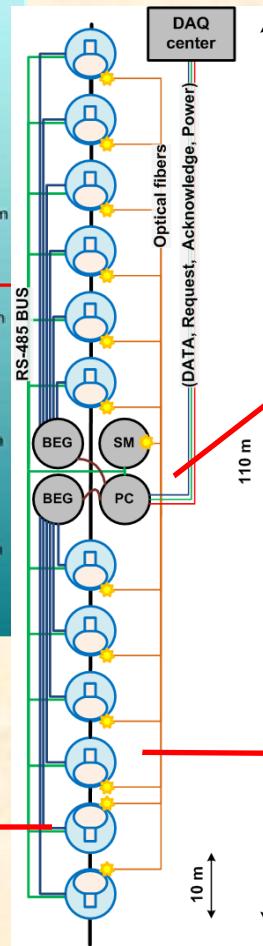
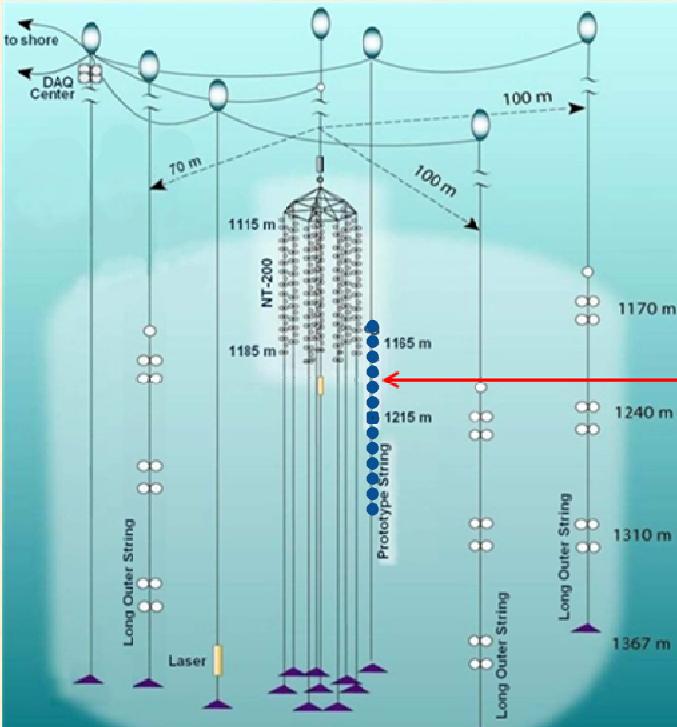
Control and monitoring of OM and LED flasher operation is provided by PC unit through RS-485 underwater bus. The main slow control functions are the regulation of PM high voltage, the control of LED flasher intensity and pulse delay, and the measuring of the rate of the PM pulses.

String PC unit - temporary solution, for operative remote correction of data acquisition, on-line analysis and data compressing algorithms.

# GVD prototype string

- 2008: Prototype of one String Section with 6 new technology OM;  
2009: Prototype of the String with two Sections:  
12 OM, 2 BEGs with FADC, PC Module, Service Module

NT<sub>200+</sub> with experimental string



String communication center



Optical module

# Cluster of strings

## 8 Strings

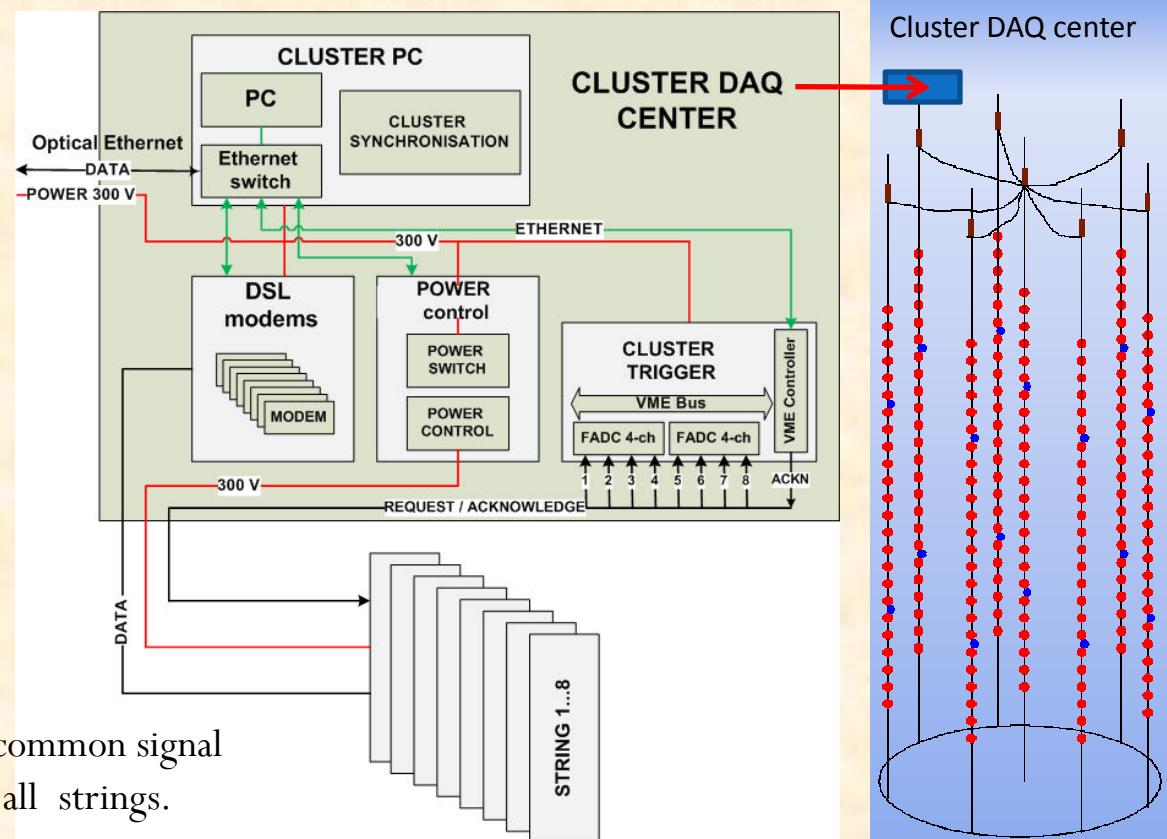
String – 2 sections ( $2 \times 12$  OM)

### Cluster DAQ Centre:

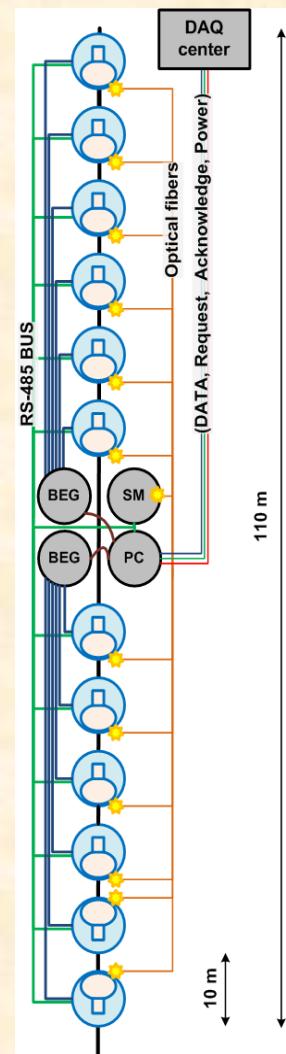
- PC-module with optical Ethernet communication to shore (data transmission and cluster synchronization)
- Trigger module with 8 FADC channel for the measure of string trigger time;
- Data communication module – 8 DSL-modems, modem data flow up to 7 Mbit/s for 1 km.
- Power control system

### Calibration system

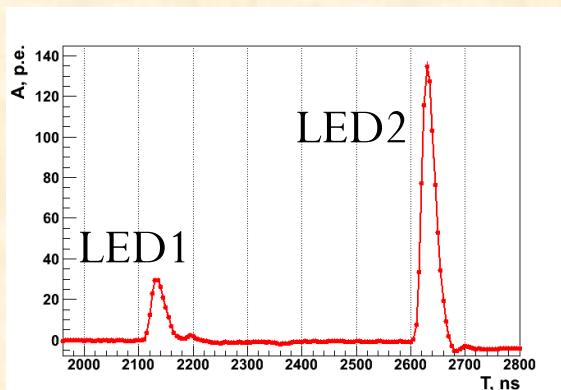
Two Lasers



# Time resolution of measuring channels (in-situ tests)

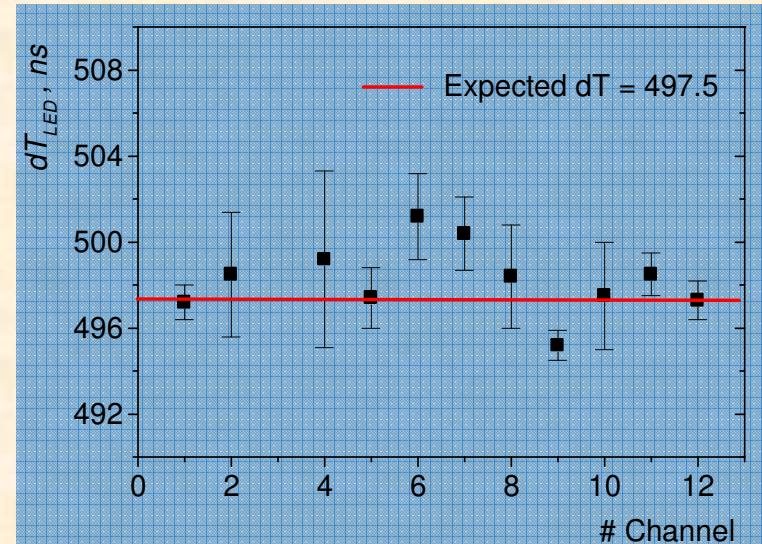


LED flasher produces pairs of delayed pulses. Light pulses are transmitted to each optical module (channel) via individual optical fibers. Delay values are calculated from the FADC data.

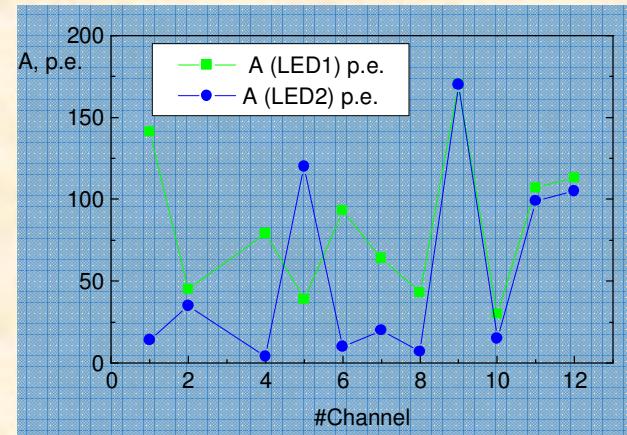


*Example of a two-pulse LED flasher event (channel #5)*

$dT$  (Expected) = 497.5 ns  
 $\langle dT \text{ (Experiment)} \rangle = 498.3 \text{ ns}$   
 $\langle \sigma(dT) \rangle = 1.6 \text{ ns}$

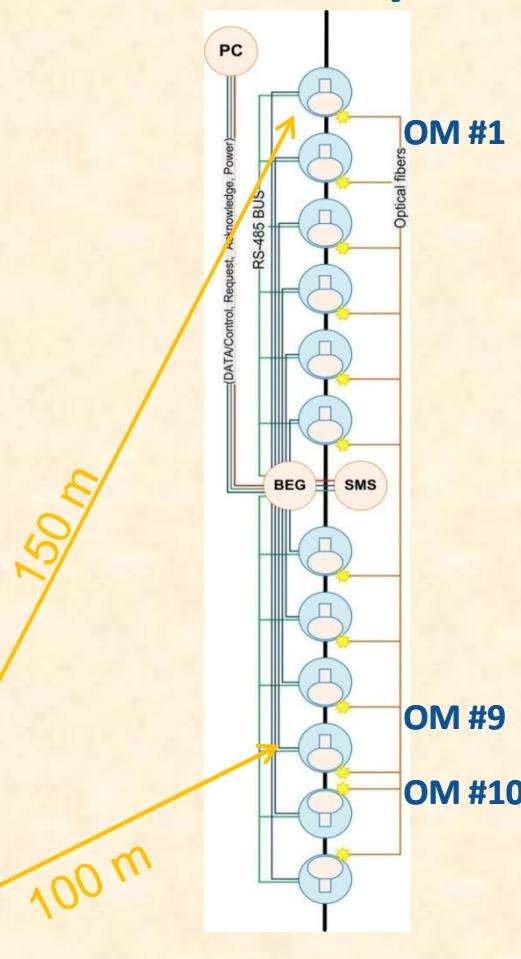


*Measured delay  $dT$  between two LED pulses*

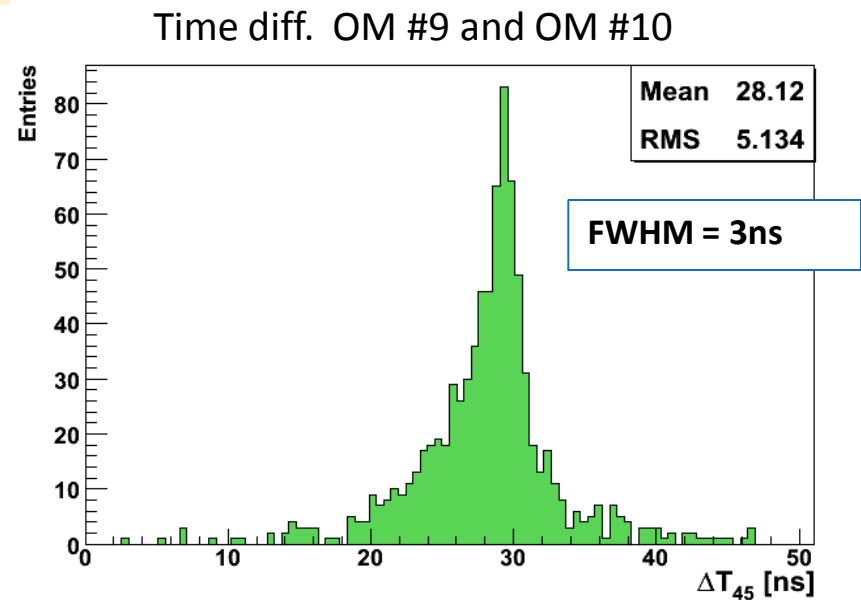
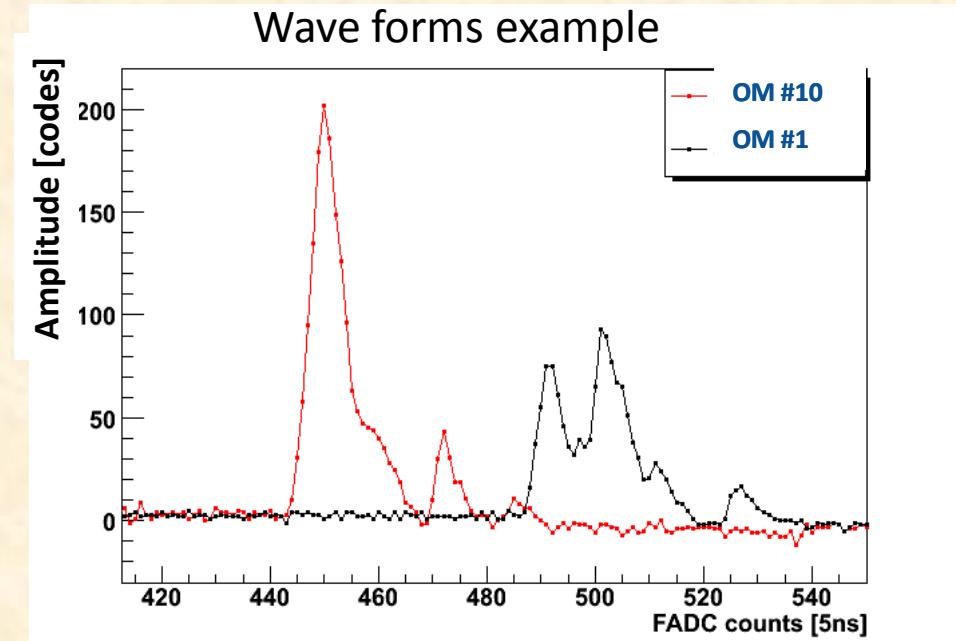


*LED1 and LED 2 pulse amplitude*

# Time accuracy of the String Section



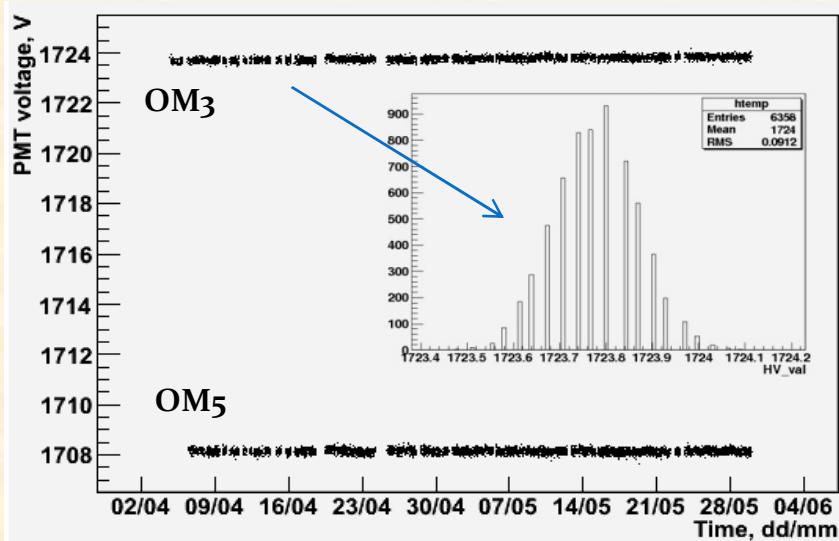
Preliminary in-situ tests with underwater laser, LED flasher and muons show good performance of all string elements



# Monitoring of Optical Module operation

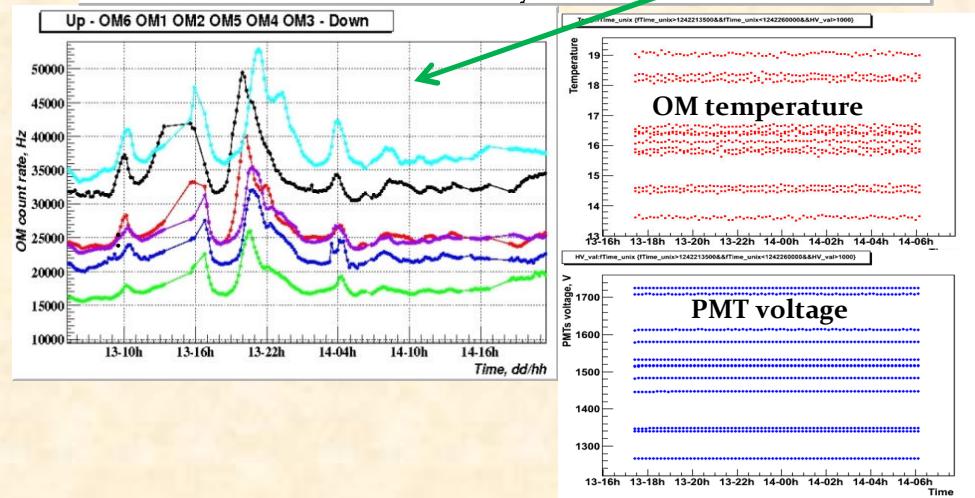
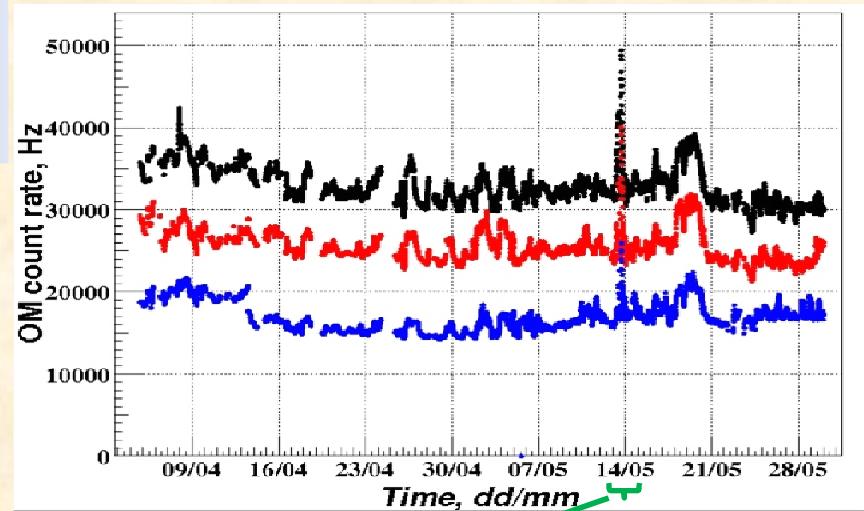
## OM monitoring parameters:

- PMT high voltage;
- PMT count rate;
- Temperature;
- OM low voltages: 12 V, 5 V, -5 V ...



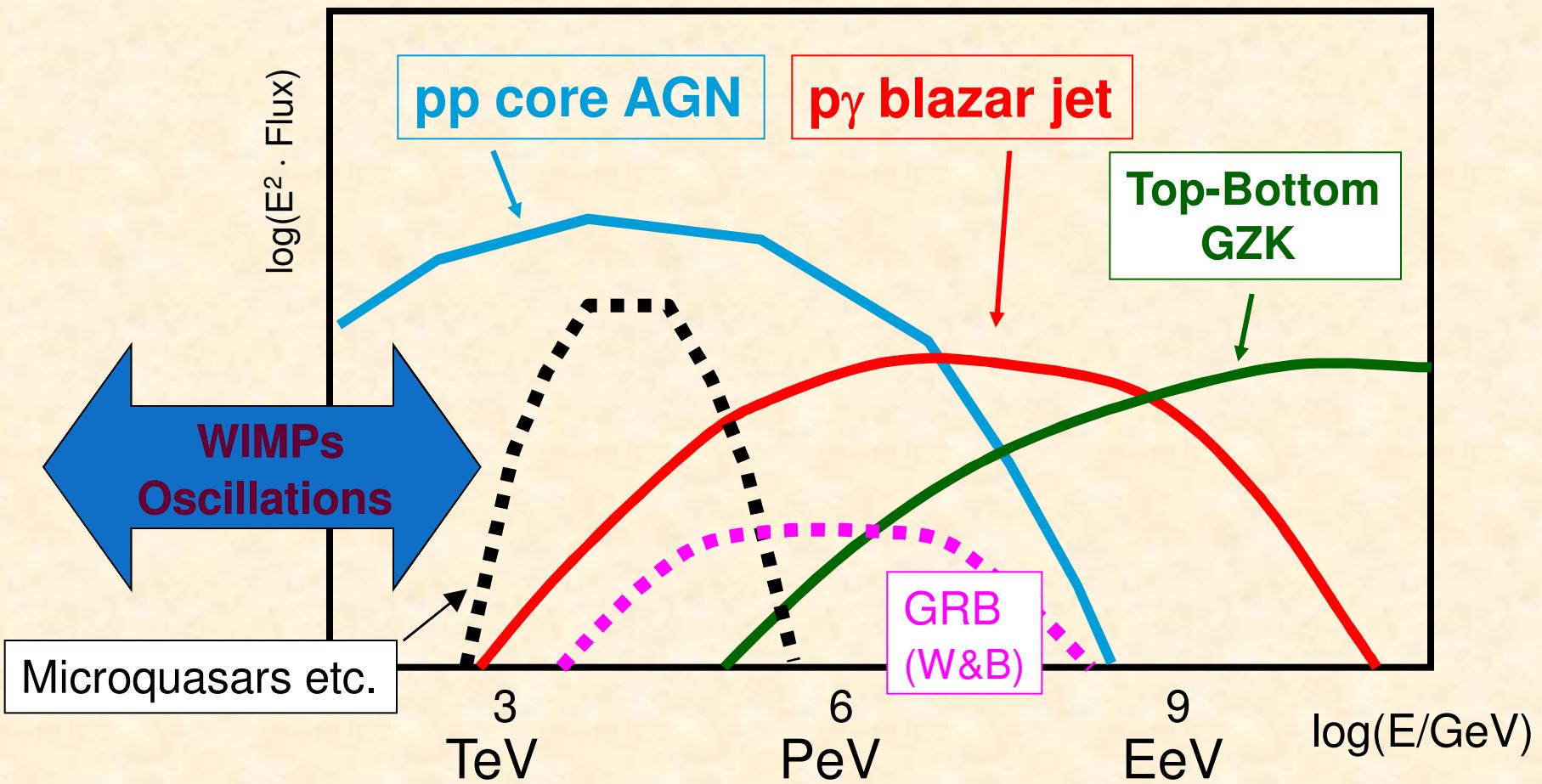
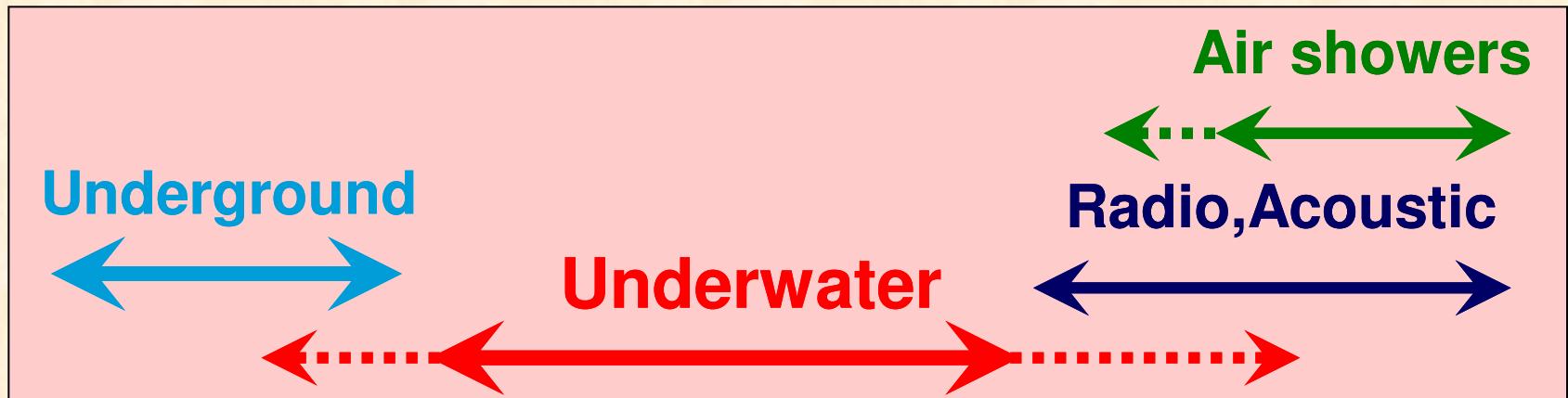
Example of PMT voltage monitoring

## Example of PMT count rate monitoring



# Schedule

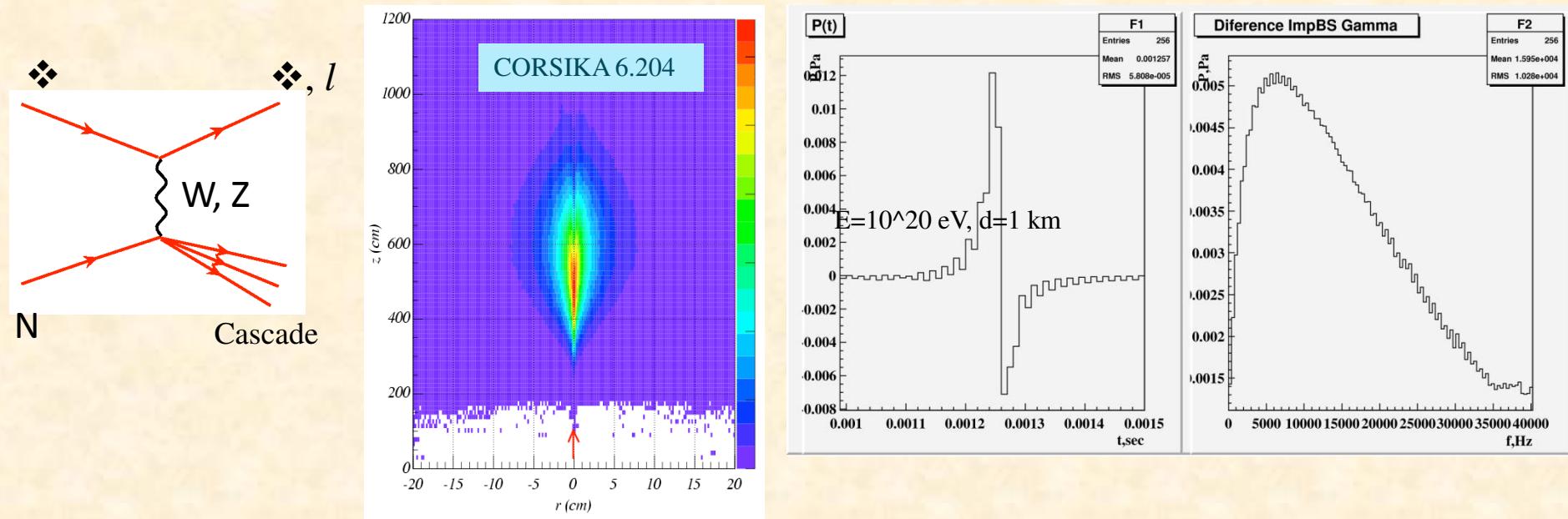
- 2009-2010 GVD R&D (supported by Russian foundation)
  - 2010 GVD Technical Design Project
  - 2010-2011 GVD Cluster Prototype
  - 2008-2014 Fabrication (OMs, electronics, cables, etc)
- 
- 2012-2013 Deployment 0.1-0.3 km<sup>3</sup>
  - 2014-2015 Deployment 0.3-0.6 km<sup>3</sup>
  - 2016-2017 Deployment 0.7-0.9 km<sup>3</sup>



# Neutrino Acoustic Detection Principal

(G. Askaryan, B. Dolgoshein, 1997)

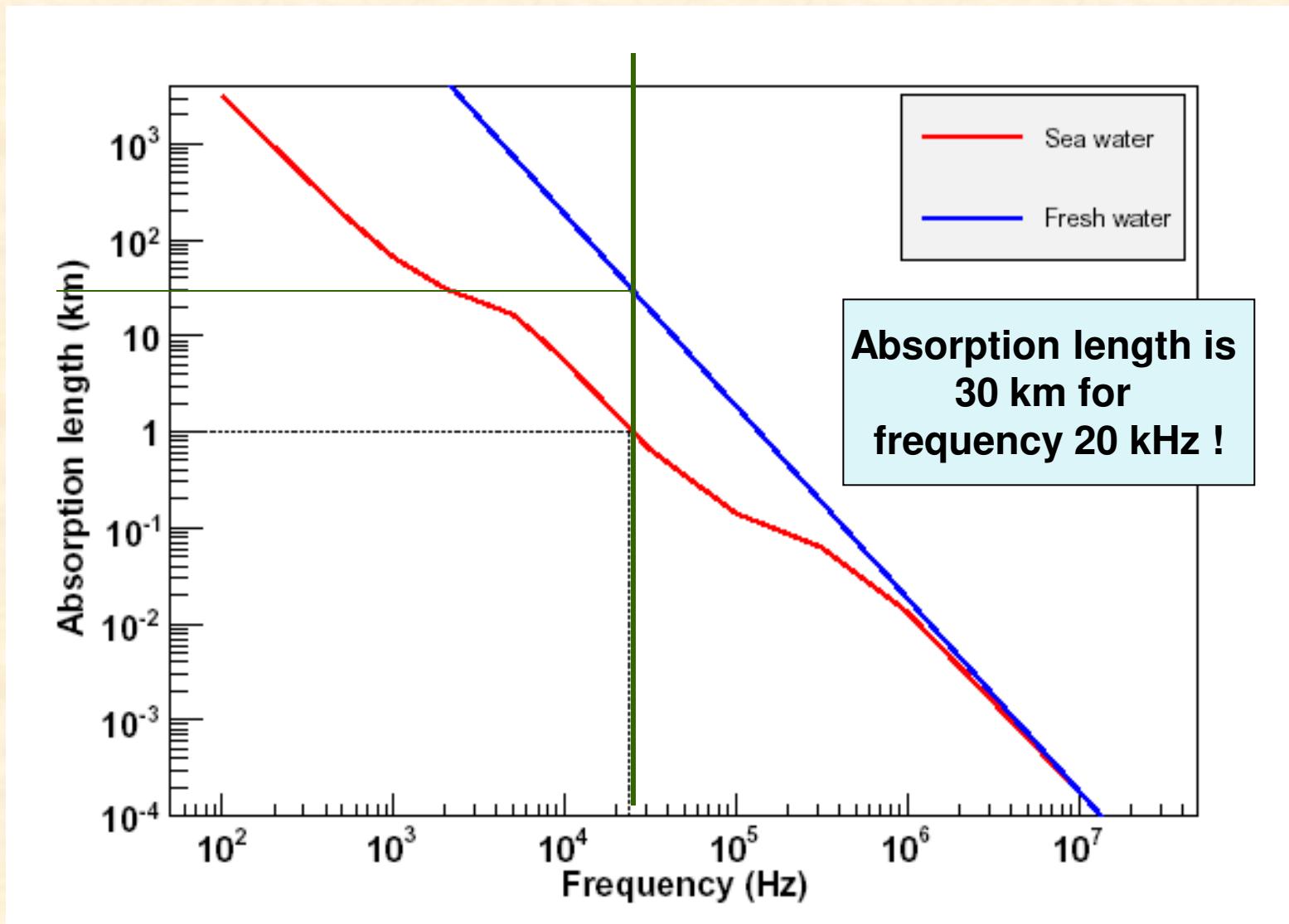
Interaction  $\longrightarrow$  Water heating      Pulse form      Spectrum



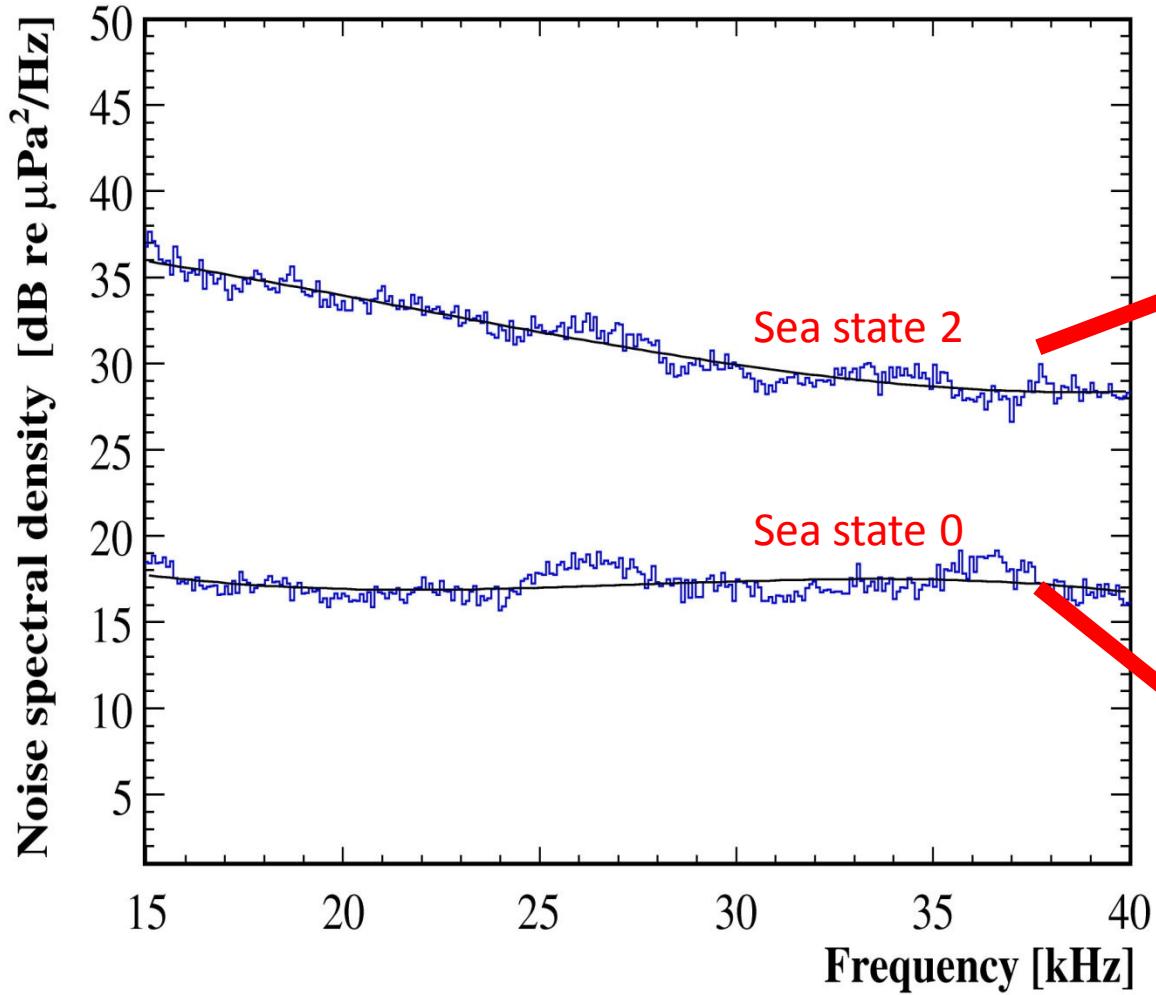
Typical cylindrical volume over which the hadronic energy is deposited is ~20m long by a few centimetres wide (95% of energy at  $10^{20}$ eV)

*The energy deposition is instantaneous with respect to the signal propagation*  
Hence the acoustic signal propagates in a narrow "pancake" perpendicular to the shower direction in analogy with light diffraction through a slit

# Absorption of sound in water



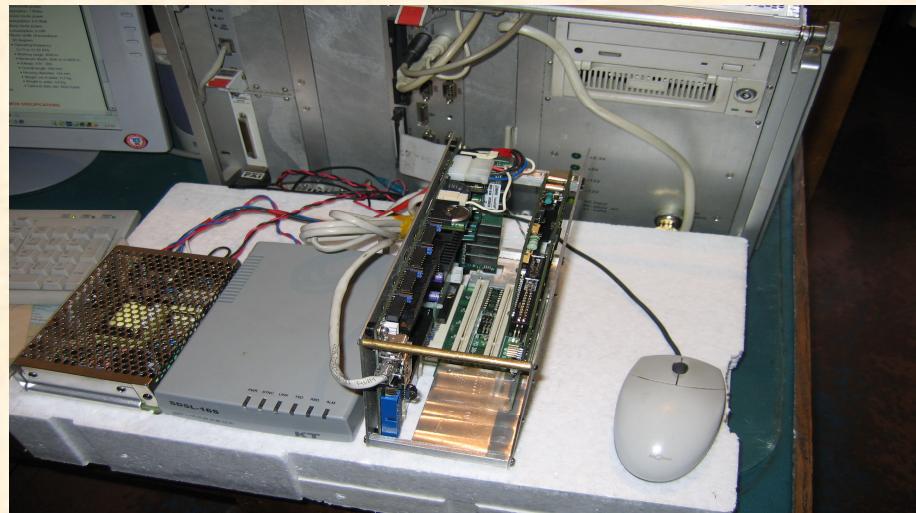
# Lake Baikal noise spectral density



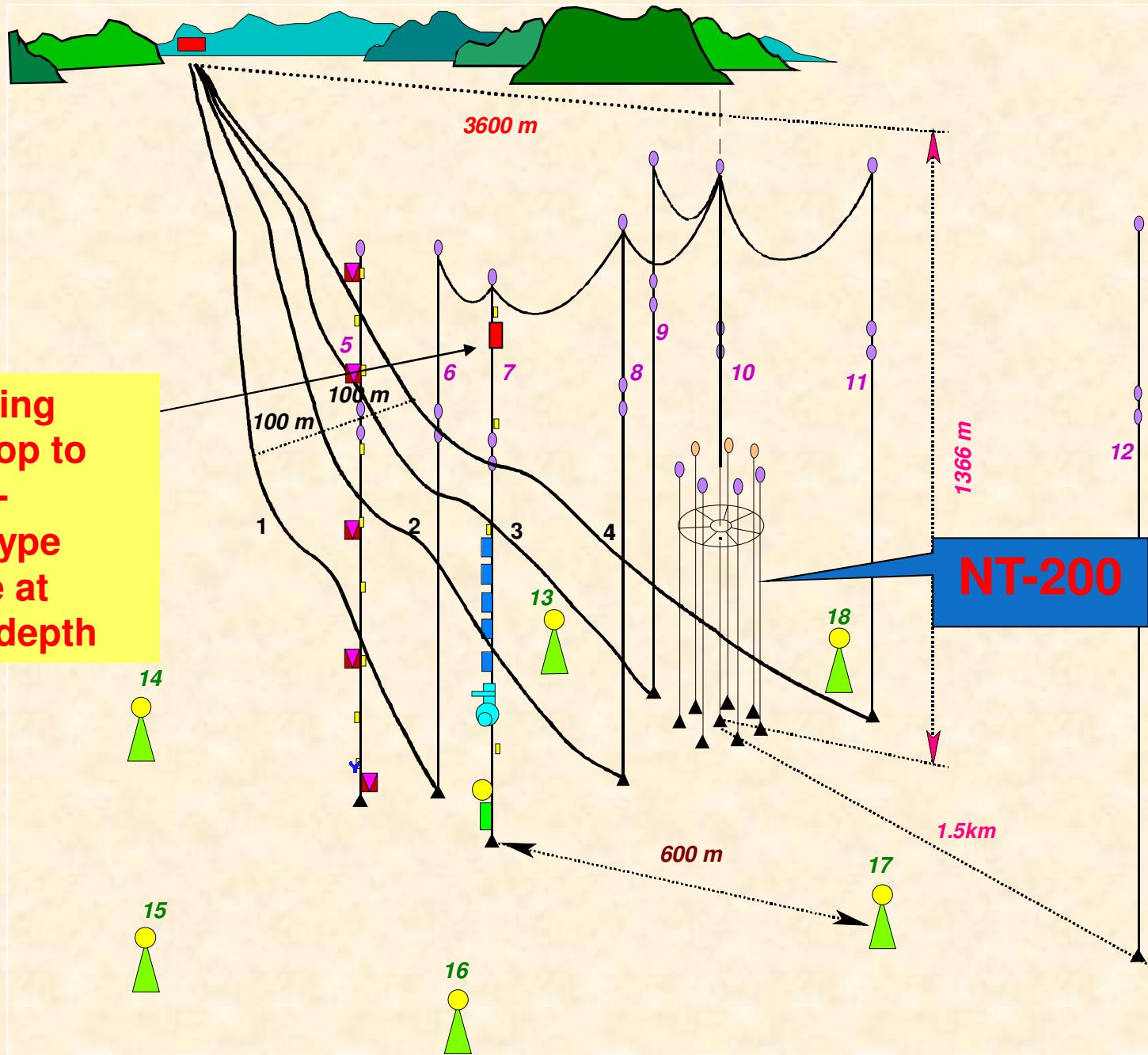
# An acoustic detector for background study



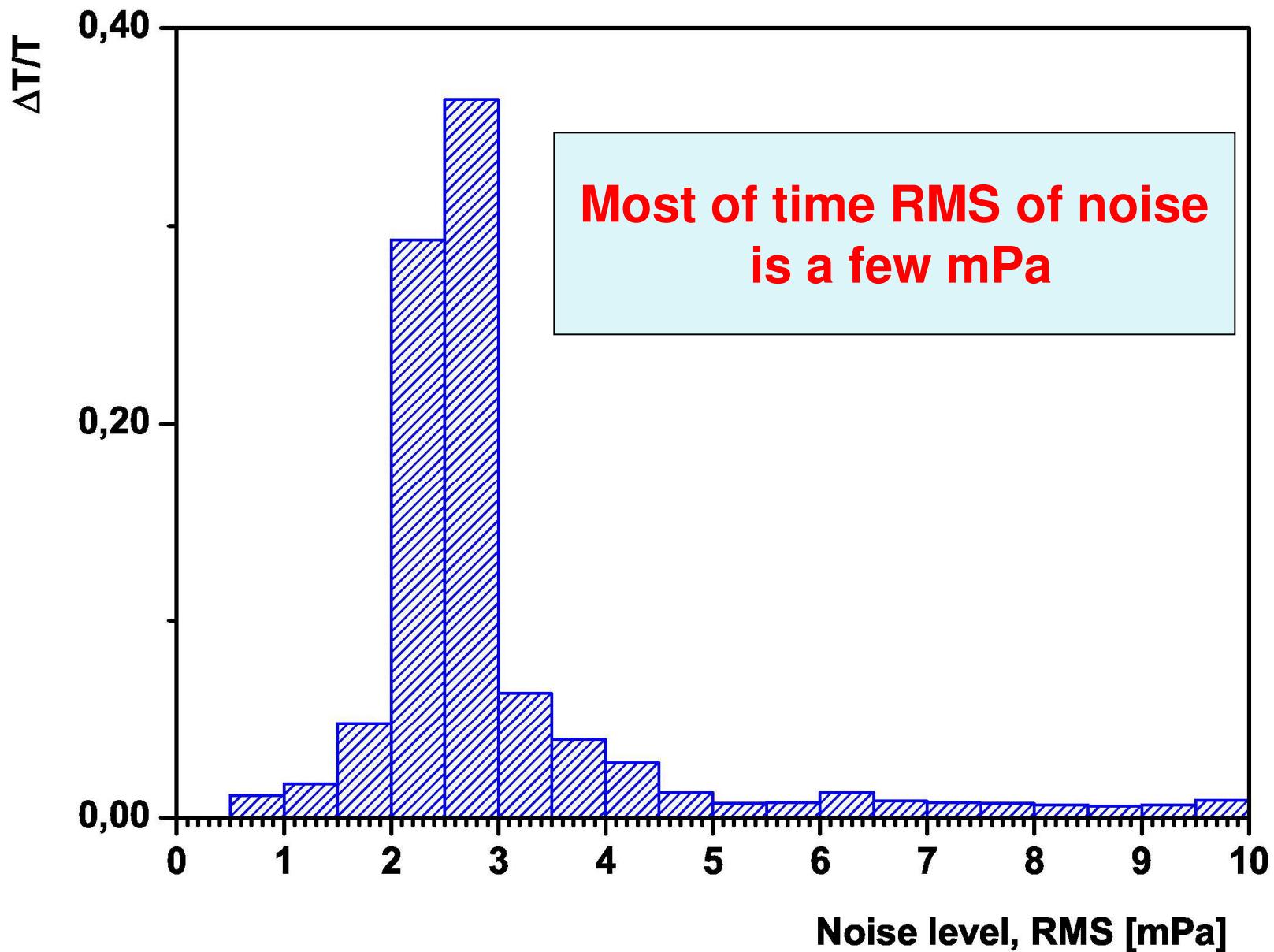
- Tetrahedral antenna 1.5m
- 4 hydrophones H2020C
- 4-ch, 195kHz, 16-bit ADC AD7722
- One-plate computer NOVA-C400
- 2 Mbit DSL modem



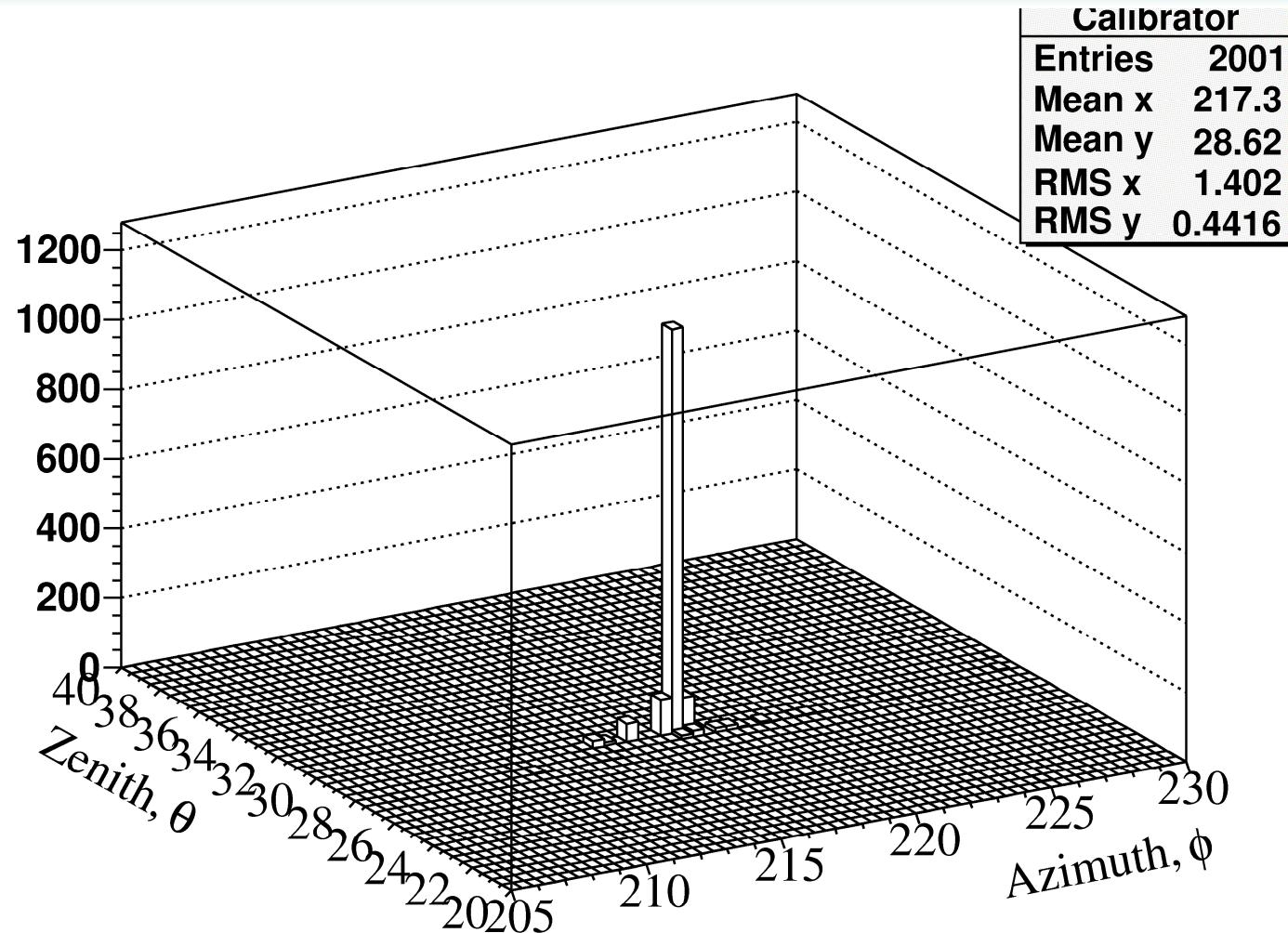
**Listening  
from top to  
down -  
prototype  
device at  
150m depth**



## Acoustic background time distribution

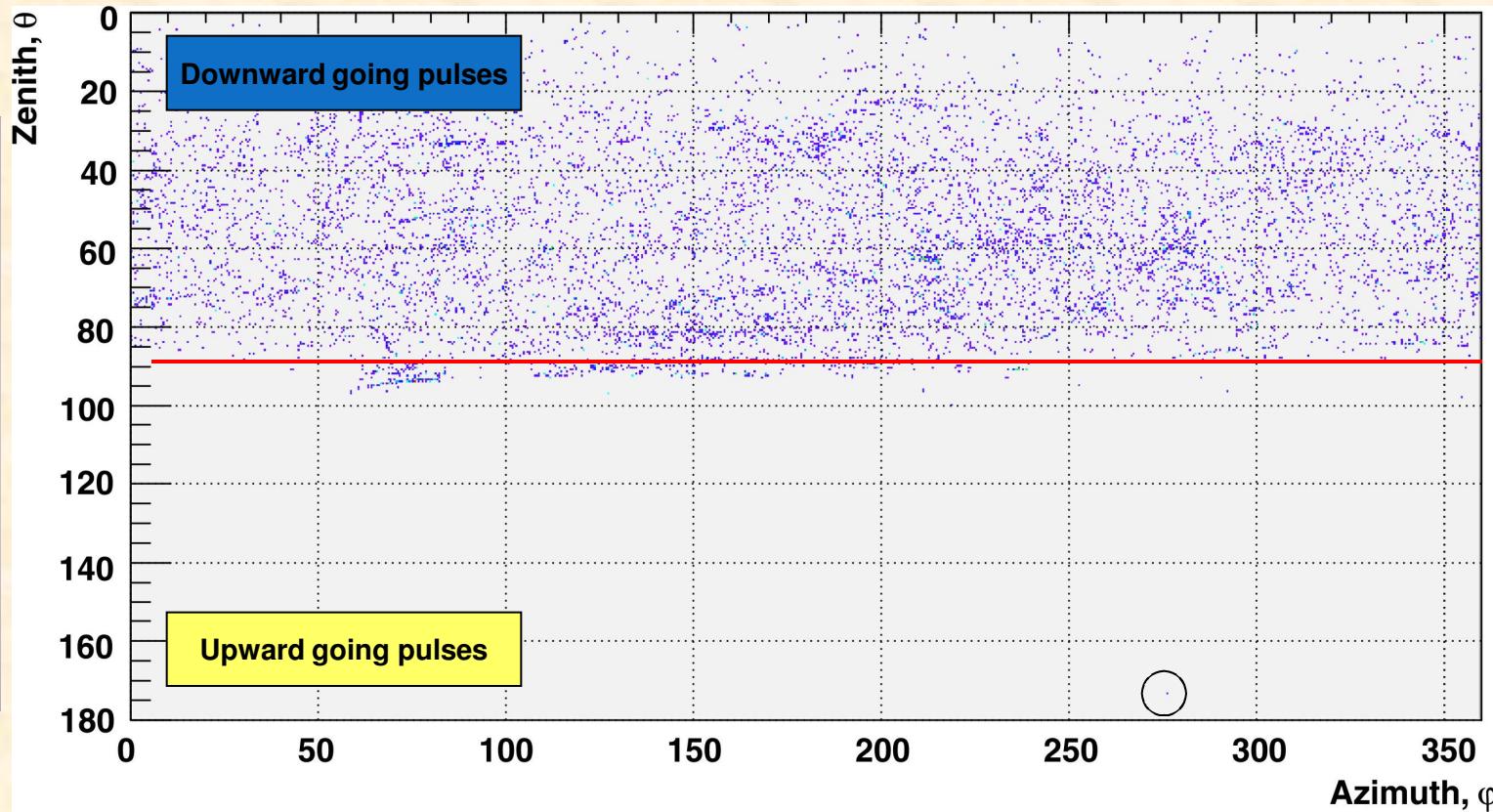
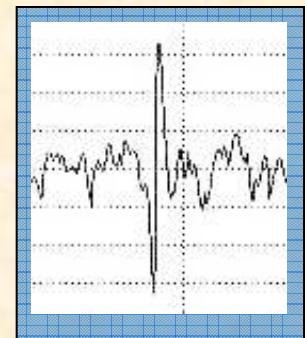


# Accuracy of direction reconstruction to the acoustic source



Angular distribution of the acoustic pulses generated by the imitator. The RMS of reconstructed angles to the calibration source are  $\sigma(\text{azimuth}) \sim 1.5$  degree and  $\sigma(\text{zenith}) \sim 0.5$ .

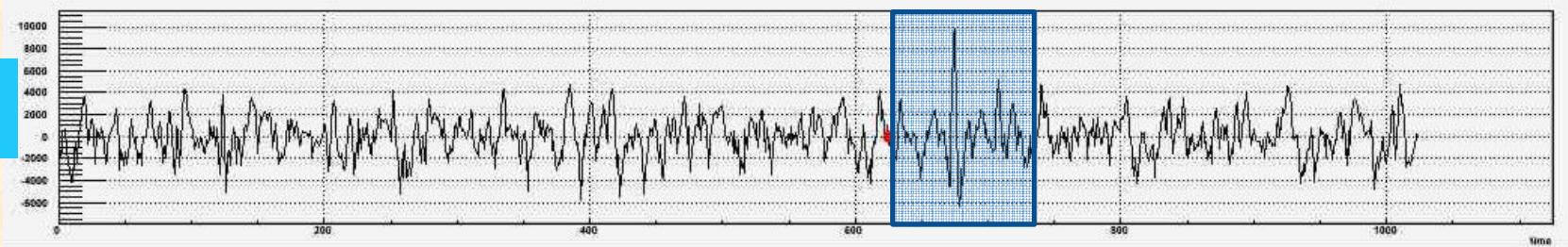
# Angular distribution of detected bipolar pulses



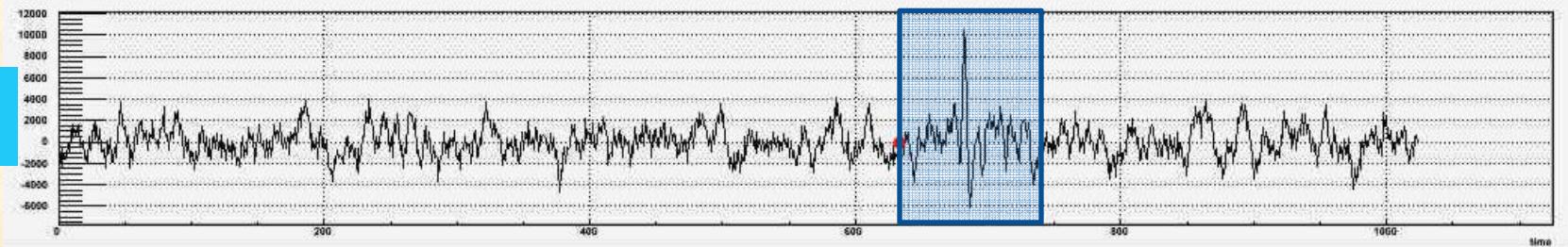
~7000 of background pulses were detected during the April-May 2009

# Signal from the deep layer of the Lake

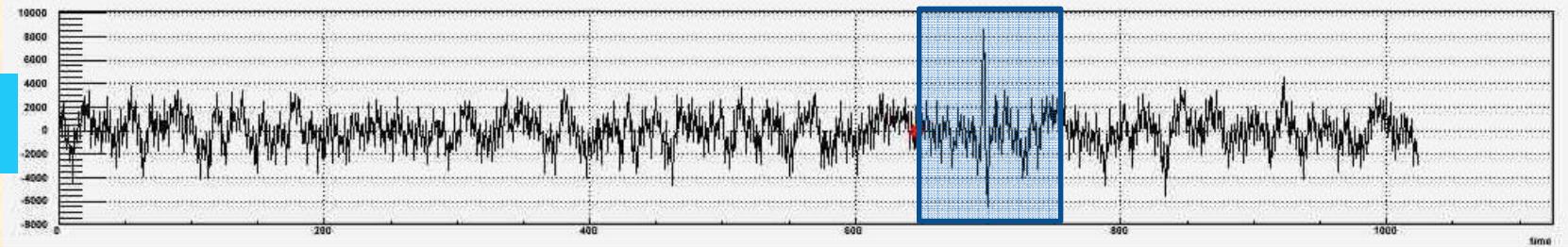
Ch.1



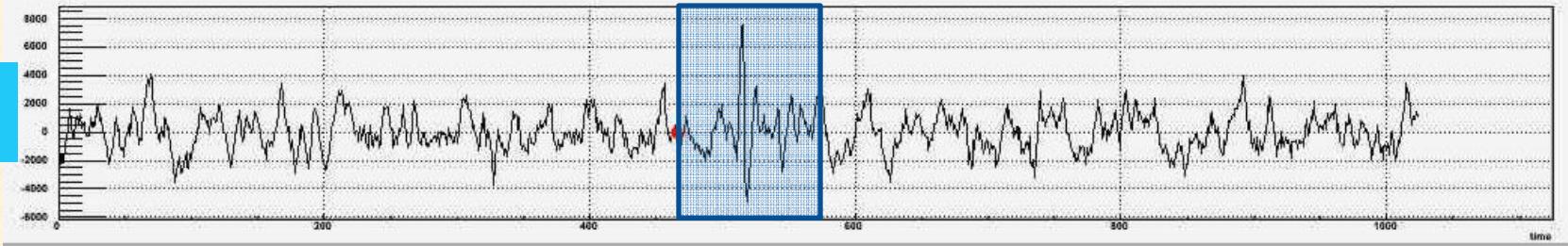
Ch.2



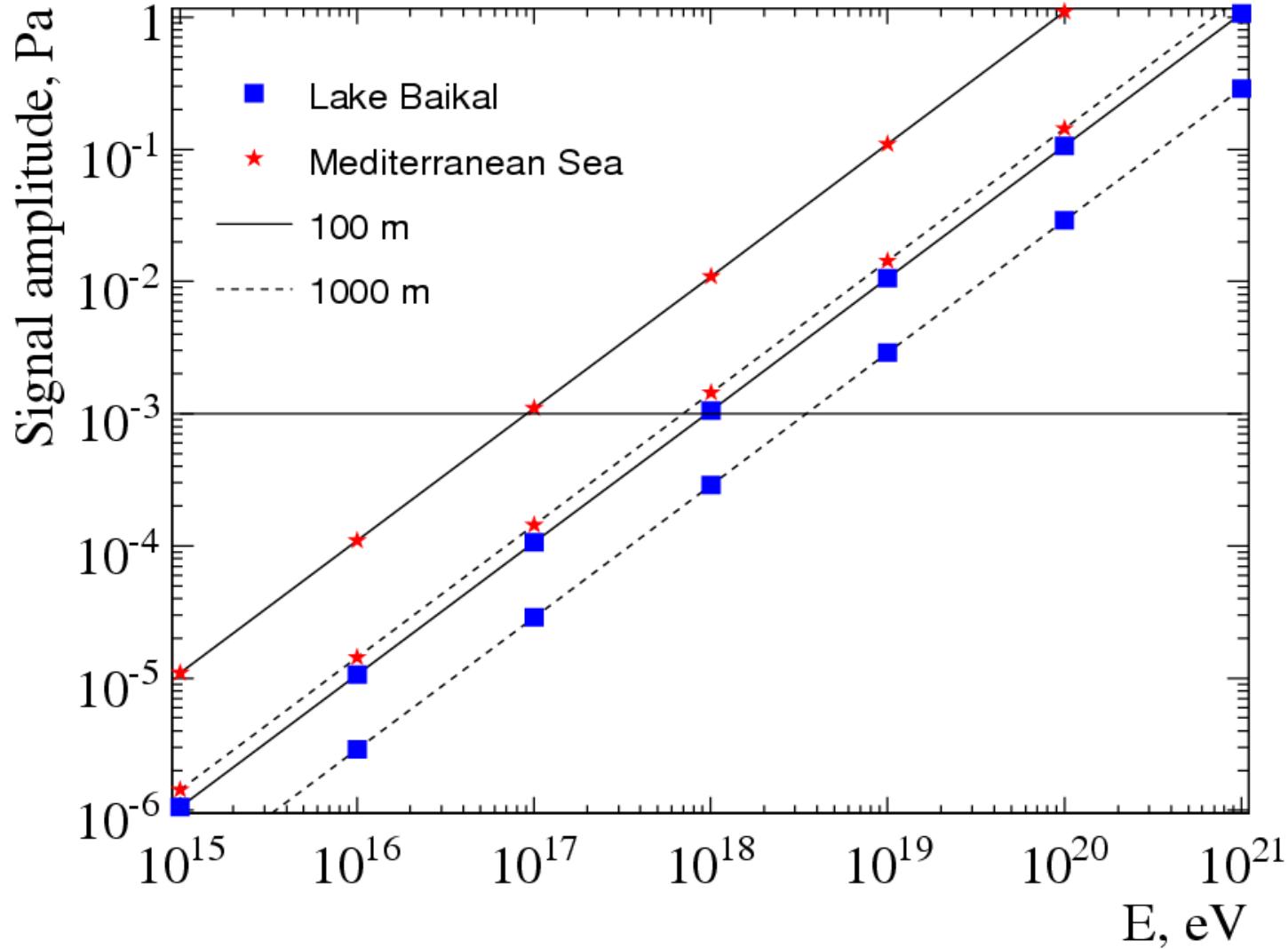
Ch.3



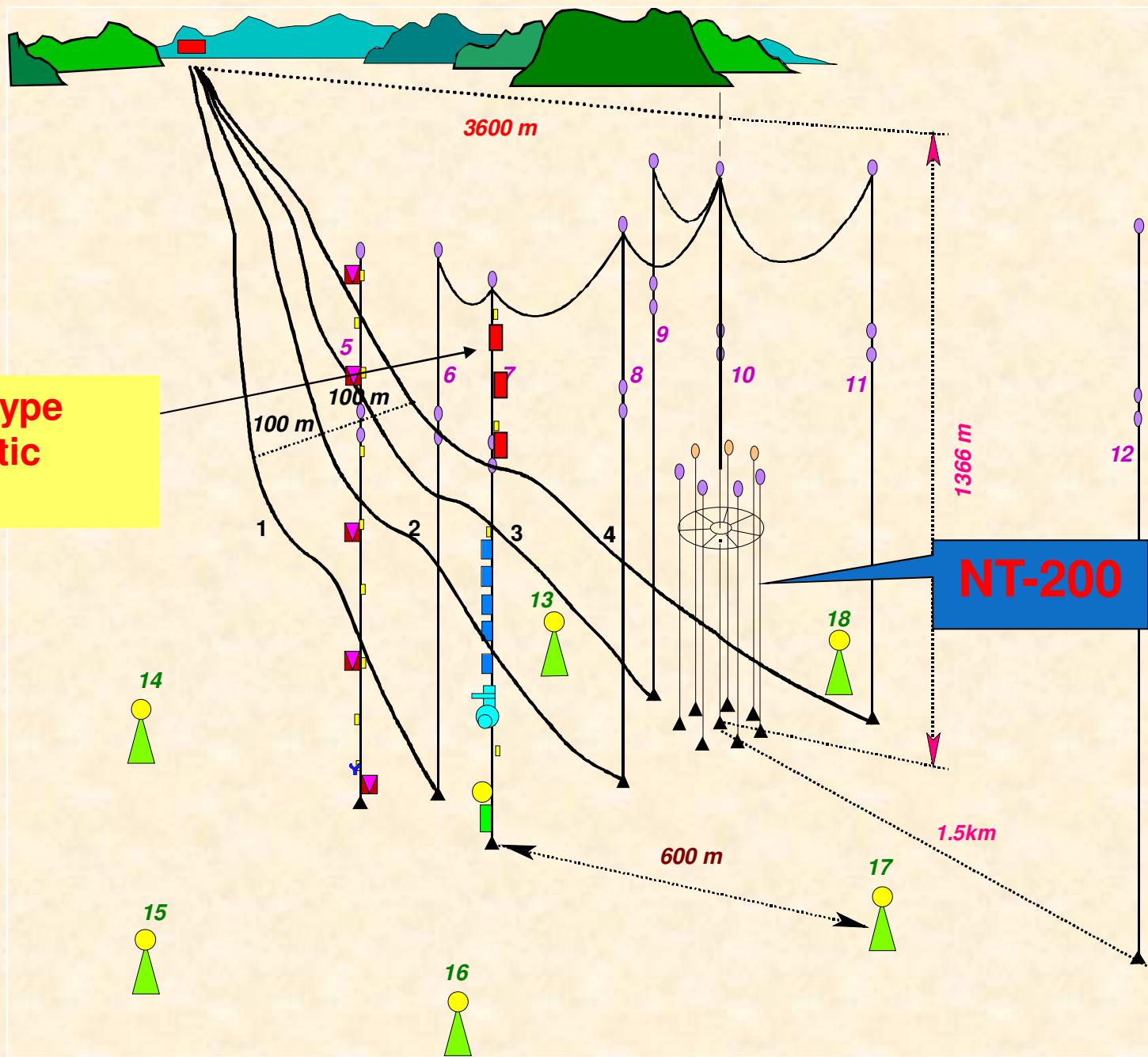
Ch.4



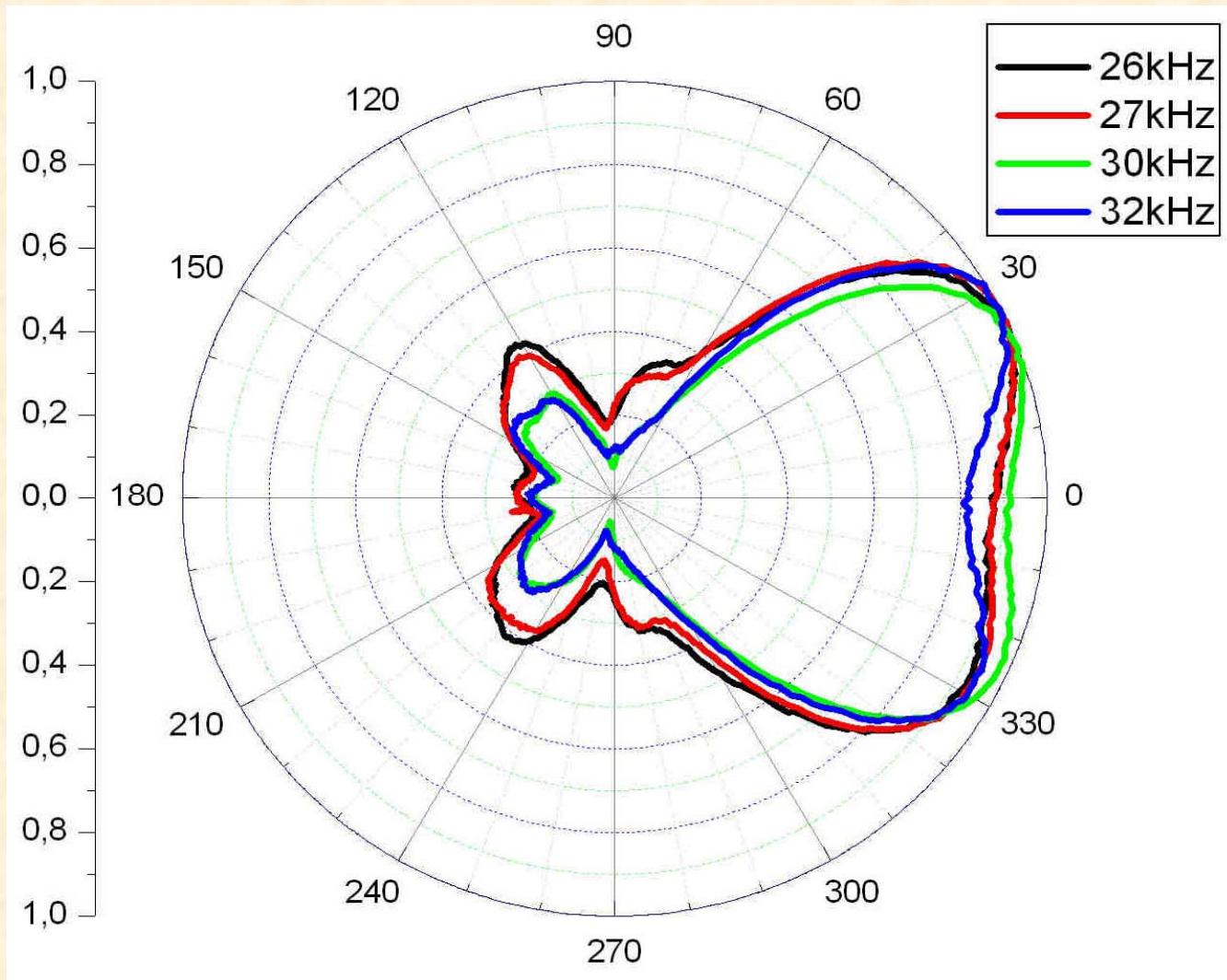
# Acoustic signal amplitude for a shower at 1 km depth



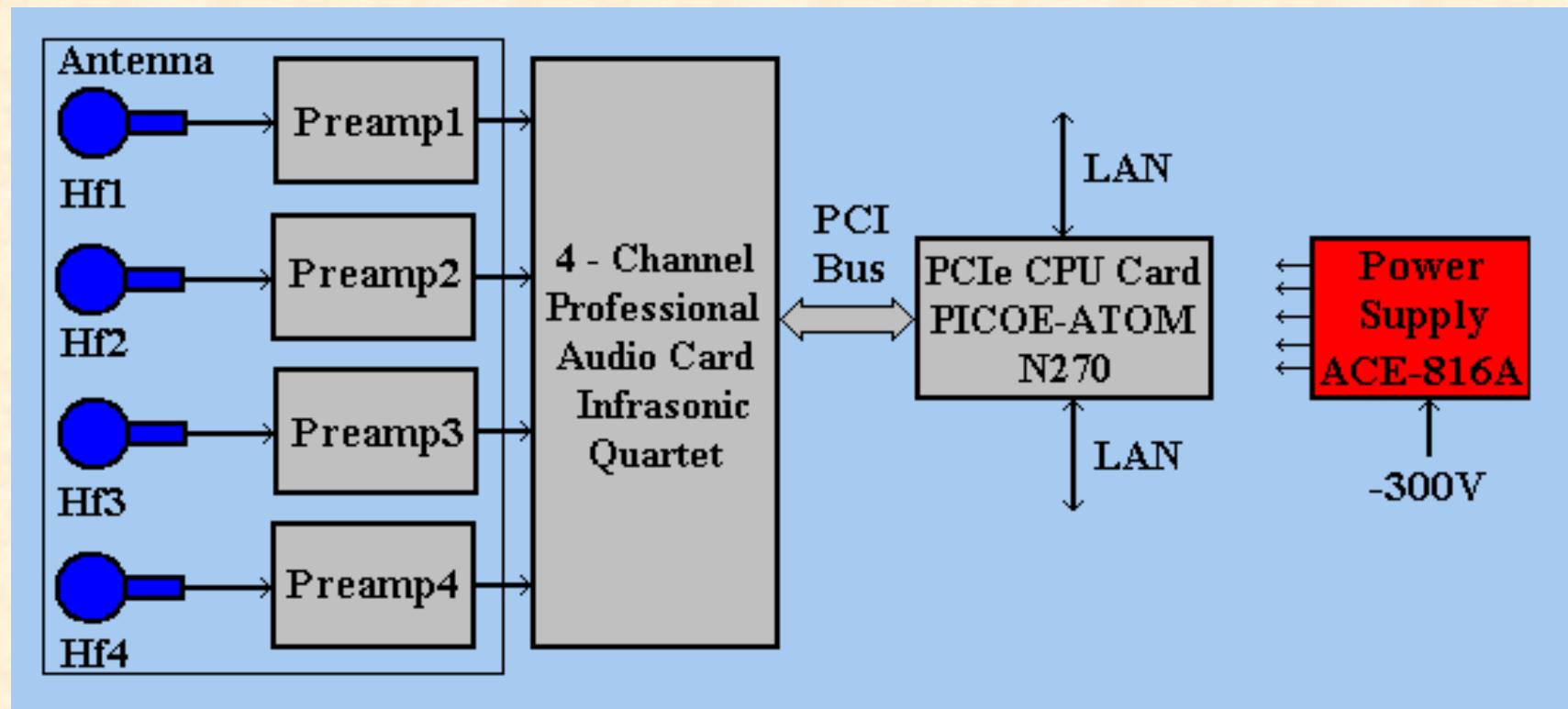
**Prototype  
acoustic  
string**



# Polar pattern of new acoustic sensors



# Acoustic module



# CONCLUSION

1. BAIKAL lake experiment is successfully running since 1993
  - The First Underwater Array
  - First Neutrino Candidates
2. NEW configuration NT200+ starts work at April 2005
  - Improved cascade reconstruction, increased effective volume for cascades;
  - NT200+ gives good possibilities to optimise the design and to investigate the key elements of future GVD detector.
3. Start R&D for Gigaton Volume (km<sup>3</sup>-scale) Detector GVD
  - A “new technology” prototype string was installed: 12 OM<sup>s</sup> with 12”/13” PMT
    - In-situ tests of the prototype string with underwater laser and LED flasher shows good performance of all string elements.
    - GVD Technical Design Report is expected at 2011
4. The results of our investigations show the feasibility of acoustic neutrino detection in Lake Baikal with a threshold energy as low as  $10^{19} - 10^{20}$  eV.

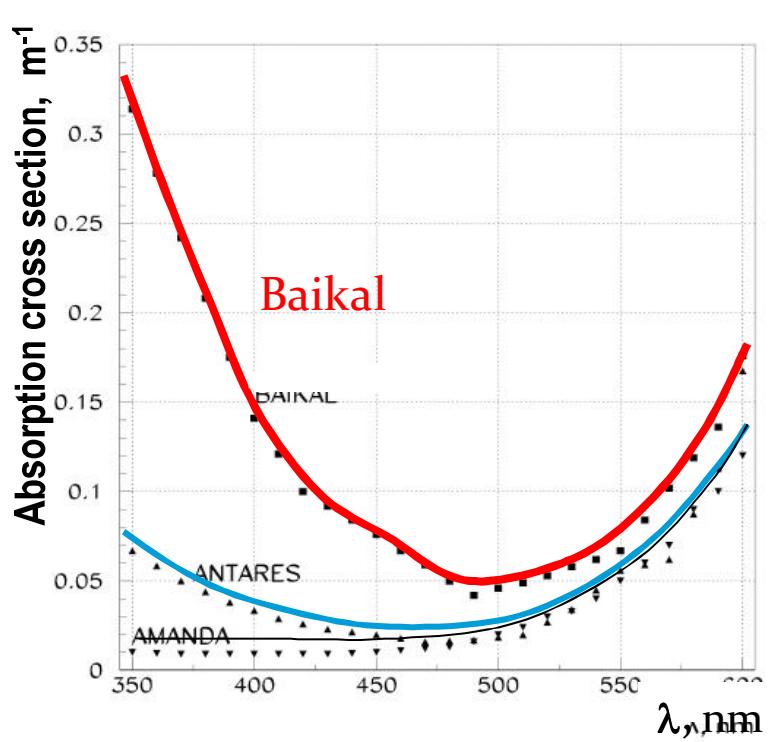
# Thank you!



A photograph of a coastal scene at sunset. The foreground is a sandy beach with some low-lying vegetation and debris. A dense line of green bushes runs along the middle ground. In the background, the ocean stretches to a dark, overcast sky. A white rectangular box is overlaid on the upper right portion of the image, containing the text "The end".

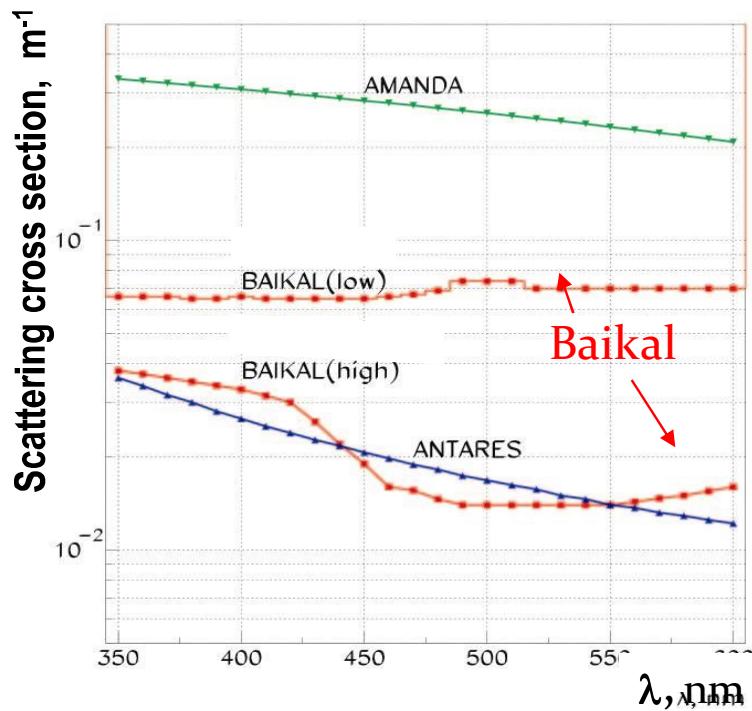
The end

## Baikal Water Cherenkov Detector



Abs.Length:  $22 \pm 2 \text{ m}$

No high luminosity bursts from biology



Scat.Length:  $30\text{-}50 \text{ m}$   
 $\langle \cos\theta \rangle: 0.85\text{-}0.90$