The BAIKAL Neutrino Experiment: status, selected physics results, and perspectives

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for the Baikal Collaboration
(RICAP07, Rome, 2007)

Collaboration

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

Baikal Neutrino Project

Milestones:

>1983: site / water studies;

R&D: large area PMT, u-water techn.;

physics small setups (exotics search)

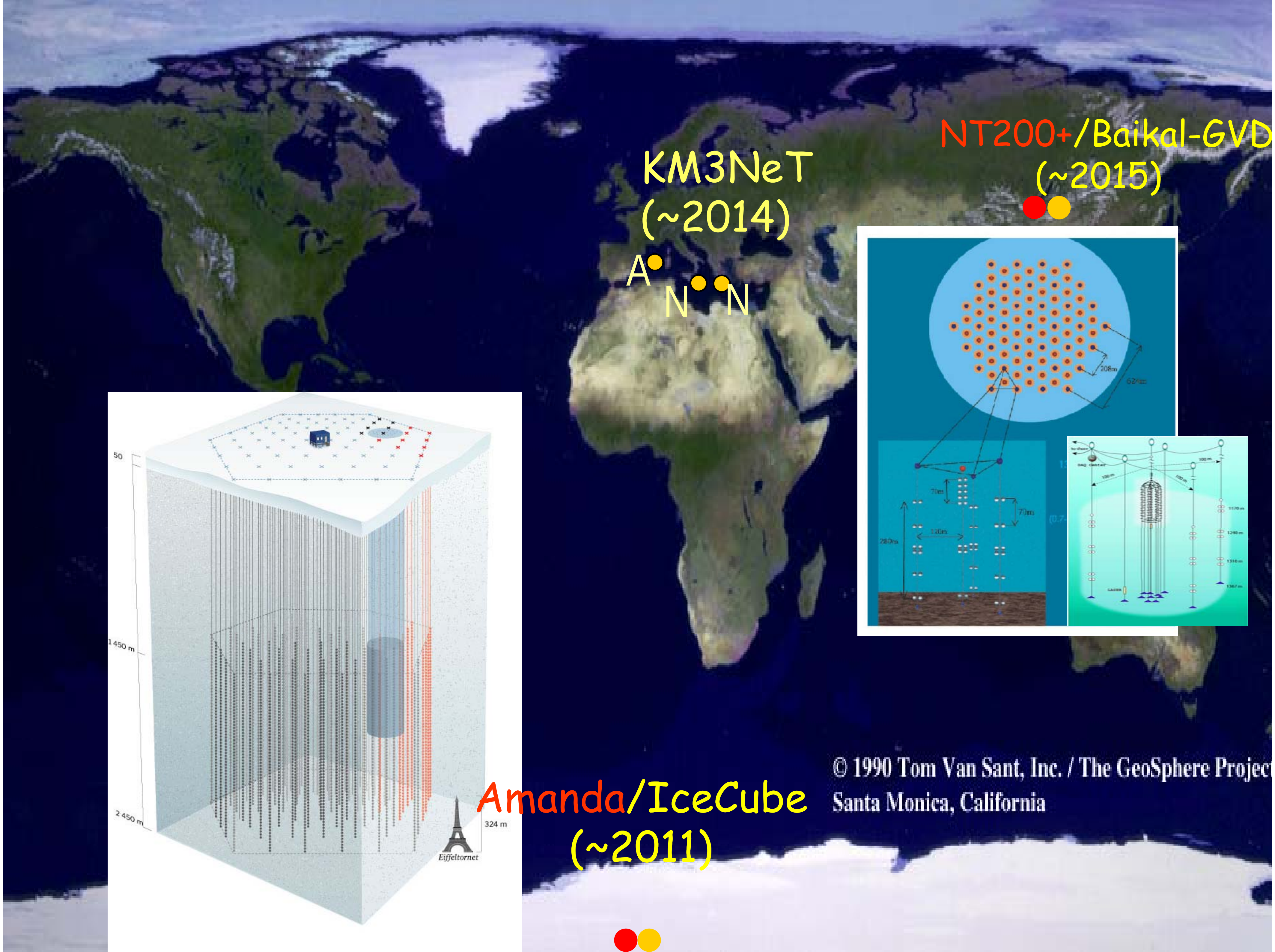
1991: Proposal for NT200 detector in Lake Baikal submitted

1993: NT36 – the first underwater array operates

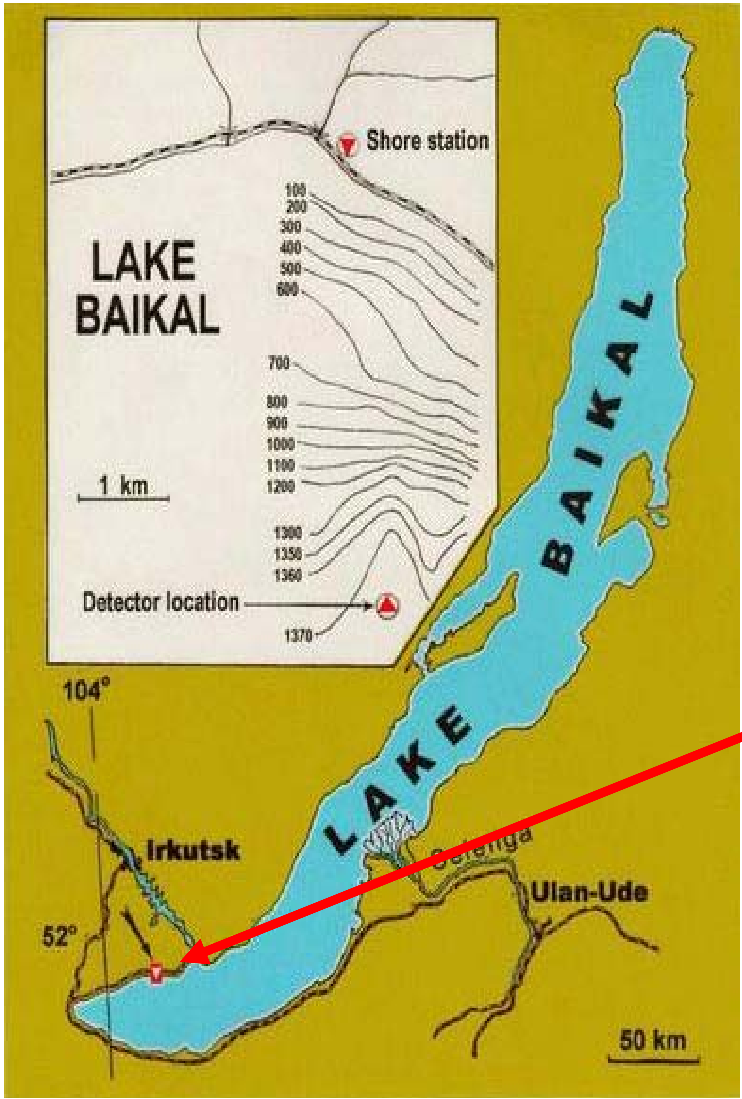
1998: NT200 commissioned

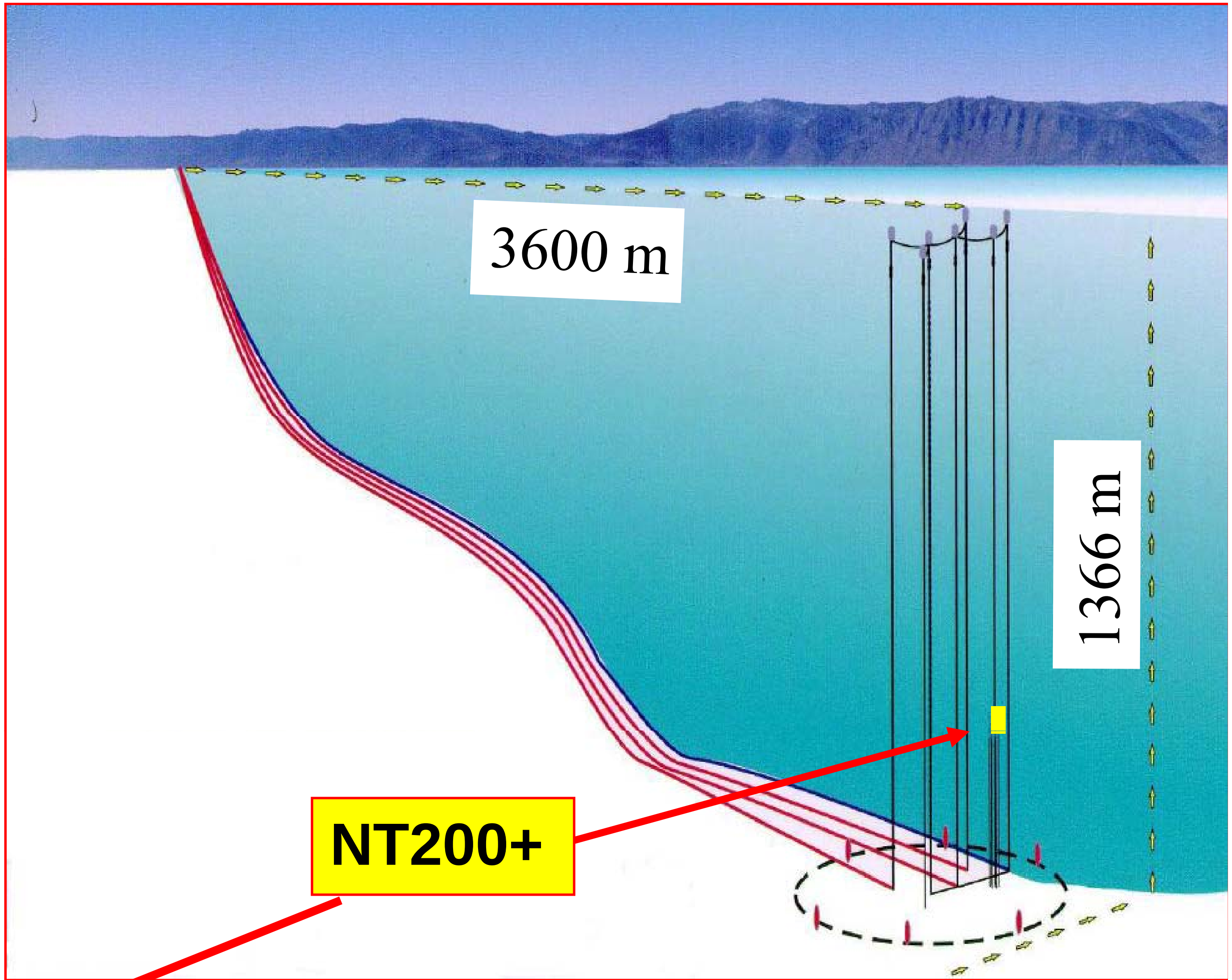
2005 - 2006: NT200+ completed and currently is operating

>2006: Activity towards Gigaton Volume Detector in Lake Baikal


NT200+/Baikal-GVD
(~2015)
KM3NeT
(~2014)
A
N
N
50
1 450 m
2 450 m
324 m
Eiffeltornet
Amanda/IceCube
(~2011)
© 1990 Tom Van Sant, Inc. / The GeoSphere Project
Santa Monica, California

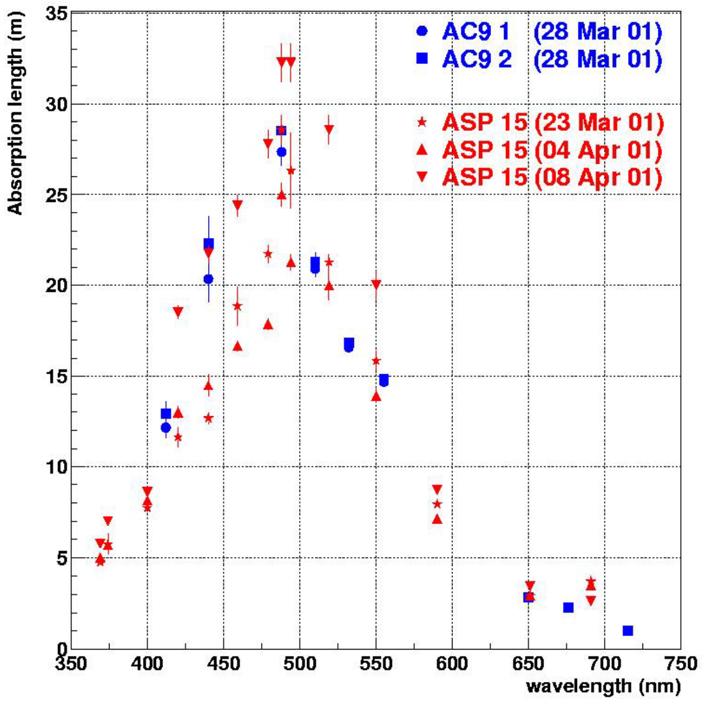
The Site

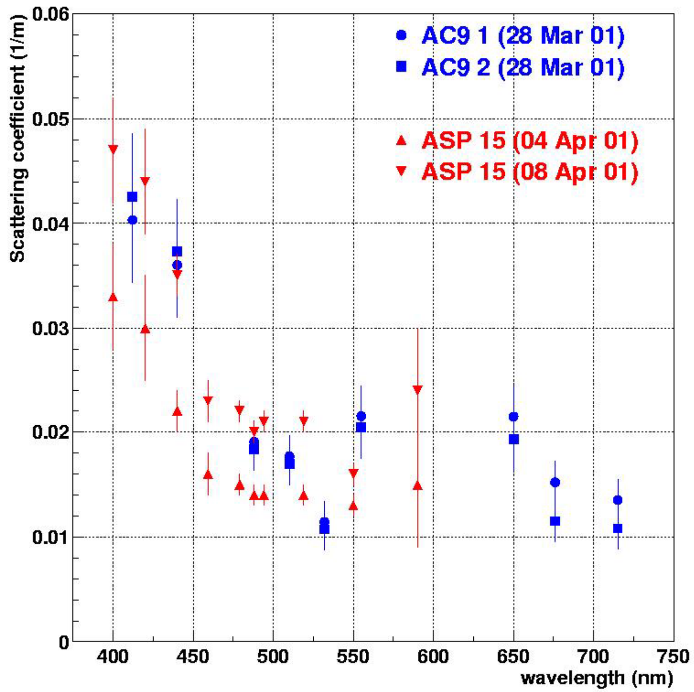




- 4 cables x 4km to shore.
- 1100m depth

Baikal - Optical Properties





Abs. Length: ~25 m

Scatt. Length (geom) ~ 30-60 m
$\langle \cos \Theta \rangle$ ~ 0.85-0.9

AC9 (trnasmissometer), used by the NEMO group

ASP15 (Absorption, Scattering and Phase function meter), used by the BAIKAL group

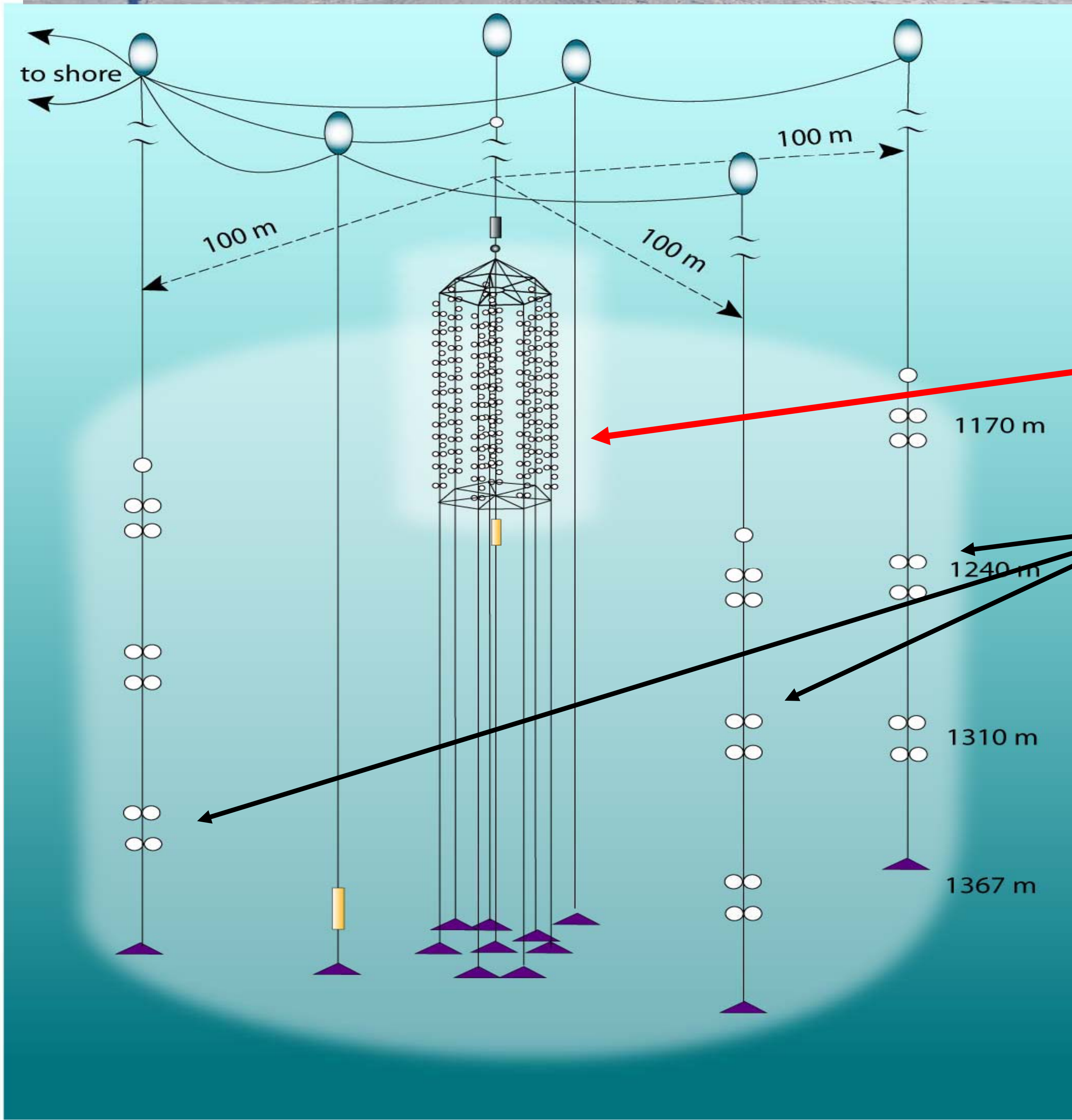
NIM A498 (2003) 231

Ice as a natural deployment platform

Ice stable for 6-8 weeks/year:

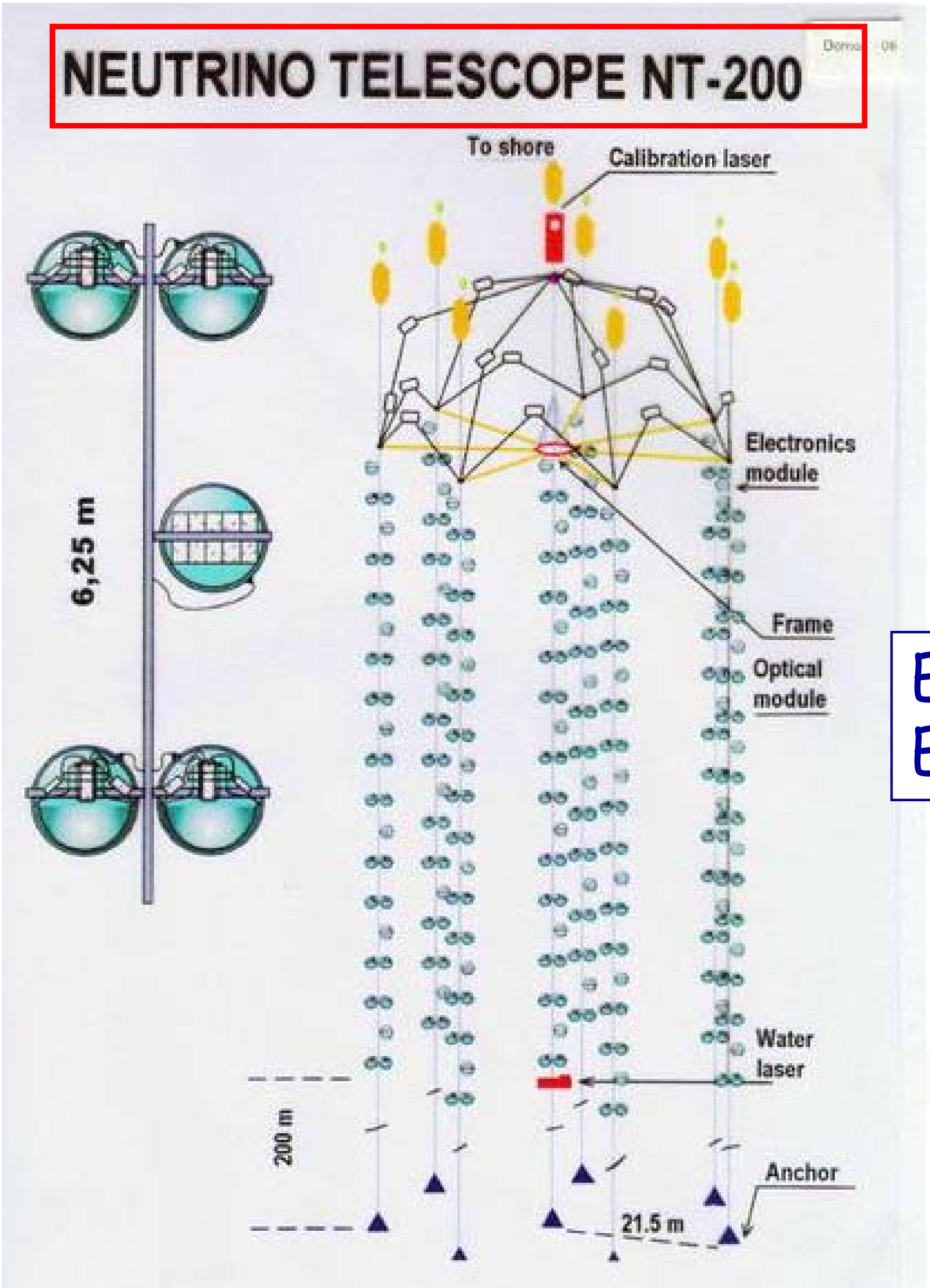
- **Maintenance & upgrades**
- **Test & installation of new equipment**

Winches used for deployment



NT200+
=
NT200
+
3 long outer strings

- **Height = 210m**
- **∅ = 200m**
- **Volume ~ 5 Mton**



- 8 strings: 72m height
- 192 optical modules
  = 96 pairs (coincidence)
- measure T, Charge
  - σ_T ~ 1 ns
  - dyn. range ~ 1000 p.e.

Effective area: 1 TeV ~2000 m^2
Eff. shower volume: 10TeV ~0.2Mt

Height x ∅ = 70m x 40m, $V_{inst}=10^5 m^3$

Quasar PM:
d=37cm

Outline:

- Physics Results (selected) : NT200 1998-2002

- Gigaton Volume Detector in Lake Baikal
- a) NT200+   (10 Mt Detector) - intermediate stage to GVD
- b) present and nearest future activities toward GVD

- Conclusion

NT200 - Selected Results

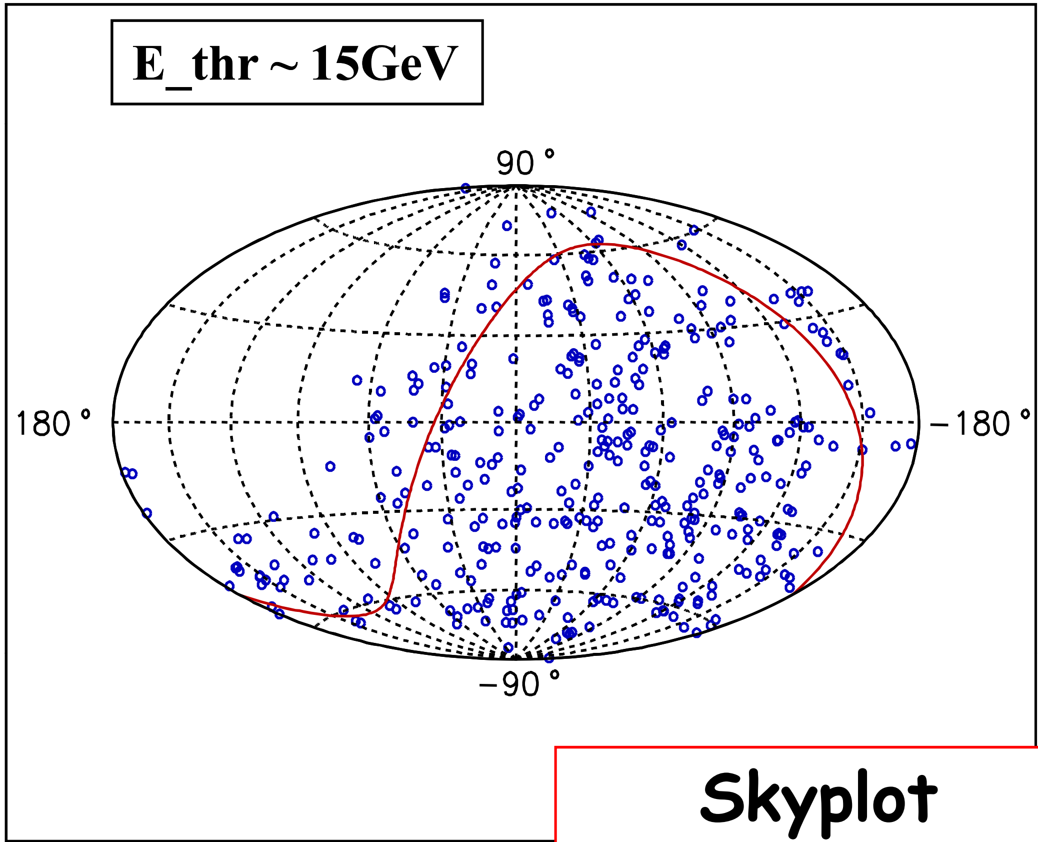
Data sample - 1998-2002: 1038 days (Apr.98-Feb.03)

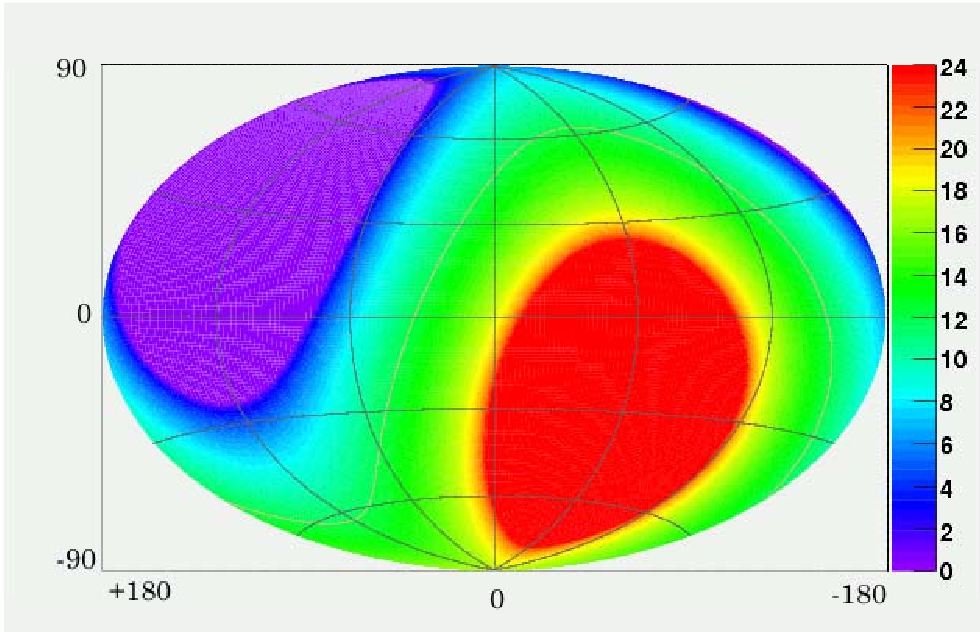
- Low energy phenomena:

- Atmospheric neutrinos

- WIMP Neutrinos

Atmospheric Muon-Neutrinos





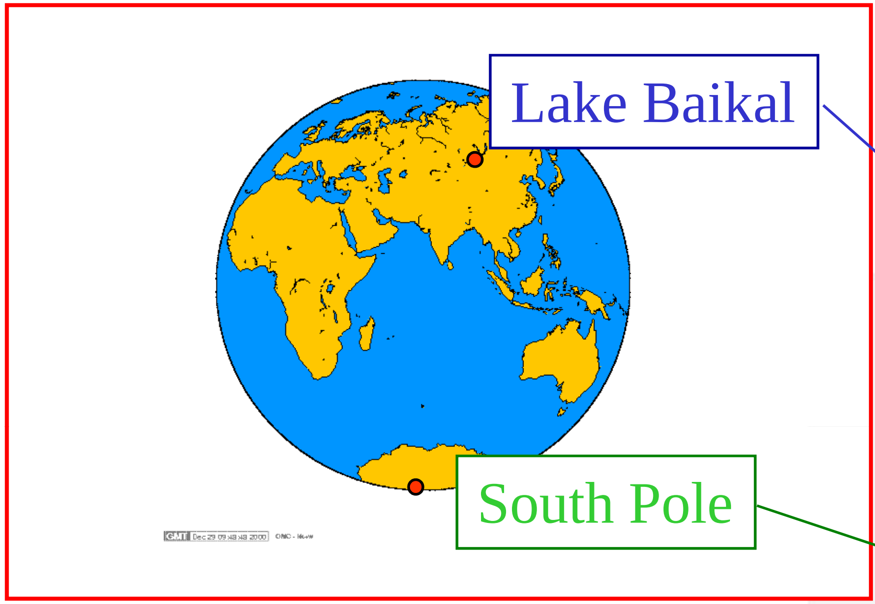
Skyplot
(galactic coordinates)

- With weaker cuts, 1998-2002: 372 events. N_μ(>15GeV)/N_μ(>1GeV)~1/7
  → A higher statistics neutrino sample for Point-Source Search.
- MC: 385 ev. Expected (15%BG).

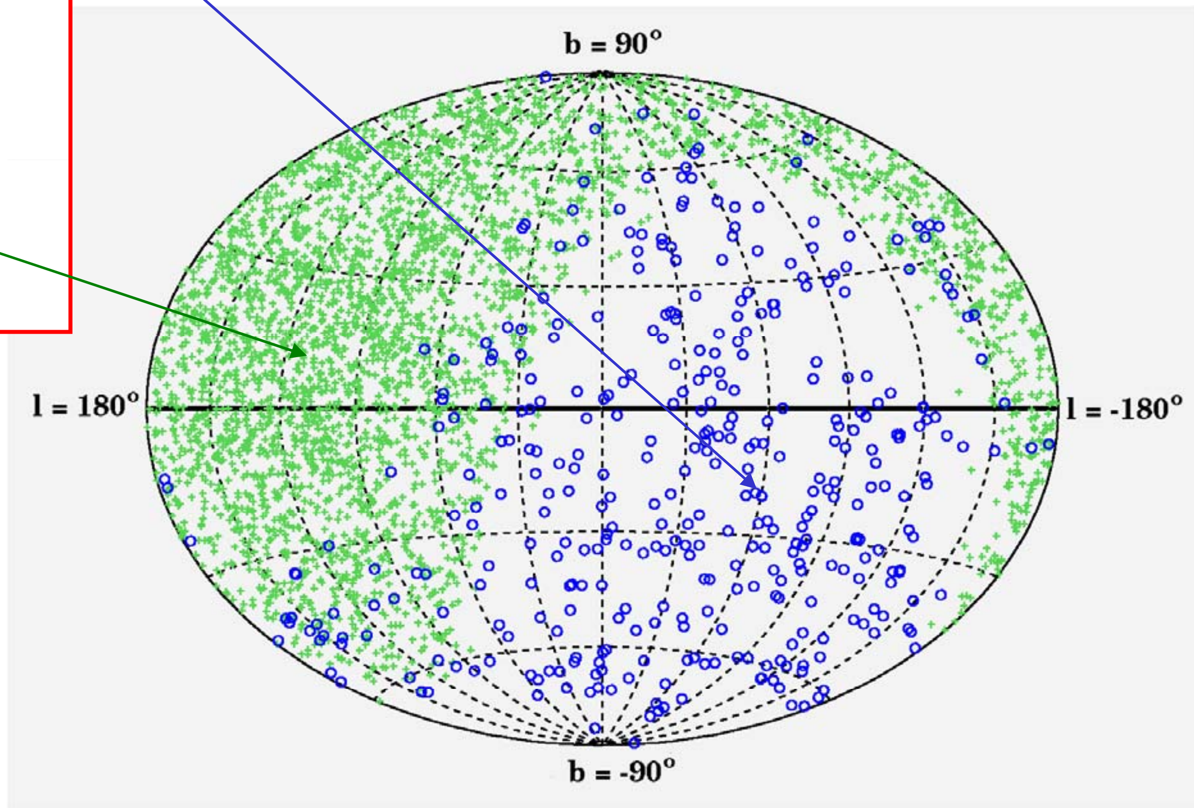
Atmospheric Muon-Neutrinos

Lake Baikal (NT200) & South Pole (Amanda)

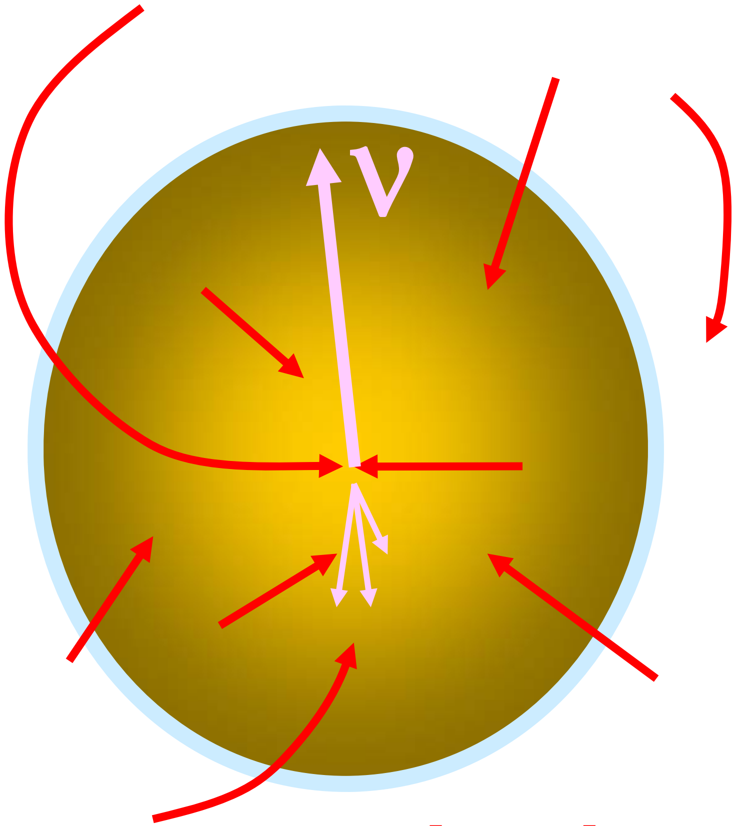
Complete sky coverage including central parts of Galaxy



Skyplot of neutrino events



WIMP Neutrinos from the Center of the Earth

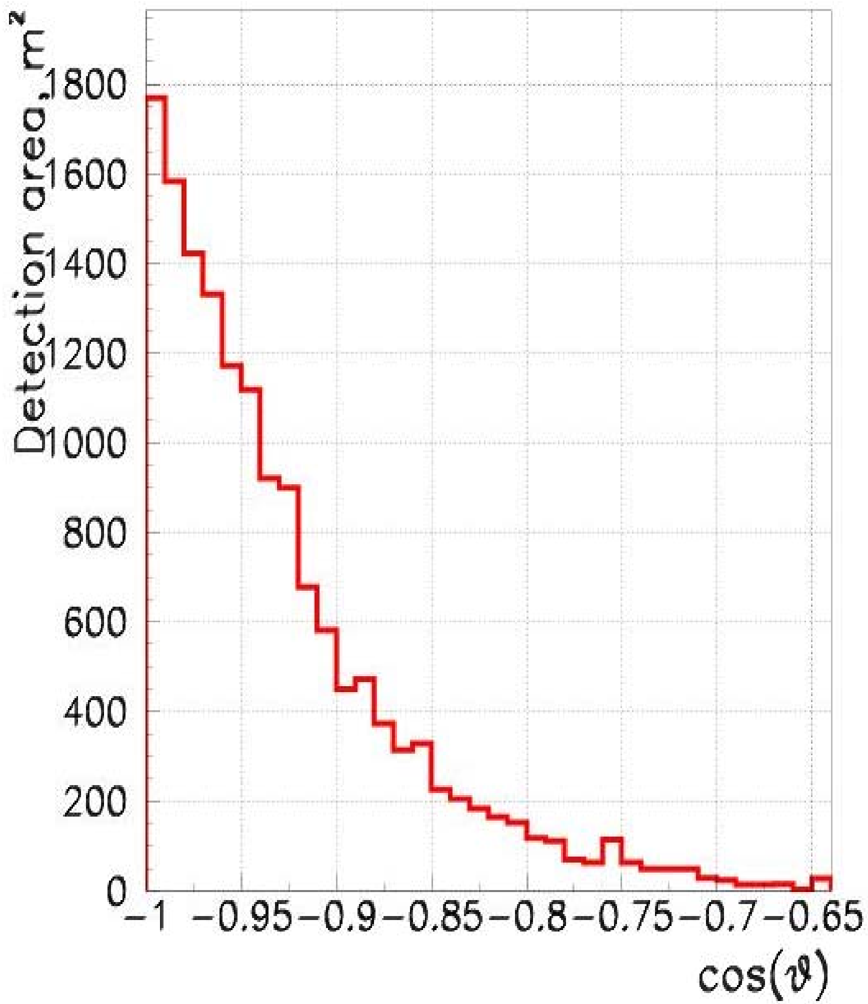


$$\chi + \chi \rightarrow b + b$$

$$\searrow c + \mu + \nu_\mu$$

$$\rightarrow W^+ + W^-$$

Detection area of NT-200 for vertically up-going muons detection (after all cuts)



WIMP Neutrinos from the Center of the Earth

Data analysis

Livetime – 1038 days (April 1998 – February 2003)

	Trigger: $N_{hit} > 3$	**---**	**3.45×10^8**	**events detected**
after	**Cut 1**	**---**	**90653**	**events selected**
after	**all Cuts**	**---**	**48**	**events selected**

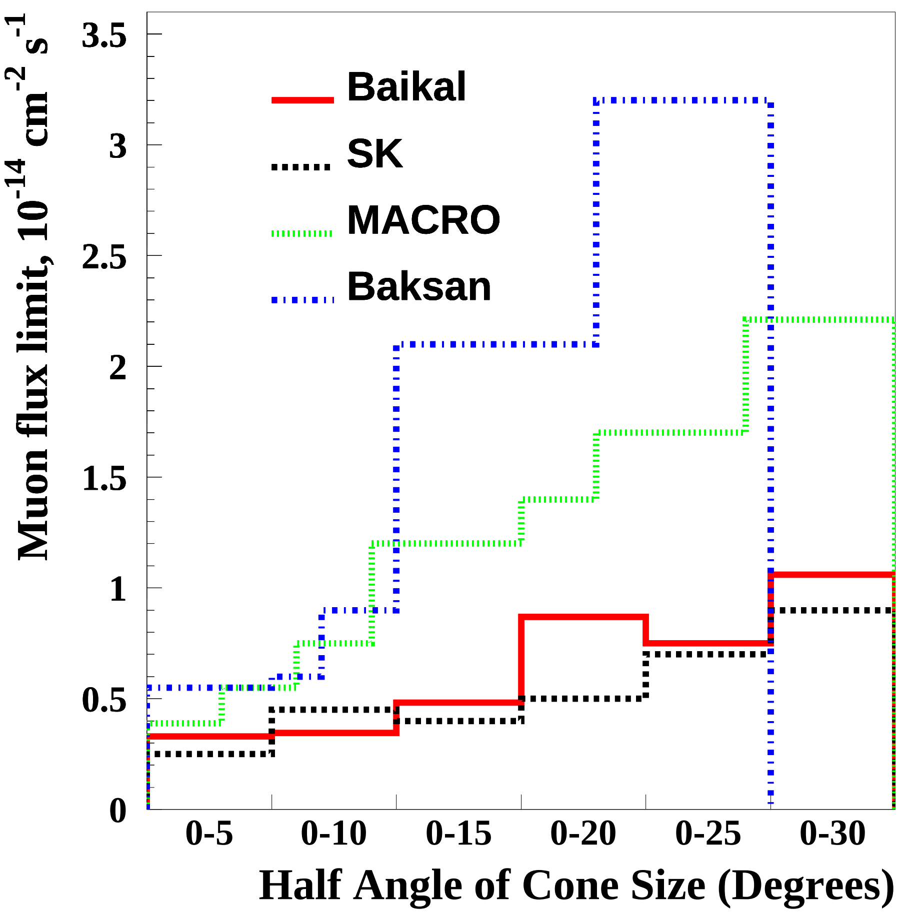
Atm. neutrinos	**---**	**73.1**	**events without oscillations**
(expectation)	**---**	**56.6**	**events with oscillations**
Atm. muons (background)	**---**	**3.6**	**events expected**

Systematic uncertainties: 24%

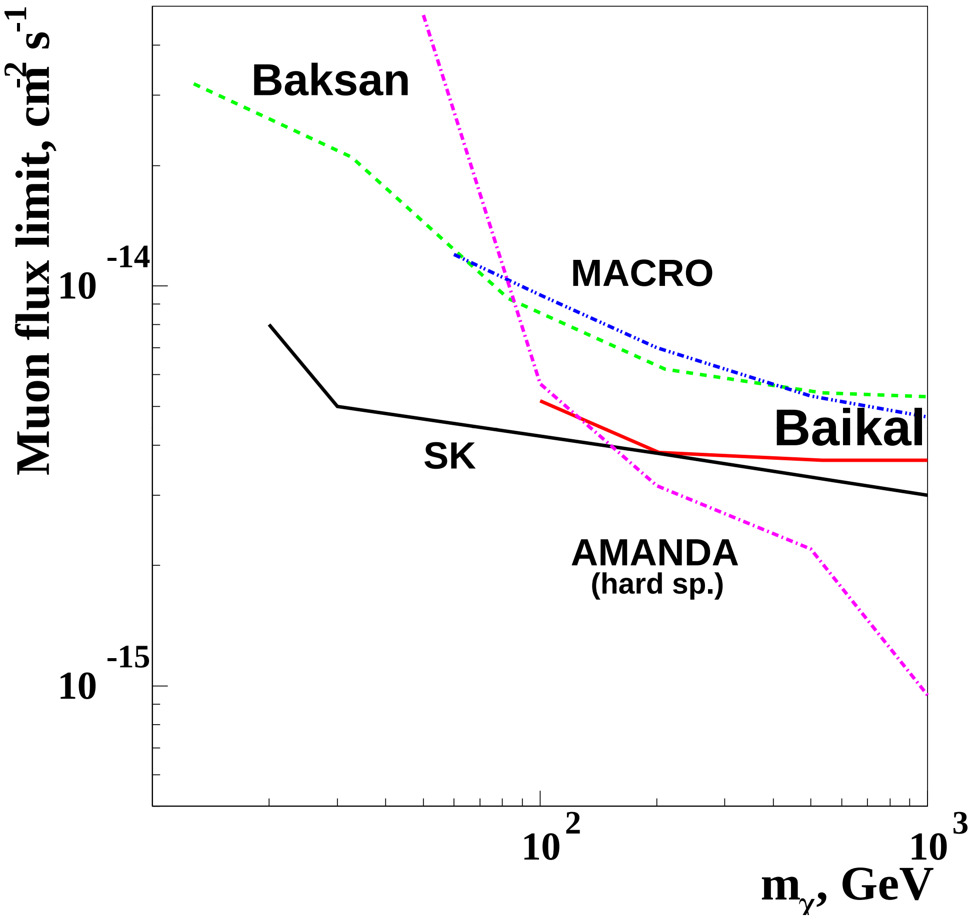
Within stat. and syst. uncertainties 48 detected events are compatible with the expected background induced by atmospheric neutrinos with oscillations.

90% C.L. upper limit on the excess muon flux

	Baikal	Amanda	SK	Baksan	MACRO
T, days	1038	422	1680	5402	1298



$E_\mu > 1$ GeV



Using Baksan estimations for MSSM(P=0.5; m_a =52.5GeV; tgβ=8))

NT200 - Selected Results

Data sample - 1998-2002: 1038 days (Apr.98-Feb.03)

High-energy phenomena:

- Diffuse neutrino flux
- Neutrinos from GRB
- Prompt muons and neutrinos
- Exotic HE muons

- **Search for exotic particles:**
- Relativistic magnetic monopoles

Search for fast monopoles ($\beta > 0.8$)

$N_\gamma(\lambda) = n^2 (g/e)^2 N_{\gamma\mu}(\lambda) = 8300\ N_{\gamma\mu}(\lambda)$

$g = 137/2, \quad n = 1.33$

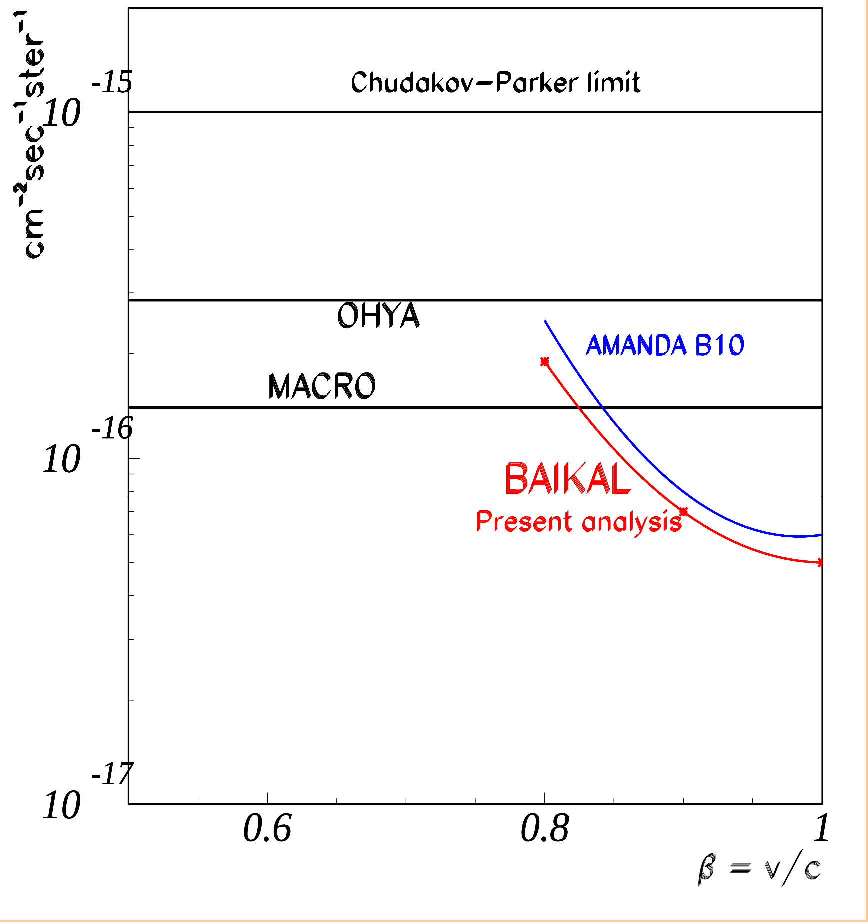
$\sim E_\mu = 10^7$ GeV

Event selection criteria:

hit channel multiplicity - $N_{hit} > 35$ ch,
upward-going monopole -
$\Sigma(z_i - z)(t_i - t)/(\sigma_t \sigma_z) > 0.45$ & $\theta > 100^o$

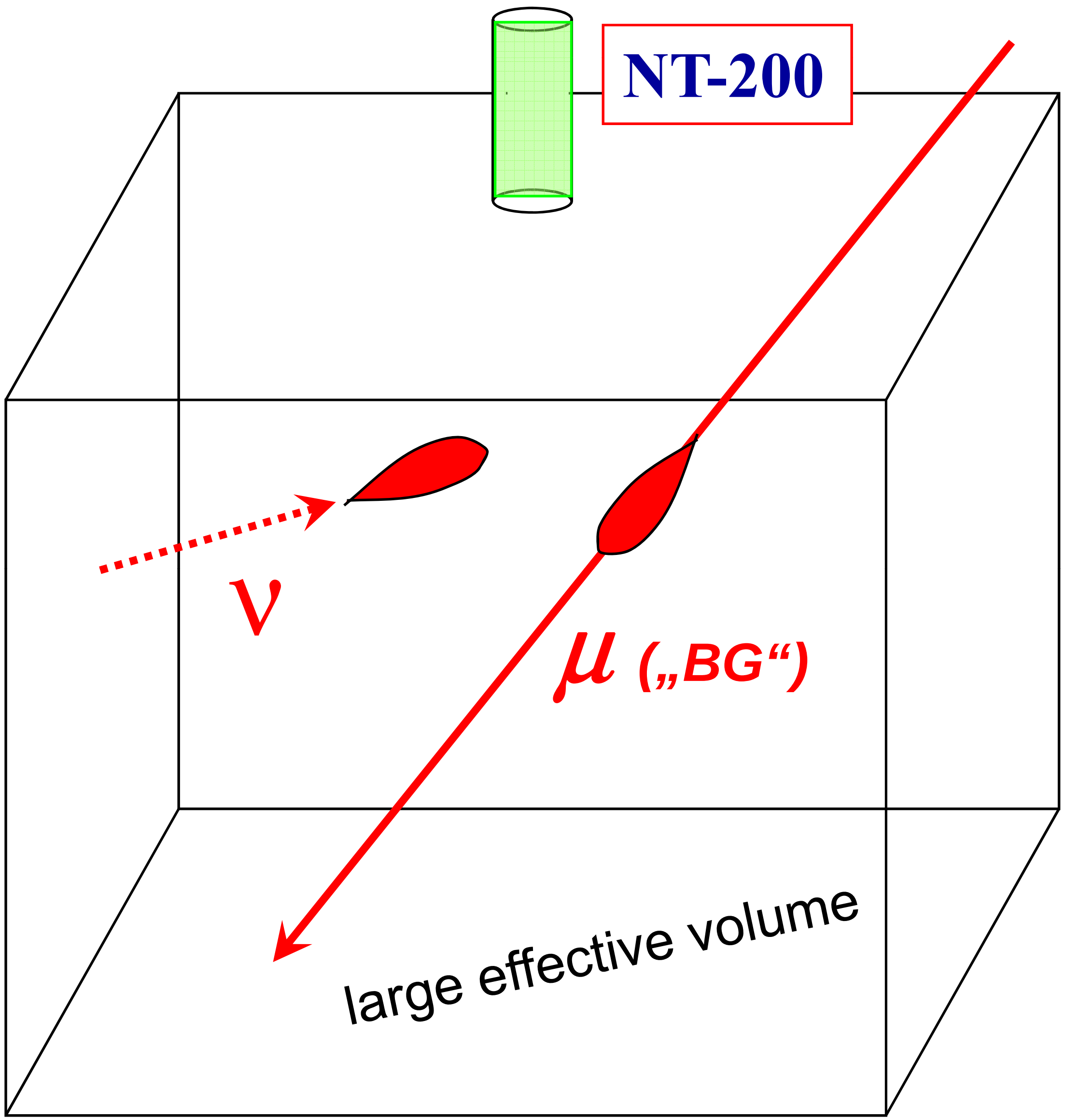
Background - atmospheric muons

Limit on a flux of relativistic monopoles: $\Phi < 4.6\ 10^{-17}$ cm^{-2} sec^{-1} sr^{-1}



90% C.L. upper limit on the flux of fast monopole (1003 livedays)

Search for High-Energy Cascades



NT-200 is used to watch the volume below for cascades.

Physics topics:

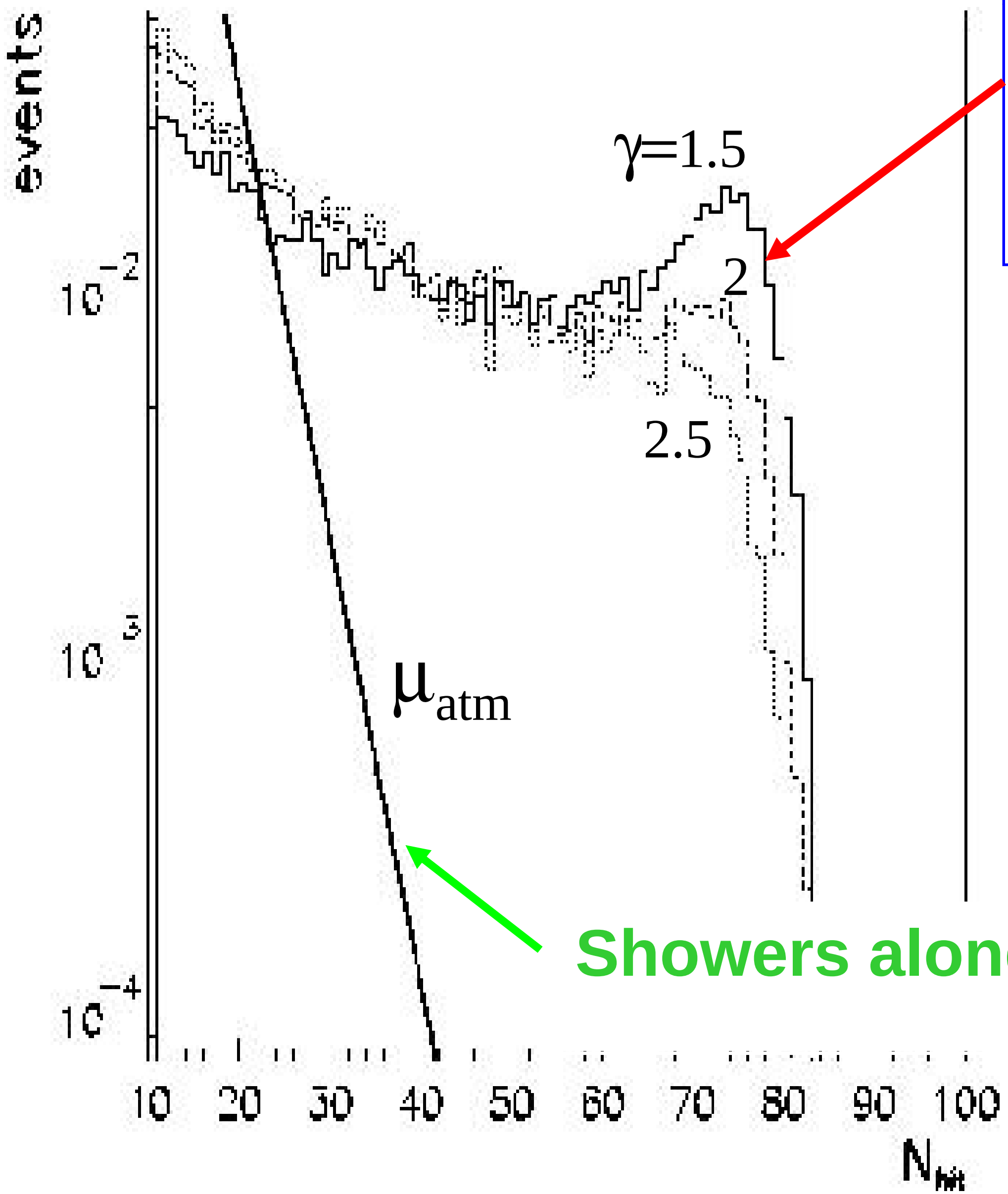
- HE cascades from $\nu_e\ \nu_\mu\ \nu_\tau$ - NC/CC
  - ❑ Diffuse astroph.flux
  - ❑ GRB correlated flux
- HE atmospheric muons (the „BG" to ν's)
  - ❑ Prompt μ
  - ❑ Exotic μ
- ...

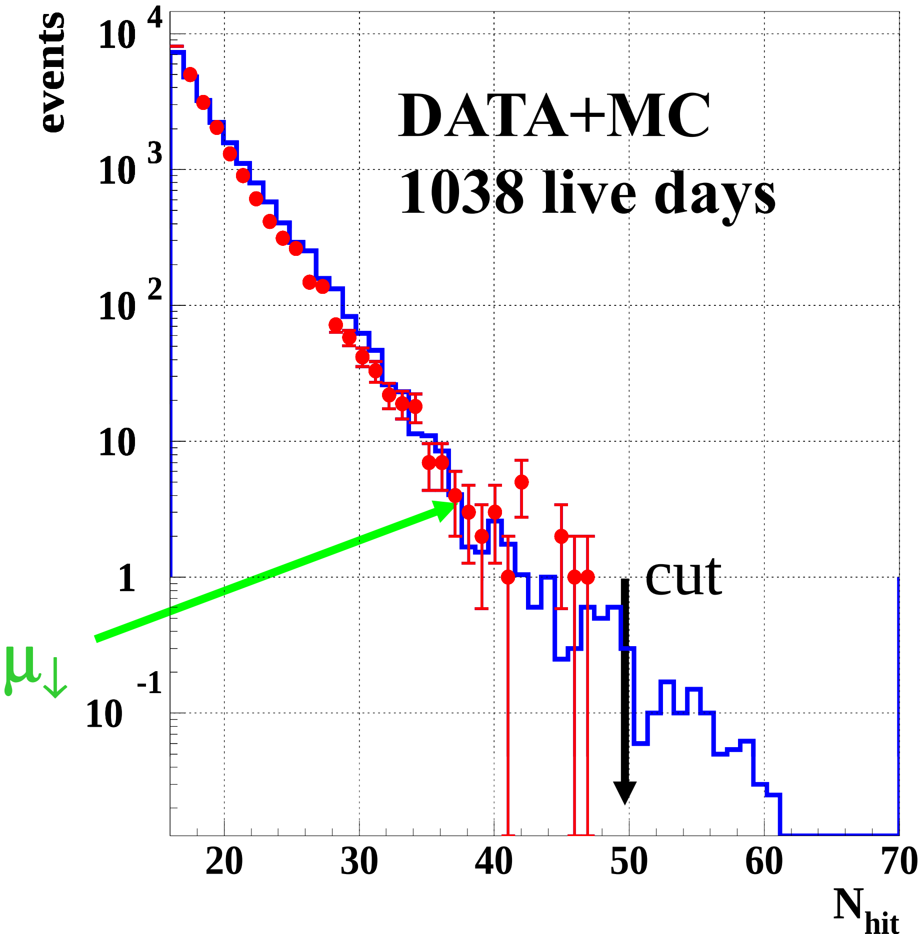
Selecting HE Cascades

<u>Hard signal spectra would pile up</u> in the "energy parameter"

N_{hit} = Number of Channels hit

Shape of signal in N_{hit} distribution for $\Phi_\nu = A\,E^{-\gamma}$ (γ=1.5, 2.0, 2.5).

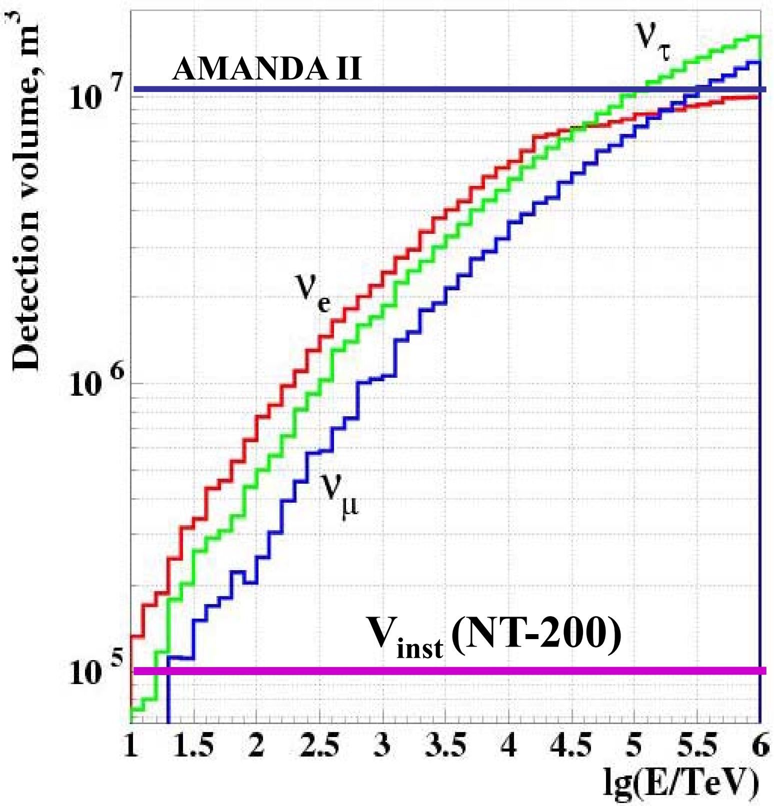




Showers along $\mu_\downarrow$

Diffuse Flux ν_e, ν_τ, ν_μ Limit

Detection Volume vs. Energy



V_{det} > 1 Mton at 1 PeV

No events observed (24% system. err.) **→ 2.5 evt exp.**

The 90% C.L. "all flavour" limit (1038 days)
for a γ=2 spectrum $\Phi_\nu \sim E^{-2}$ (20 TeV < E < 50 PeV),

and assuming ν_e:ν_μ:ν_τ = 1 : 1 : 1 at Earth (1 : 2 : 0 at source)

$E^2 \Phi_\nu < 8.1 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} (Baikal 2005)

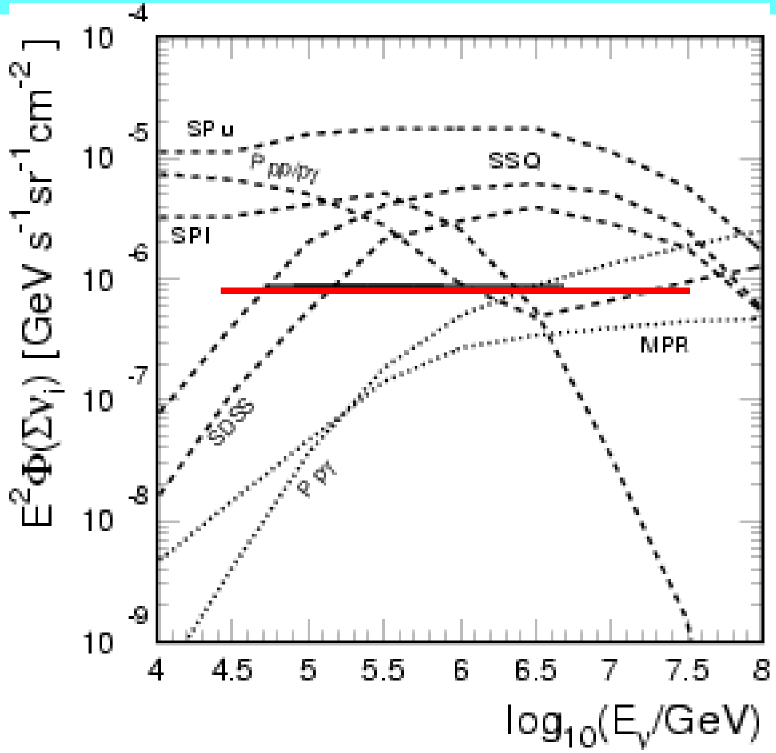
$E^2 \Phi_\nu < 2.2 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} (Muons AMANDA-II, 2007)

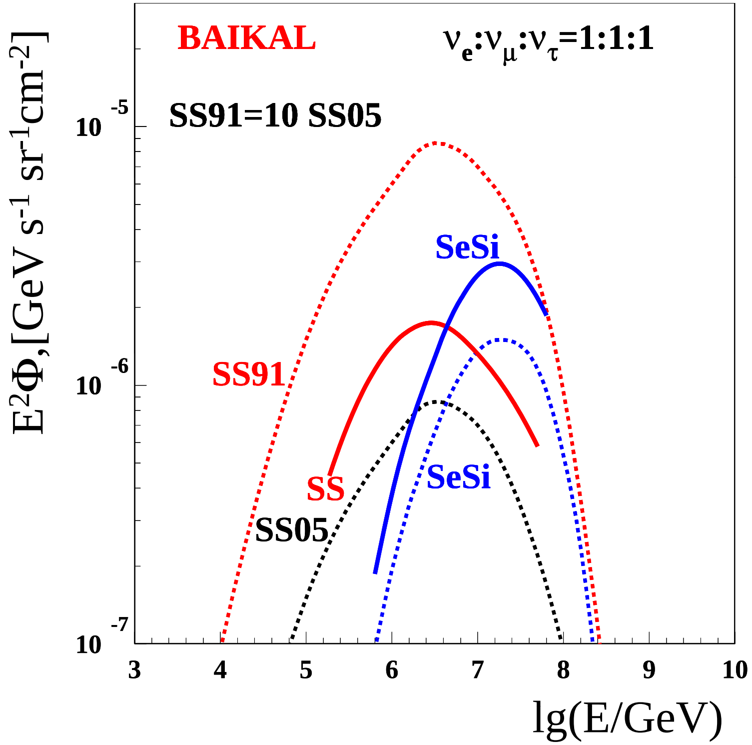
90% C.L. Limit via W-RESONANCE production
(E = 6.3 PeV, $\sigma = 5.3 \cdot 10^{-31}$ cm^2)

$\Phi_{\nu e} < 3.3 \cdot 10^{-20}$ $(cm^2 \cdot s \cdot sr \cdot GeV)^{-1}$ (Baikal 2005)

$\Phi_{\nu e} < 5.0 \cdot 10^{-20}$ $(cm^2 \cdot s \cdot sr \cdot GeV)^{-1}$ (AMANDA 2004)

Limits on neutrino fluxes predicted by different models





Model survival factor $n_{90\%}$ /N_{model}

Model	BAIKAL	AMANDA
SS05 Quasar	2.5	1.6
SP u	0.062	0.054
SP l	0.37	0.28
M pp+pγ	2.86	-
P pγ	1.14	1.99
MPR	4.0	2.0
SeSi	2.12	-

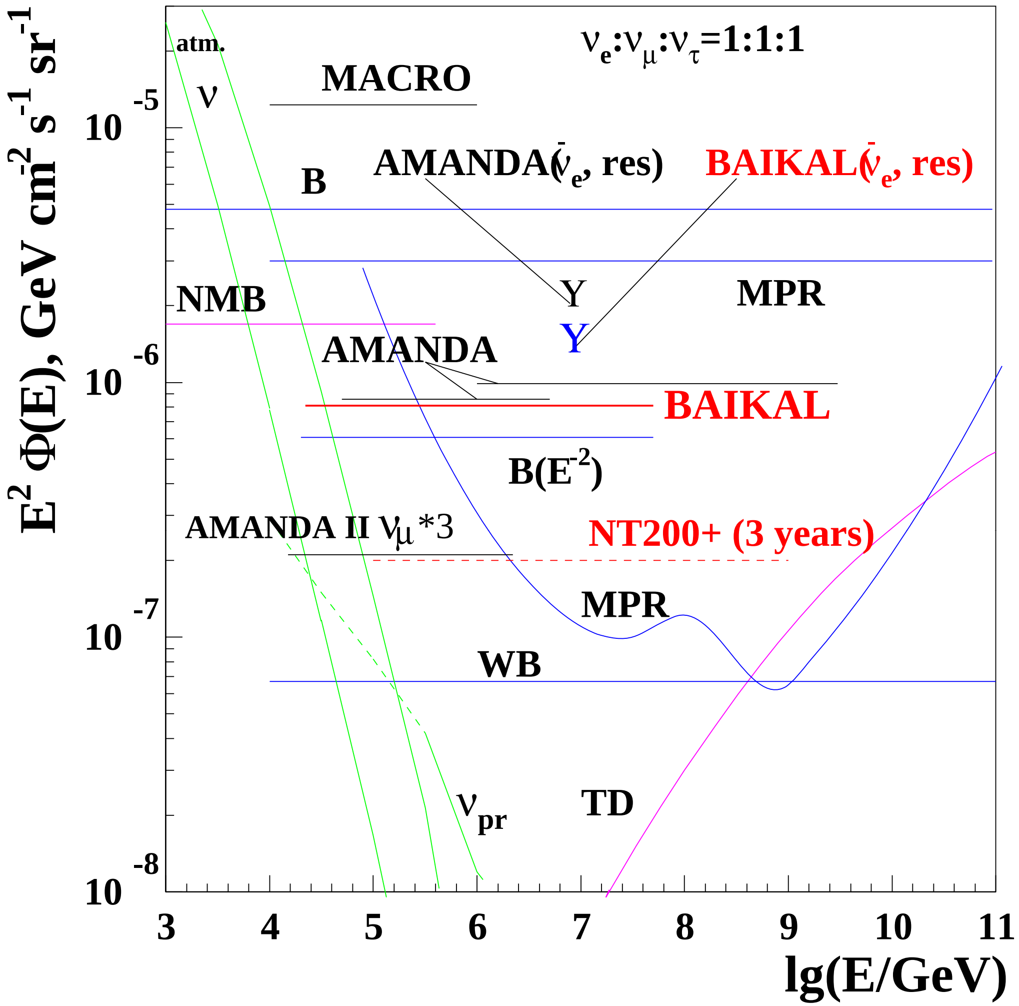
Neutrino from Quasar cores

SS – Stecker, Salamon (96,05)
SP – Szabo, Protheroe (92)

Neutrino from blazars

M pp+pγ - Mannheim (95)
P pγ - Protheroe (96)
MPR - Mannheim, Protheroe, Rachen (01)
SeSi - Semikoz, Sigl, (03)

Diffuse Flux Limits + Models



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Ultimate goal of Baikal Neutrino Project:

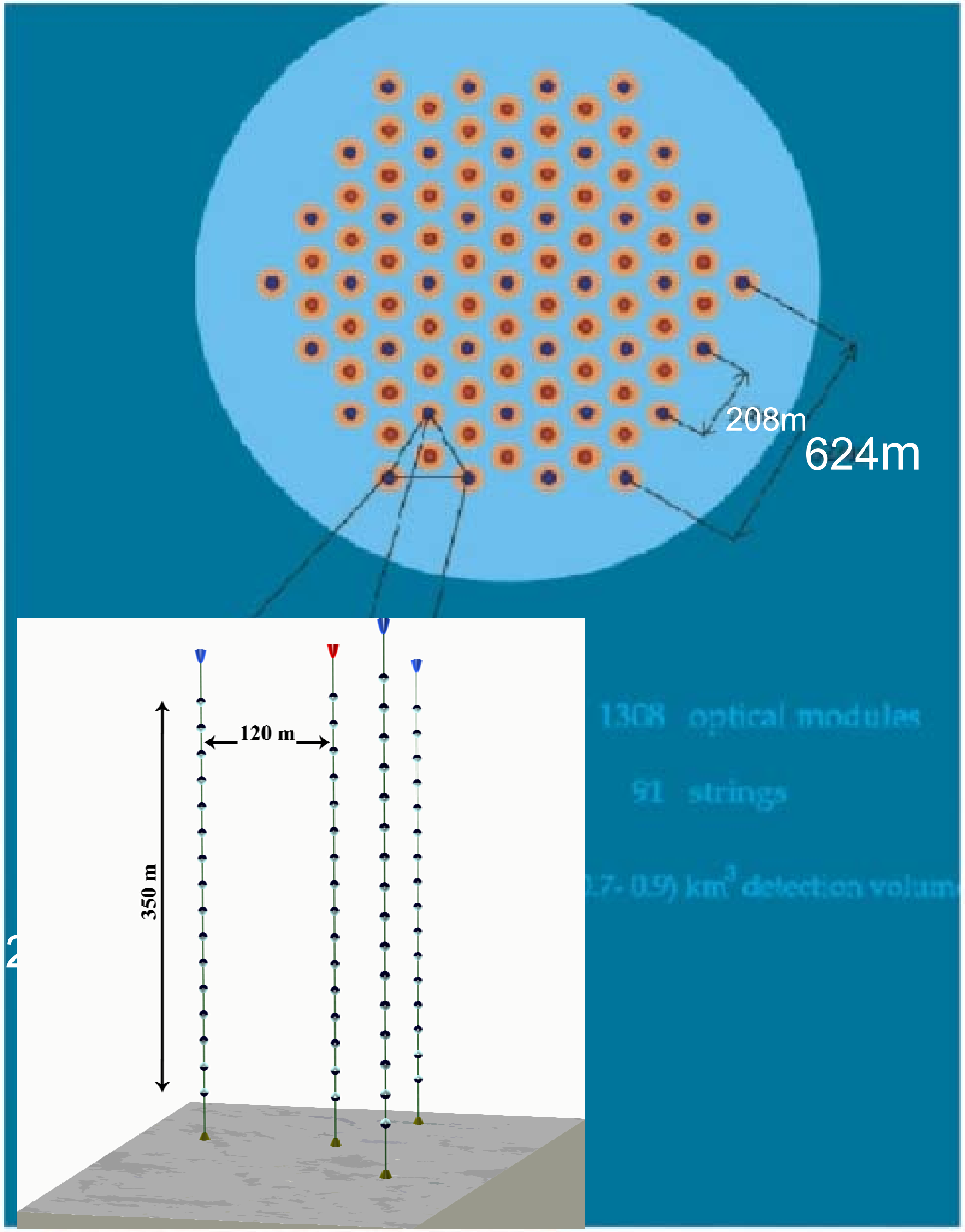
Gigaton (km3) Volume Detector in Lake Baikal

Sparse instrumentation:

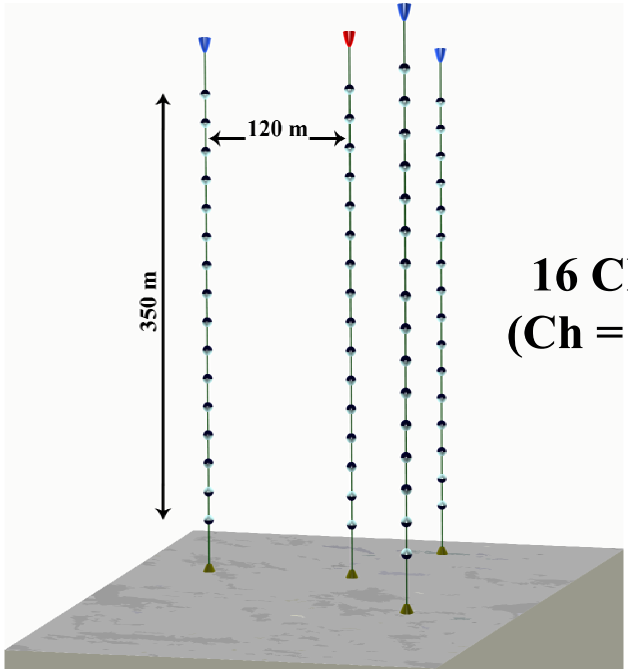
91 - 100 strings with 12 - 16 OMs
(1300 - 1700 OMs)
→ effective volume for
>100 TeV cascades ~ 0.5 -1.0 km ^{3}

$\delta \lg(E) \sim 0.1, \ \delta\theta_{med} < 4^o$

→ detects muons with
energy > 10 - 30TeV

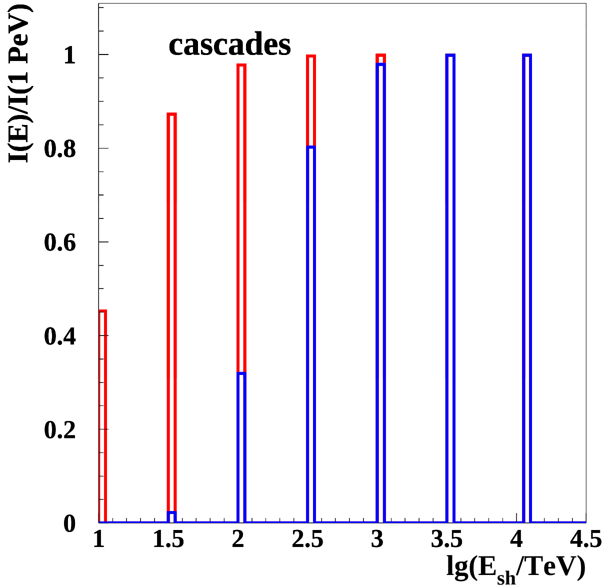


Test Configurations of GVD sub array

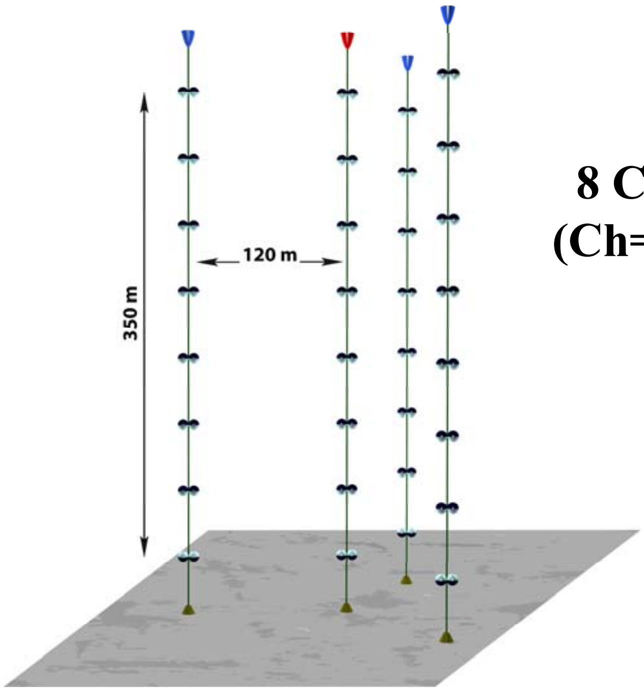


16 Ch / Str
(Ch = 1 OM)

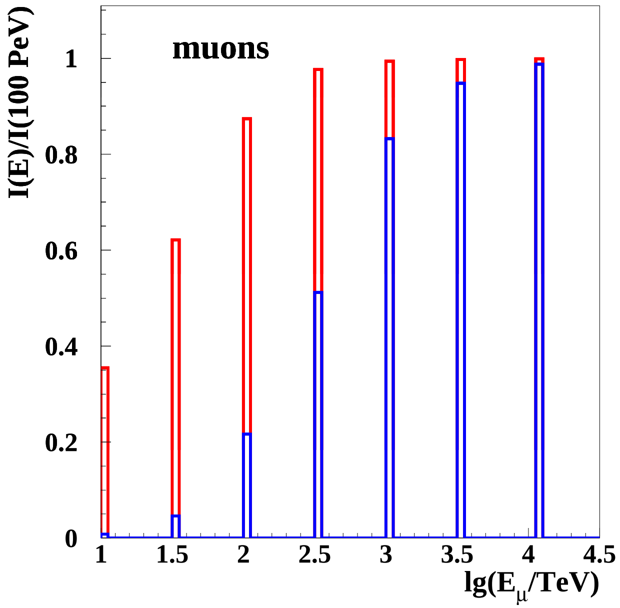
contained events



instrumented volume
V=3.5 10^8 m^3



8 Ch / Str
(Ch=2 OM)



<S>=8 10^5 m^2

2005: NT200+ - intermediate stage to Gigaton Volume Detector (km3 scale) is commissioned in Lake Baikal

Main physics goal:

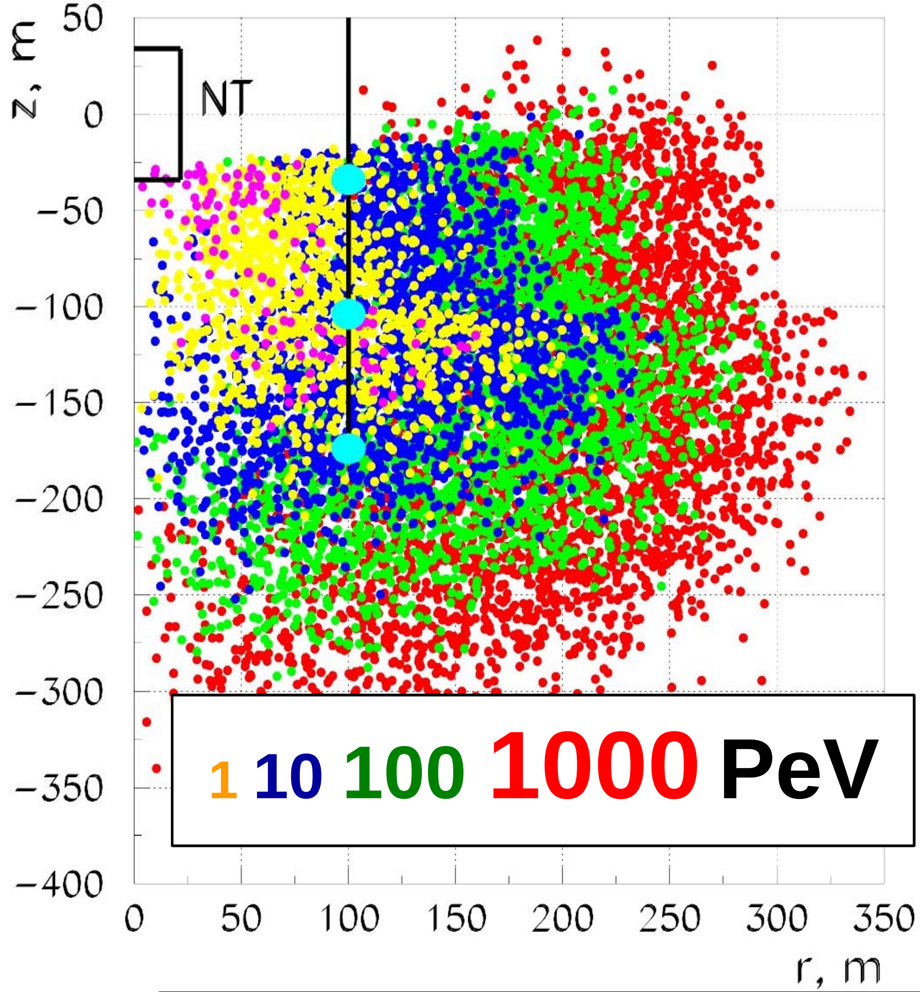
Energy spectrum of all flavor extraterrestrial HE-neutrinos (E > 100 TeV)

Total number of OMs – 228 / 11 strings

Instrumented volume – 5 Mt
(AMANDA II, ANTARES – 10 Mt)

Detection volume >10 Mt for E_ν>10Pev

- high resolution of cascade vertex and energy ⟶ neutrino energy



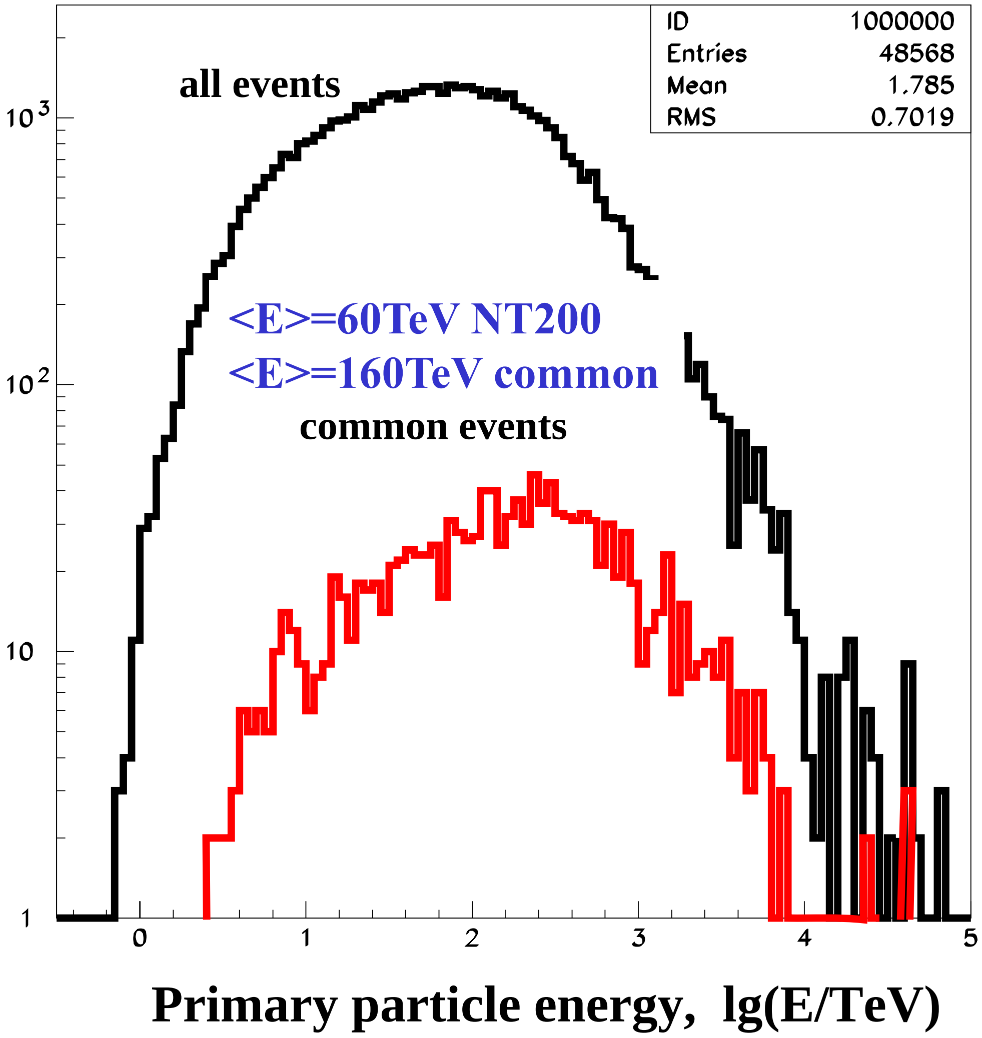
4 15 23 40 Mton

Atmospheric muon flux as a calibration source

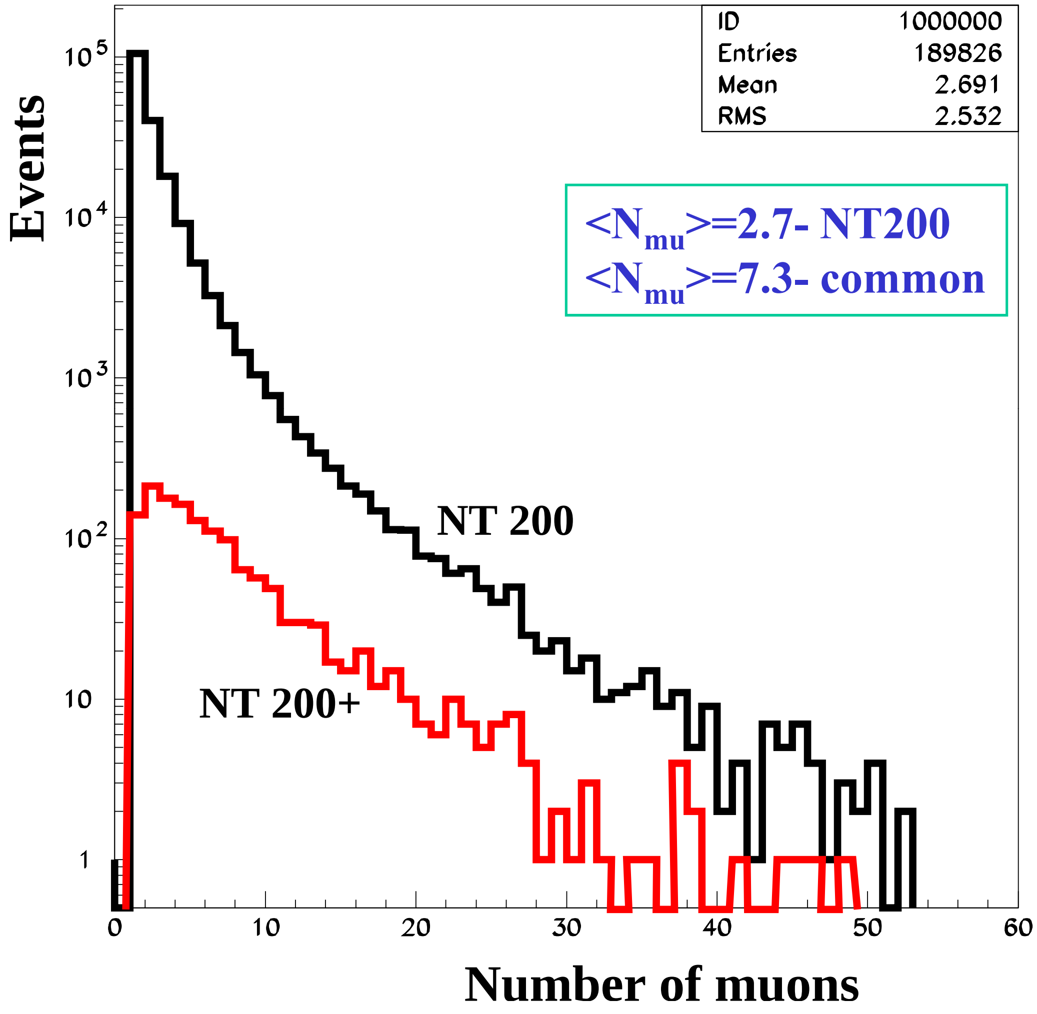
Average distance between OMs: $L_{NT200+} = 10^* L_{NT200}$

muon-bundles: 93% NT200+
45% NT200

Energy distribution of primaries



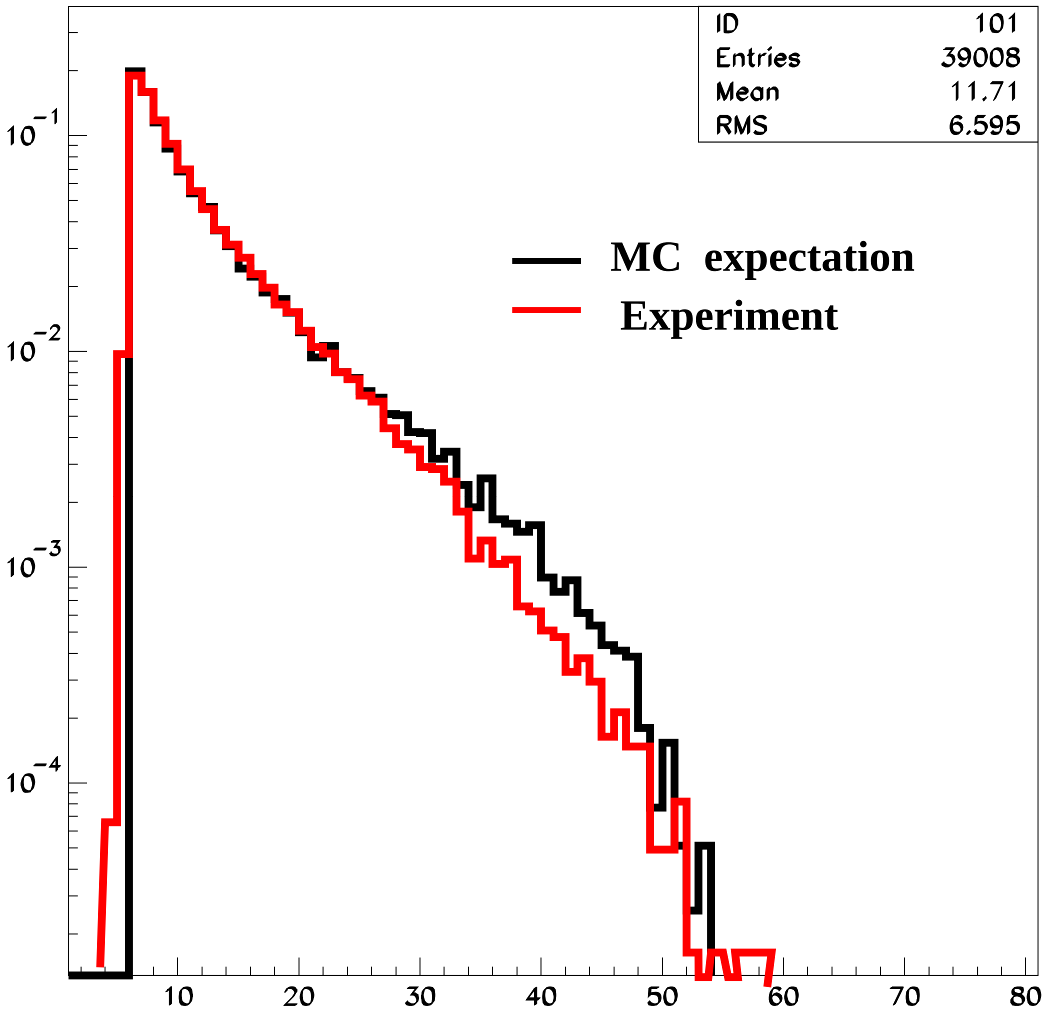
Muon multiplicity distribution



Atmospheric muon flux as a calibration source

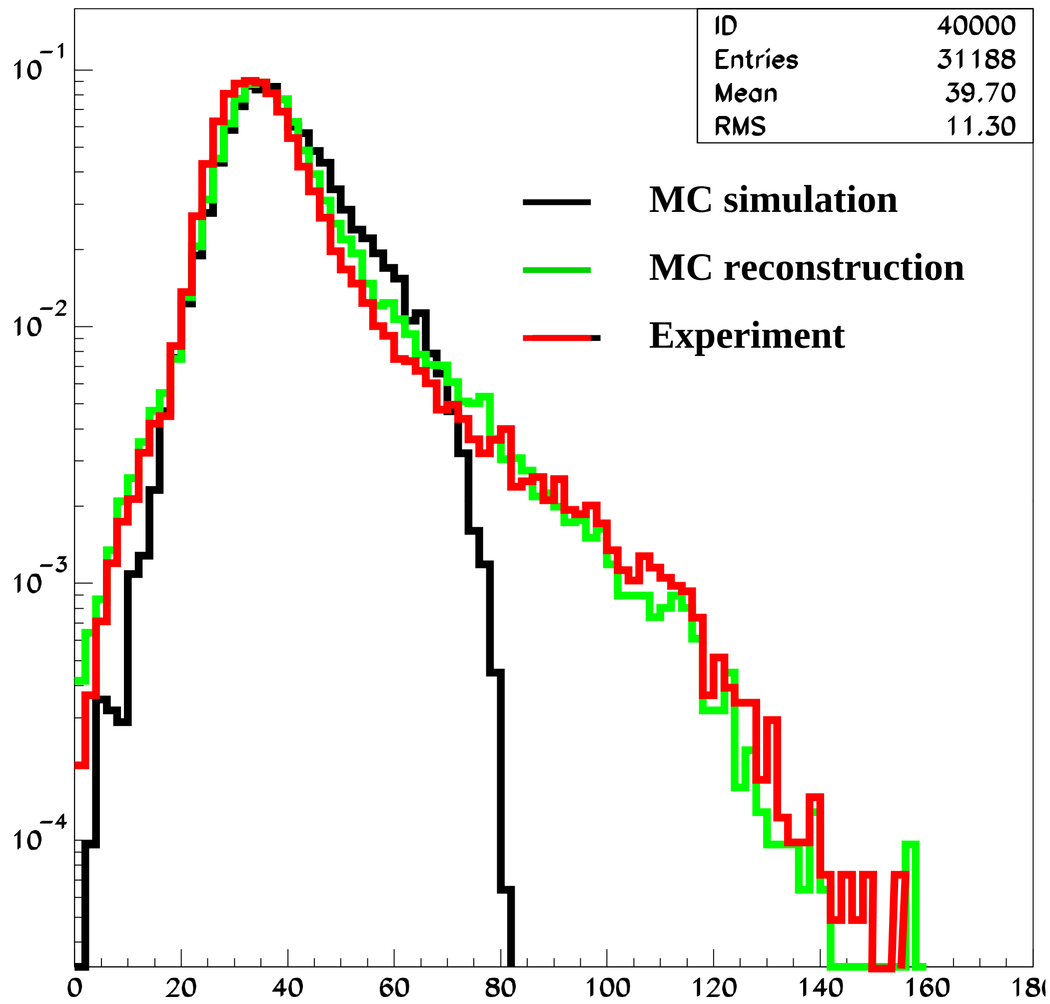
data consistent with MC-expectations

Hit channel multiplicity



Hit channels

Angular distributions

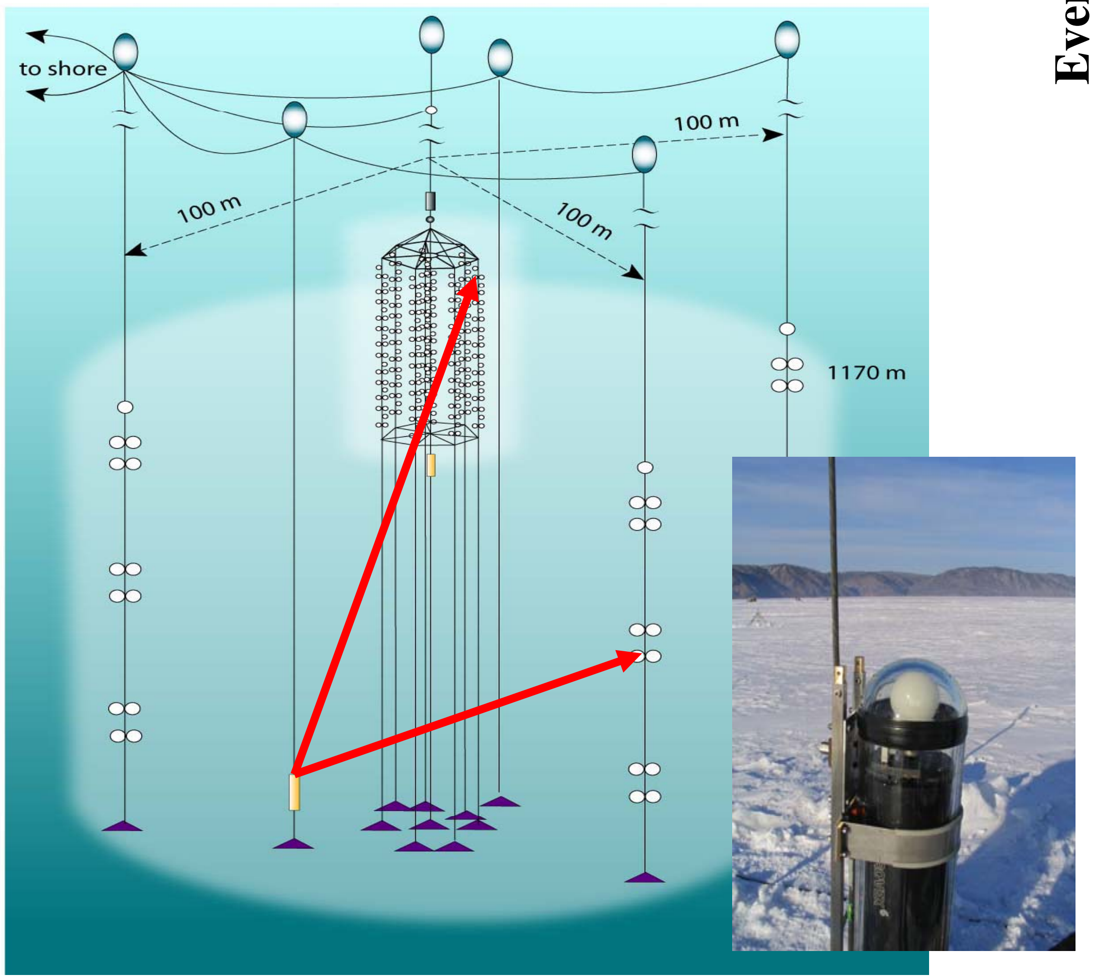


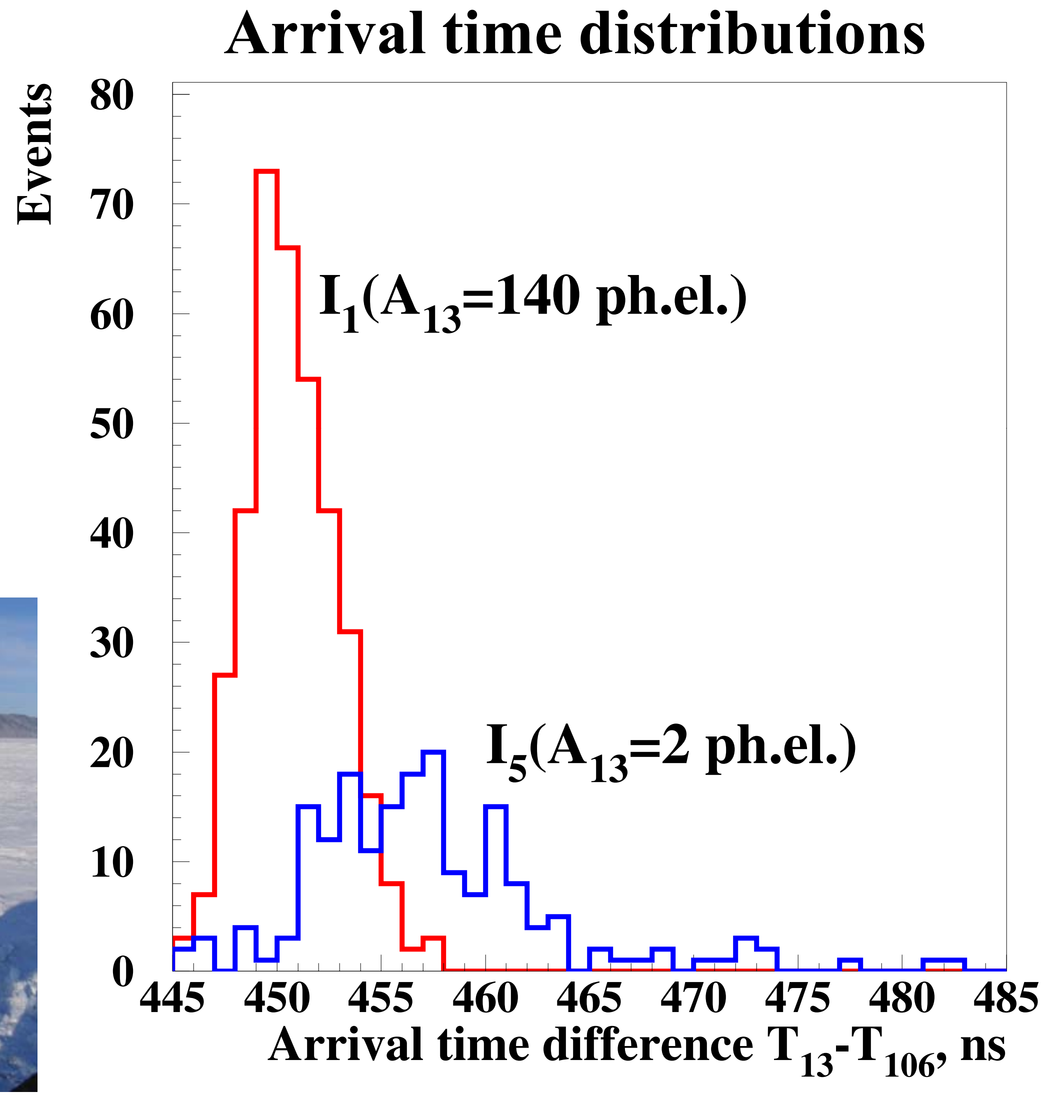
Zenith angle

NT200+ Laser pulses as high-energy cascades

Laser intensity - cascade energy:
(10^{12} – 5 10^{13}) γ/puls - (10 – 500) PeV

Ch.13 – 187 m far from laser
A_{13}=**140 ph.el.** for 5 10^{13} γ/puls
Sensitive vol./OM ~ 20 Mt

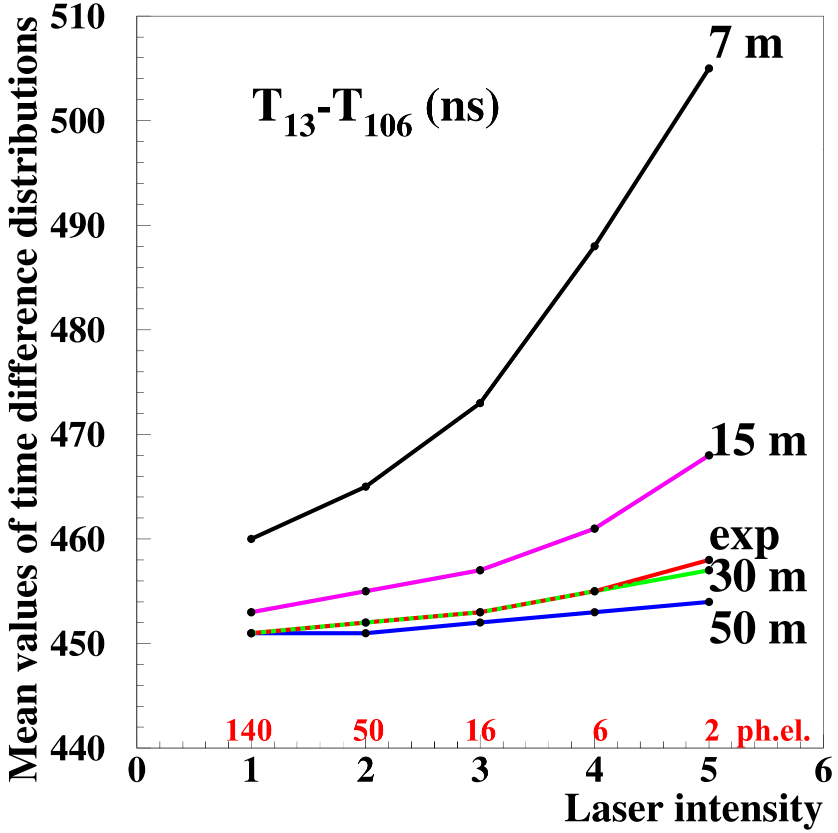




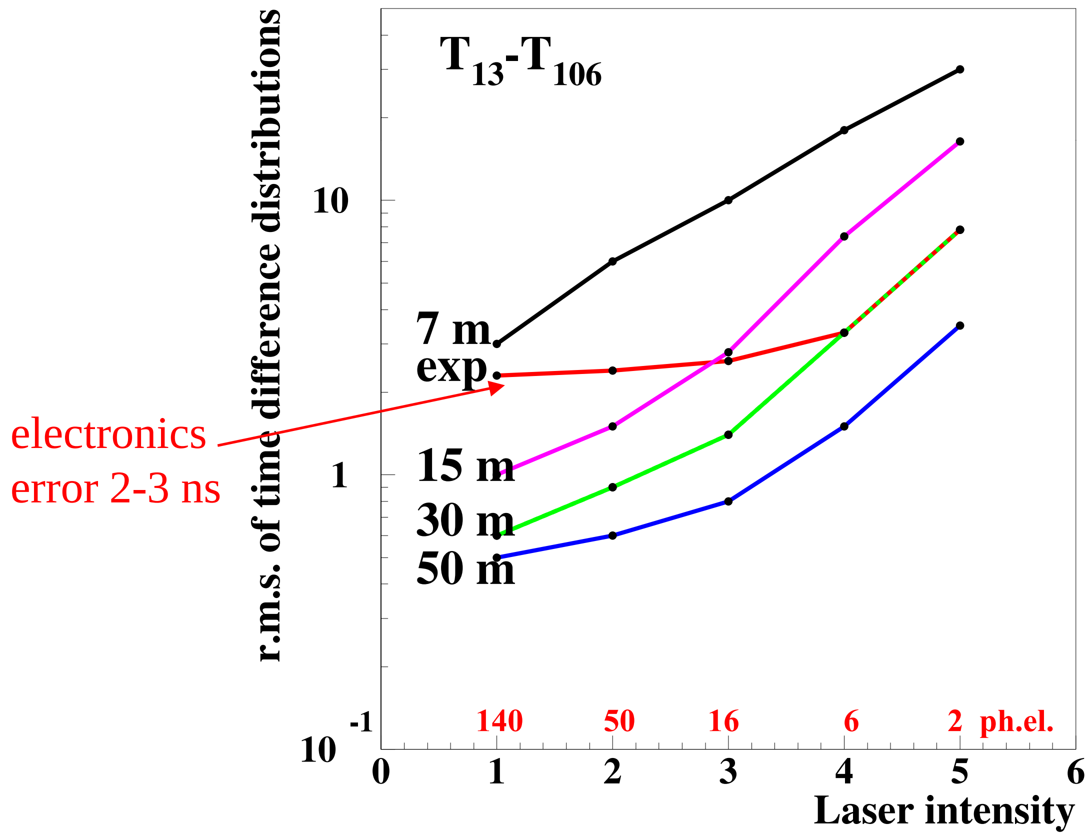
Baikal water properties: absorption - (22 – 24) m,
scattering - 30 m – (arrival time delay, wider time distribution)

Ch. 13 (187 m far, 1 ph. el. level):
arrival time delay – 7 ns
rms of arrival time distribution – 8 ns (2-3 ns from electronics)

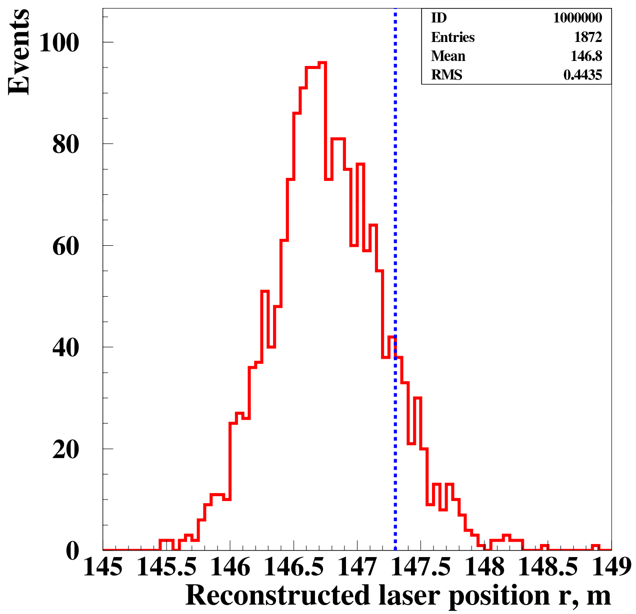
Expected mean arrival time for different scattering lengths



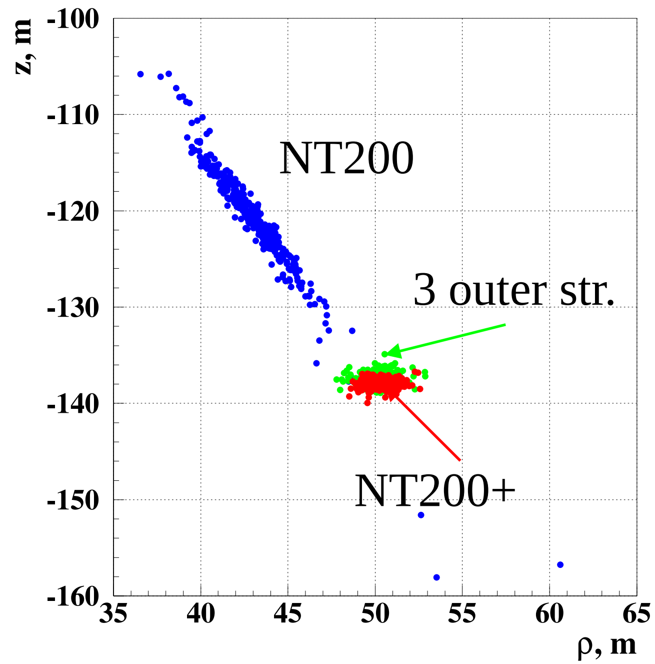
Expected rms of time distributions for different scattering lengths (without electronics error)



Laser coordinates reconstruction

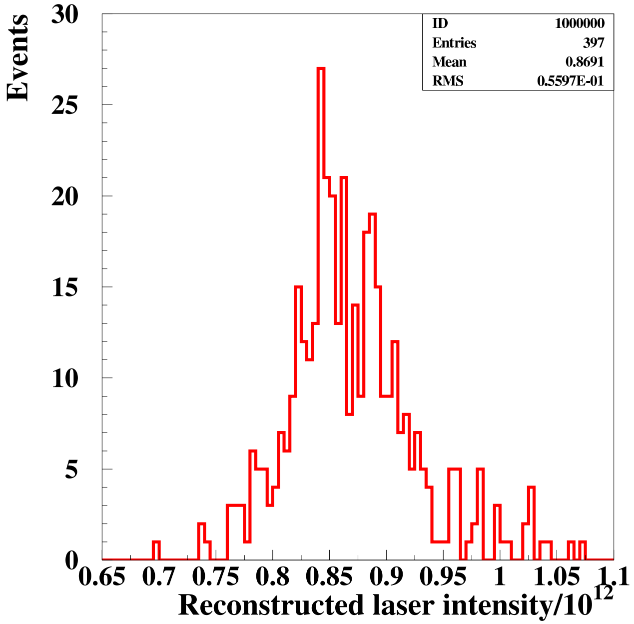


dr < 1 m



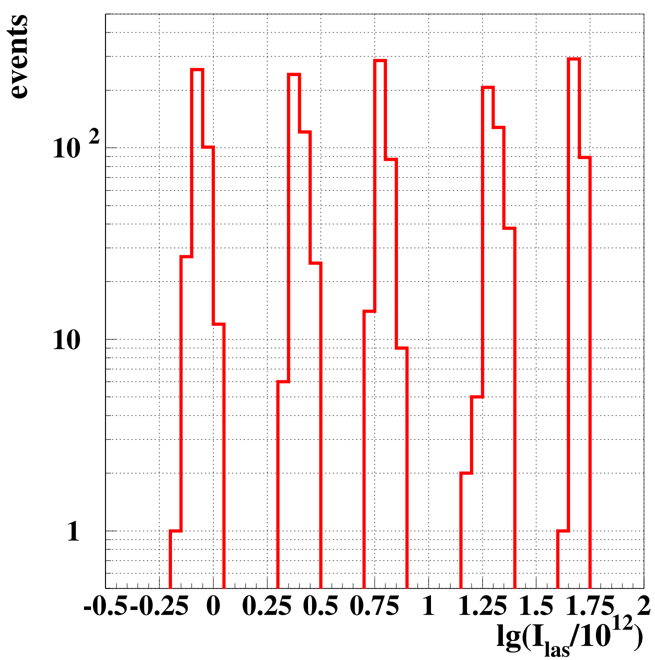
Laser intensity reconstruction

lowest intensity



δI/I ~ 6%

five laser intensities



PM selection for the km3 prototype string

Basic criteria of PM selection is its effective sensitivity to Cherenkov light which depends on

Photocathode area × Quantum efficiency × Collection efficiency

Quasar-370
$D \approx 14.6''$
Quantum efficiency ≈ 0.15

$\stackrel{?}{\approx}$

Hamamatsu R8055
$D \approx 13''$
Quantum efficiency ≈ 0.20

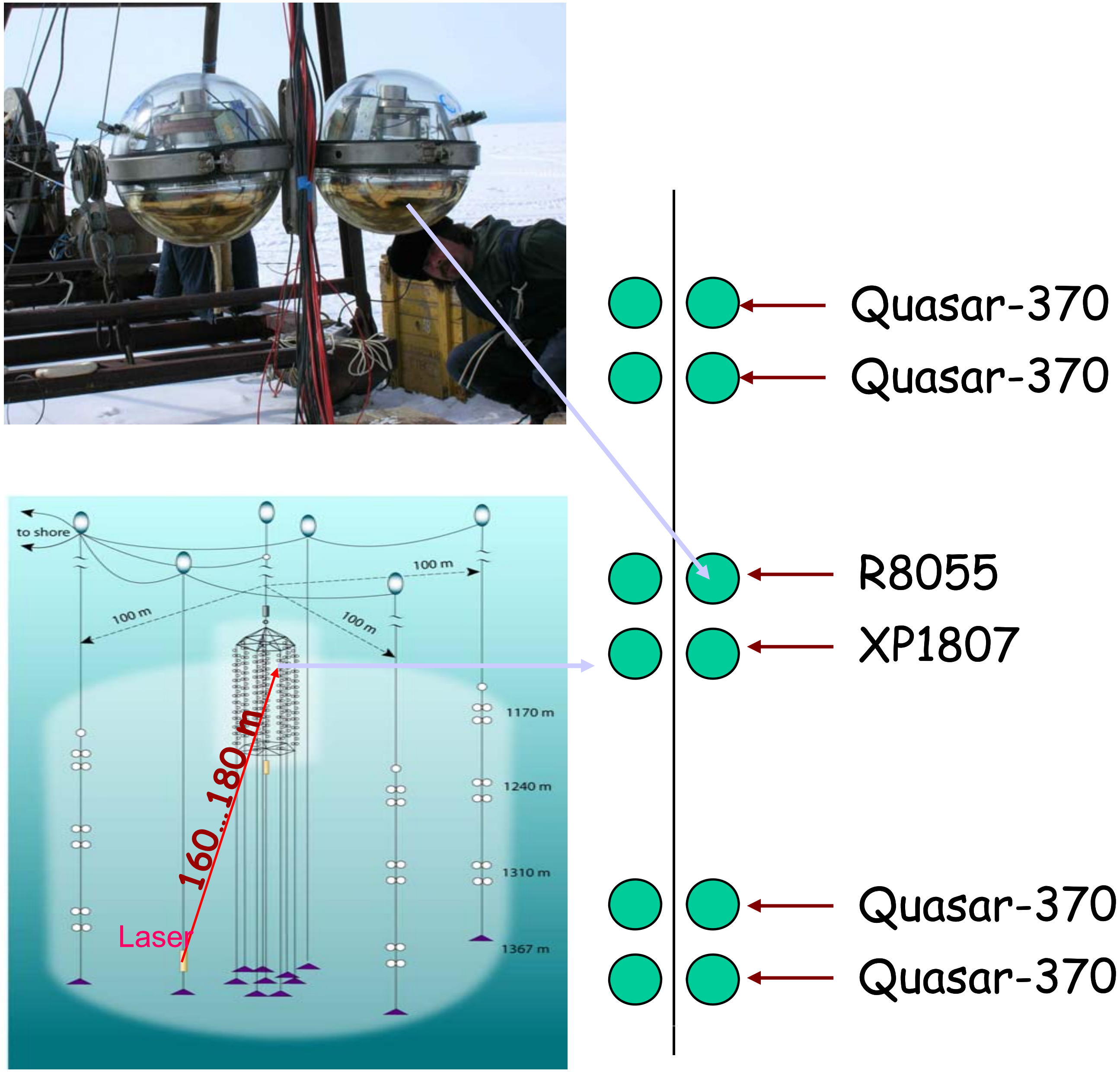
$\stackrel{?}{\approx}$

Photonis XP1807
$D \approx 12''$
Quantum efficiency ≈ 0.24

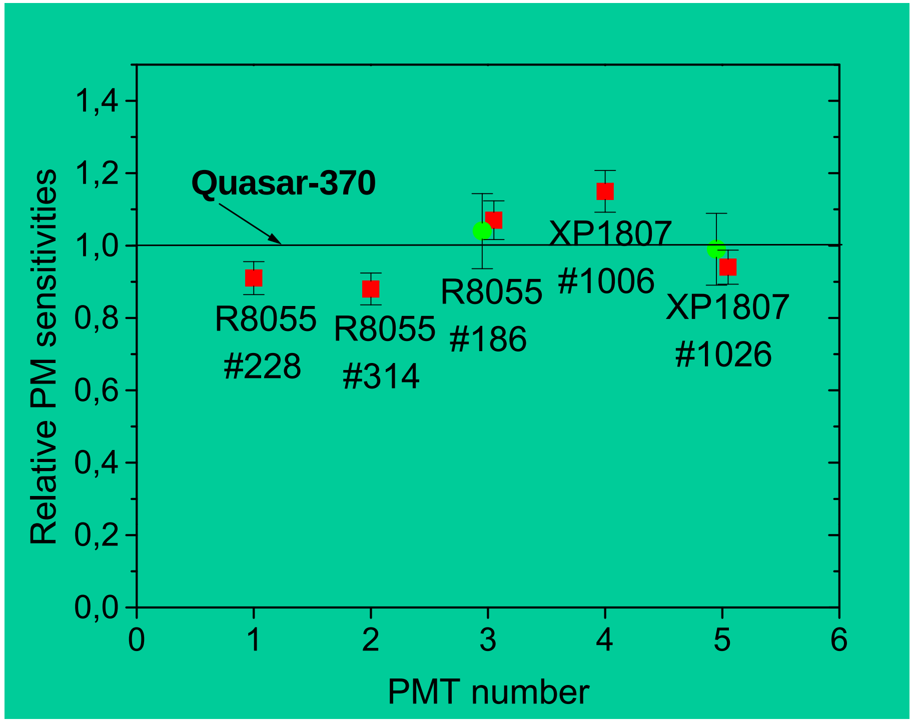
PM selection: Underwater tests (2007)

4 PM R8055 (Hamamatsu) и 2 XP1807 (Photonis) were installed to NT200+ detector (April 2007).

4 PM: central telescope NT 200;
2 PM R8055: outer string, FADC prototype.



Relative effective sensitivities of large area PMs (preliminary results)

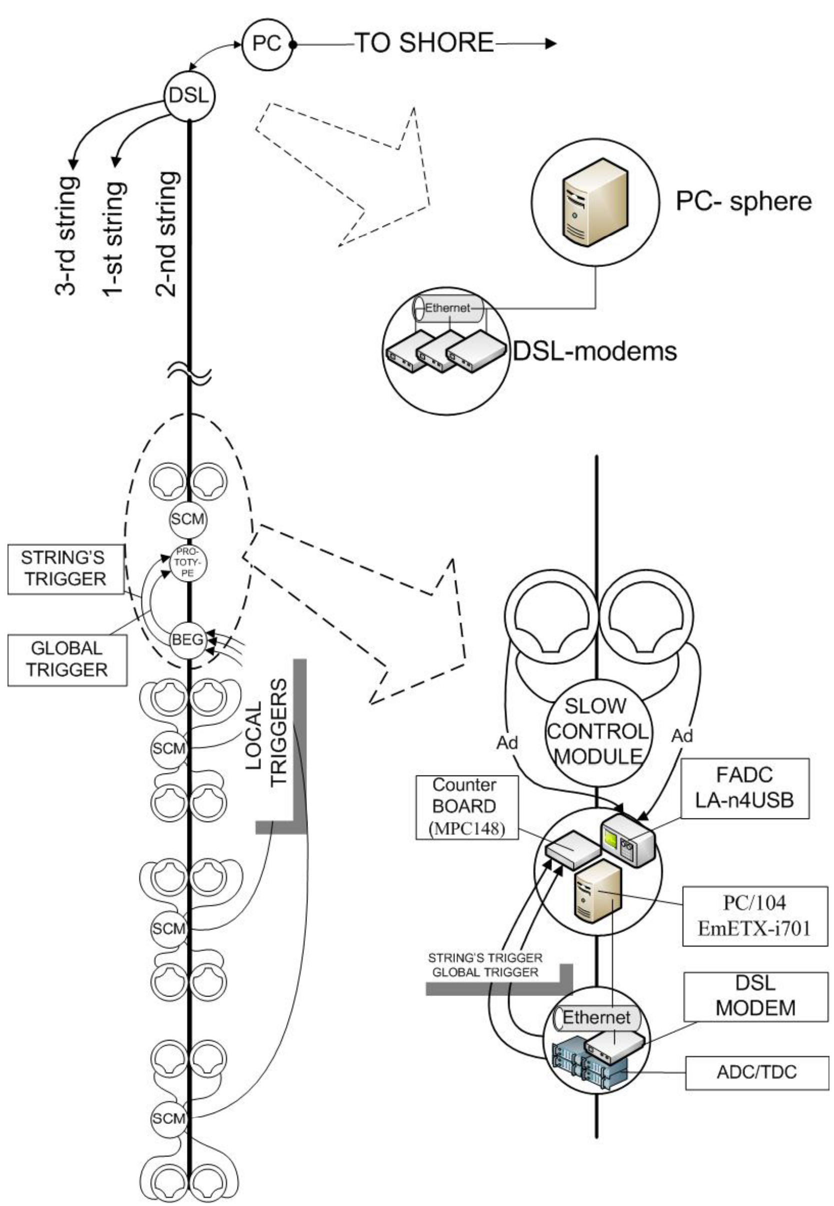


Smaller size (R8055, XP1807) tends to be compensated by higher photocathode sensitivities.

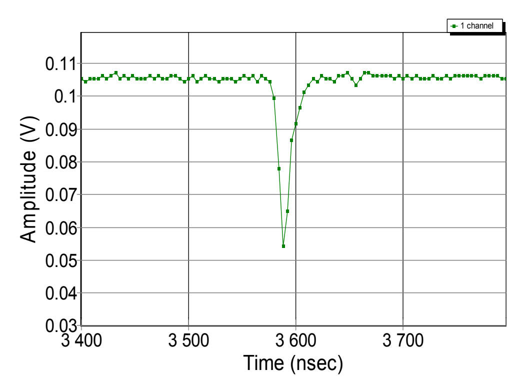
Relative effective sensitivities of large area PMs R8055/13" , XP1807/12" and Quasar-370/14.6". Laboratory measurements (squares), in-situ tests (dots).

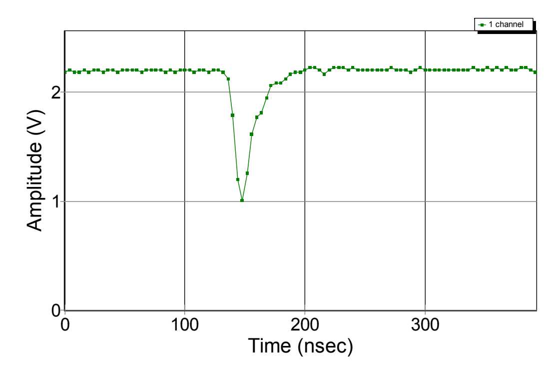
Prototype of FADC based system

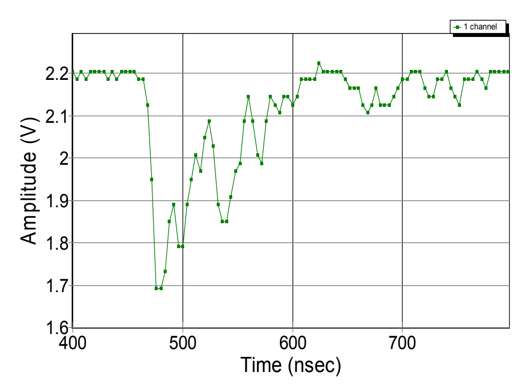
2-channel FADC prototype was installed during expedition 2007



Purposes:
- optimal sampling time window
- dynamic range
- obtainable pulse parameter precision
-algorithms for online data handling







Examples of FADC pulses for different classes of events:

1. One p.e. noise hit
2. A muon trigger (multi-p.e.)
3. Backward illumination by a calibration laser

Prototype string
for a km3 Baikal neutrino telescope

Installation of a "new technology"
prototype string as a part of
NT200+ (spring 2008)

- Investigation and in-situ tests of basic knots of future detector: optical modules, DAQ system, new cable communications.

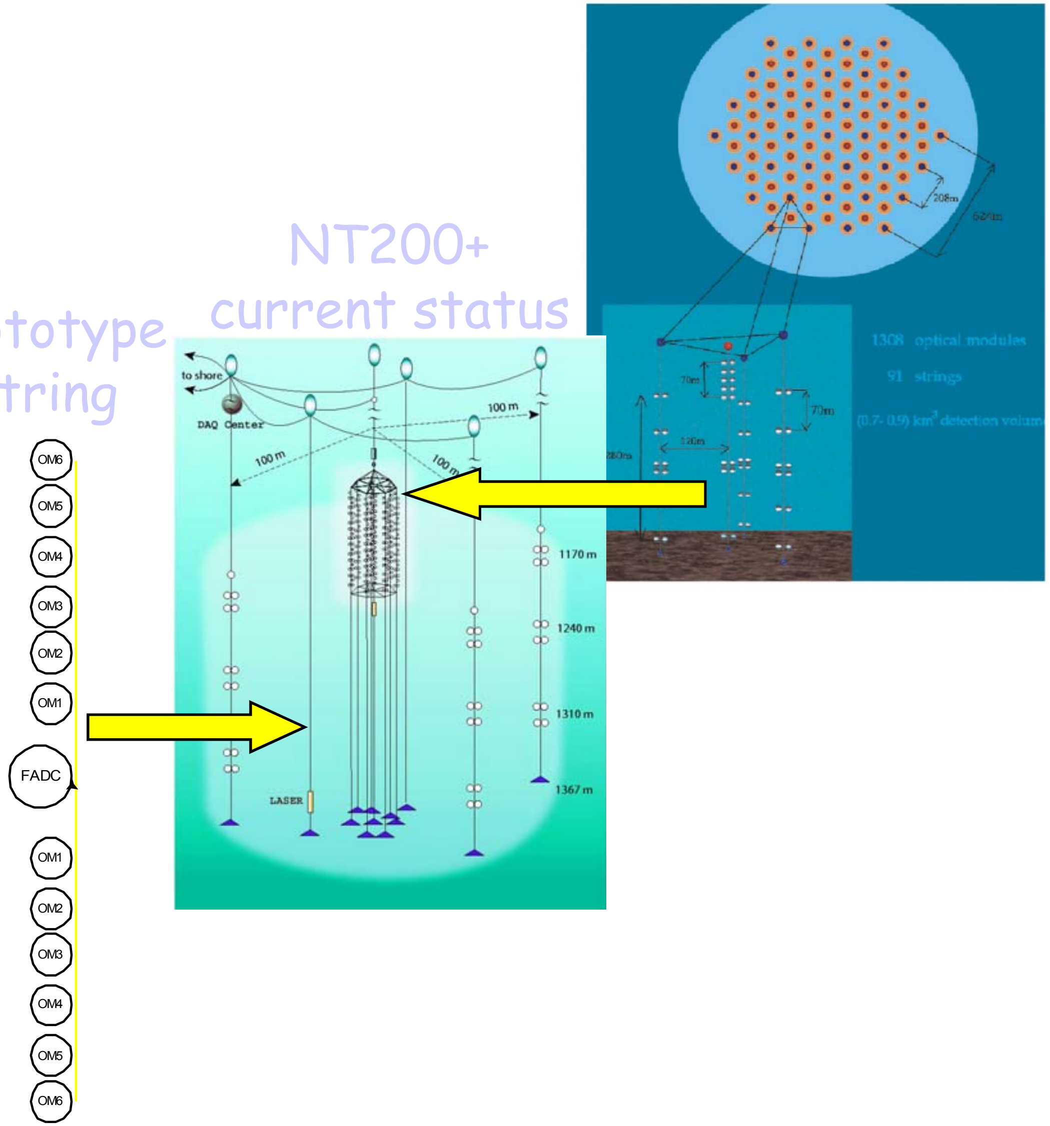
- Studies of basic DAQ/Triggering approach for the km3-detector.

- Confrontation of classical TDC/ADC approach with FADC readout.

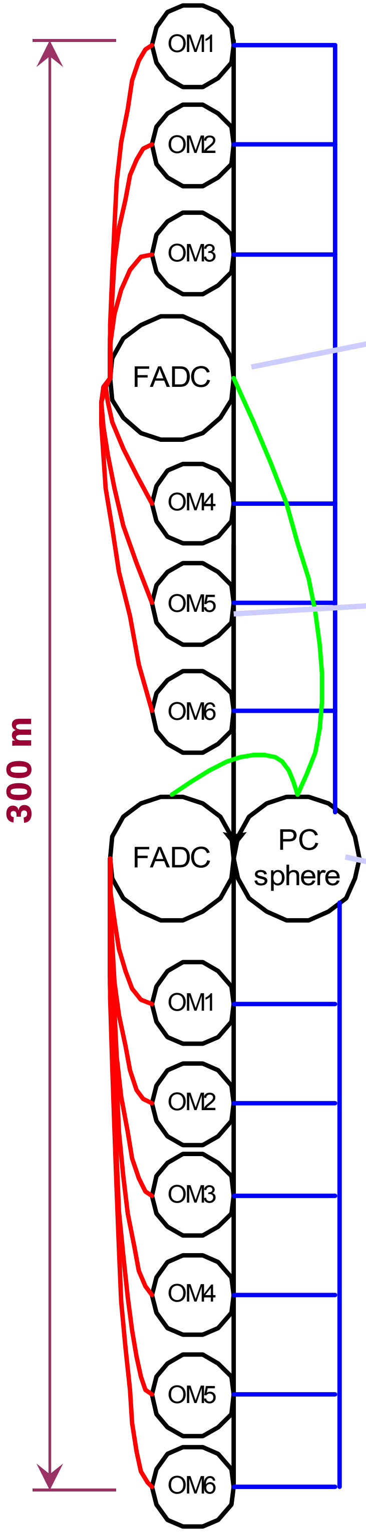
Project of km3 Baiakl Neutrino Telescope

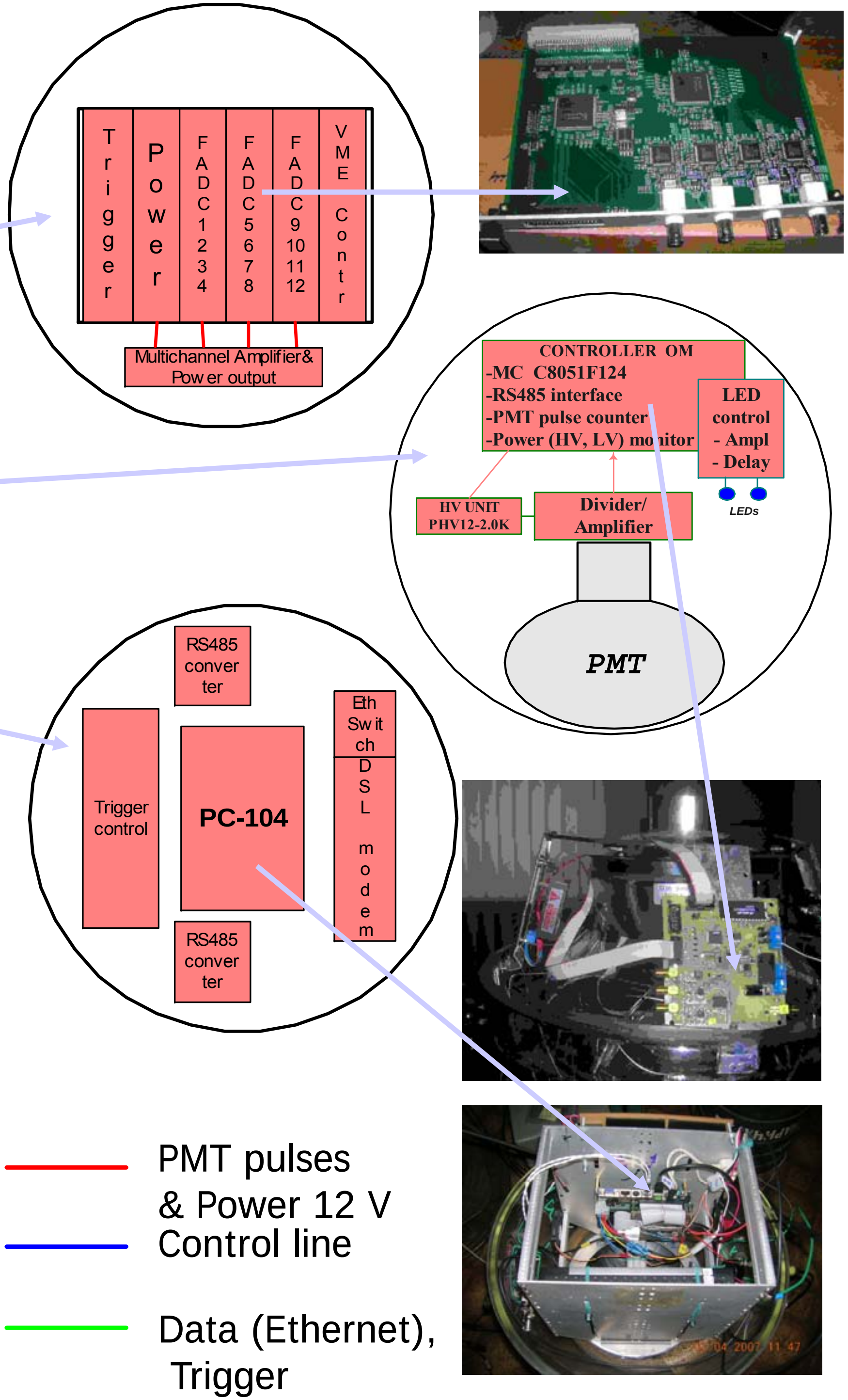
NT200+ current status

Prototype string



Design of Prototype string





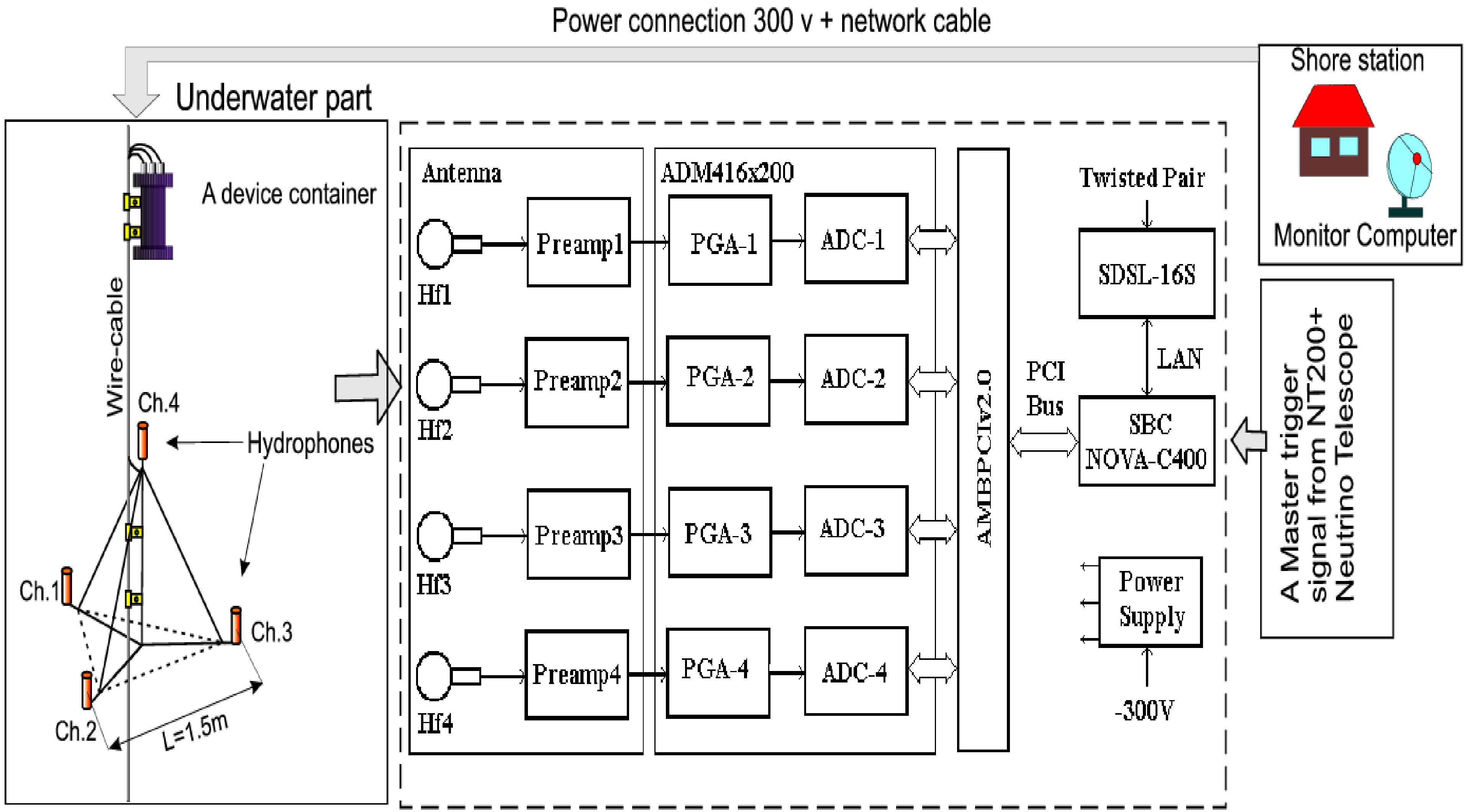
FADC unit is operating now in Tunka detector (astro-ph/0511229)

Basic features

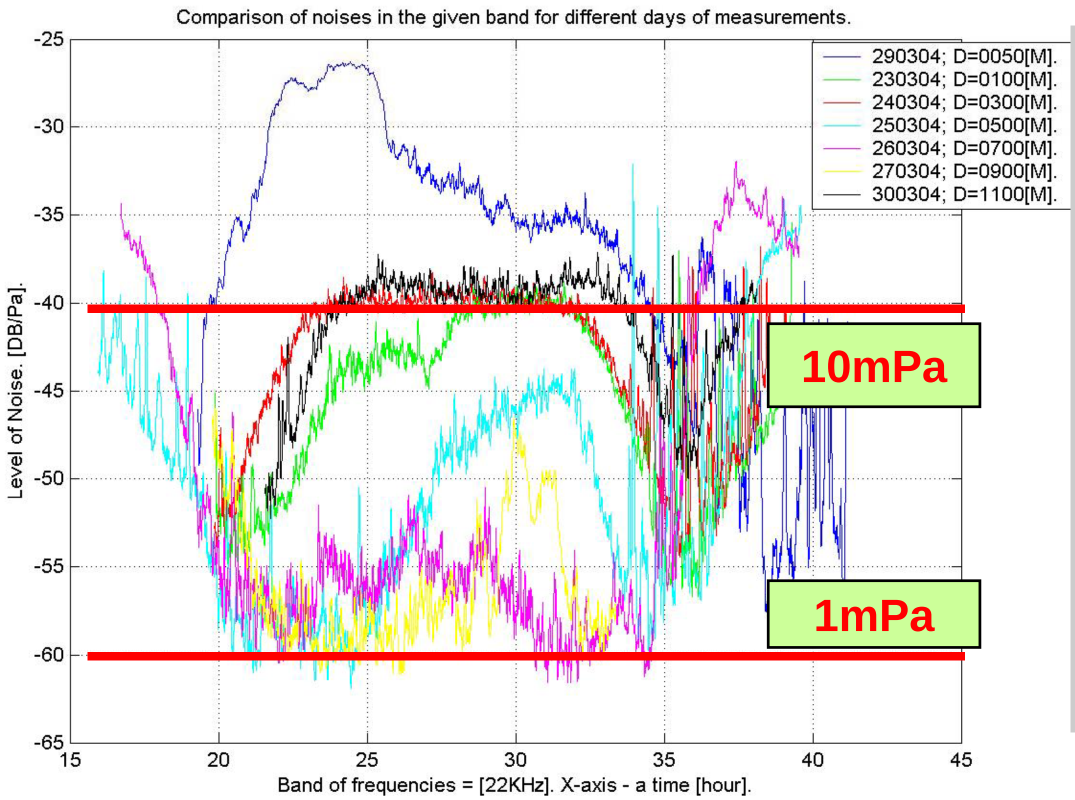
- String lengths ~300 m
- String contains 12…16 OM
- Optical modules contains only PM and control electronics
- 12 bit 200 MHz FADC readout is designed as multi channel separate unit.
- Half-string FADC controllers with ethernet-interface connected to string PC unit
- String PC connected by string DSL-modem to central PC unit

Acoustic method for neutrino detection – extension to UHE range

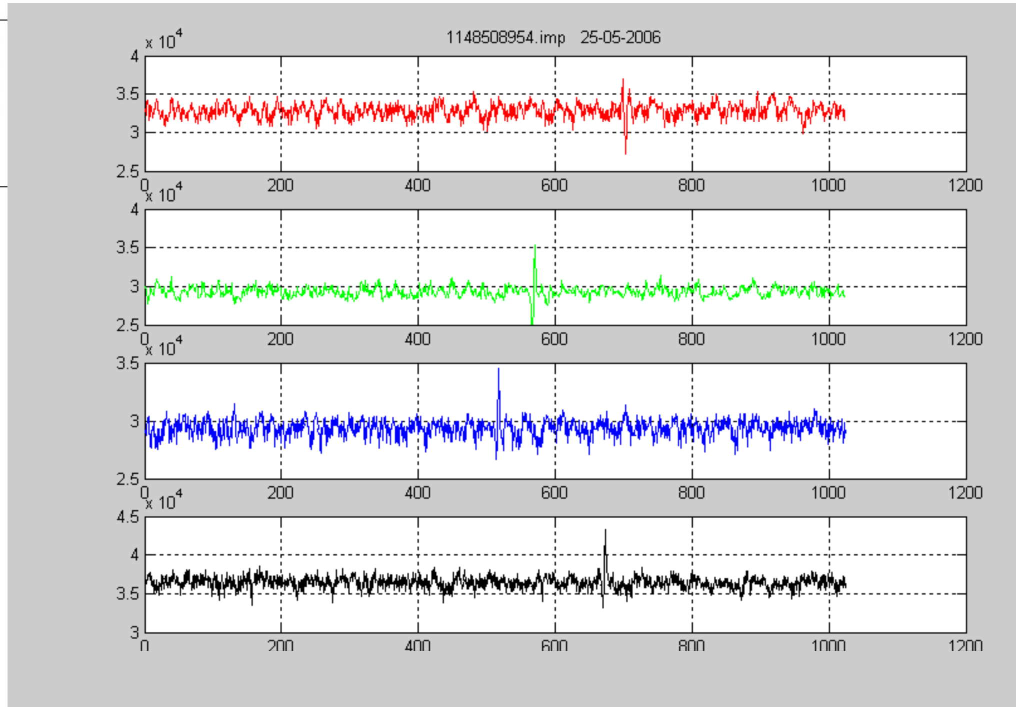
Schematic view of underwater 4-channel digital device for detection of acoustic signals



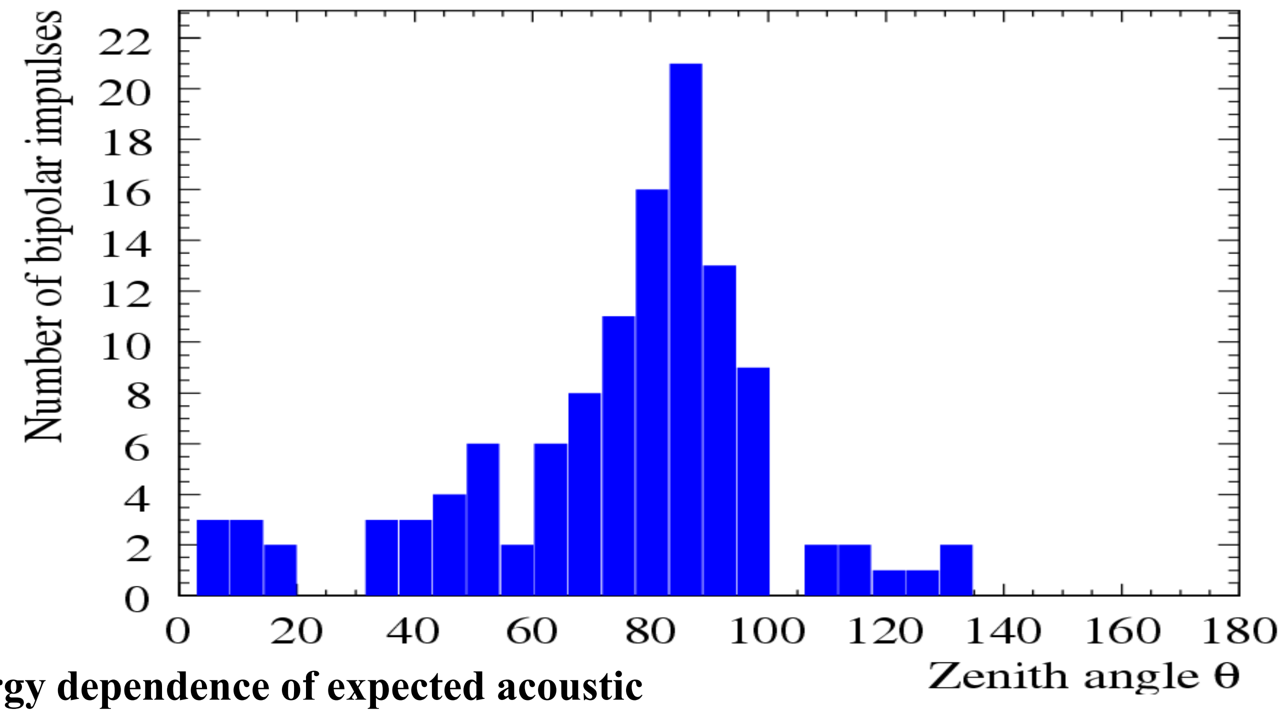
Acoustic noise within 22-44 kHz frequency band at different depths



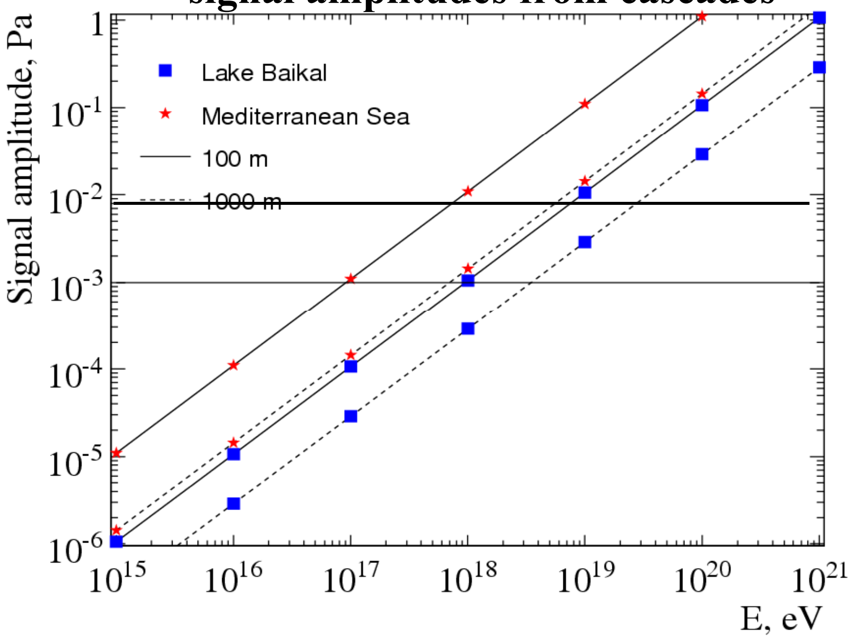
Example of bipolar pulses



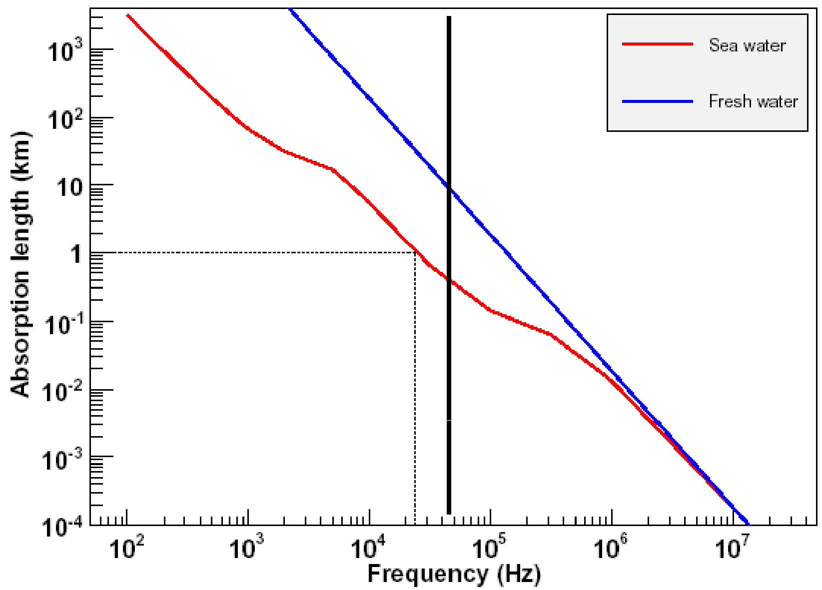
Angular distribution of detected events after all cuts



Energy dependence of expected acoustic signal amplitudes from cascades



Absorption length of acoustic signal in water



Baikal – GVD
Schedule Milestones

- 06-07 R&D, Testing NT200+
- 08 Technical Design
- 08-14 Fabrication (OMs, cables, connectors, electronics)
- 10-12 Deployment (0.1 – 0.3) km3
- 13-14 Deployment (0.3 – 0.6) km3
- 15-16 Deployment (0.6 – 0.9) km3

Overall cost ~ 20 MEuro

Detector ~ 16 MEuro Logistics, including infrastructure ~ 4 MEuro

Summary

1. The Baikal Telescope NT200 is in operation since 1998.

2. NT200 is focusing on search for HE-diffuse neutrinos: A “Mton-detector” with only 100kt enclosed volume.

   - Diffuse flux limits for 4 years (98-02) are challenging AGN-models.

3. <u>NT200+ commissioned in April, 2005:</u>

   - <u>NT200+ is tailored to diffuse cosmic neutrinos</u>
   - 5 Mton equipped volume; V_{det} > 10 Mton at 10 PeV

     → sensitivity improvement by ~4×

4. R&D on Gigaton Volume Detector (km3 scale) on the base of experience of NT200+ operation


First step to BAIKAL-GVD