The Baikal Experiment -

Status, Results and Perspectives

Zh. Dzhilkibaev for the Baikal Collaboration

The Baikal Collaboration

1. Institute for Nuclear Research, Moscow, Russia.

2. Irkutsk State University, Irkutsk, Russia.

3. Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia.

4. DESY-Zeuthen, Zeuthen, Germany.

5. Joint Institute for Nuclear Research, Dubna, Russia.

6. Nizhny Novgorod State Technical University, Nizhny Novgorod, Russia.

1. St.Petersburg State Marine University, St.Petersburg, Russia.

2. Kurchatov Institute, Moscow, Russia.

Deep underwater/underice particle detection

1960 - M.Markov: neutrino detection in natural transparent media (lakes, ocean, ice):

- **- huge size (up to km^3 scale) detectors (AMANDA II ~ 1.5 Mton)**
- **- given optical parameters of medium, detection volume/area depends on cascades/muons energy (Baikal (NT-200) ~ (0.1 - 6) Mton for (10^3 - 10^6) Gev cascades energies)**

Cherenkov radiation intensity $F_\gamma(L) \sim I_\gamma(E)\ \exp(-L/L_{at})$

$I_\gamma \sim 0.6\ E_\mu/\mathrm{TeV}$, $I_\gamma \sim 10^8\ E_{sh}/\mathrm{TeV}$

Nowadays operating neutrino telescopes:

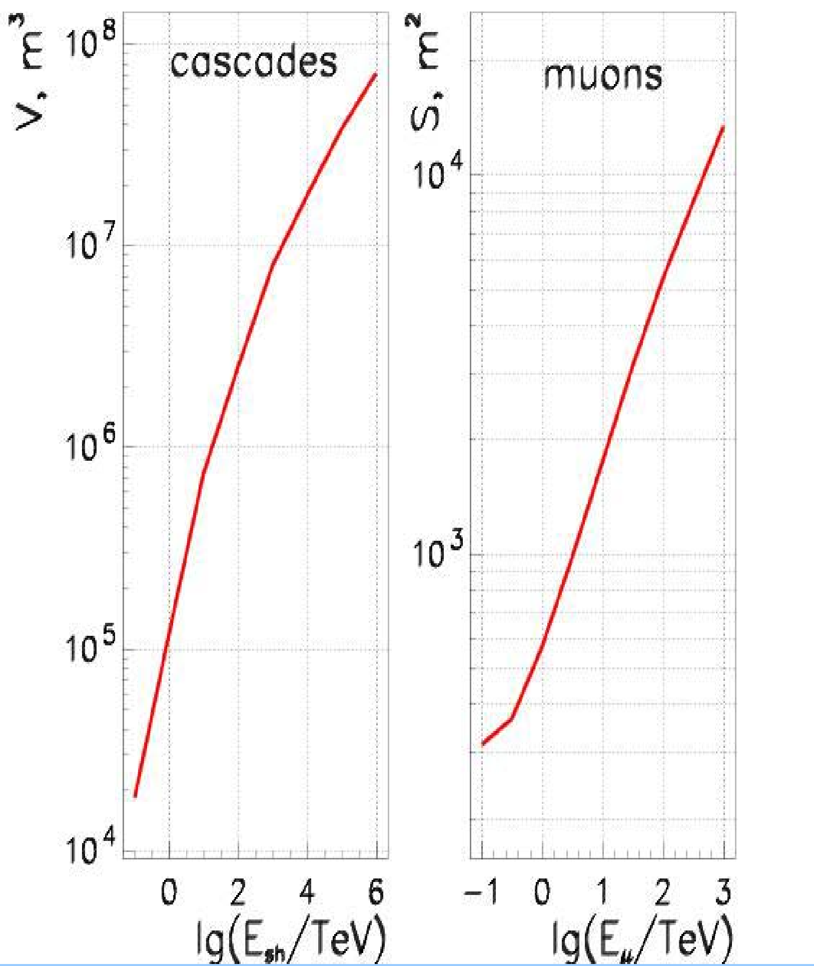
Baikal (NT-200) - Lake Baikal

AMANDA II - South Pole

Optical properties

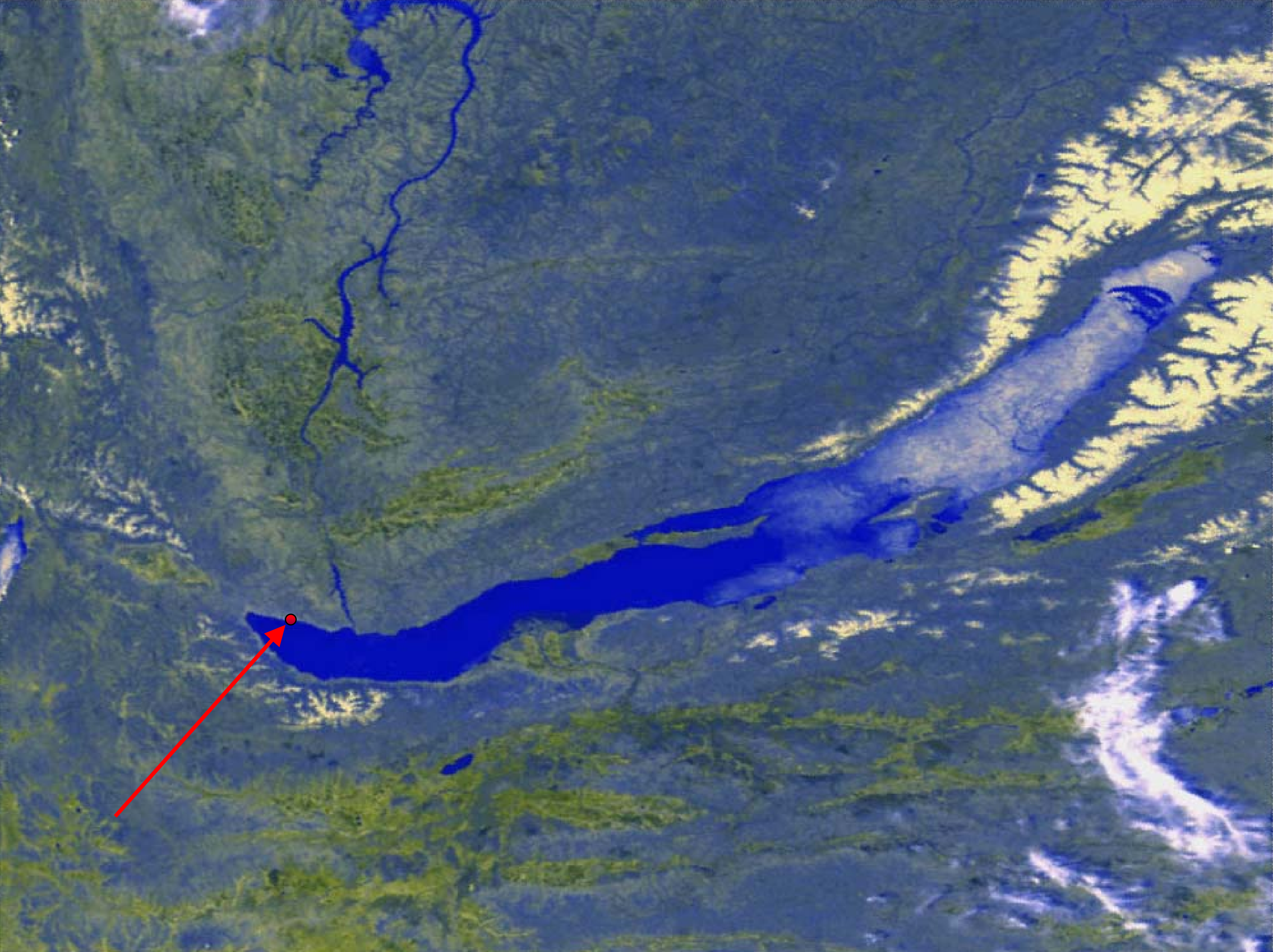
	abs.,m	scatt., m	Las, m	dt, ns (60 m from μ)
Baikal	22-24	30-50	18-20	1.5
AMANDA	~100	~3	24-27	250-400

Optical Module sensitivity (Baikal experiment)

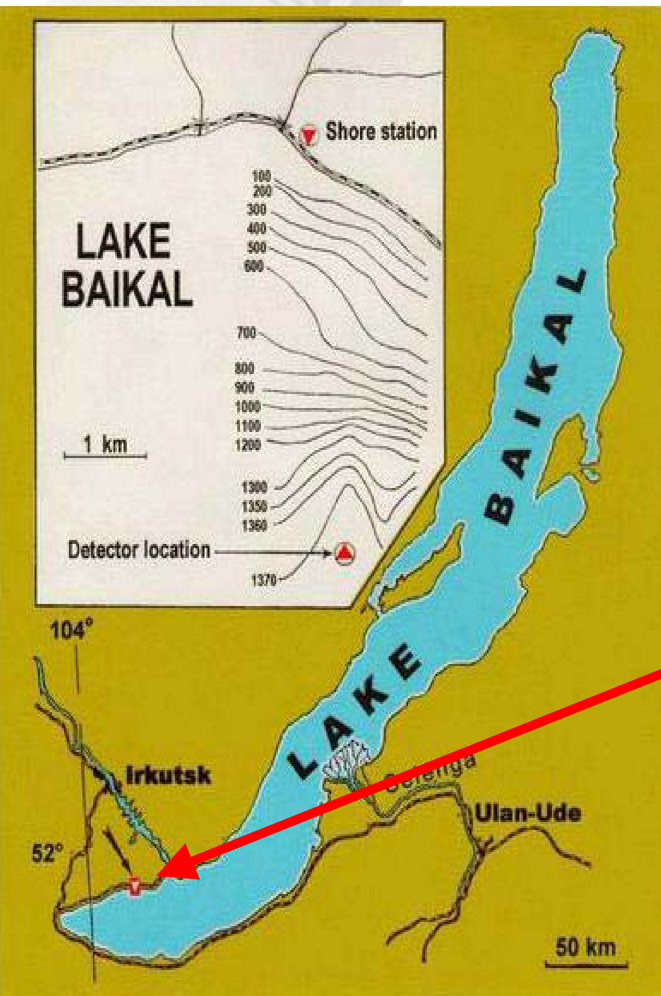


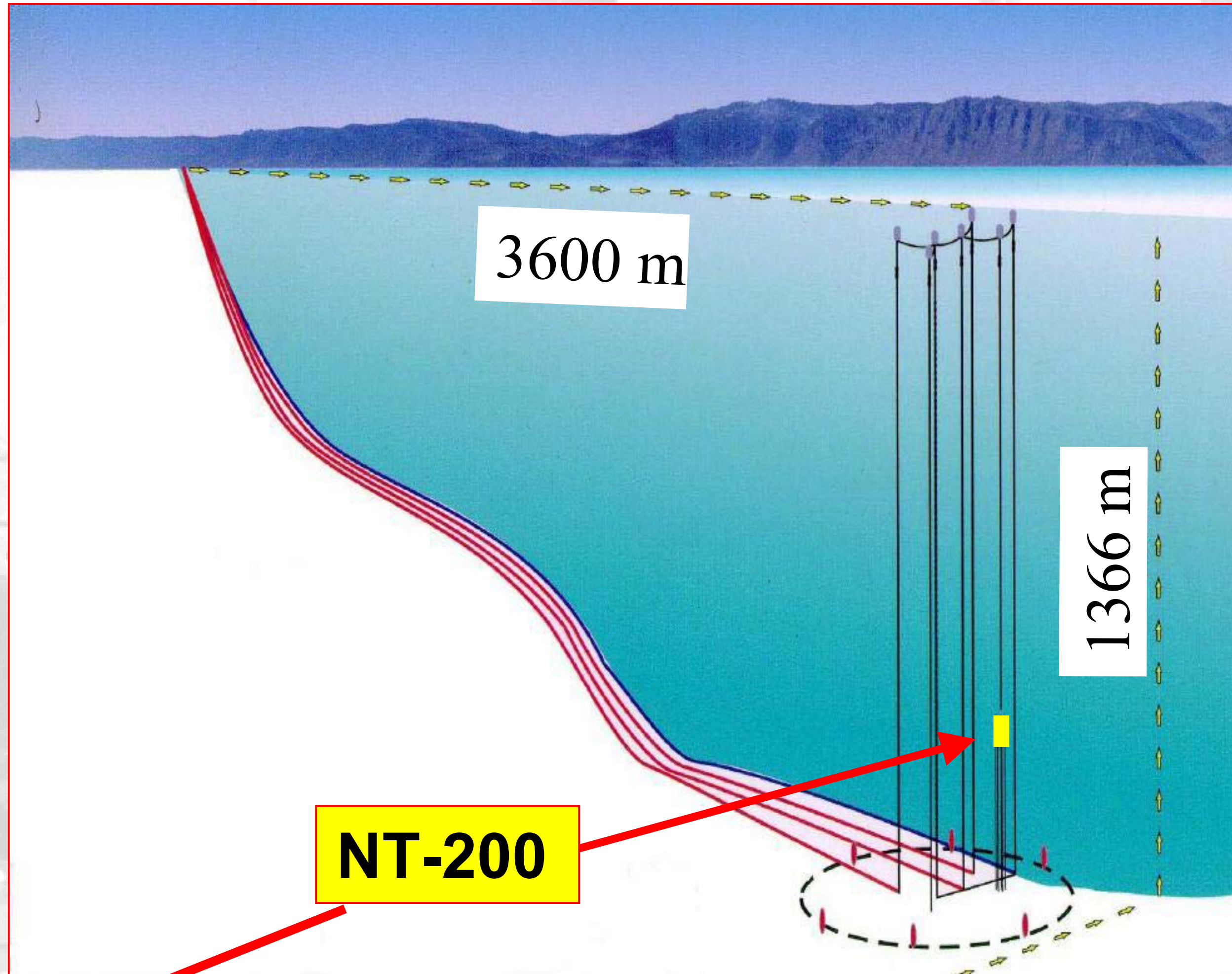
The Baikal Telescope NT-200

- NT-200 location and design
- Selected results
- NT-200+ status
- Conclusion



The Site





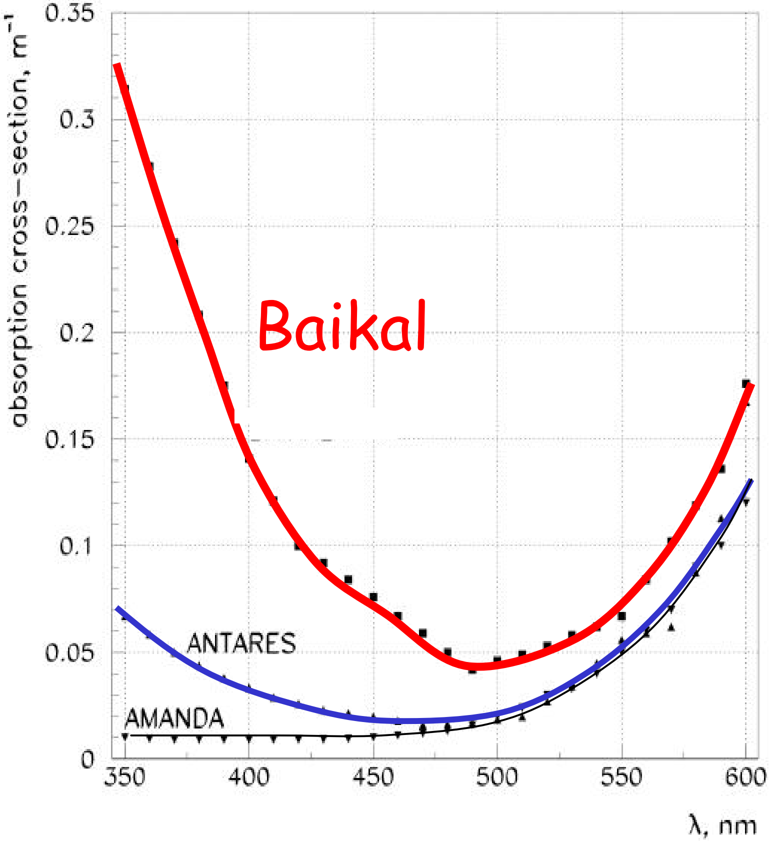
- 4 cables x 4km to shore.
- 1070m depth

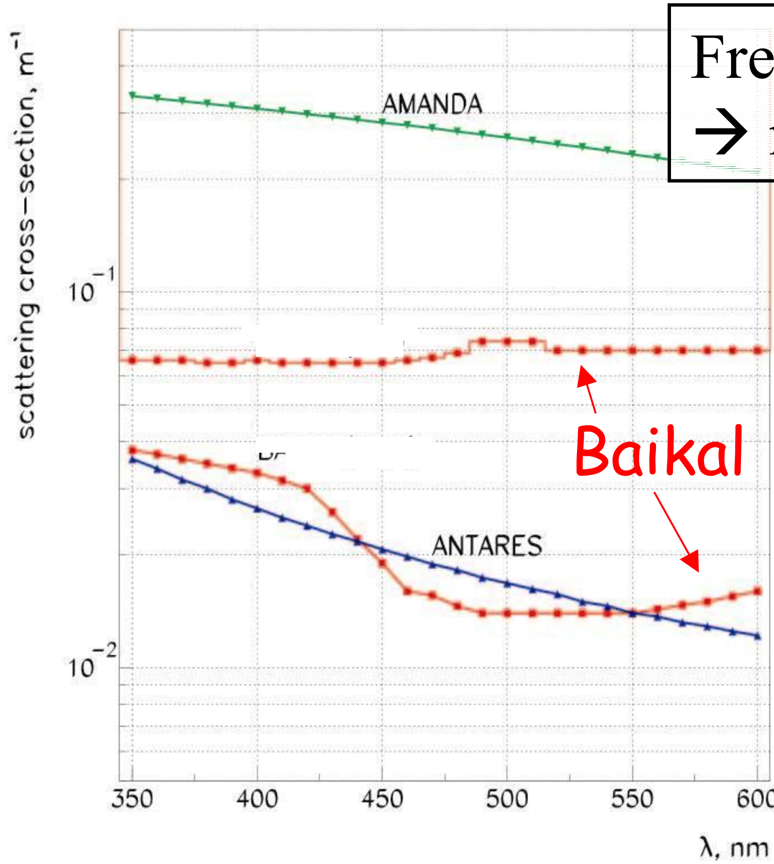
Ice as a natural deployment platform

- Ice stable for 6-8 weeks/year:
  - Maintenance & upgrades
  - Test & installation of new equipment
  - Operation of surface detectors (EAS

- Winches used for deployment operations →

Baikal - Optical Properties



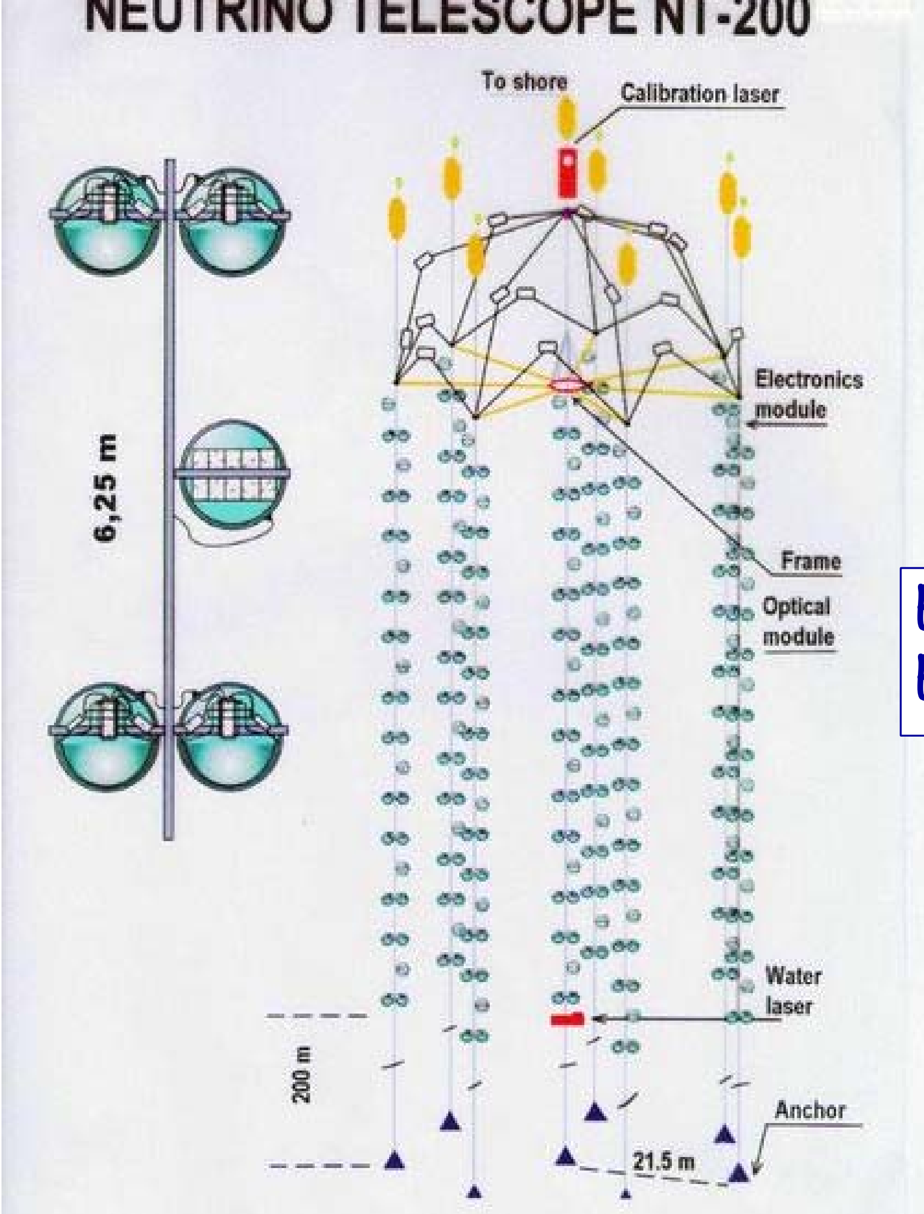


FreshWater
→ no K40 BG

Abs. Length: 22 ± 2 m

In-situ measurements

Scatt. Length (geom) ~ 30-50 m
⟨cos Θ⟩ ~ 0.85-0.9



Height x & = 70m x 40m, V=$10^5 m^3$

- 8 strings: 72m height
- 192 optical modules
- pairwise coincidence
  → 96 space points
- calibration with N-lasers
- timing ~ 1 nsec
- Dyn. Range ~ 1000 pe

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

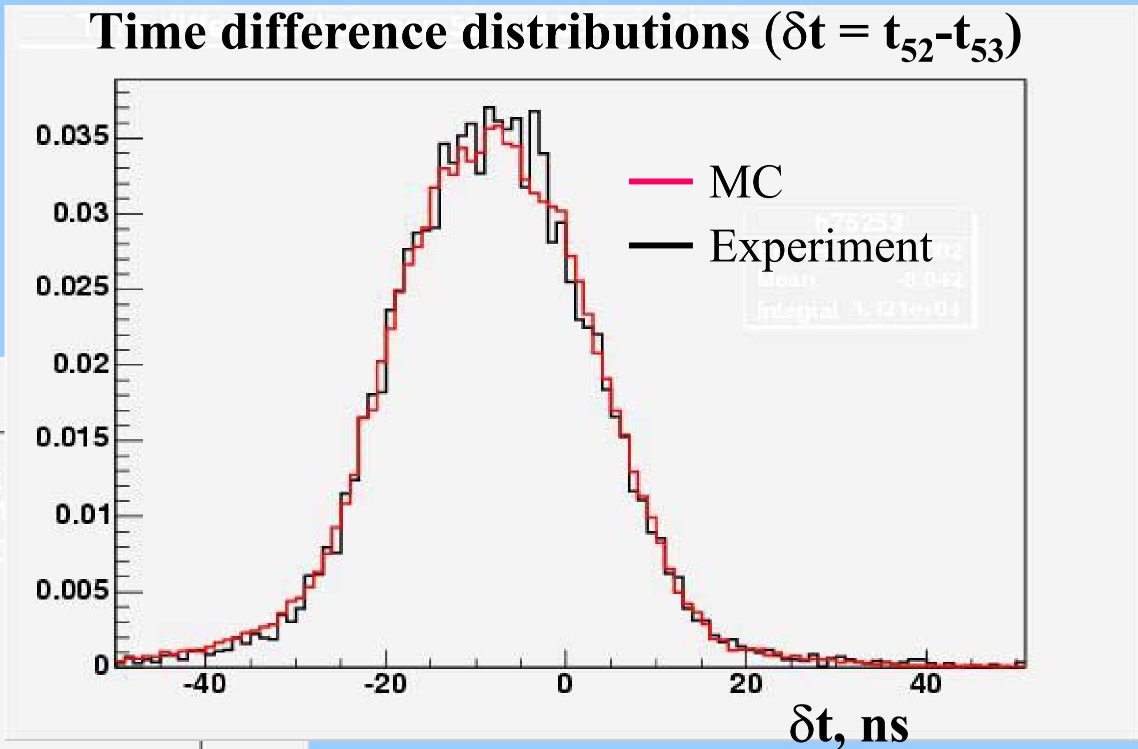
Quasar PMT: d = 37cm

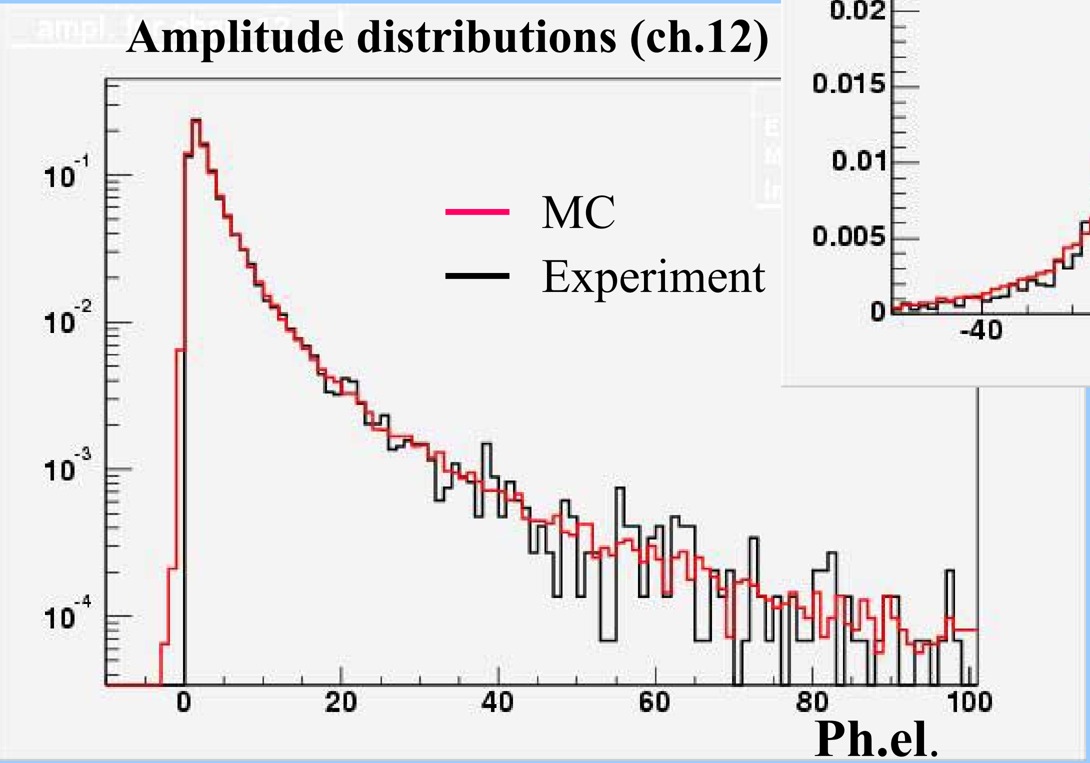
Optical Module – Pair (Coincidence)

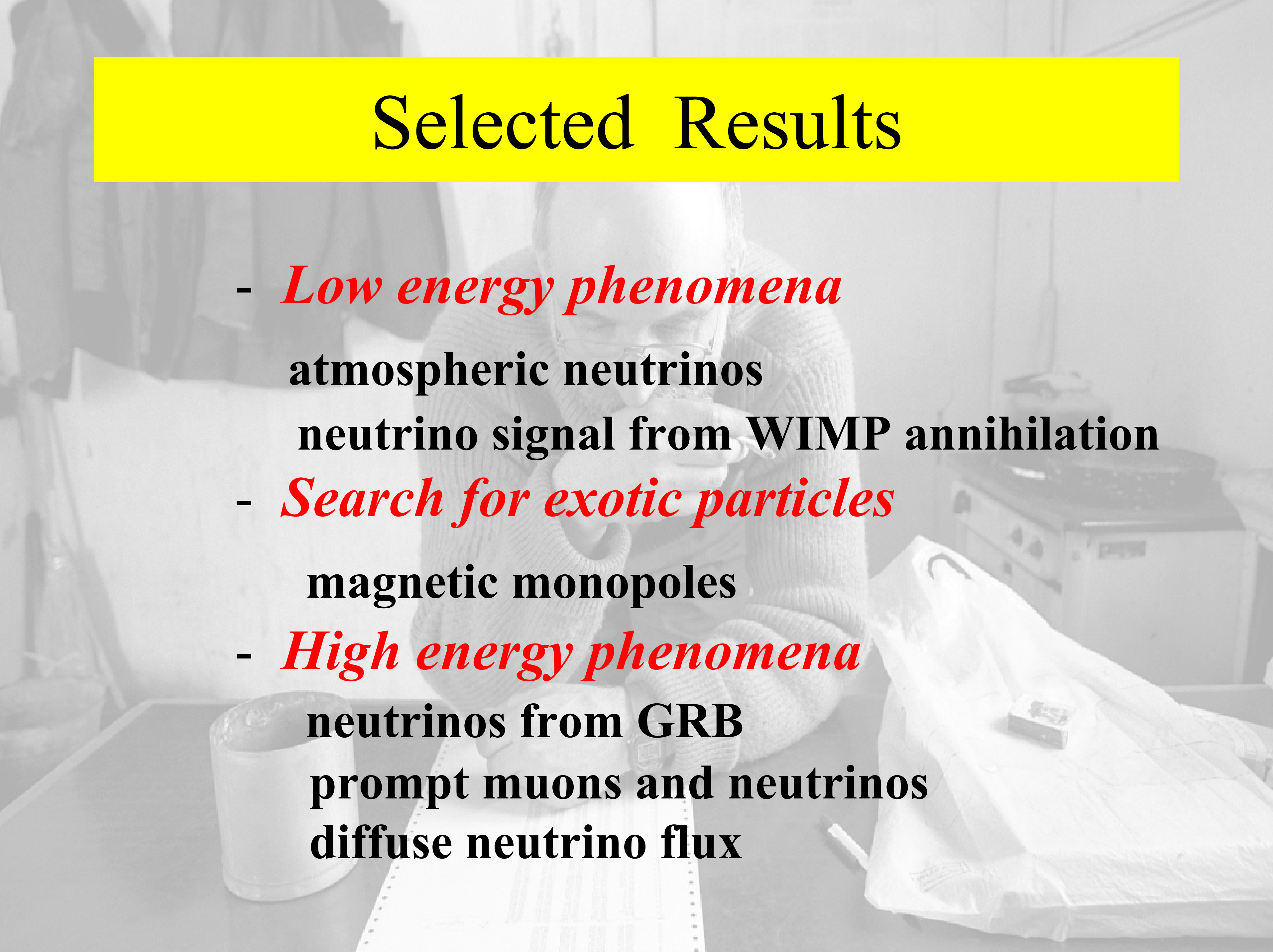
rs

hats“ against

Atmospheric muon flux as a calibration source







Selected Results

- *Low energy phenomena*

  atmospheric neutrinos

  neutrino signal from WIMP annihilation

- *Search for exotic particles*

  magnetic monopoles

- *High energy phenomena*

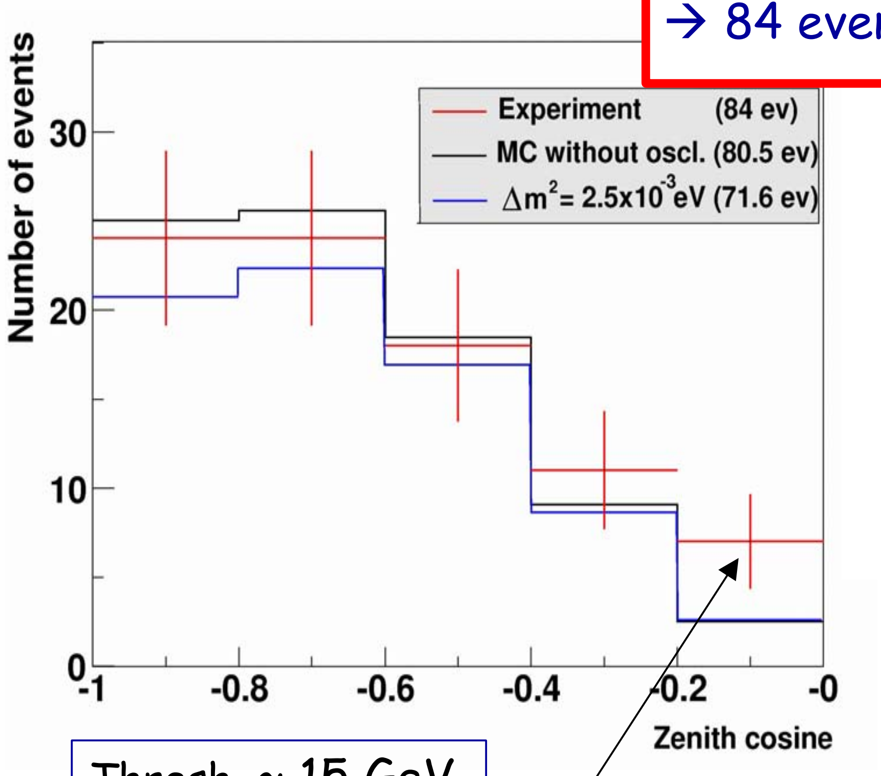
  neutrinos from GRB

  prompt muons and neutrinos

  diffuse neutrino flux

Atmospheric Muon-Neutrinos

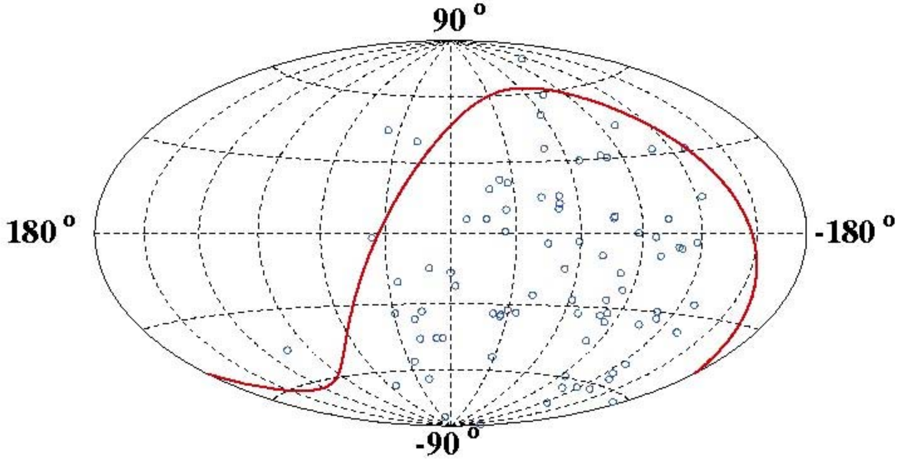
3-dimensional reconstruction
→ 84 events 1998+99



Thresh. ~ 15 GeV

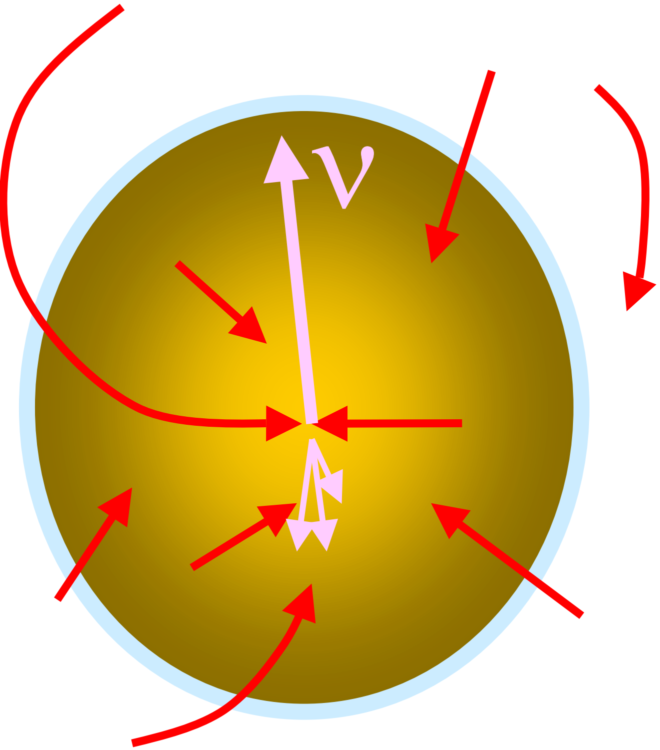
BG dominated bin

$\Delta\Psi \sim 3°$



Skyplot
(galactic coordinates)

WIMP Neutrinos from the Center of the Earth

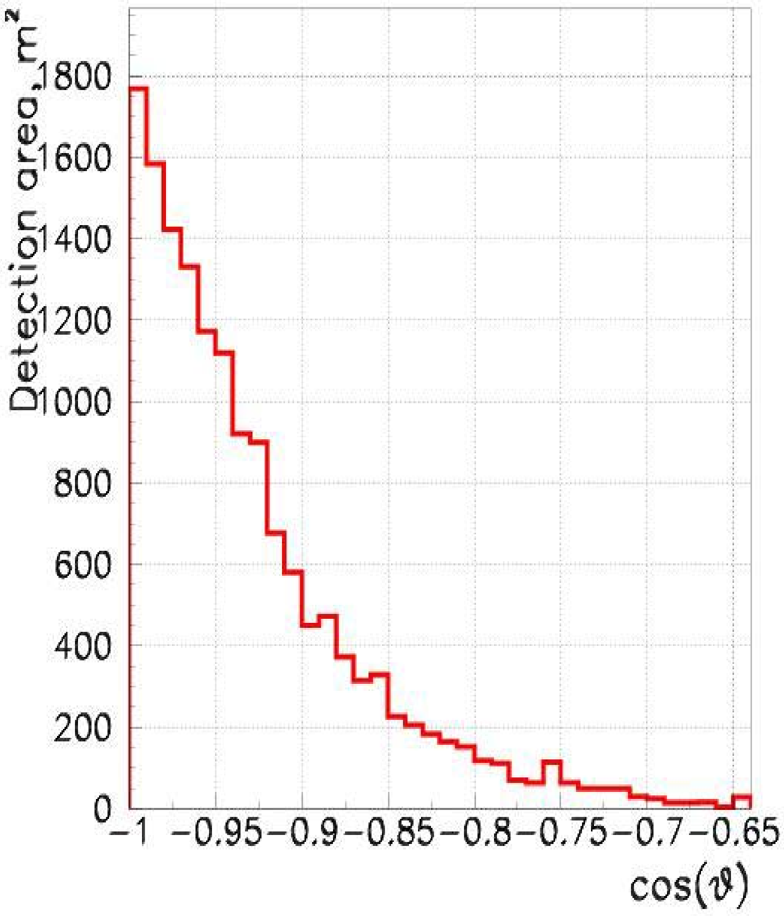


$$\chi + \chi \rightarrow b + b$$

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

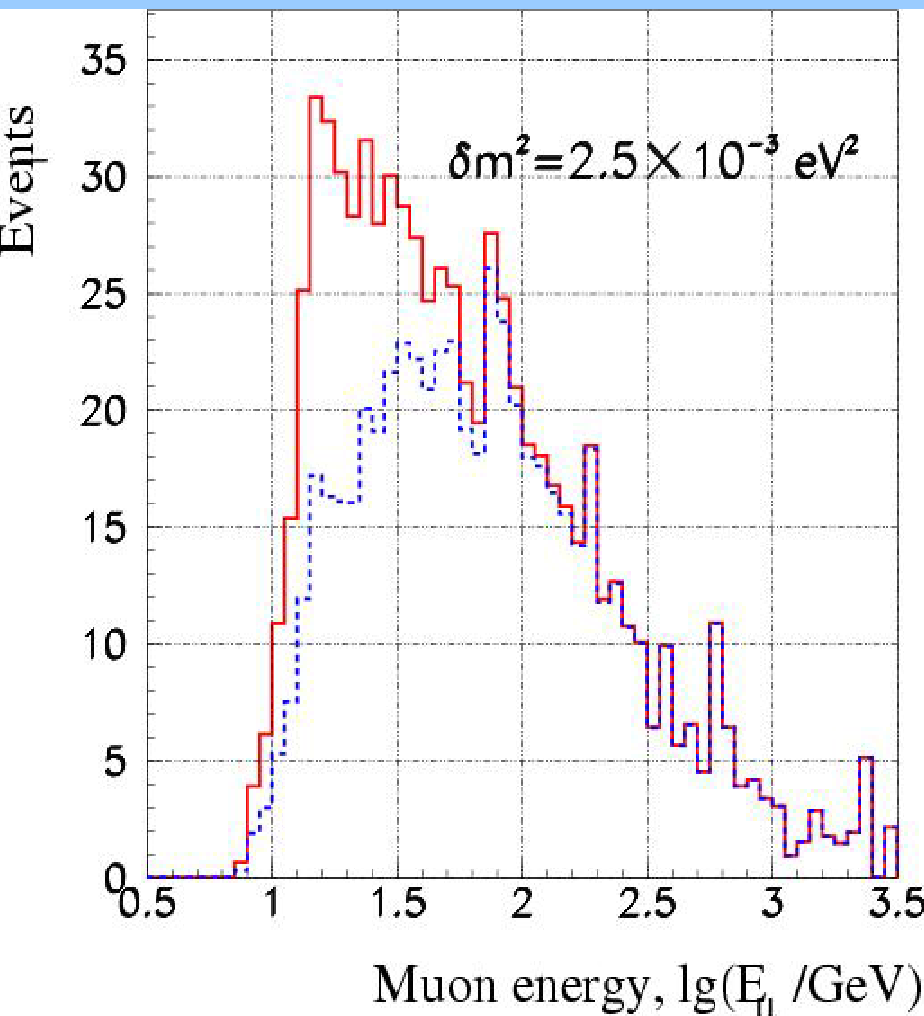
$$\rightarrow W^+ + W^-$$

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

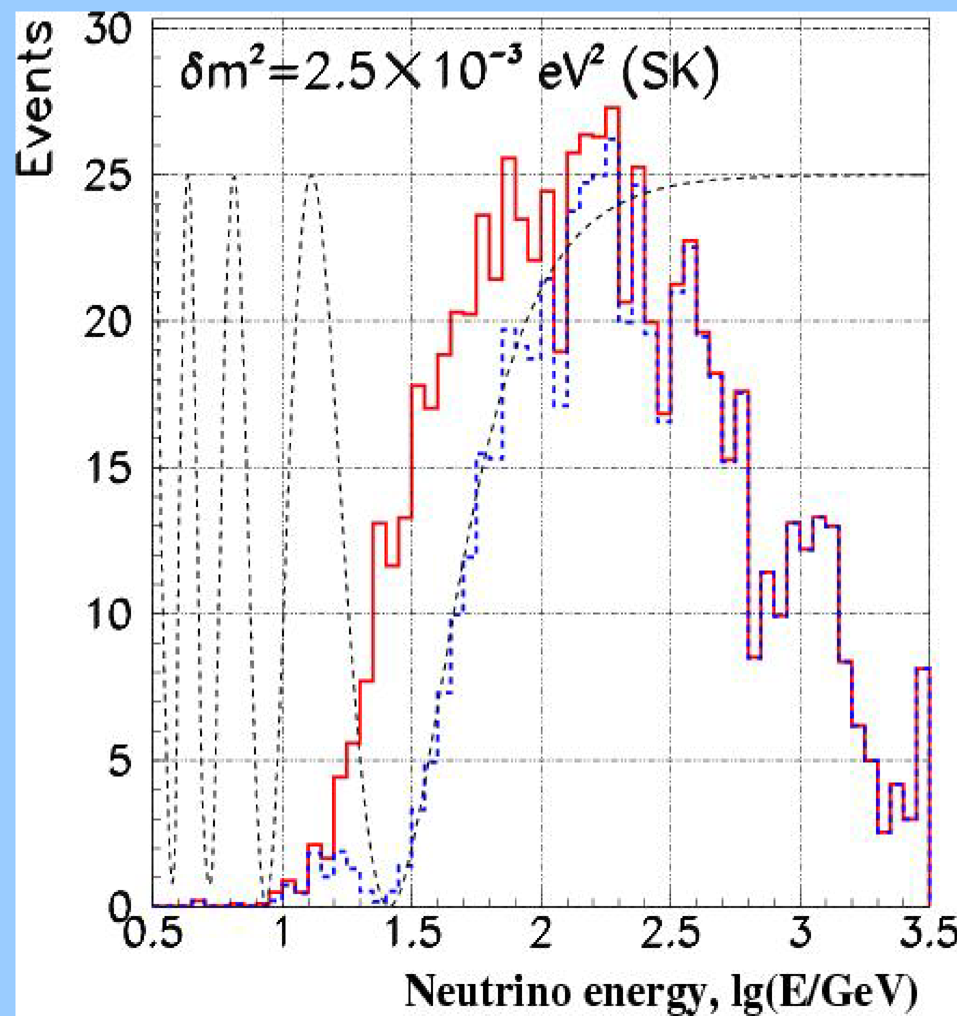


WIMP Search

Neutrino induced muons
$E_{thr} = 10$ GeV

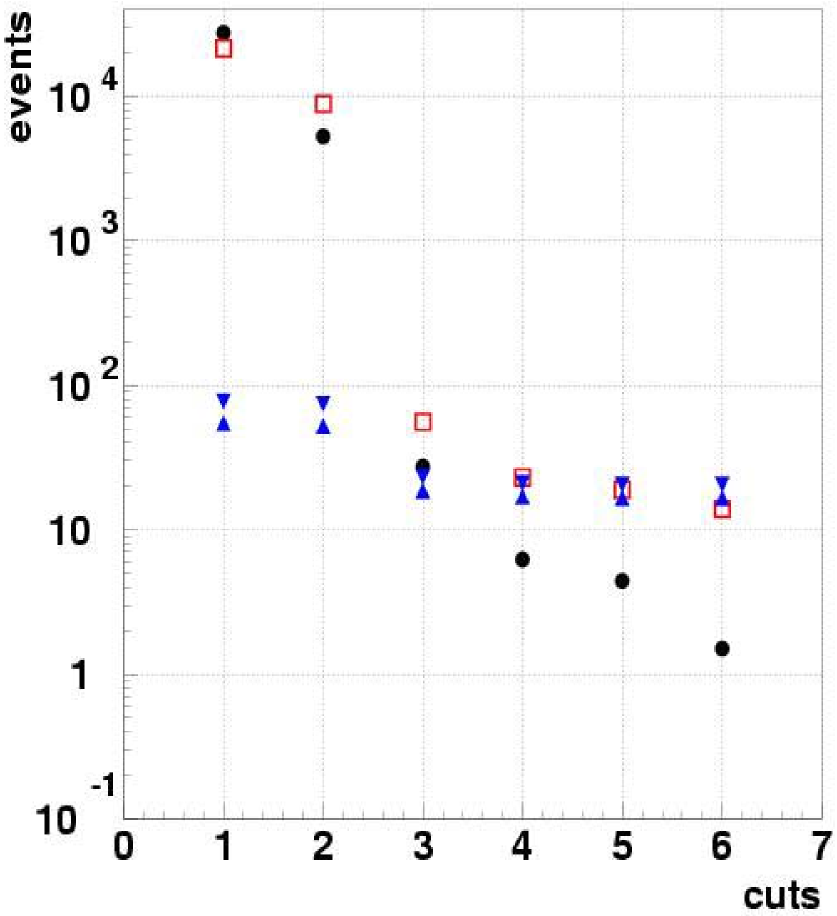


Atmospheric neutrinos
(Bartol-96 flux, oscillations - SK, K2K)



WIMP Search

Applied cut's efficiency



□ - experiment

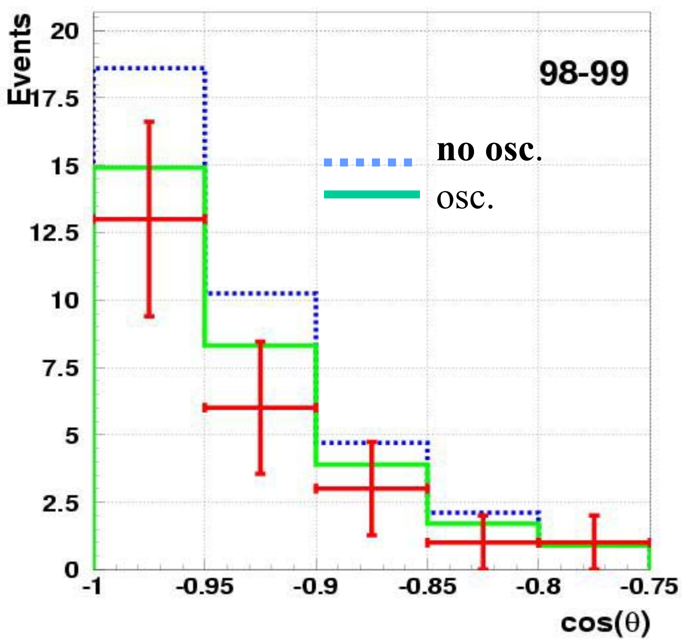
• - atm. muons (expectation)

▲ - neutrinos (with oscillations)

▼ - neutrinos (without oscillations)

WIMP Search

Angular distributions
(502 days, NT-200)



atm. neutrino flux - Bartol-96

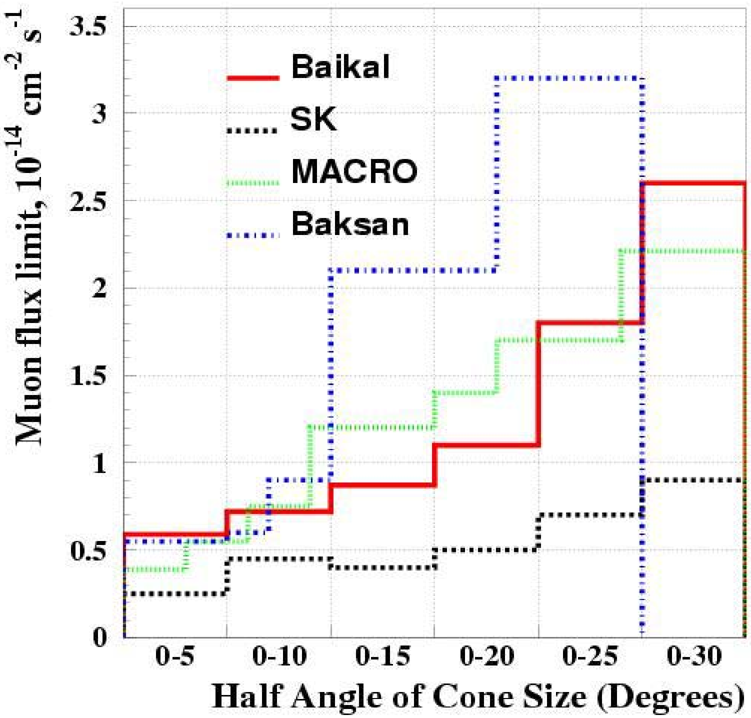
F $_{\nu}$(Honda et al. - 04) = 0.7 F $_{\nu}$(Bartol-96)

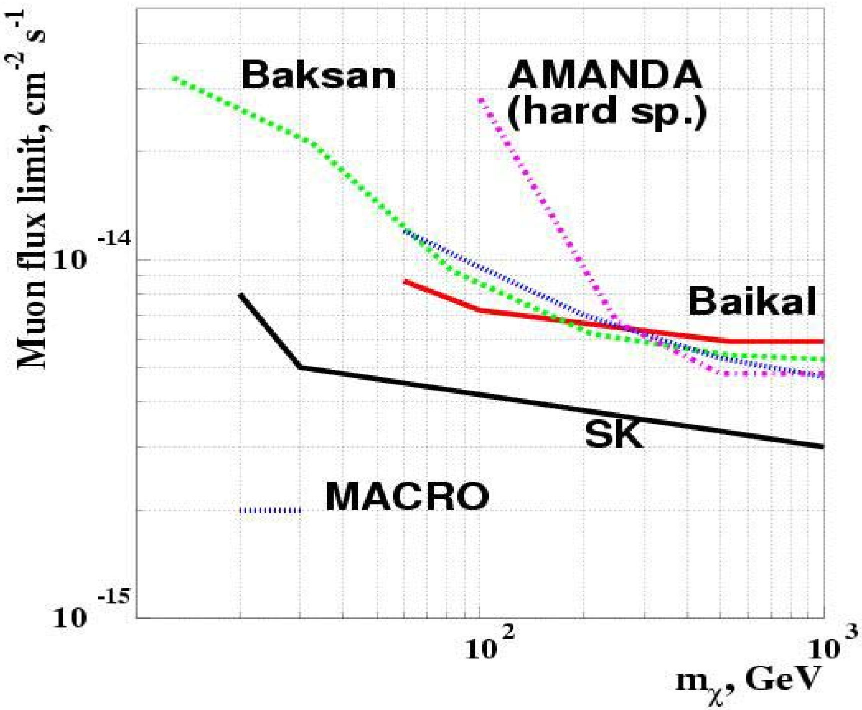
24 events - experiment
36.6 events - expected without oscillations
29.7 events - expected with oscillations

WIMP Search

Excess neutrino induced upward muon flux 90% c.l. limits from the Earth (502 days of NT-200 livetime, $E_{\mu} > 10$ GeV)

	Baikal	Amanda	SK	Baksan	MACRO
T, days	502	130	1680	5402	1298





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

$$N_\gamma(\lambda) = n^2 (g/e)^2 N_{\gamma\mu}(\lambda) = 8300\, N_{\gamma\mu}(\lambda)$$
$$g = 137/2, \quad n = 1.33$$

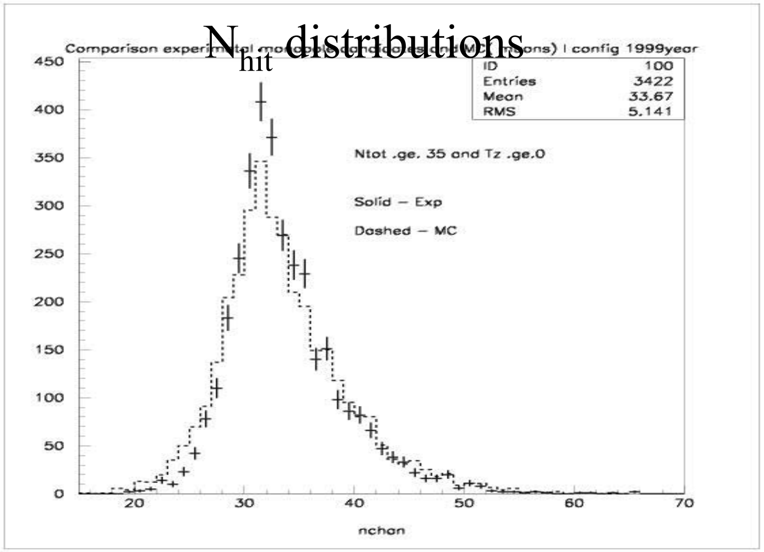
Event selection criteria:

hit channel multiplicity - $N_{hit} > 35$ ch,

upward-going monopole -

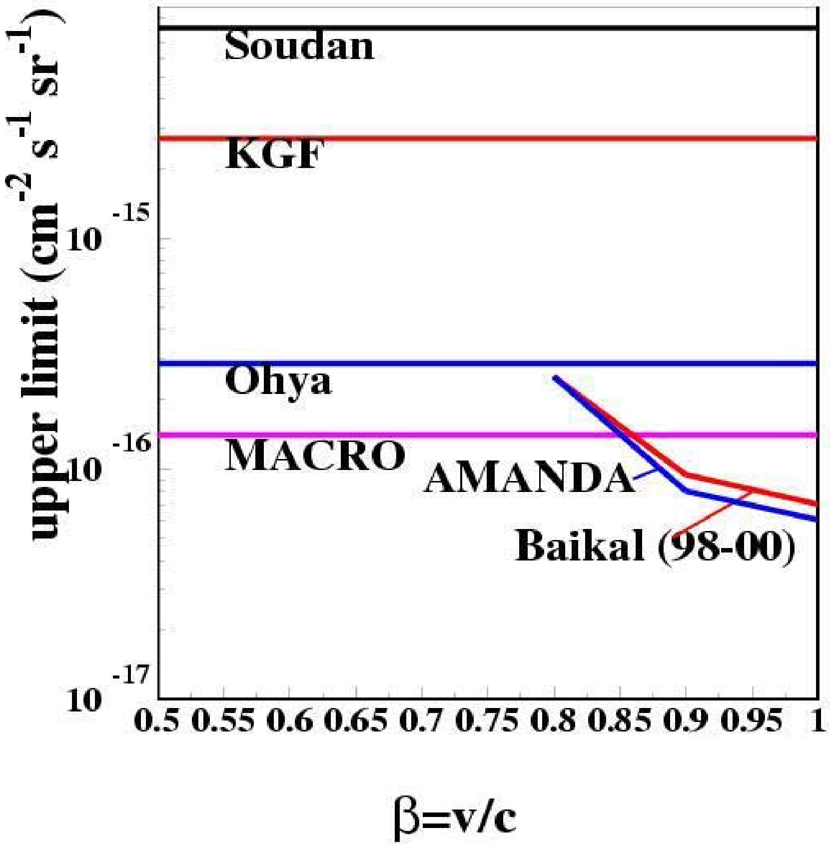
$\Sigma(z_i - z)(t_i - t)/(\sigma_t \sigma_z) > 0.45$ & $\theta > 100^o$

Background - atmospheric muons



780 livedays

Monopole limit (90% C.L.)



Search for slow massive monopoles ($10^{-5} < \beta < 10^{-3}$)

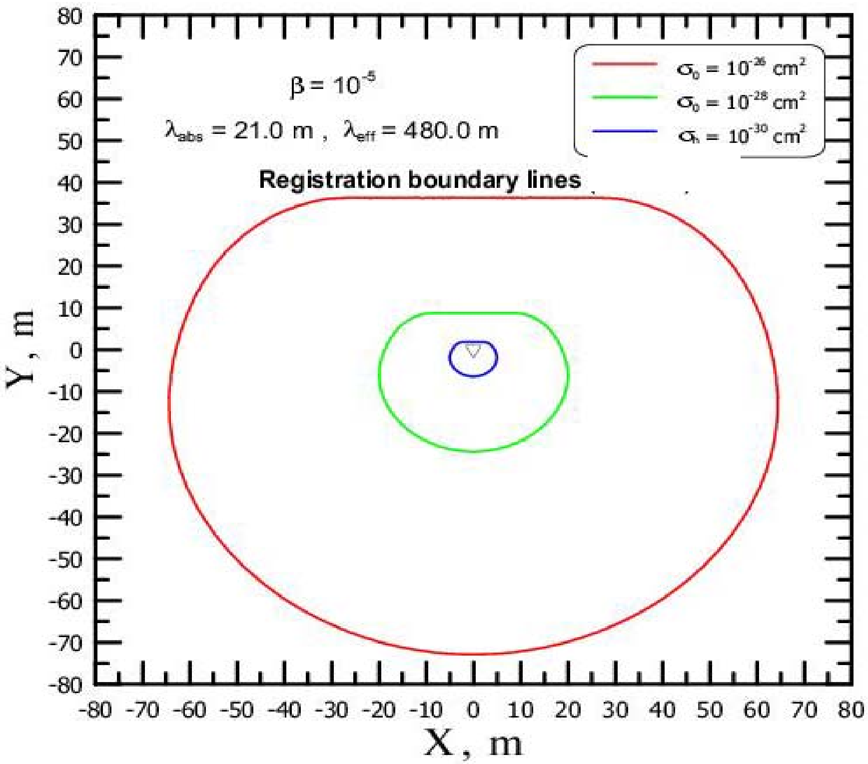
$\sigma_{cat} = 0.17\sigma_0/\beta^2, \ 10^{-5} < \beta < 10^{-3}$

$M + p \rightarrow M + e^+ (+\pi\ldots), \ N_\gamma \sim 10^5$

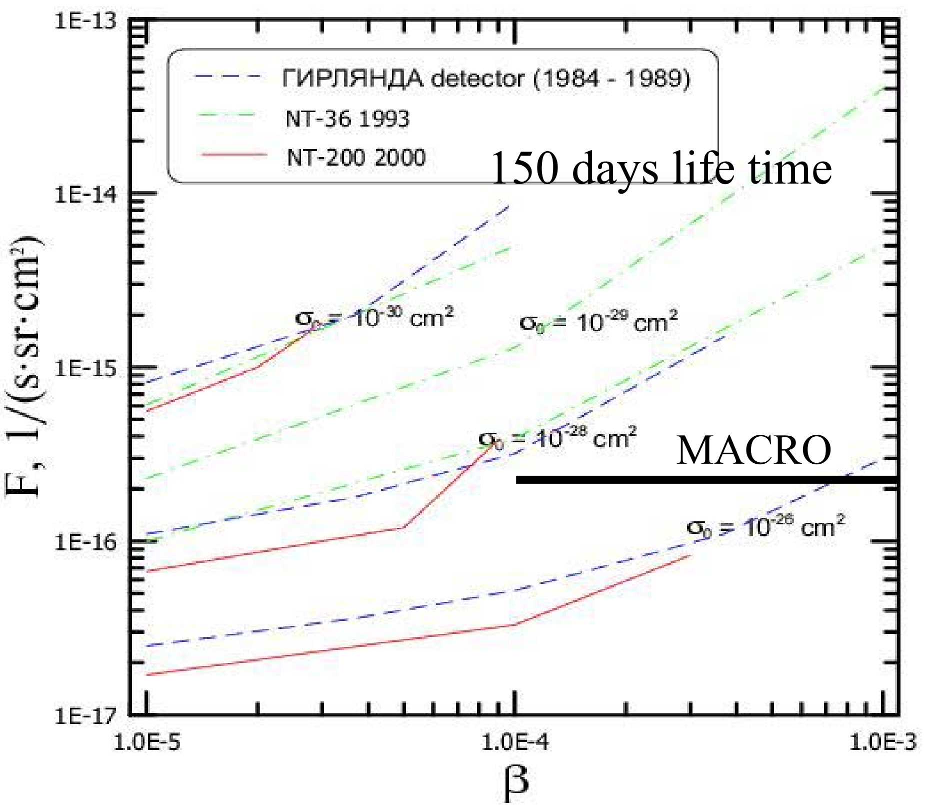
NT-200 - detection of massive bright objects (GUT-monopoles, nuclearites, Q-balls …)

monopole trigger: $N_{hit} > 4$ within $dt = 500\mu sec$

selection requirements - $N_{ch} > 1$ with $N_{hit} > 14$

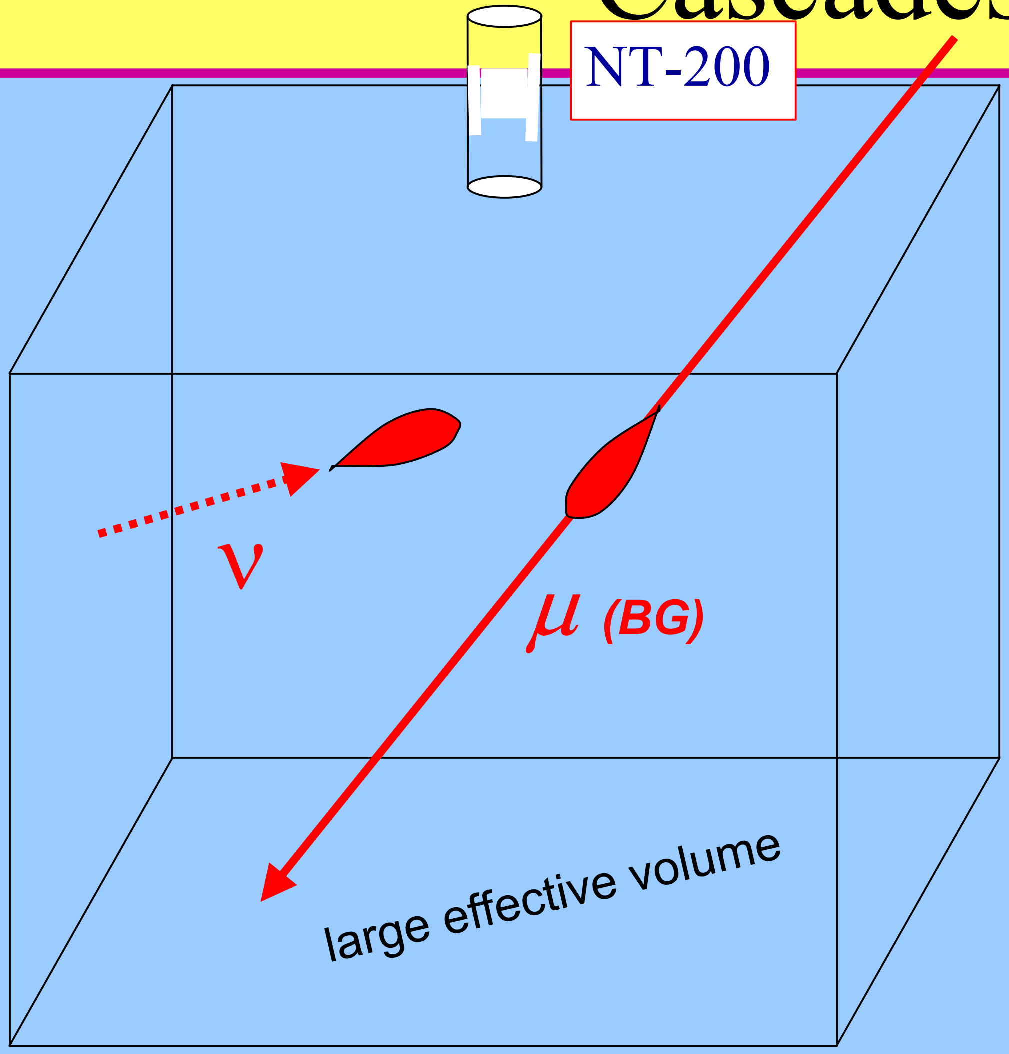


Magnetic monopole detection boundaries



Magnetic monopole flux limits

Search for High Energy - Cascades



Look for upward moving light fronts.

Signal:
isolated cascades from neutrino interactions

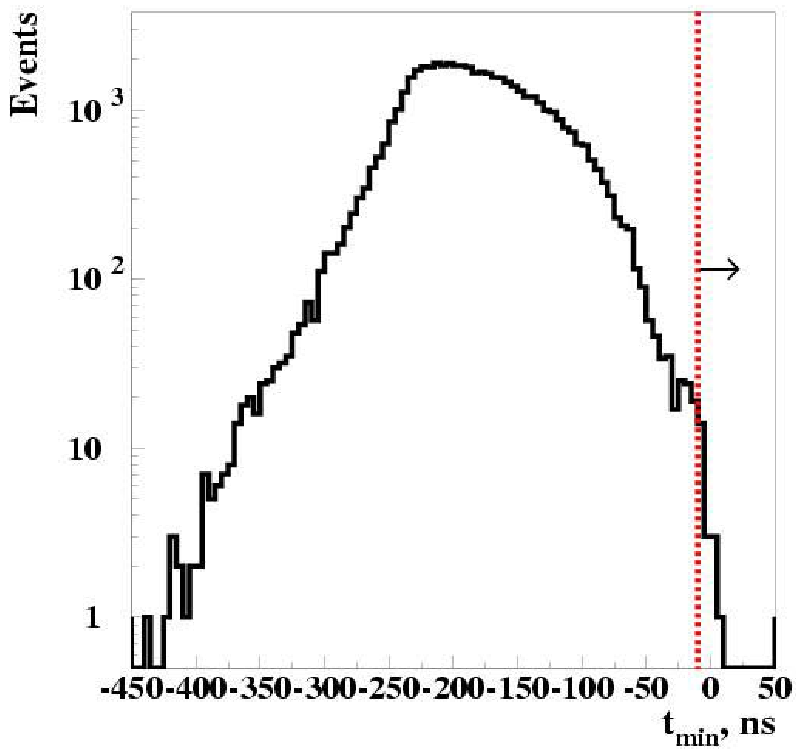
Background:
Bremsshowers from h.e. downward muons

Final rejection of background by „energy cut" ($N_{channel}$)

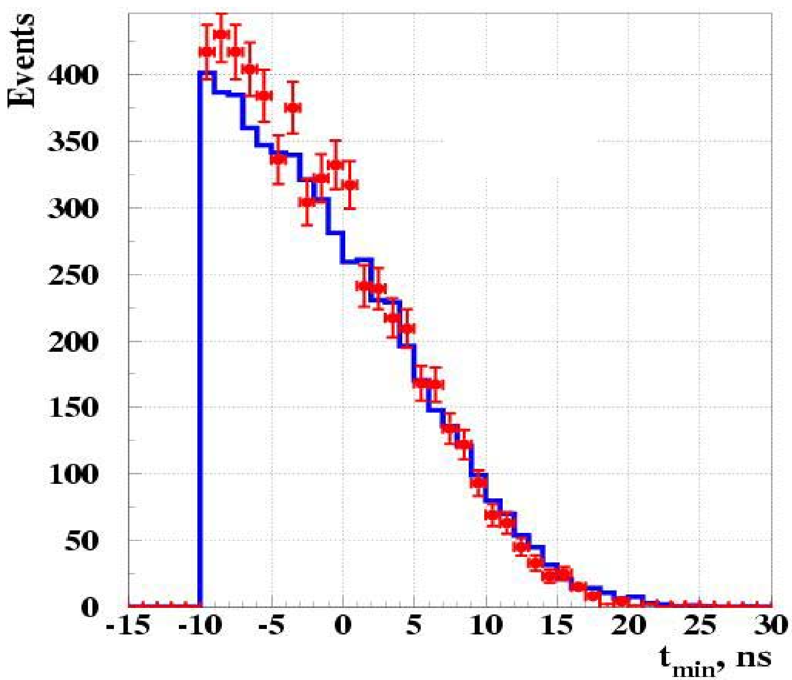
High energy cascade selection:

$t_{min} = \min(t_i - t_j), \quad j > i$ - cascades below NT-200

$N_{hit} > 15$ ch. - hit channel multiplicity

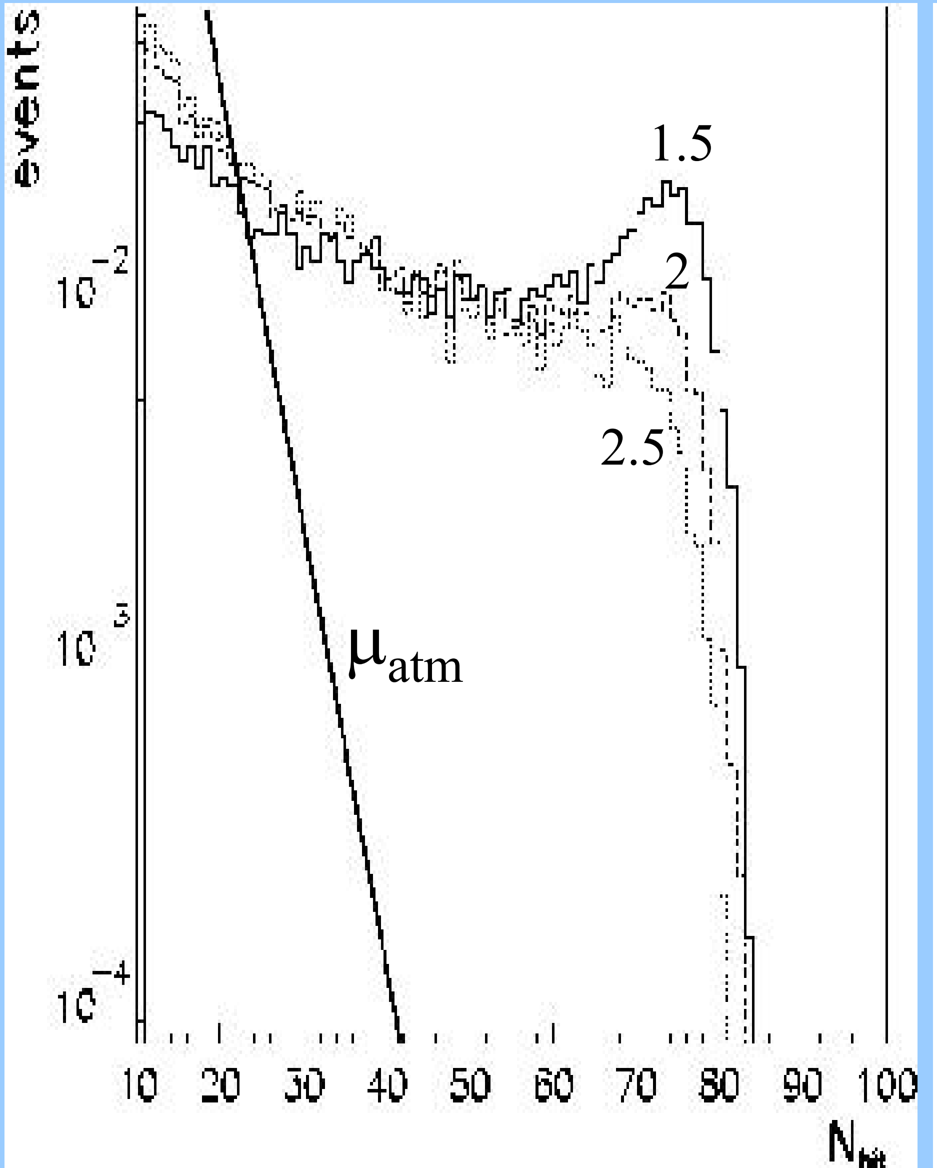


Data (N_{hit}>40 ch.)

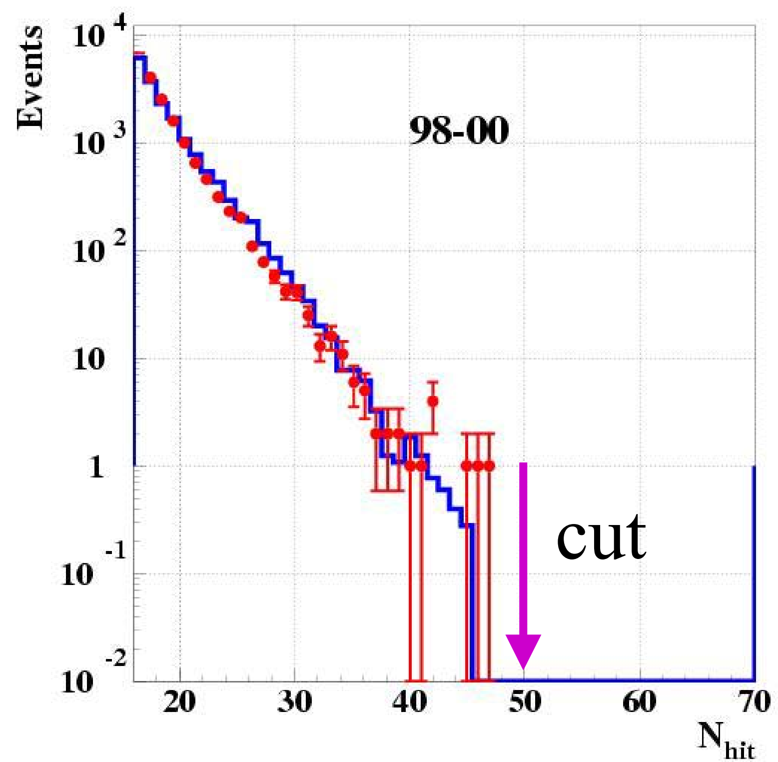


Data (t_{min}>-10 нс)

$\Phi_\nu = AE^{-\gamma}$
hit channel multiplicity



Hit channel multiplicity (experiment)



Search for neutrinos correlated to Gamma Ray Bursts

April 1998 - February 2001:
N_{tot}= 722 BATSE events
NT-200: N_{hit}>10 & t_{min}>-10 ns &
t_{BATSE}-100 ns < t < t_{BATSE}+100 ns

	Triggered GRB		All GRB	
N	Signal	Backgr.	Signal	Backgr.
15	91	94	172	167
20	11	13	22	23
25	1	2.8	5	5.2
30	1	0.86	3	1.6
35	0	0.28	1	0.47
40	0	0	0	0.056

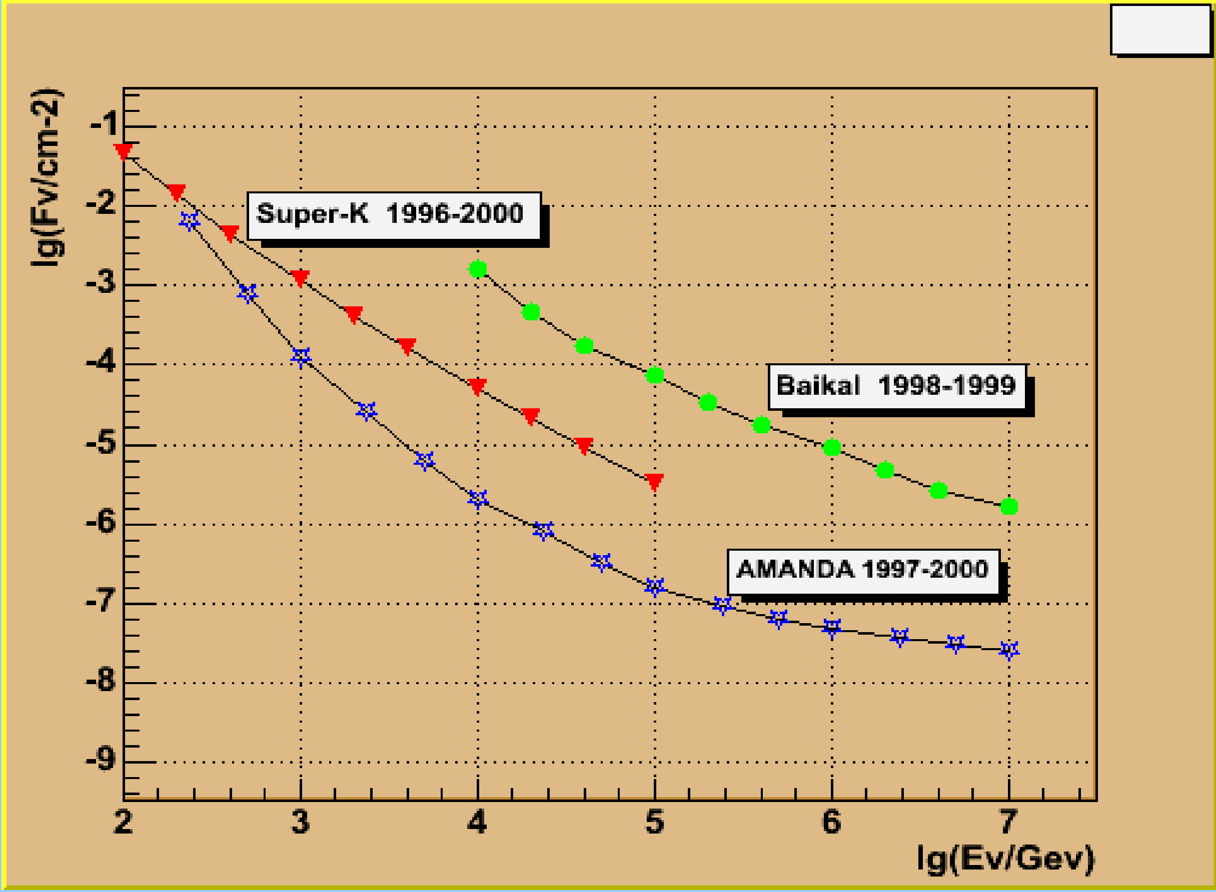
Data consistent with expected background from atm. muons

90% C.L. limits on neutrino flux from GRBs:

N_{hit}>34 → 1 selected event, N_{bg}=0.47

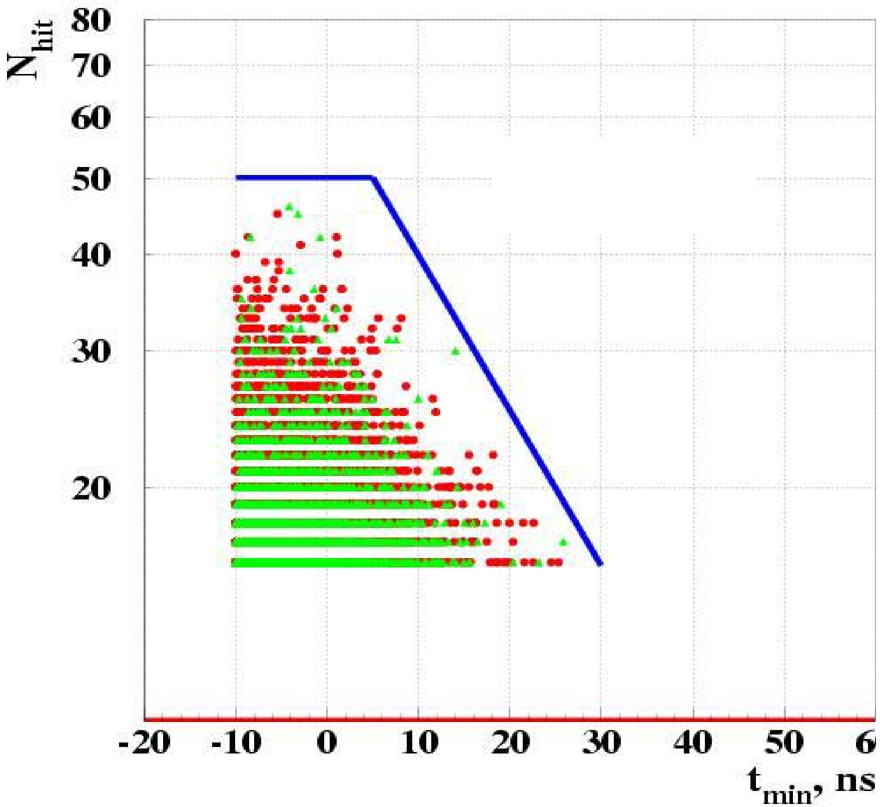
$F(E)=A_{tot}\,\delta(E-E_0)$, $A_{tot}=N_{90}/S(E_0)$

$$A_{GRB} = A_{tot}/N_{tot}$$

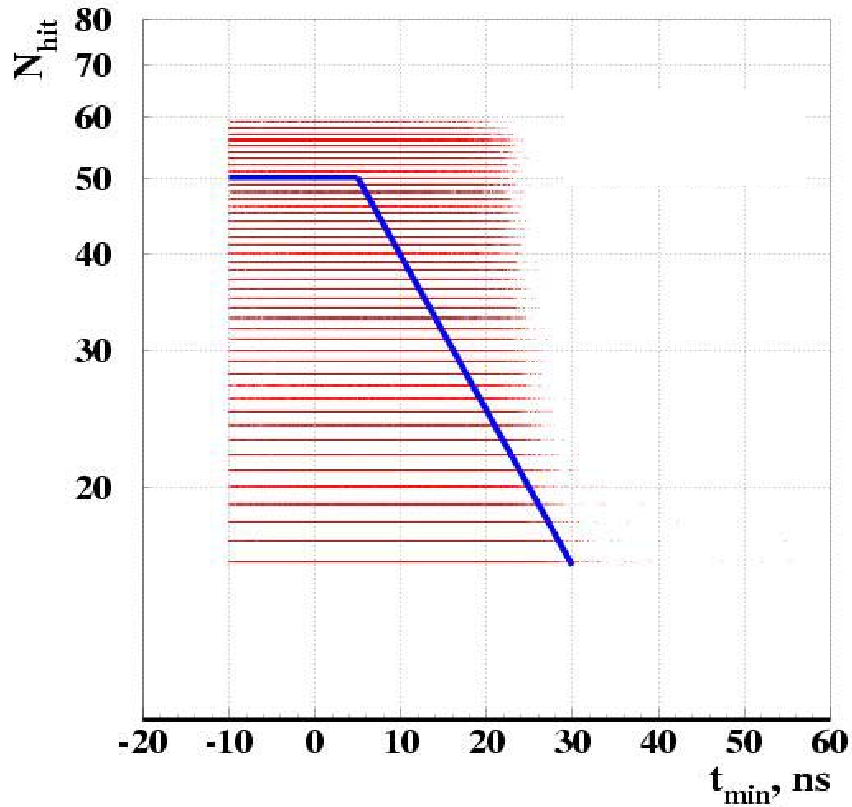


Event selection criteria

- \- experiment
- \- atm. muons background



High energy cascades

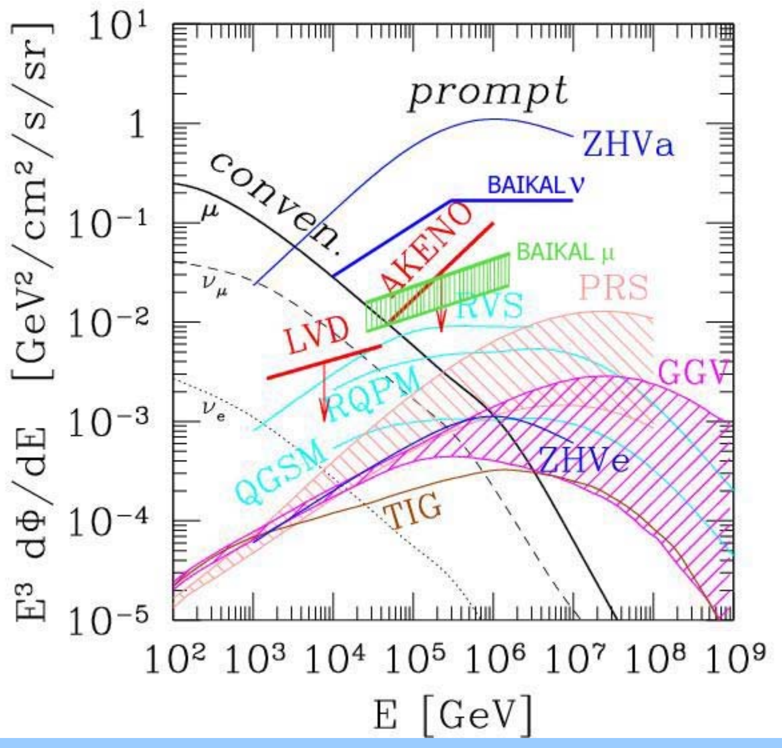


Prompt atmospheric muons and neutrinos
(*source of background for neutrino telescopes*)

Sources - decays of short-lived particles (Λ, D, …)

$\Phi_\mu \sim \Phi_\nu$ – isotropic for $E < 10^7$ GeV

90% c.l. limits for prompt μ and ν_e fluxes (780 life days)



Neutrinos - ν_μ, ν_e: cascades (CC, NC)

$$\Phi_\nu = \begin{cases} A_\nu E^{-2.6}, & E<E_b=3\ 10^5\ \text{GeV} \\ A_\nu E_b^{0.4} E^{-3}, & E>E_b=3\ 10^5\ \text{GeV} \end{cases}$$

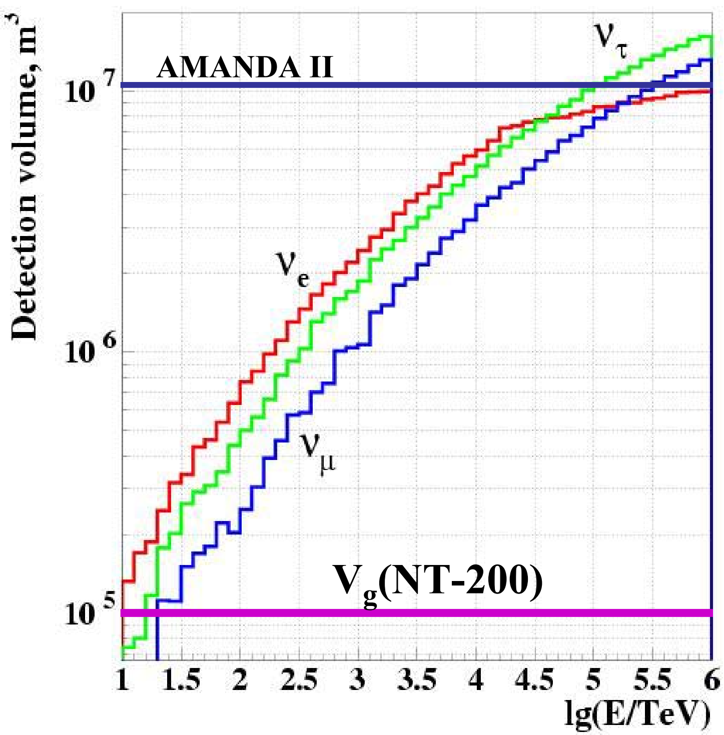
Muons: cascades (e^+e^-, brem, ph.-nucl.)

$$\Phi_\mu = A_\mu E^{-2.6}$$

Predictions:

ZHV - E.Zas, F.Halzen, R.Vazquez-93
RVS - O.Ryazhskaya, L.Volkova, O.Saavedra-02
QGSM, RQPM - E.Bugaev et al.-89
TIG - M.Thunman, G.Ingelman, P.Gondolo-96
GGV - G.Gelmini, P.Gondolo, G.Varieschi-02
(hep-ph/0209111)

Diffuse flux of ν_e, ν_τ, ν_μ: cascades



The 90% C.L. Limits Obtained With NT-200 (780 days) DIFFUSE NEUTRINO FLUX

$(\Phi_\nu \sim E^{-2}$, 10 TeV < E < 10^4 TeV)

$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ (AGN)

$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ (Earth)

$E^2 \Phi_\nu < 1.0 \cdot 10^{-6}$ GeV $cm^{-2} s^{-1} sr^{-1}$

$E^2 \Phi_\nu < 8.6 \cdot 10^{-7}$ GeV $cm^{-2} s^{-1} sr^{-1}$ (AMANDA04)

W-RESONANCE

(E = 6.3 PeV, $\sigma = 5.3 \cdot 10^{-31}$ cm^2)

$\Phi_{\nu e} < 4.2 \cdot 10^{-20} (cm^2 \cdot s \cdot sr \cdot GeV)^{-1}$

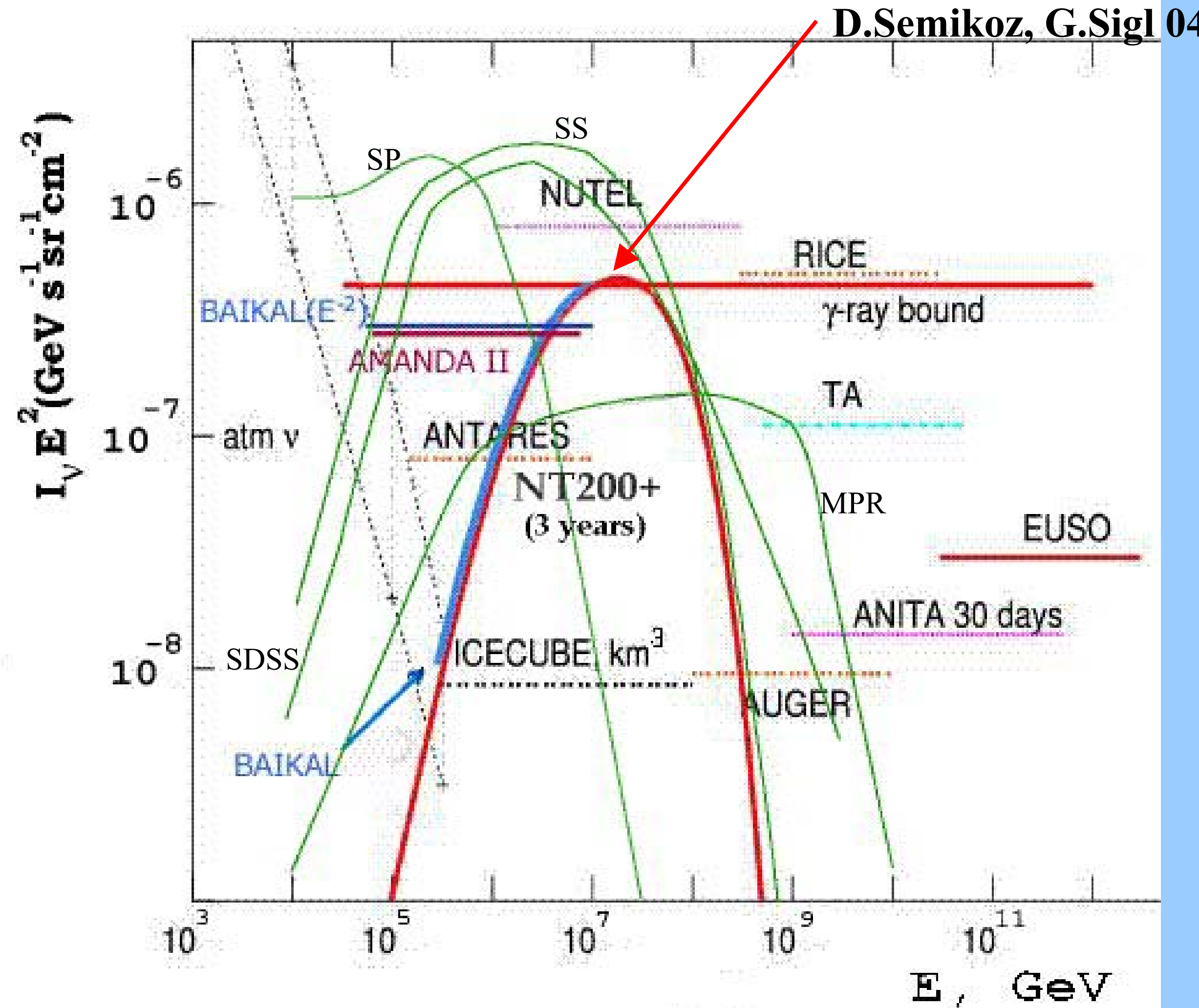
$\Phi_{\nu e} < 5.0 \cdot 10^{-20} (cm^2 \cdot s \cdot sr \cdot GeV)^{-1}$ (AMANDA04)

Diffuse flux of ν_e, ν_τ, ν_μ: *cascades*

Experimental limits and theoretical predictions

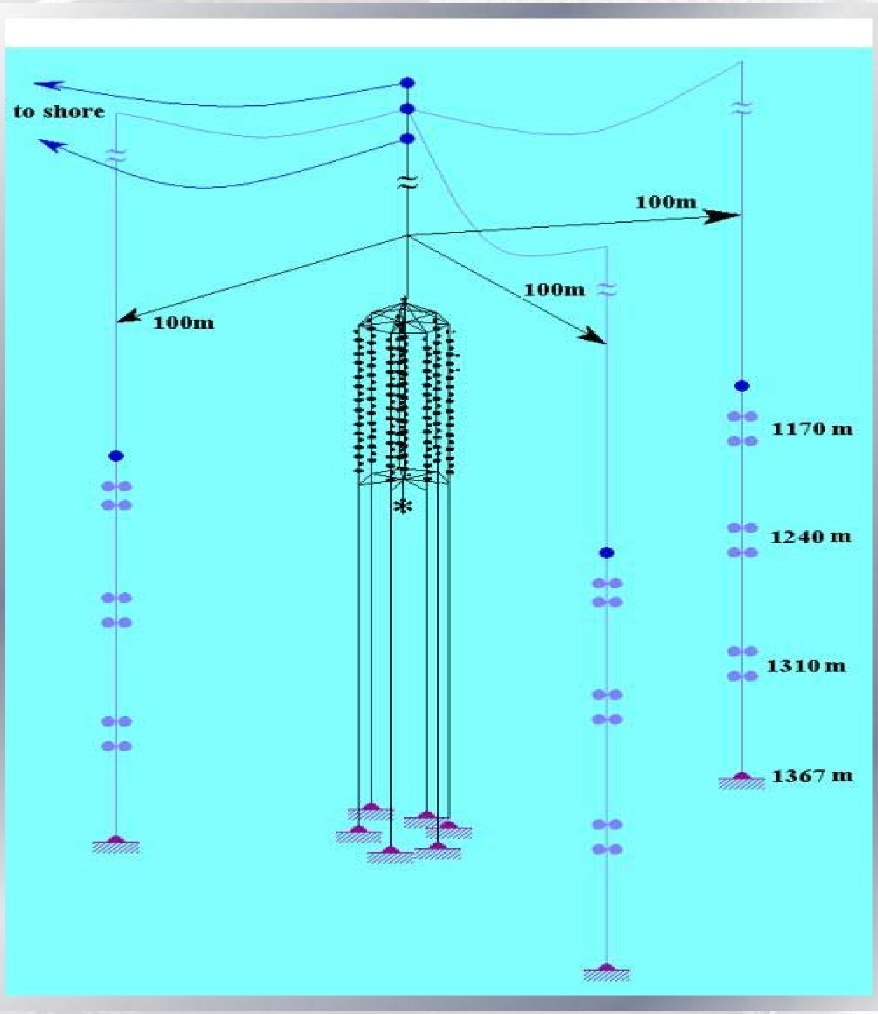
Models ruled out by AMANDA04
SDSS - Stecker et al.92
SS - Stecker, Salamon96
SP - Szabo, Protheroe92

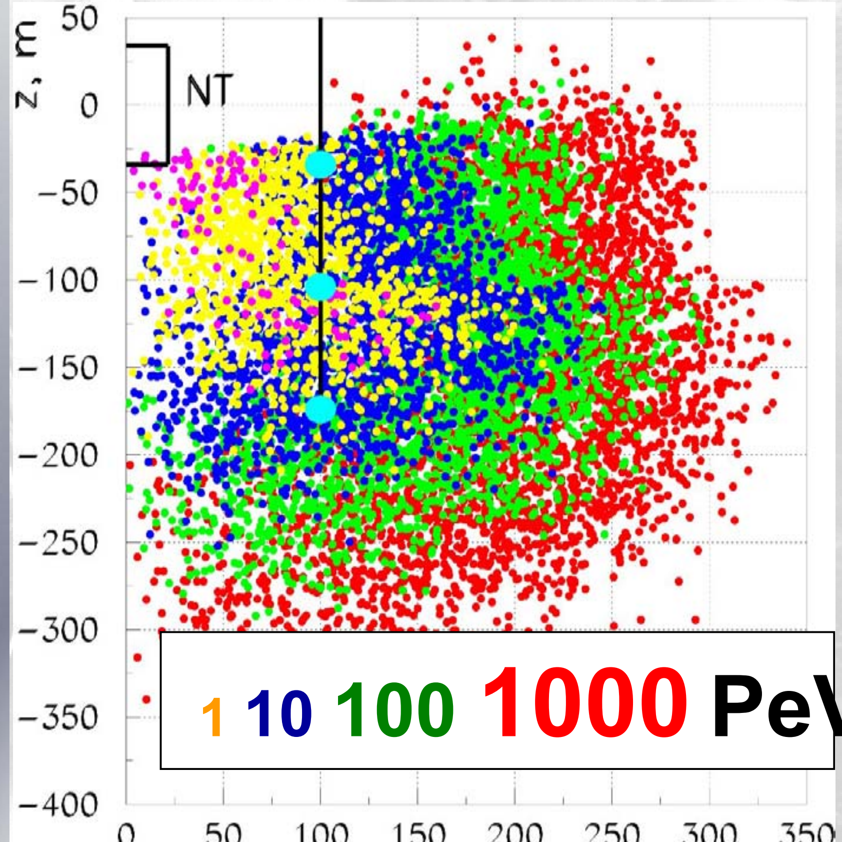
MPR - Mannheim, Protheroe, Rachen



Upgrade to NT-200+

2004: two distant test string
2005: completion





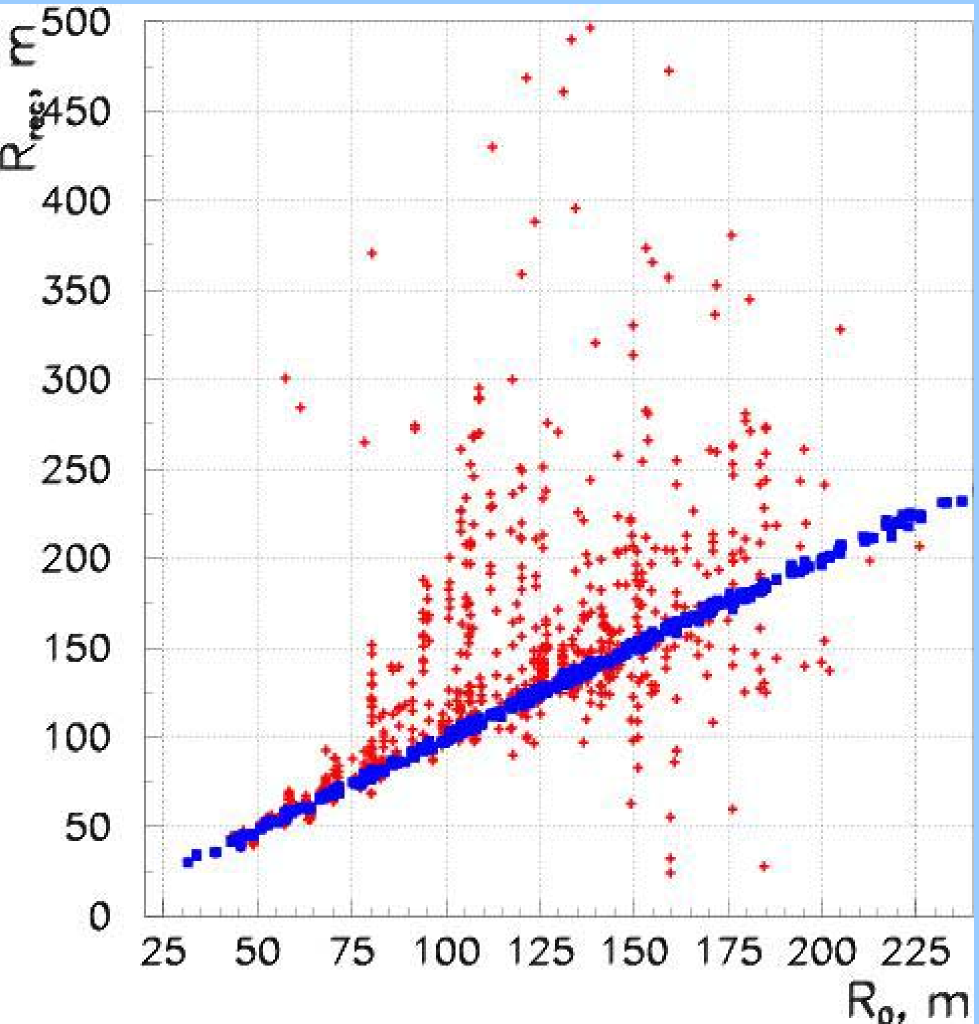
1 10 100 1000 PeV

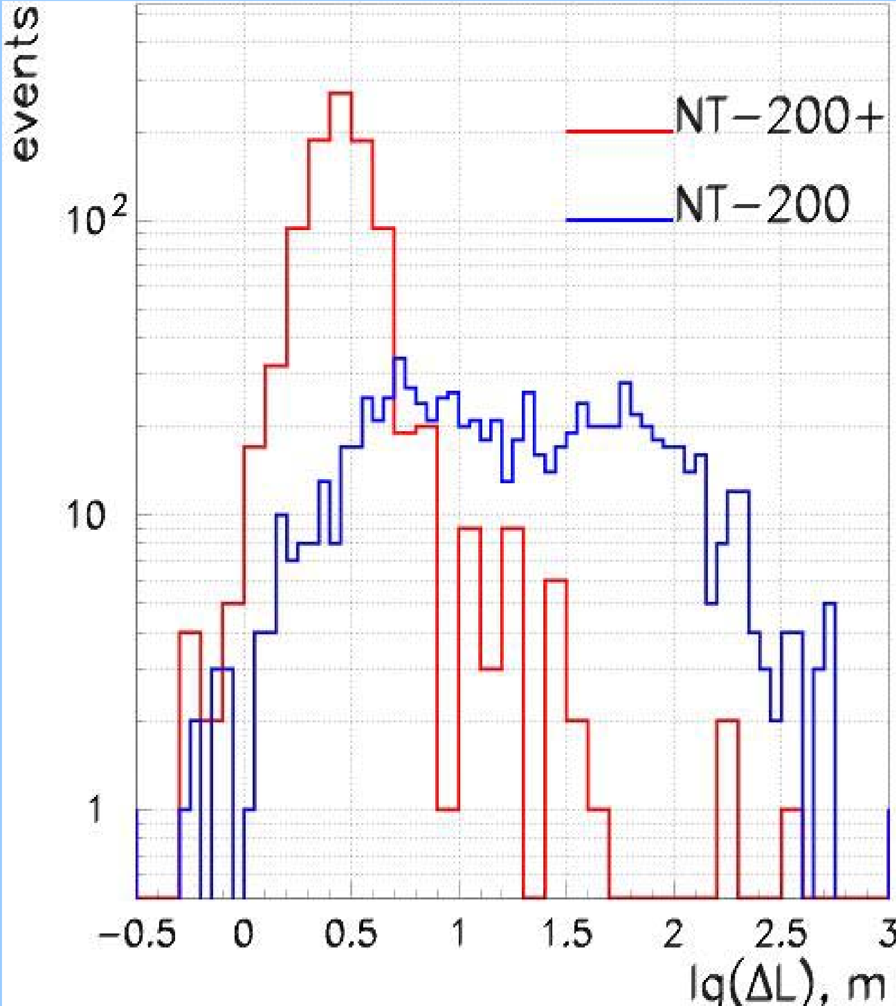
4 15 23 40 Mton

36 additional PMTs on 3 far 'strings'
→ 4 times better sensitivity !

NT - 200+

Cascade coordinates (energy) reconstruction efficiency

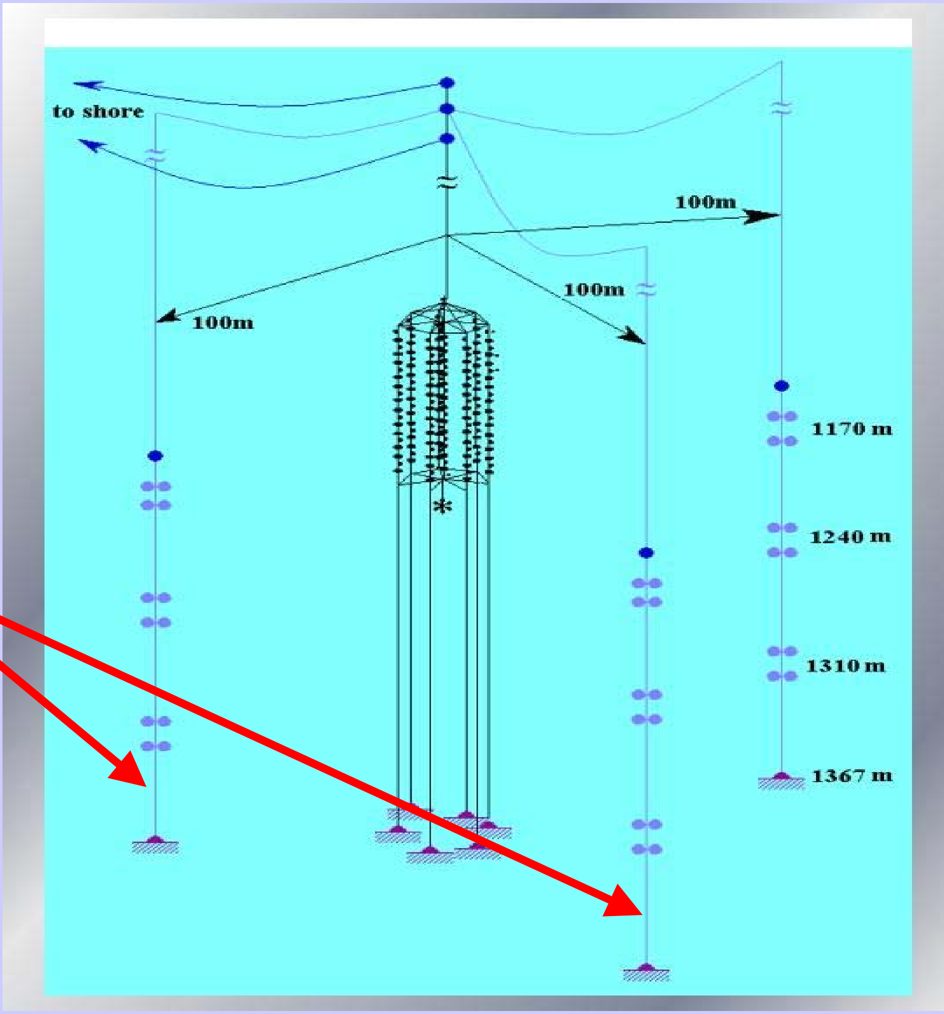




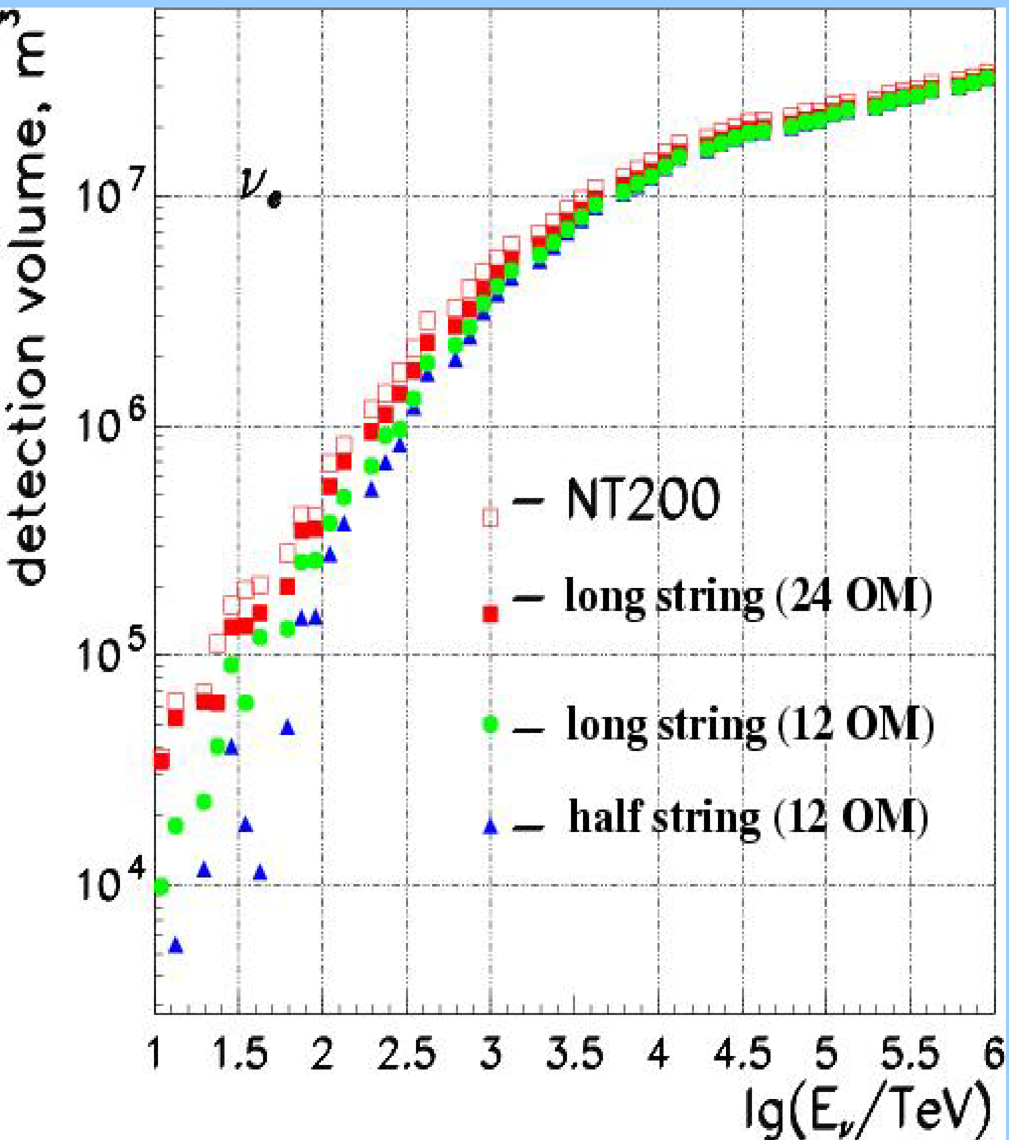
NT-200+ status

2004:
- new cable to shore
- DAQ system has been improved
- two of three outer strings are installed

2.3 10^4 common events are taken during 364 hours life time (0.017 Hz)



NT - 200+



NT - 200+ as subunit for a Gton scale detector

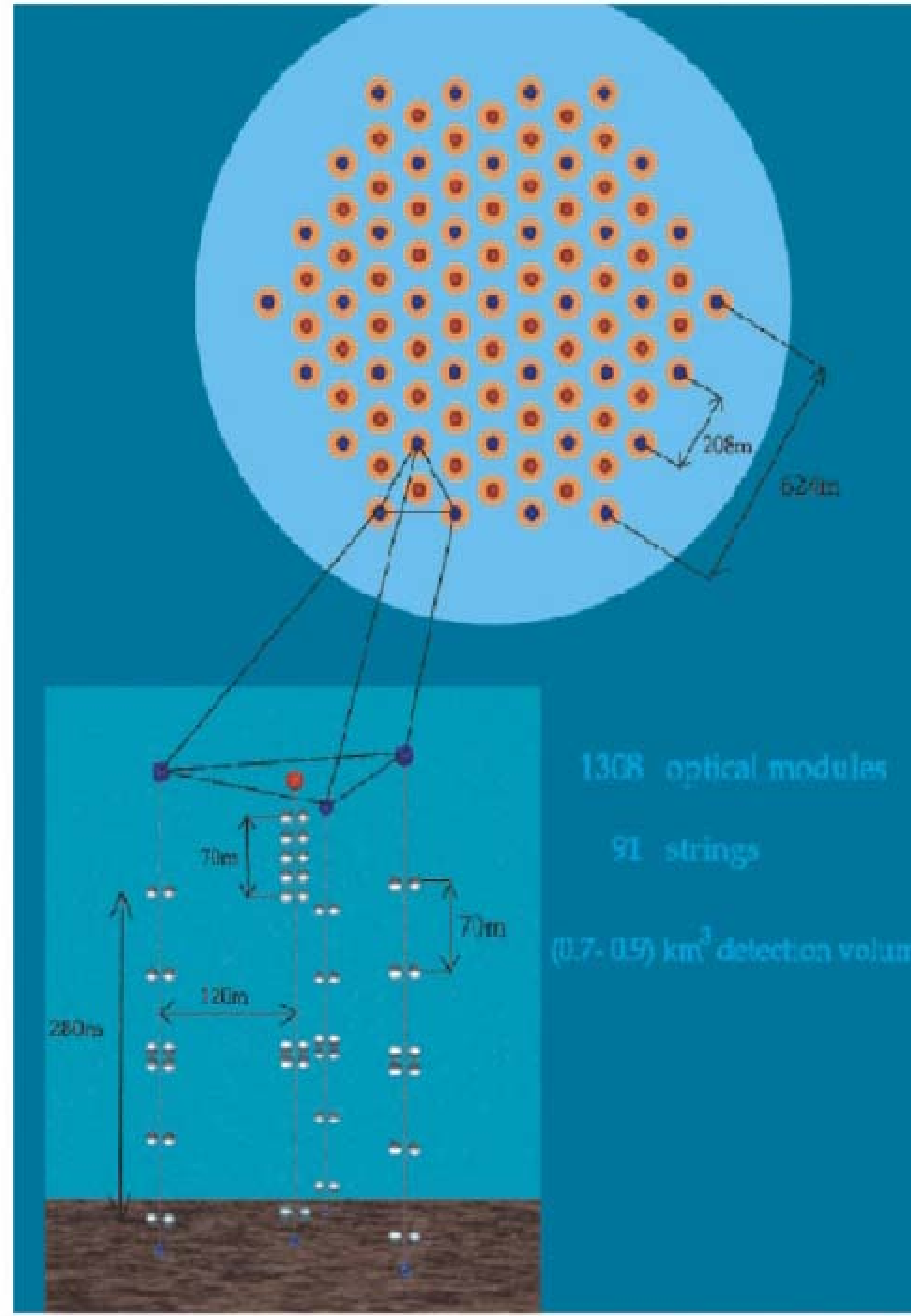
A Gigaton (km3) Detector in Lake Baikal.

Sparse instrumentation:

91 strings with 12 OM
 = 1308 OMs

→ effective volume for
100 TeV cascades
~ 0.5 -1.0 km^3!

→ muon threshold
between
10 and 100 TeV



CONCLUSION

- successfully running since 10 years

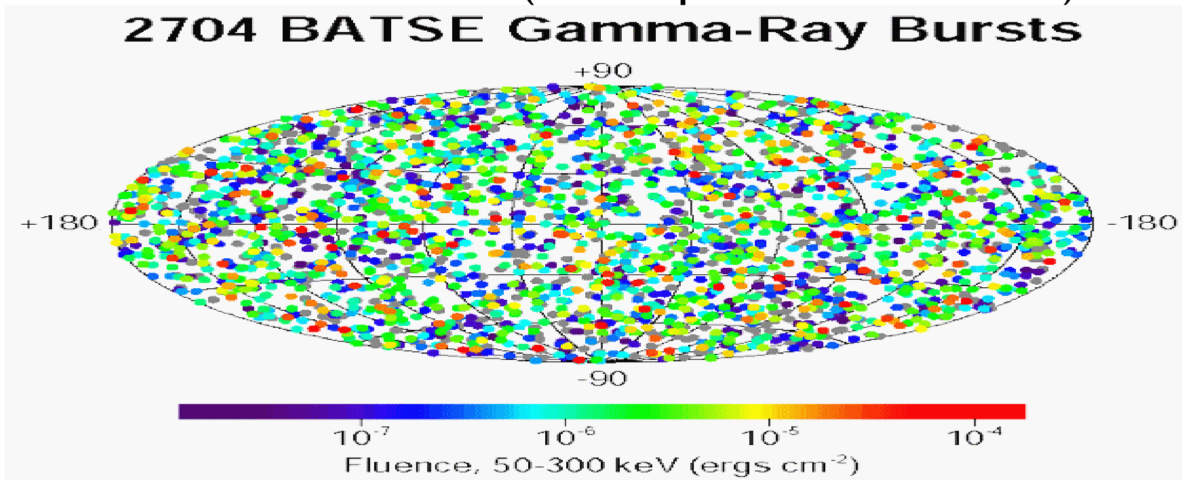
- strong in HE-diffuse search (shower) and exotic particles (monopoles): “Mton detector”
- good GRB-sensitivity, complementary to AMANDA
- relevant other results: WIMP
- upgrade to NT-200+ in 2005
- R&D Gigaton Volume Detector (km3)

10 year anniversary celebration

- **1993 - 2003**

Экспериментальный материал

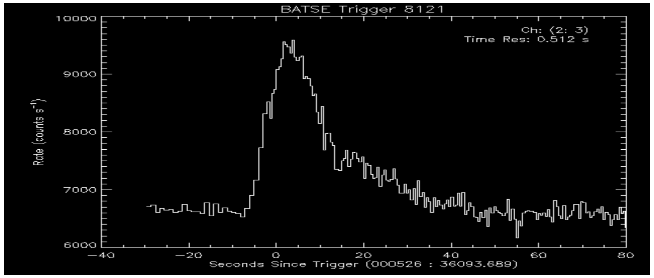
Гамма-всплески (эксперимент BATSE)



BATSE GRB Final Sky Map

Основные параметры GRB

- время регистрации
- длительность
- направление на вспышку
- энергия вспышки



T_90

Темп регистрации ~ 1 событие/день

Основной каталог BATSE (triggered GRB)

Каталог Штерна (non-triggered GRB) ~ 80%

Данные с 1991 по 2000 год

Экспериментальный материал
События NT-200

Основные параметры событий

T - время регистрации

M - множественность триггированных ОМ (характеризует энергию ливня)

Δ *t* - разность времен срабатываний ОМ (характеризует направление прихода)

Критерии отбора событий

M > 10 OM

Δ *t* < *10 ns*

Эффективно отбираются горизонтальные ливни и ливни из нижней полусферы

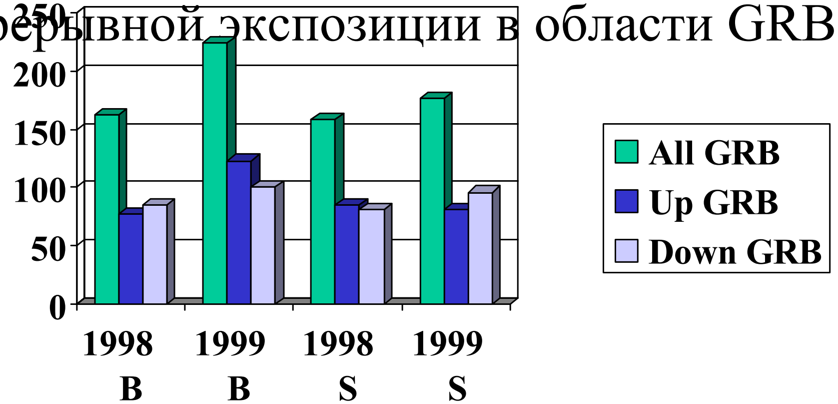
Темп регистрации - ~10^{-2} с

Данные апрель 1998 - февраль 2000

Поиск временных корреляций

Статистика экспериментальных данных

В анализируемый период апрель 1998 - февраль 2000 с периодом чувствительности NT-200 совпало 386 GRB по основному каталогу BATSE и 336 по каталогу Штерна (>1 часа непрерывной экспозиции в области GRB).



Количество GRB из основного каталога BATSE (B) и каталога Штерна (S)
Up, Down – GRB из верхней и нижней полусферы

Поиск временных корреляций

Поиск коррелированных во времени событий в области GRB

Оценивалось количество событий в интервалах
dt = 1, 2, ... 5 секунд в области GRB (поиск кластеров событий с множественностью К)

	K=2		K=3	
dt	Сигнал	Фон	Сигнал	Фон
1	8	5.6	0	0.045
2	14	16.8	1	0.40
3	23	27.9	1	1.4
4	34	38.9	1	2.0
5	50	49.9	2	3.4

Поиск временных корреляций

Анализ корреляций для различных порогов регистрации

Оценивалось суммарное количество событий для всех GRB при различных множественностях M

	Triggered GRB		All GRB	
M	Сигнал	Фон	Сигнал	Фон
15	91	94	172	167
20	11	13	22	23
25	1	2.8	5	5.2
30	1	0.86	3	1.6
35	0	0.28	1	0.47
40	0	0	0	0.056

Предел на поток нейтриино

$$F = \frac{N_{90}}{S} \qquad f(E_\nu) = \frac{N_{90}}{s(E_\nu)} \qquad F^{-1} = \int \frac{\lambda(E_\nu)}{f(E_\nu)} dE_\nu$$

N_{90} - верхний 90% предел на количество событий
S - эффективная площадь
λ - нормированный поток нейтрино

Sef