The BAIKAL Neutrino Telescope: Results and Plans

Ralf Wischnewski

DESY-Zeuthen

Amanda-IceCube Meeting, Uppsala, October 2004

- **The detector: NT-200**

- **New Results:**
    - **Atm. Neutrinos, WIMPs, Monoples,**
    - **Cascades → AP neutrinos, HE-muons, GRB**

  1998-2000 data sample: Neutrino2004/Paris, ECRS2004/Florence

- **The smart upgrade: NT-200+**

  …commisioning in April 2005

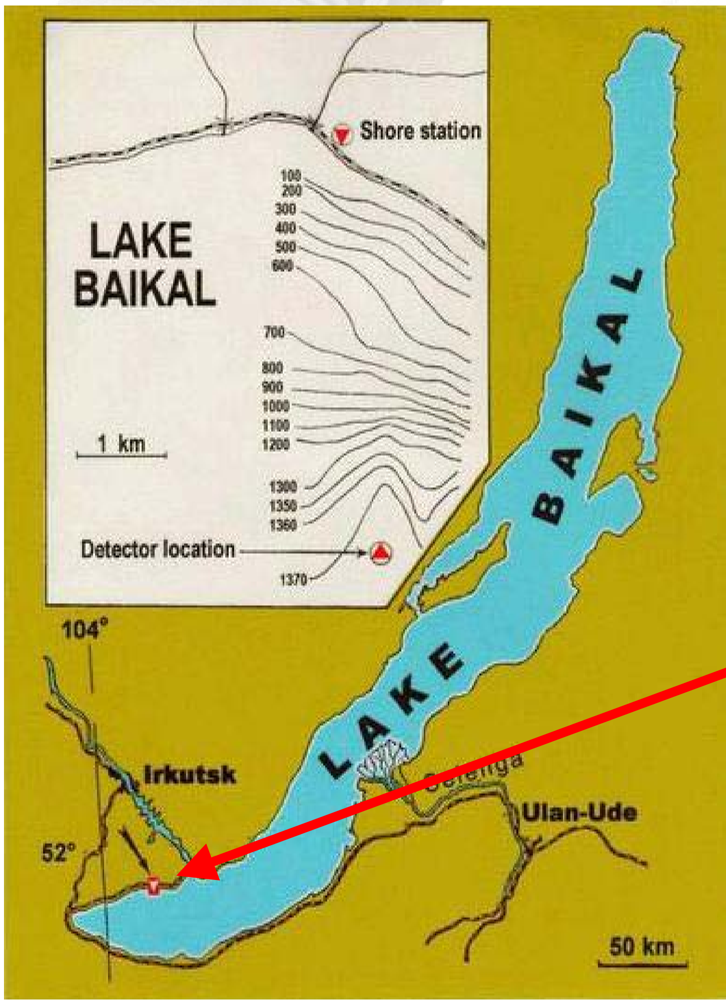
Collaboration

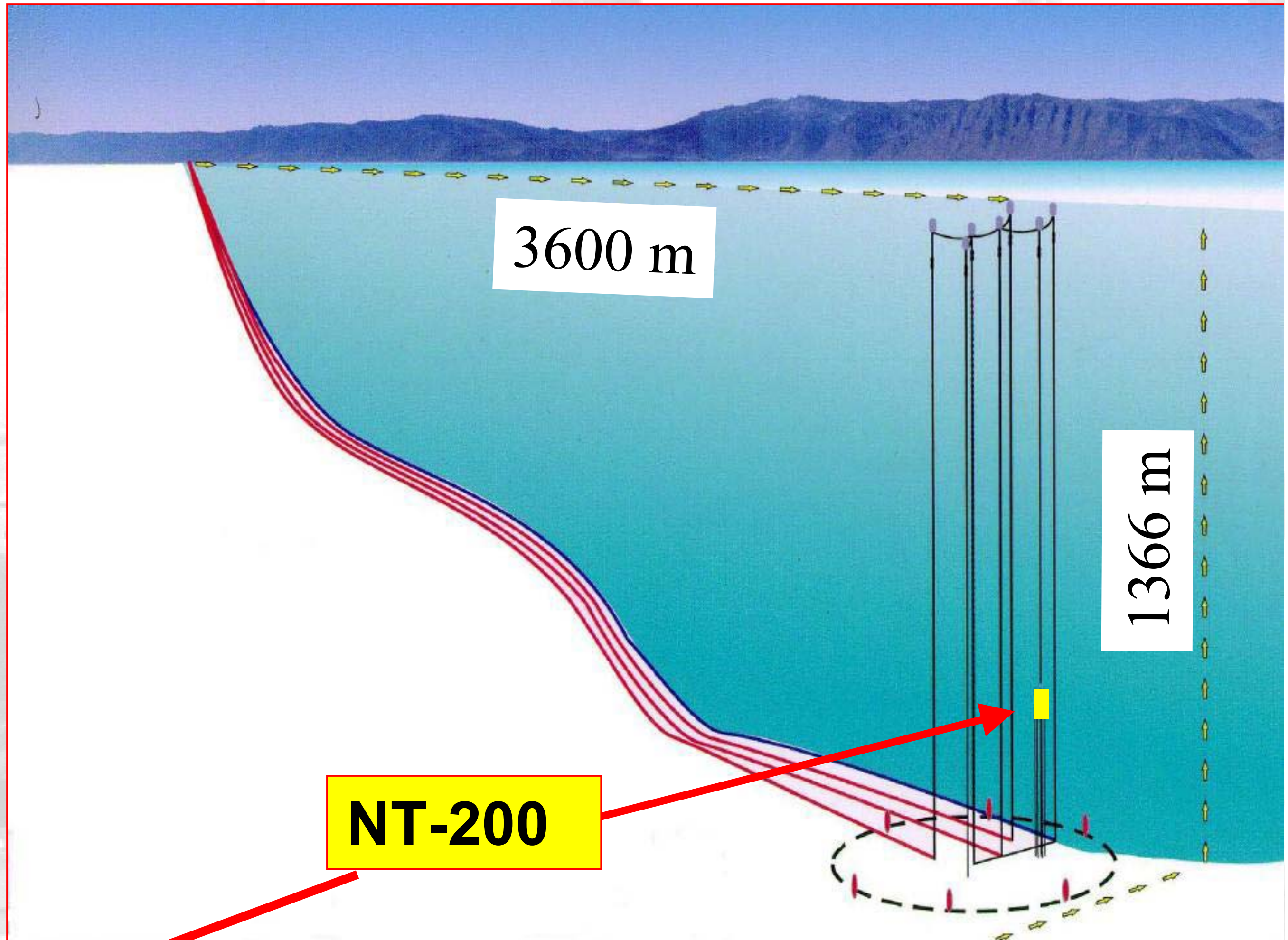
Russia – Germany

- Institute of Nuclear Research, Moscow
- Moscow State University
- DESY Zeuthen
- Irkutsk State University
- Nishni Novgorod State Technical University
- State Marine Technical University, St.Petersburg
- Kurchatov Institute, Moscow
- JINR, Dubna

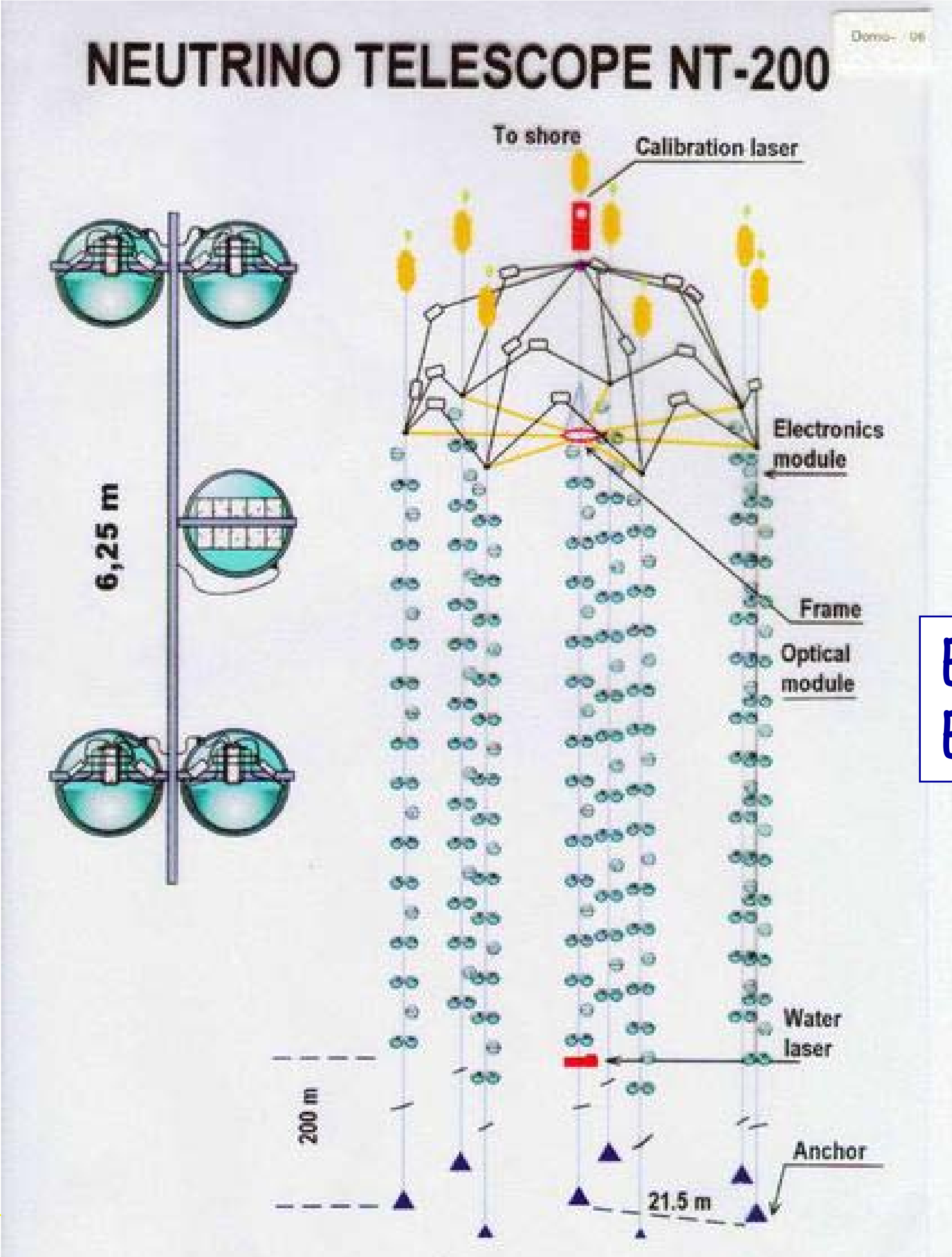
~45 authors

The Site





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



Height x ∅ = 70m x 40m, $V_{geo}=10^5 m^3$= 0.1Mton

- -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)

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Baikal - History

- Since 1980 – Site test + early R&D started
- 1989/90 - Proposal NT-200, start construction

- 1993 – NT-36 *started 13.4.93* (36 PMTs at 3 strings)
  - The First Underwater Array ever built
  - 3-dimensional Muon reconstruction
  - Verify MC: BG-suppression & Water ...

- 1998 – NT-200 *commissioned 06.04.98* (192 PMTs at 8 strings)
  - Start full Physics program
- since 1998: Routine operation

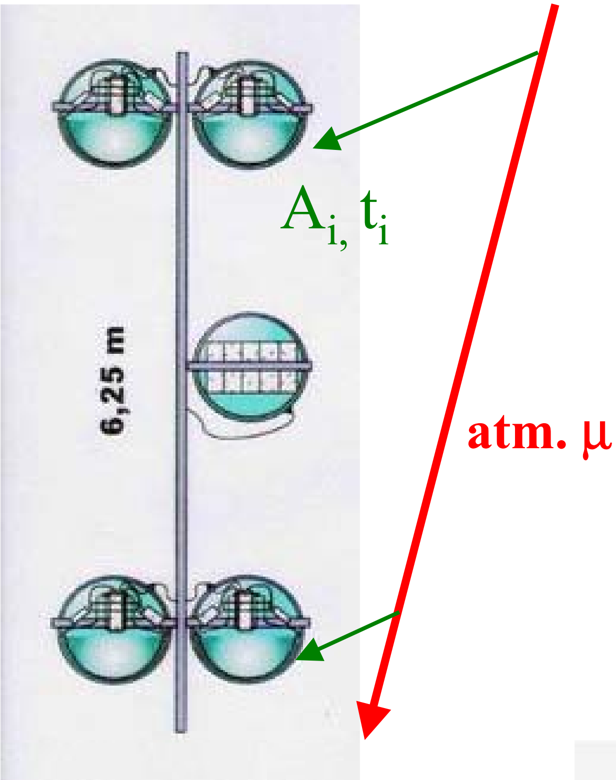
Selected Results

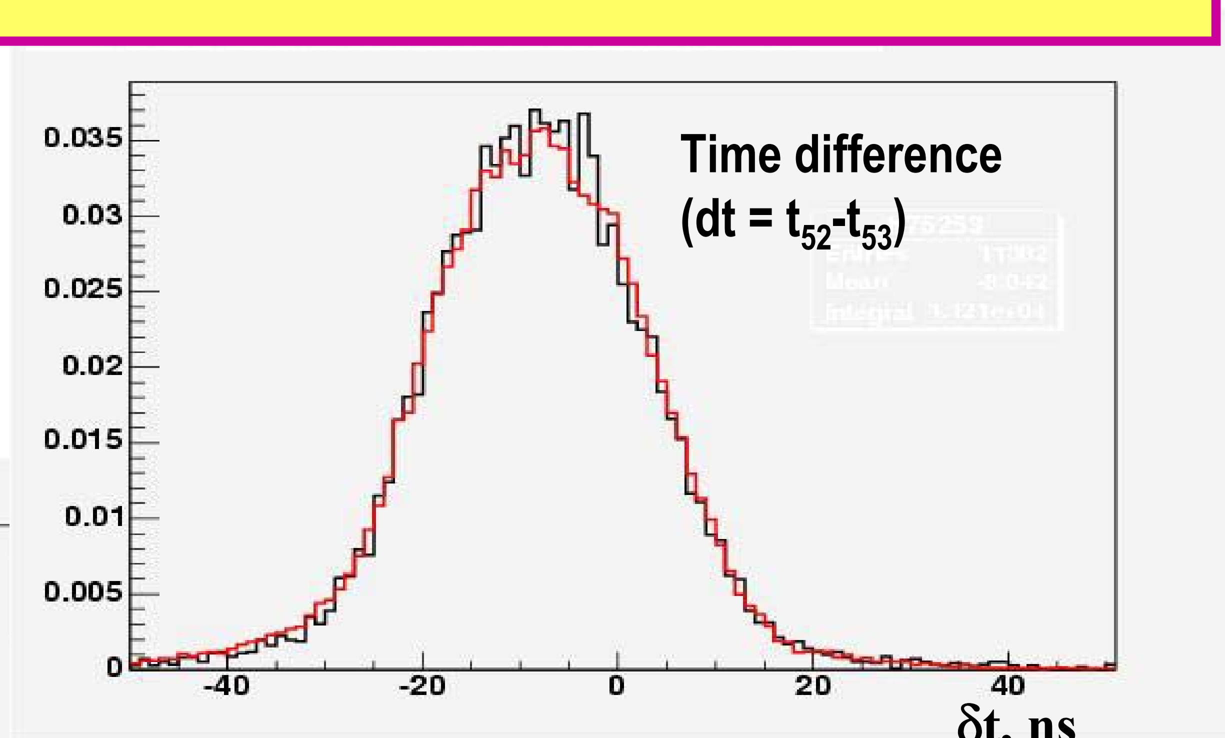
- **Low energy phenomena**
  - Atmospheric neutrinos
  - WIMP Neutrinos
- **Search for exotic particles**
  - Magnetic monopoles
- **High energy phenomena**
  - Diffuse neutrino flux
  - Neutrinos from GRB
  - Prompt muons and neutrinos

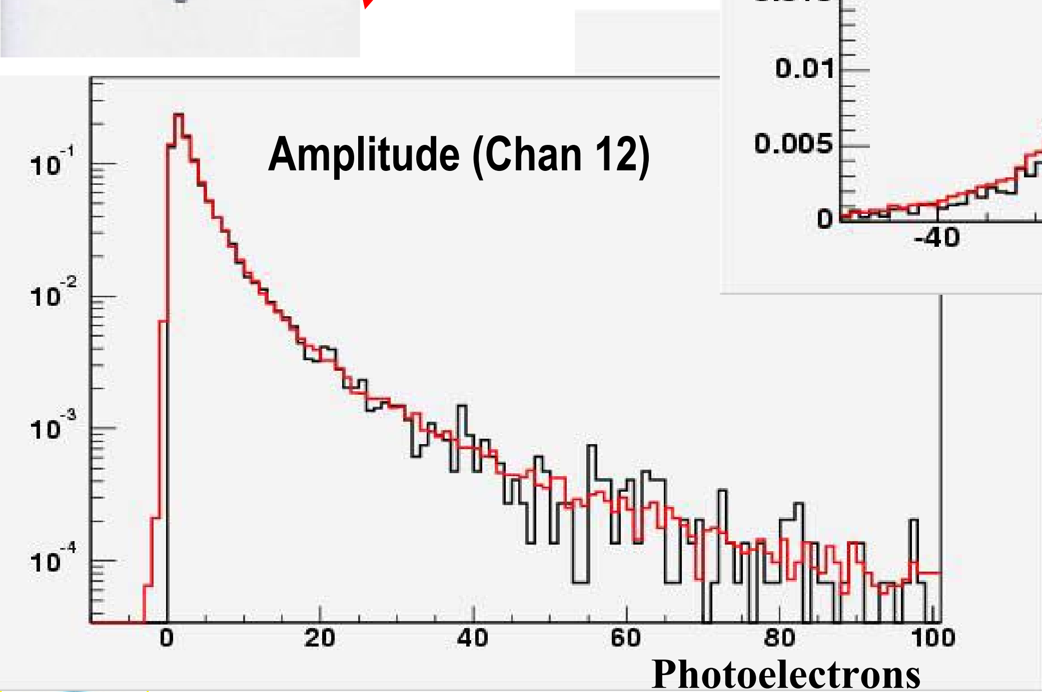
Data samples NT-200

- 1998-1999:
  502 livetime days
  (Apr.98-Feb.00)
- 1998-2000:
  780 livetime days
  (Apr.98-Feb.01) (this work)
- 2001-2002:
  in progress

Atmospheric muons: Calibration Beam







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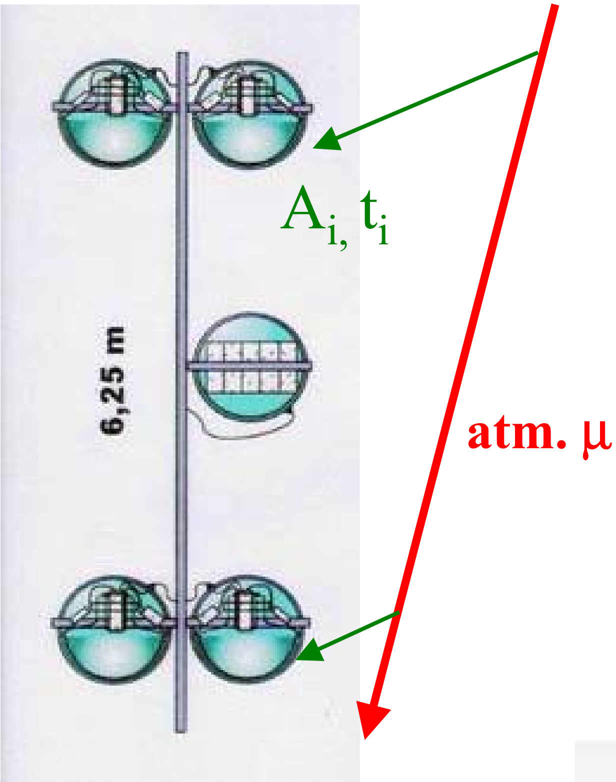
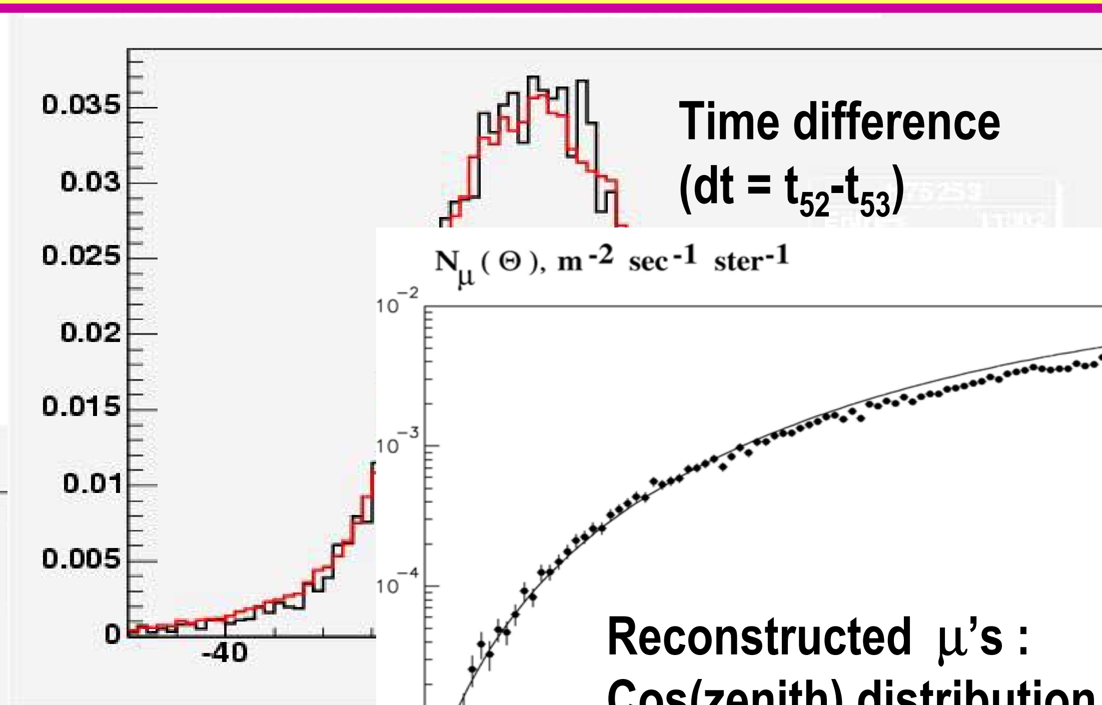
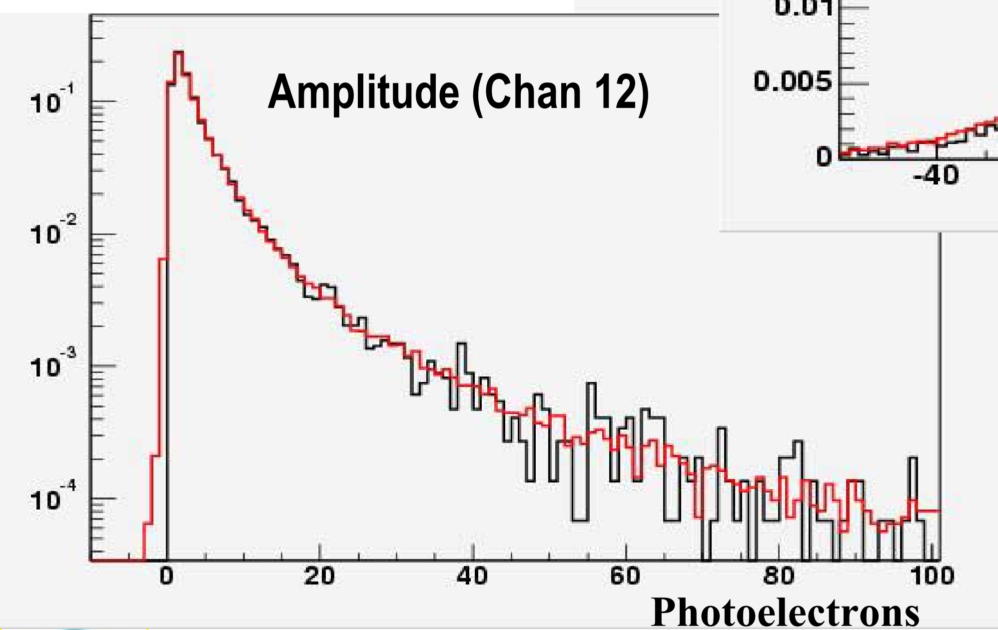
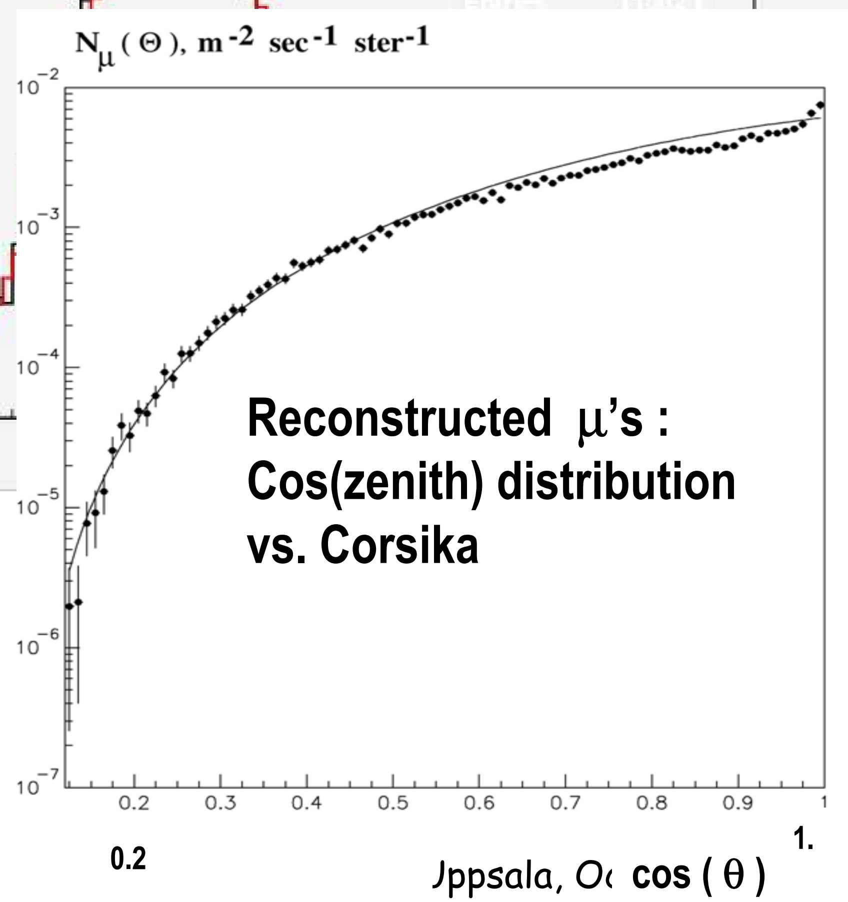
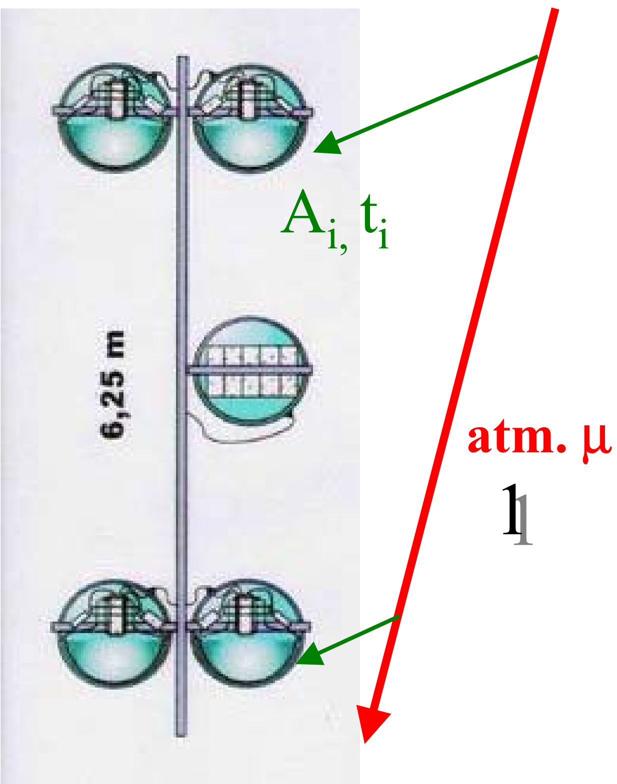


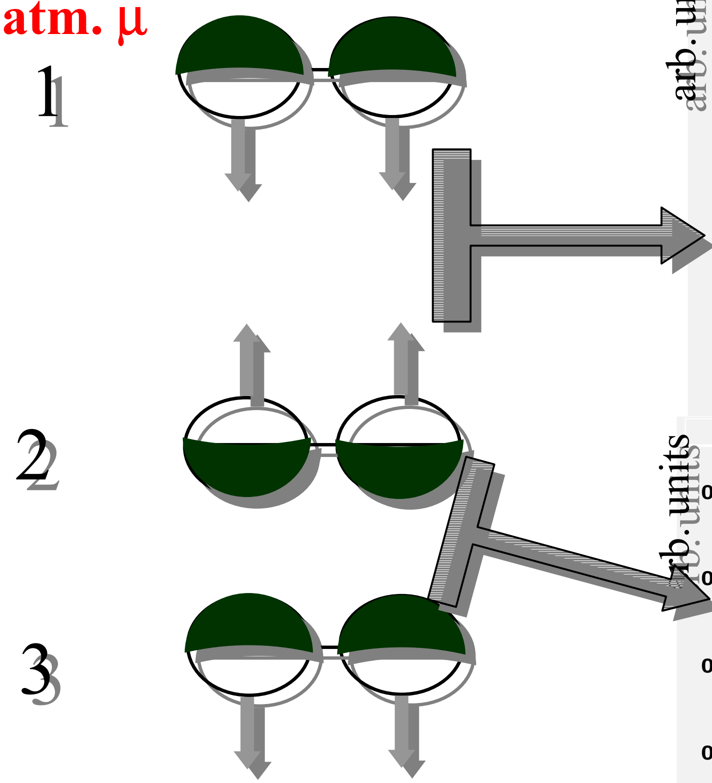


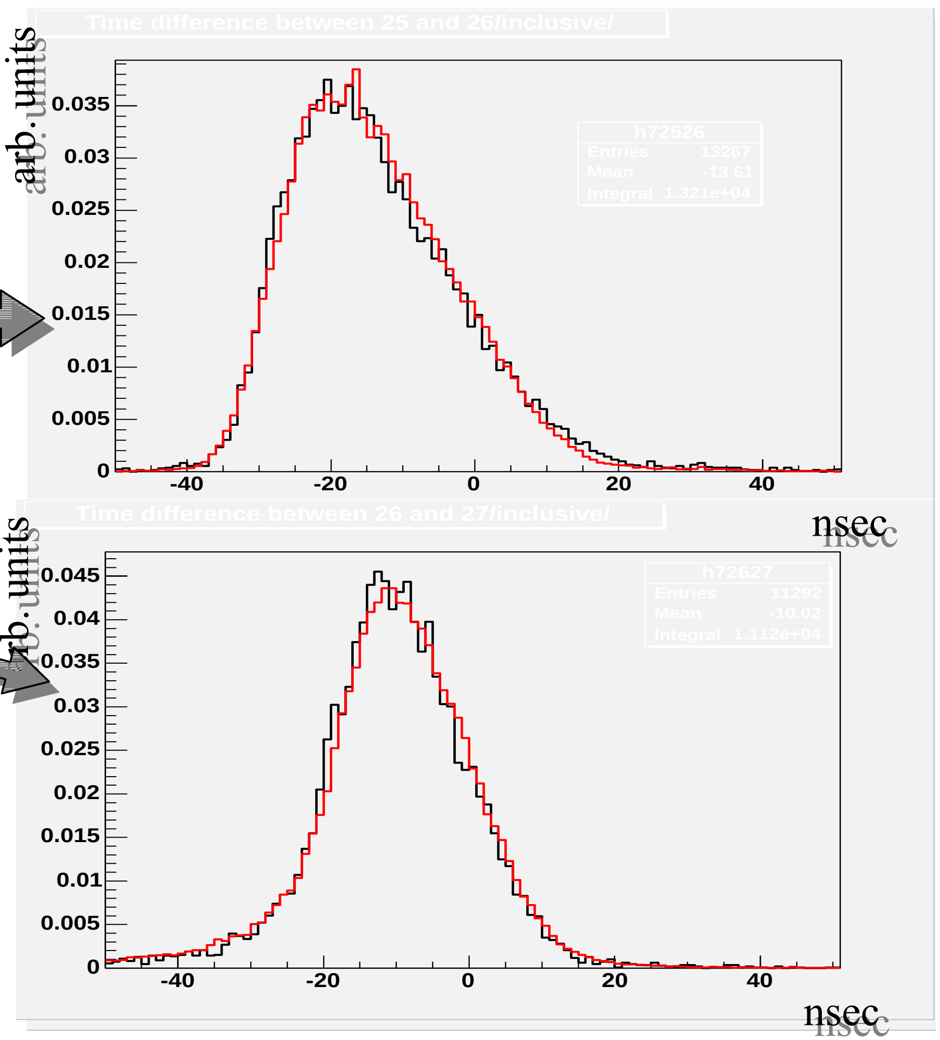




Atmospheric muons (2): Calibration Beam



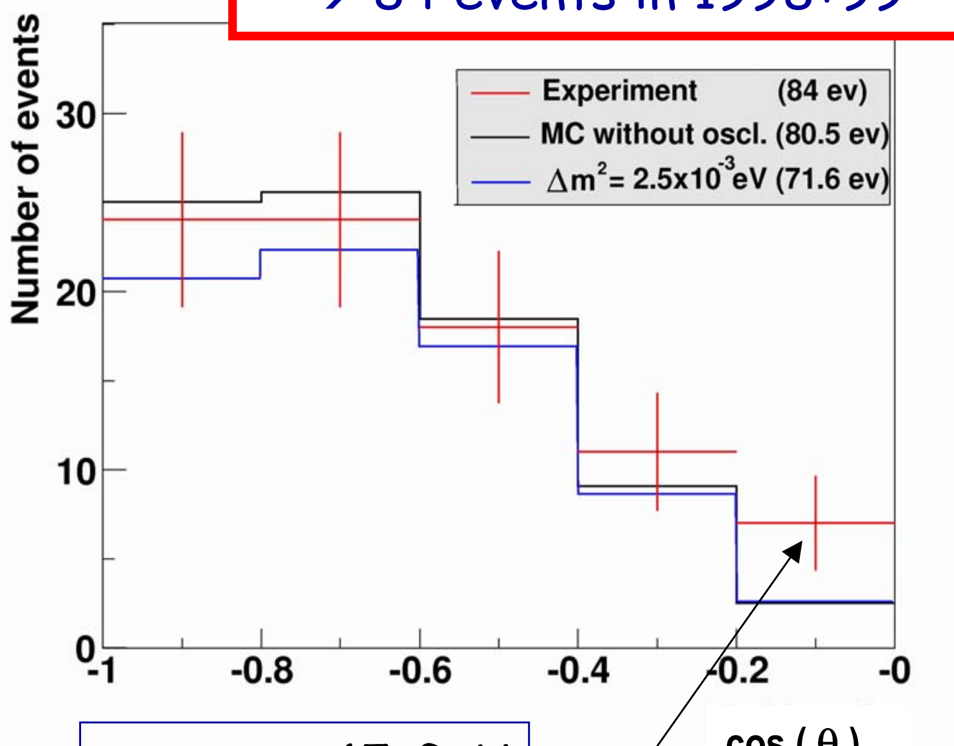




Time Differences $dt_{ij}=t_i - t_j$
vary for topological configuration,
threshold, …

Atmospheric Muon-Neutrinos

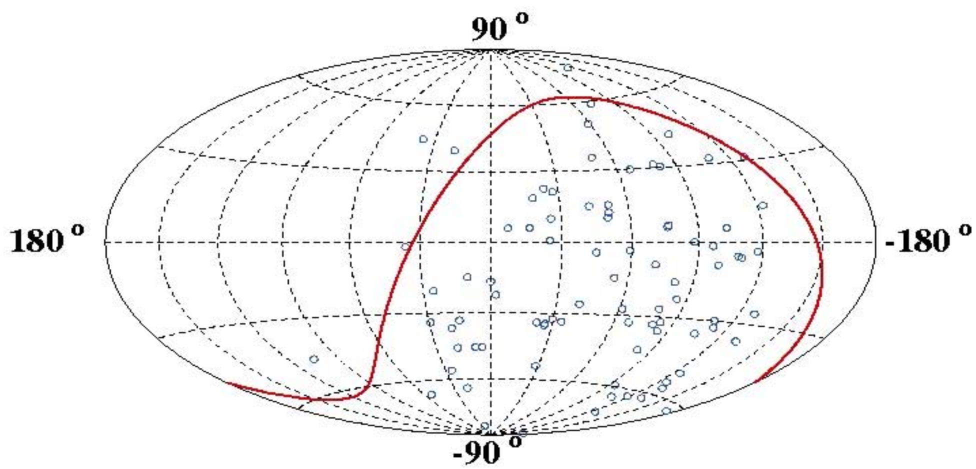
- 3-dimensional track reconstruction
- high BG suppression
  → 84 events in 1998+99



Thresh. ~ 15 GeV

BG dominated bin

$\Delta\Psi \sim 3°$



Skyplot
(galactic coordinates)

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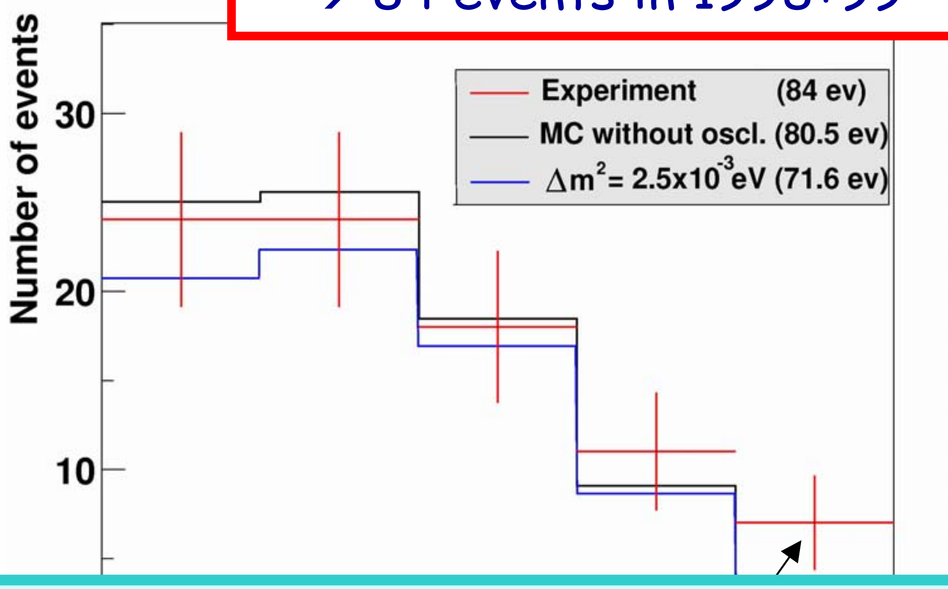

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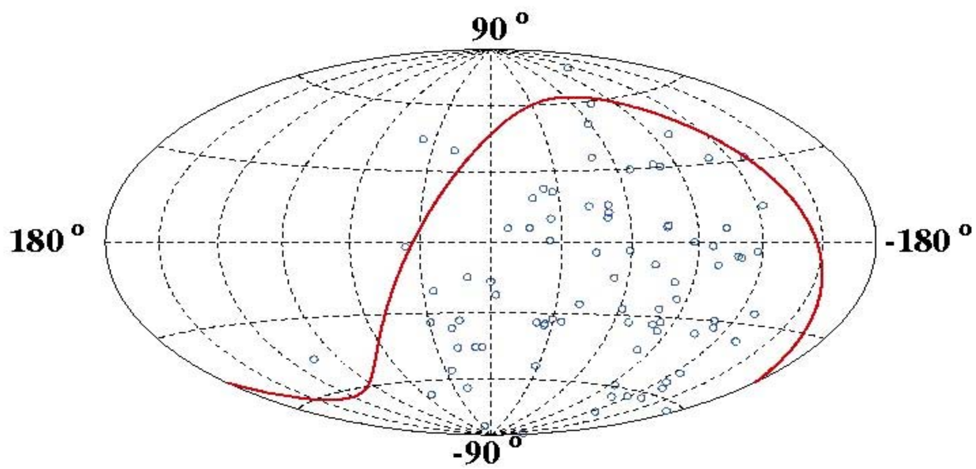


Soon to come:
- a higher statistics neutrino sample („weaker criteria") for PointSource Search
- Muon-Neutrino GRB analysis

BG dominated bin

Skyplot
(galactic coordinates)

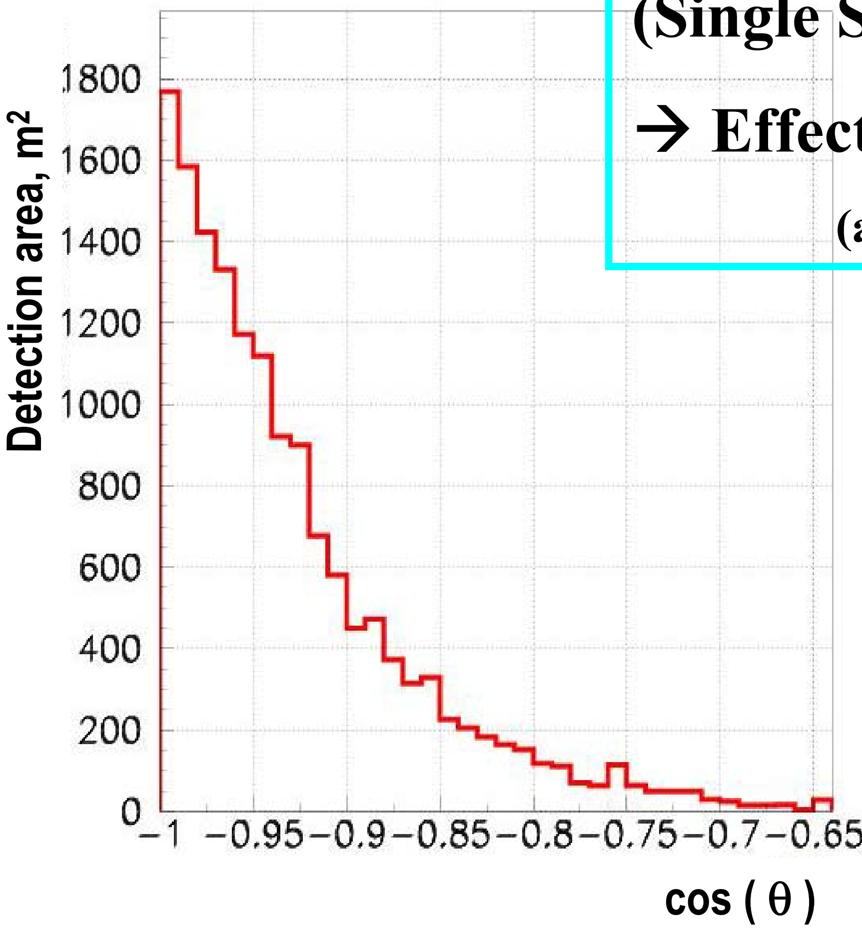
WIMP Search from Earth

Tailored "Vertical Track Reconstruction"

(Single String detection to maximize A_{eff})

→ Effective Area > 10^3 m^2

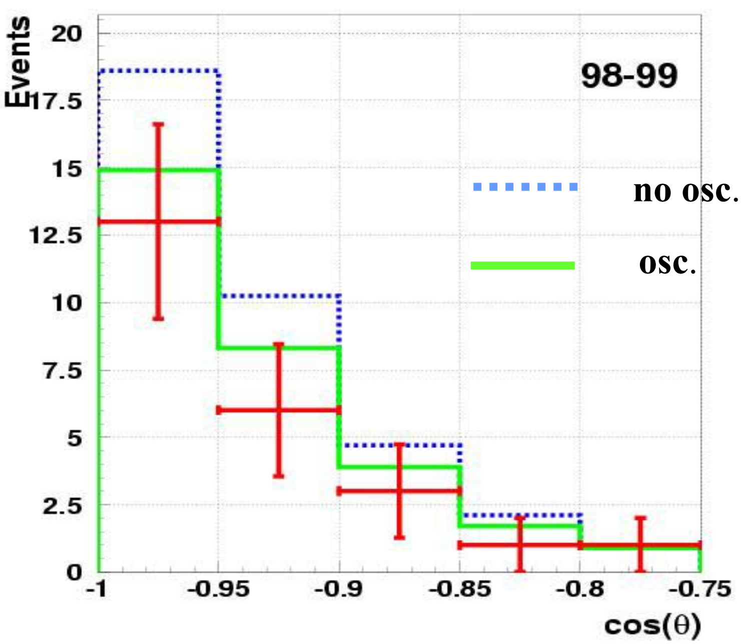
(after all cuts)



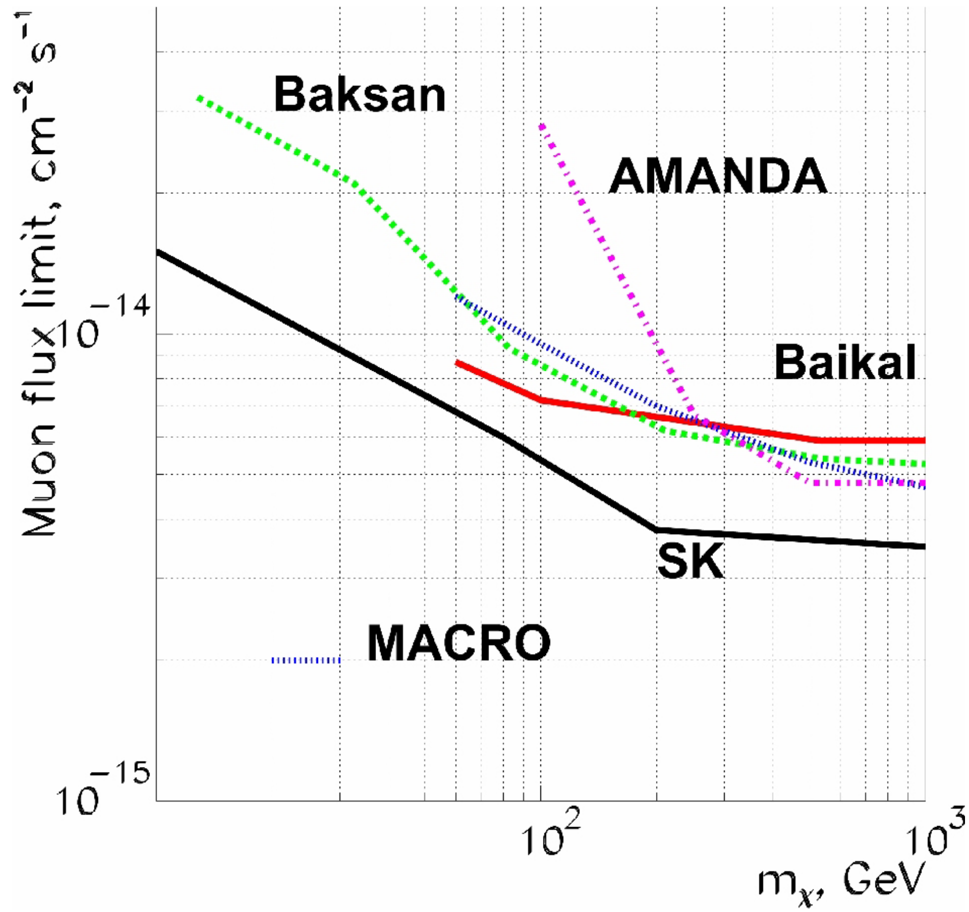
WIMP Search from Earth

502 days livetime NT-200 (98+99)
MC: Bartol-96

24 evts - experiment
36.6 evts - prediction w/o oscillations
29.7 evts - prediction w/ oscillations



Limit on excess neutrino induced upward muon flux 90% c.l. limits from the Earth
(502 days NT-200 livetime, E_μ > 10 GeV)



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

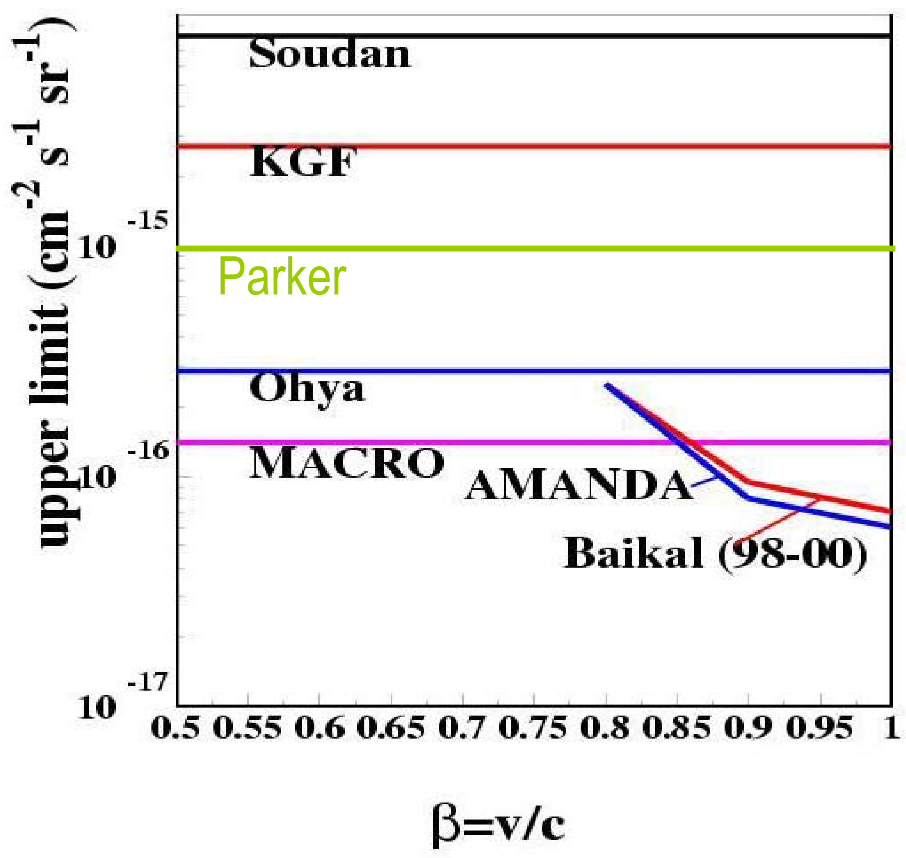
$$N_{\gamma\, monop}(\lambda) = n^2 (g/e)^2 N_{\gamma\mu}(\lambda) = 8300\, N_{\gamma\mu}(\lambda)$$

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

Bright light source: 8300 x muon

Monopole limit (90% C.L.)

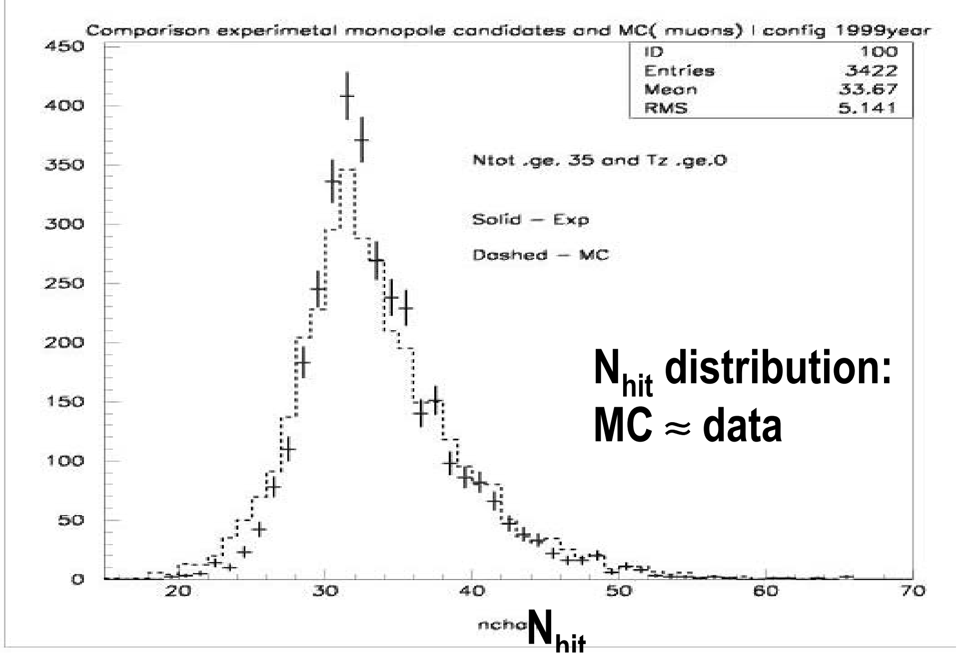
780 livedays



Monopole selection criteria:

- **hit channel multiplicity:** $N_{hit} > 35$ ch,
- **upward track:** $\Sigma(z_i - z)(t_i - t)/(\sigma_t \sigma_z) > 0.45$, $\theta_\mu > 100^o$

Background : **atmospheric muons**



Search for Slow Massive Monopoles $(10^{-5} < \beta < 10^{-3})$

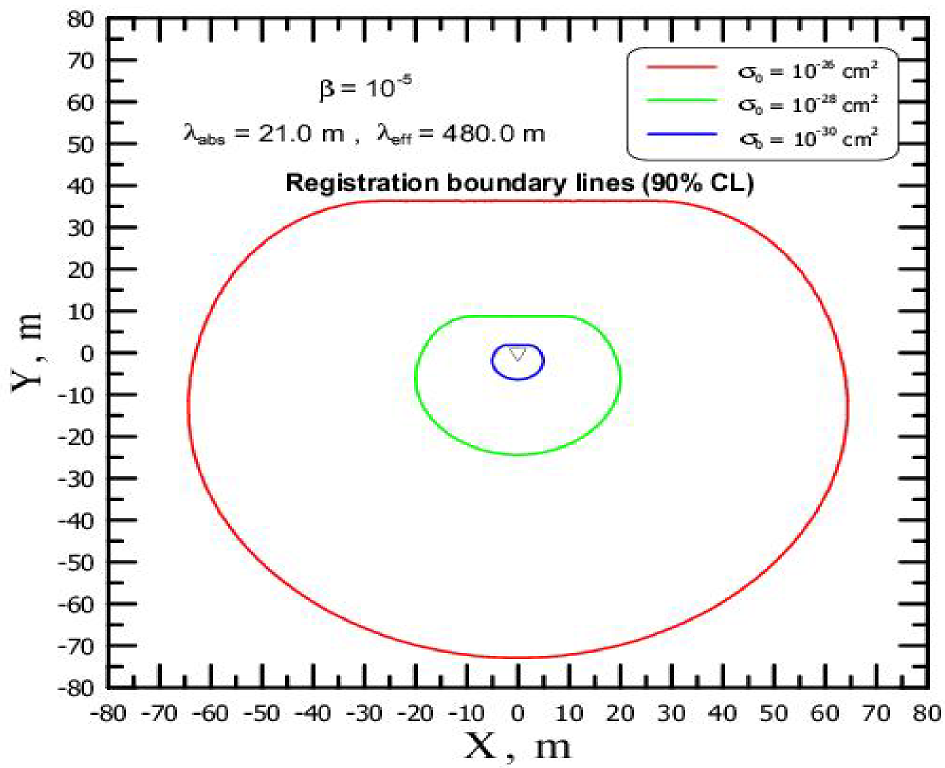
$\sigma_{cat}=0.17\sigma_0/\beta^2, \; 10^{-5}<\beta<10^{-3}$

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

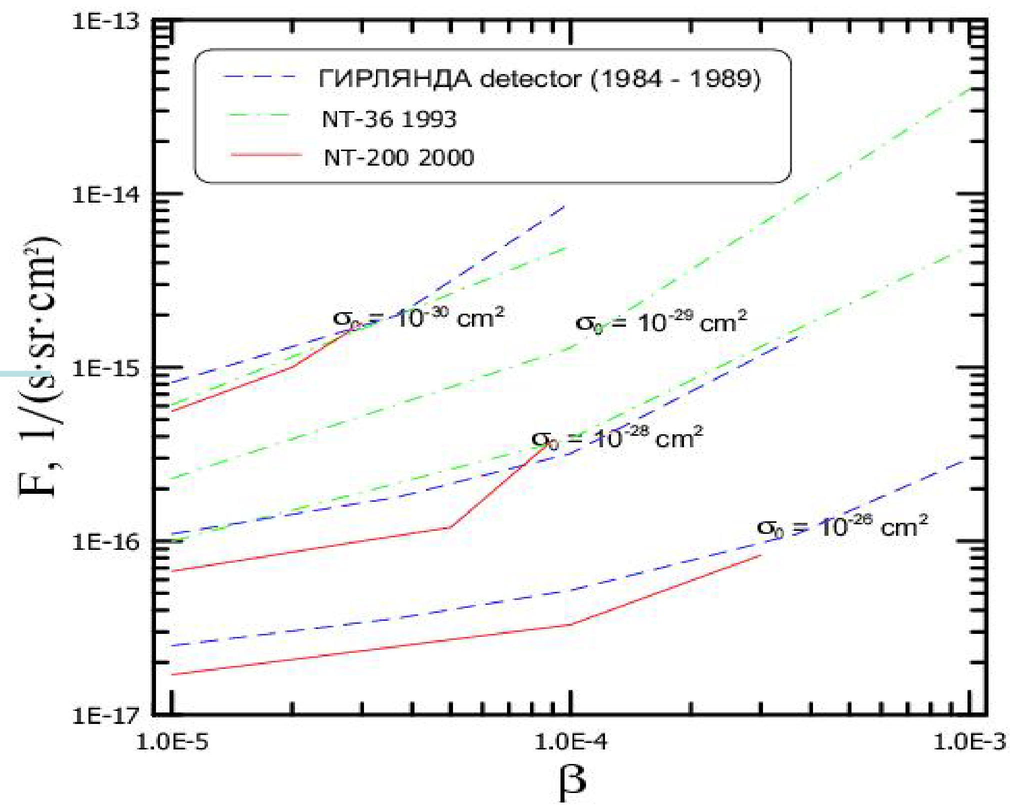
NT-200 – capable to detect massive bright objects (GUT-monopoles, nuclearites, Q-balls …):

Monopole Trigger: $N_{local}>4$ within dt=500μsec

Selection: $N_{ch}>1$ with $N_{local}>14$



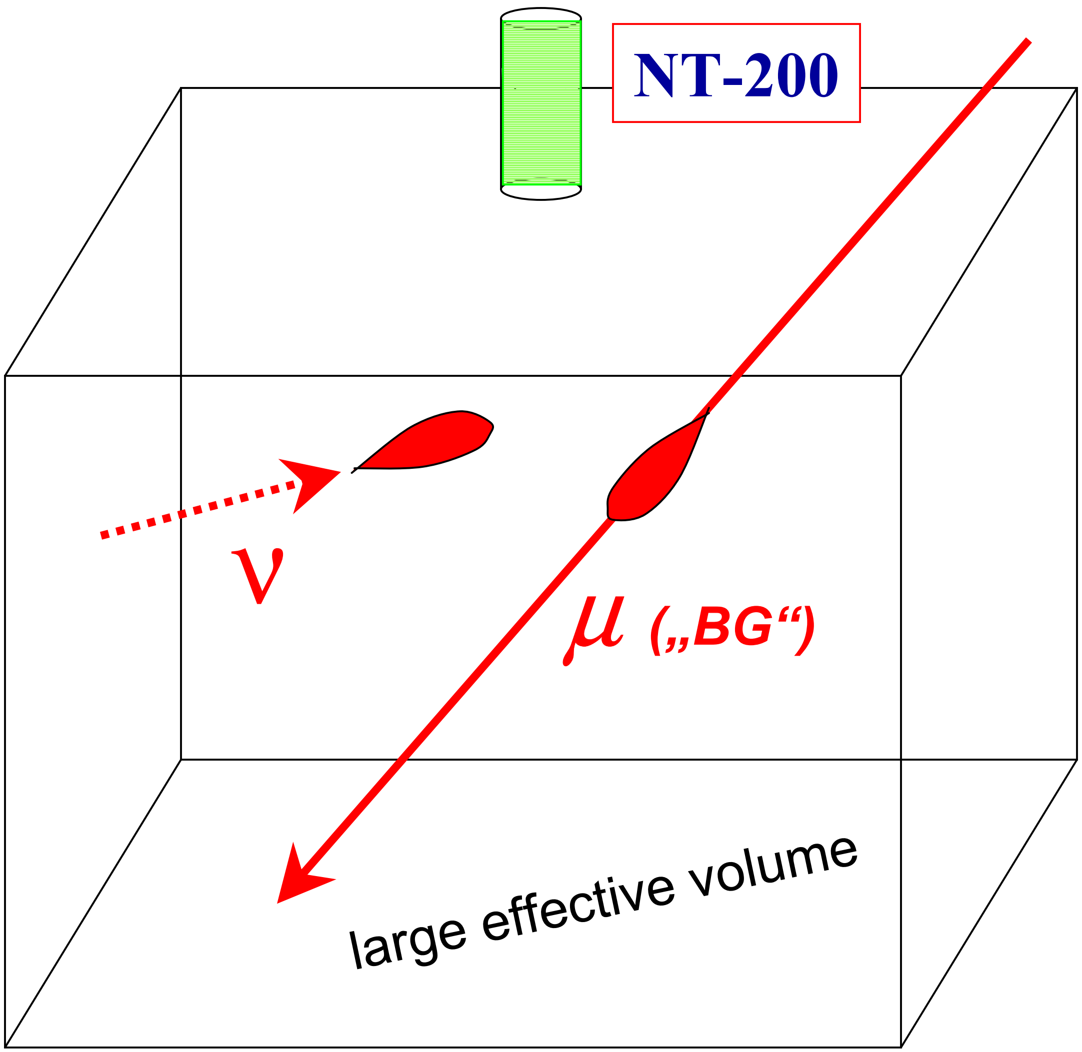
Magnetic monopole visibility boundaries



Magnetic monople Flux limit

Search for High Energy Cascades

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



Look for upward moving light fronts.

Signal:
isolated cascades from neutrino interactions

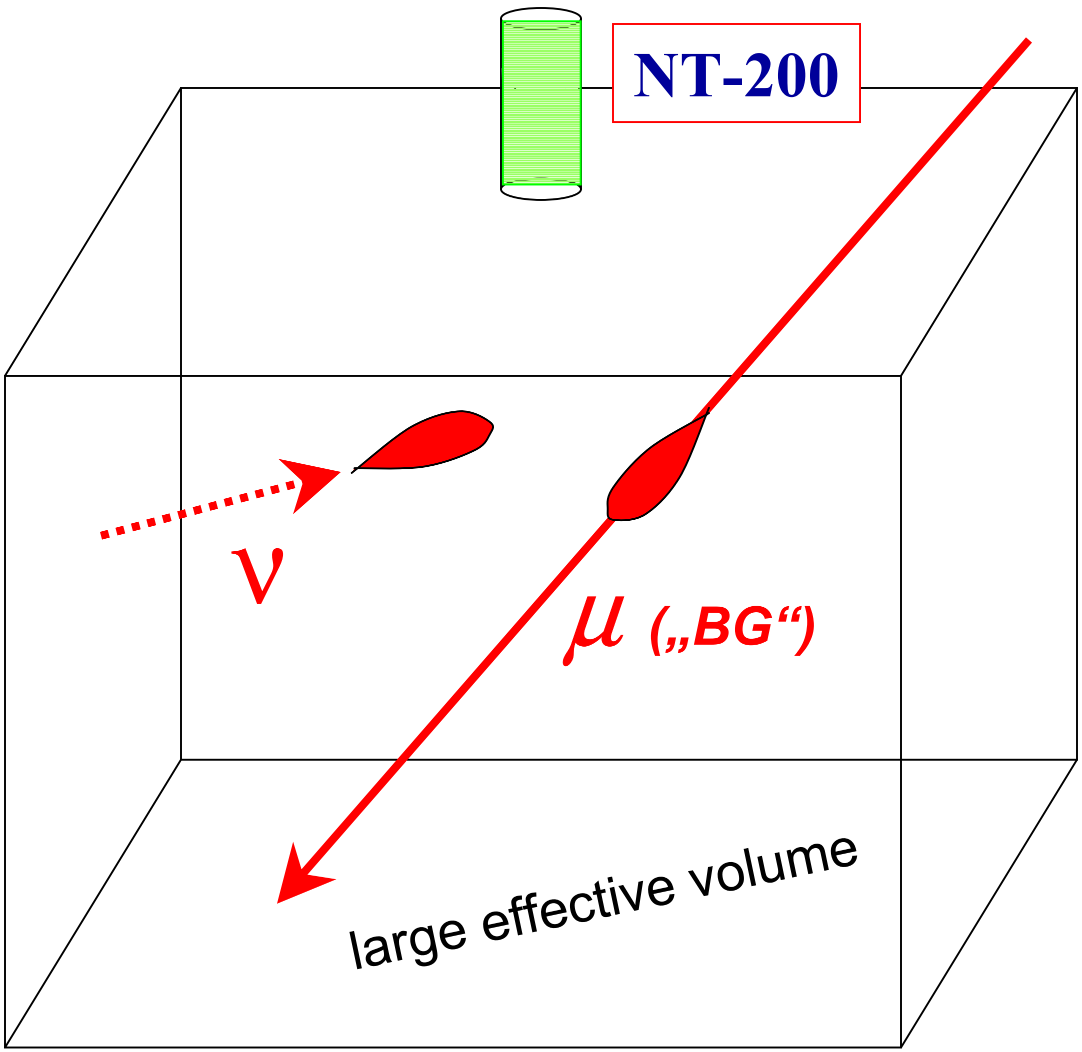
Background :
Bremsshowers from h.e. downward muons

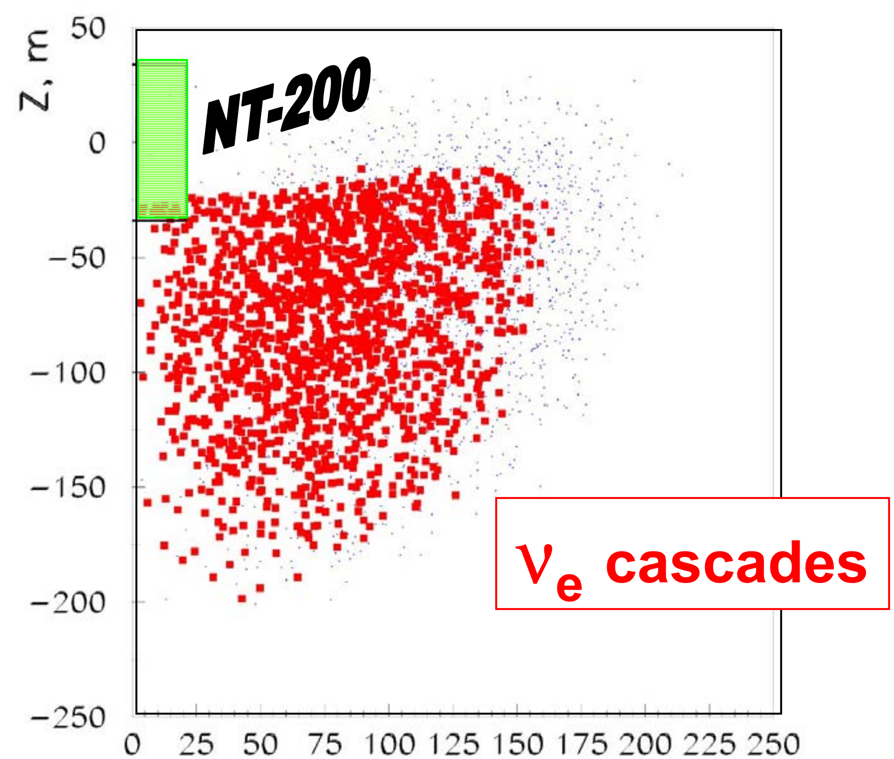
Final rejection of background by „energy cut“ (N_{hit})

Search for High Energy Cascades

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

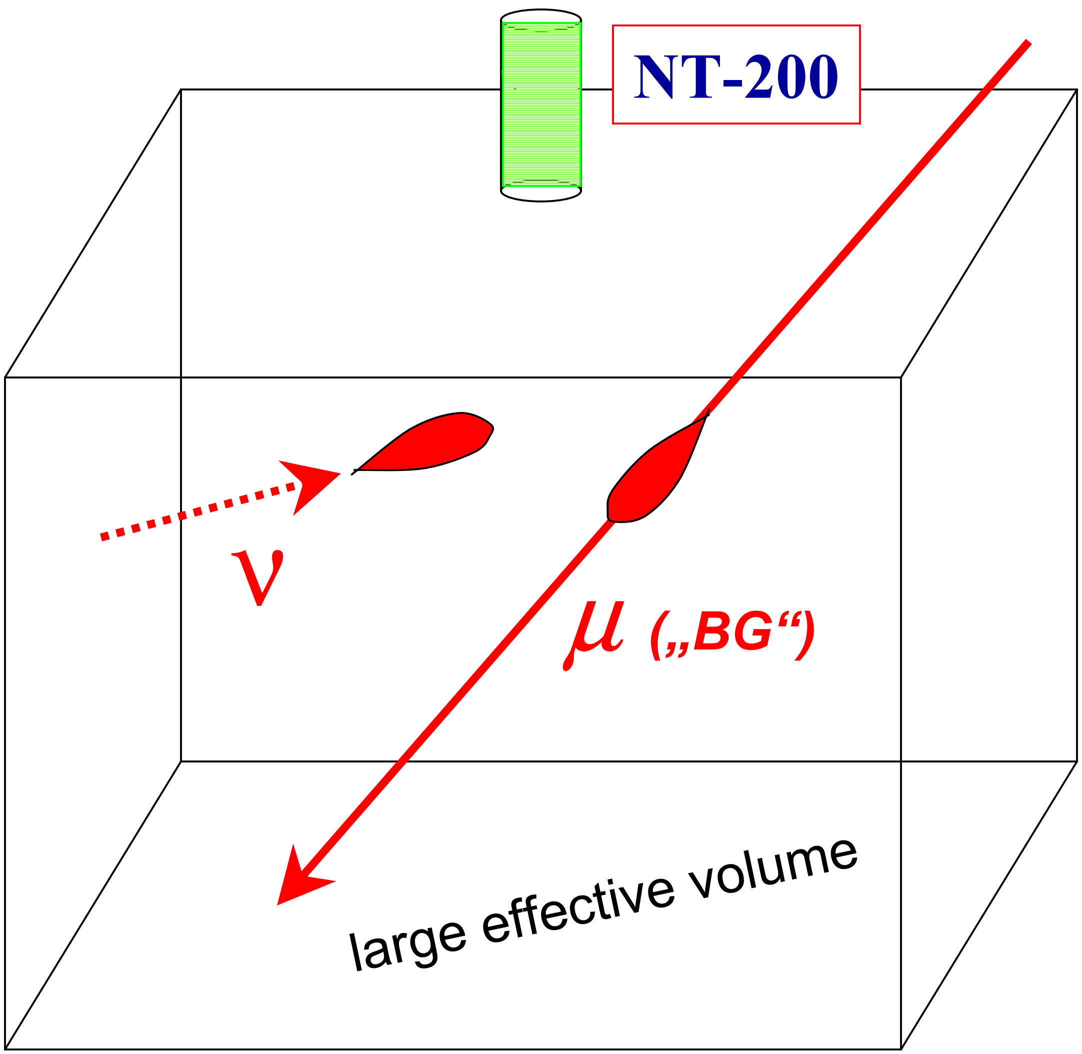
Look for upward moving light fronts.





Allowed by excellent scatt Λ_{scatt}=30-50m

Search for High Energy Cascades



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

Physics topics:

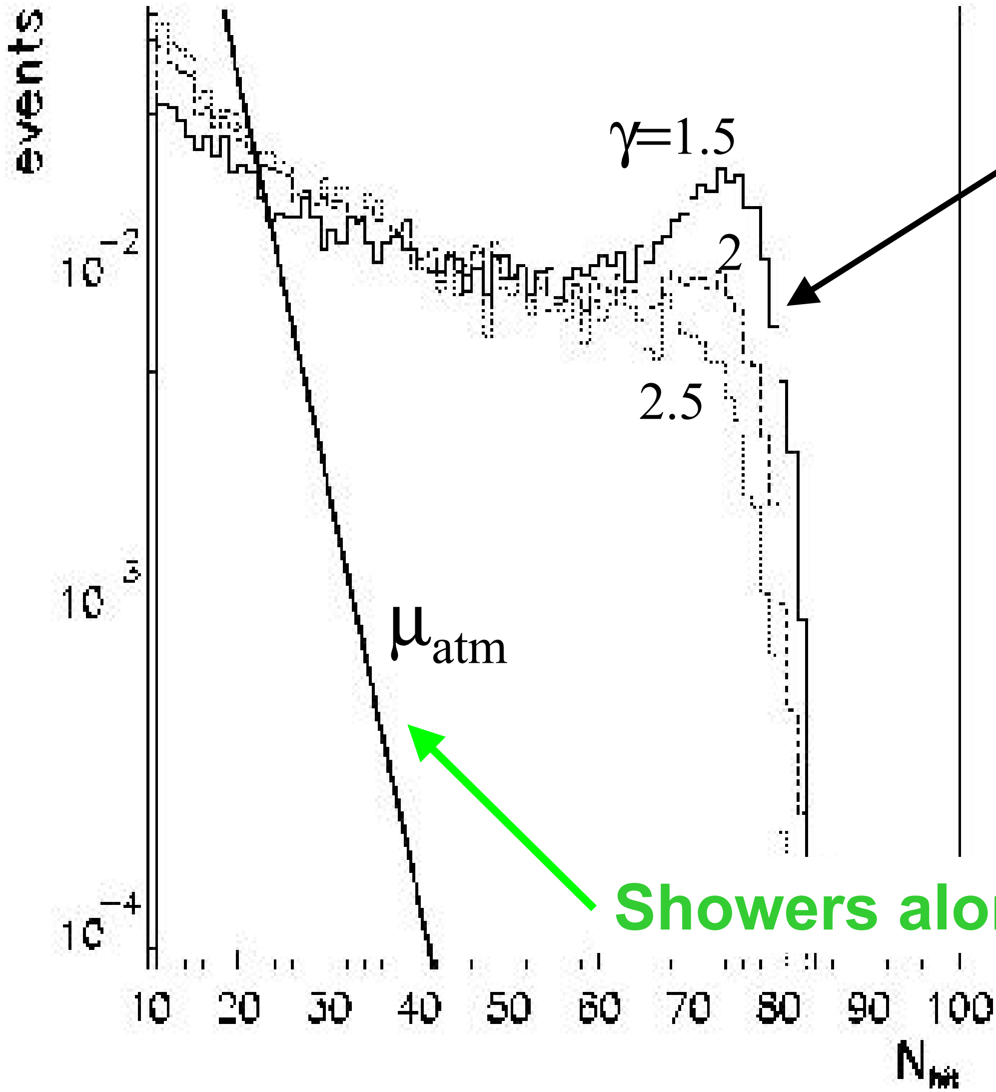
- HE cascades from
  ν_e ν_μ ν_τ - NC/CC
  - ❑ Diffuse astroph.flux
  - ❑ GRB correlated flux
- HE atmospheric muons
  (the „BG“ to ν's)
  - ❑ Prompt μ
  - ❑ Exotic μ
- ...

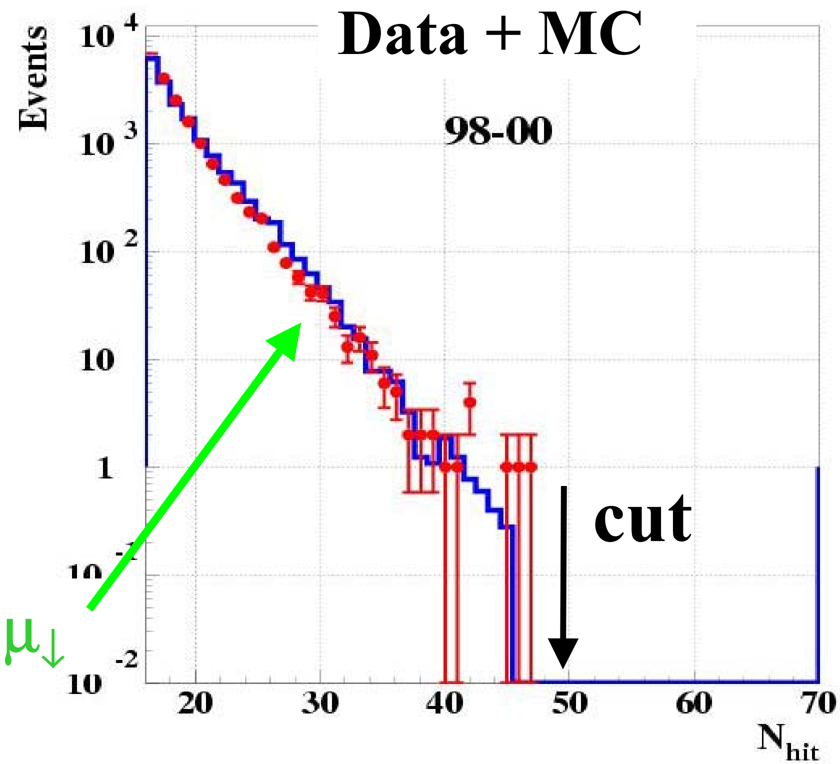
Selecting HE Cascades

Hard spectra pile up in the "energy parameter" N_{hit}

$\Phi_\nu = AE^{-\gamma}$

Shape of signal in N_{hit} distribution (γ=1.5,2.0,2.5)

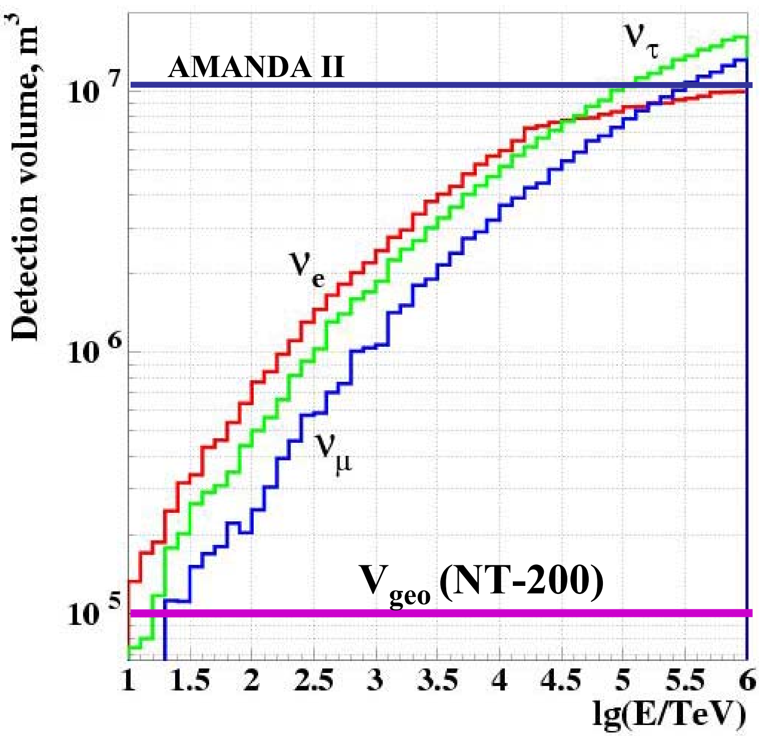




Showers along $\mu_\downarrow$

Diffuse Flux ν_e, ν_τ, ν_μ Limit

Effective volume vs. E



V_{eff} > 1 Mton at 1 PeV

The 90% C.L. "all flavour" Limit from NT-200 (780 days) on the DIFFUSE NEUTRINO FLUX

Assuming $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at Earth (1 : 2 : 0 at source)

+ for a γ=2 spectrum $\Phi_\nu \sim E^{-2}$ (10 TeV < E < 10^4 TeV)

$E^2 \Phi_\nu < 1.0 \cdot 10^{-6}$ GeV $cm^{-2} s^{-1} sr^{-1}$ (Baikal 2004)

$E^2 \Phi_\nu < 0.86 \cdot 10^{-6}$ GeV $cm^{-2} s^{-1} sr^{-1}$ (AMANDA-II 2004)

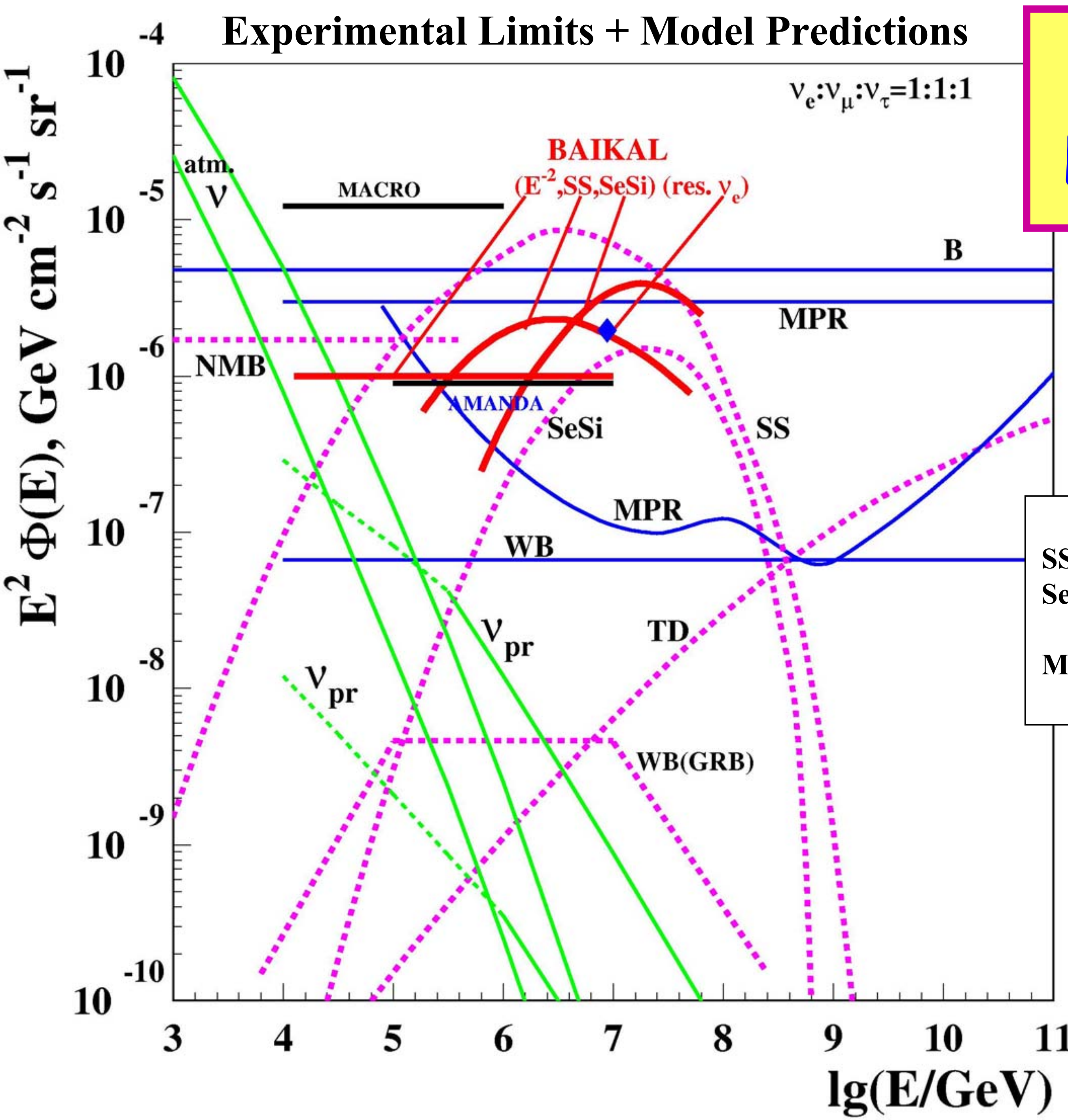
90% C.L. Limit via W-RESONANCE production

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

$\Phi_{\bar{\nu}_e} < 4.2 \cdot 10^{-20} (cm^2 \cdot s \cdot sr \cdot GeV)^{-1}$ (Baikal 2004)

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

Diffuse Flux Limits + Models



SS - Stecker, Salamon 1996

SeSi - Semikoz, Sigl 2003

Models/Exp. are rescaled for 3 flavour sum

Search for ν's correlated with GRBs

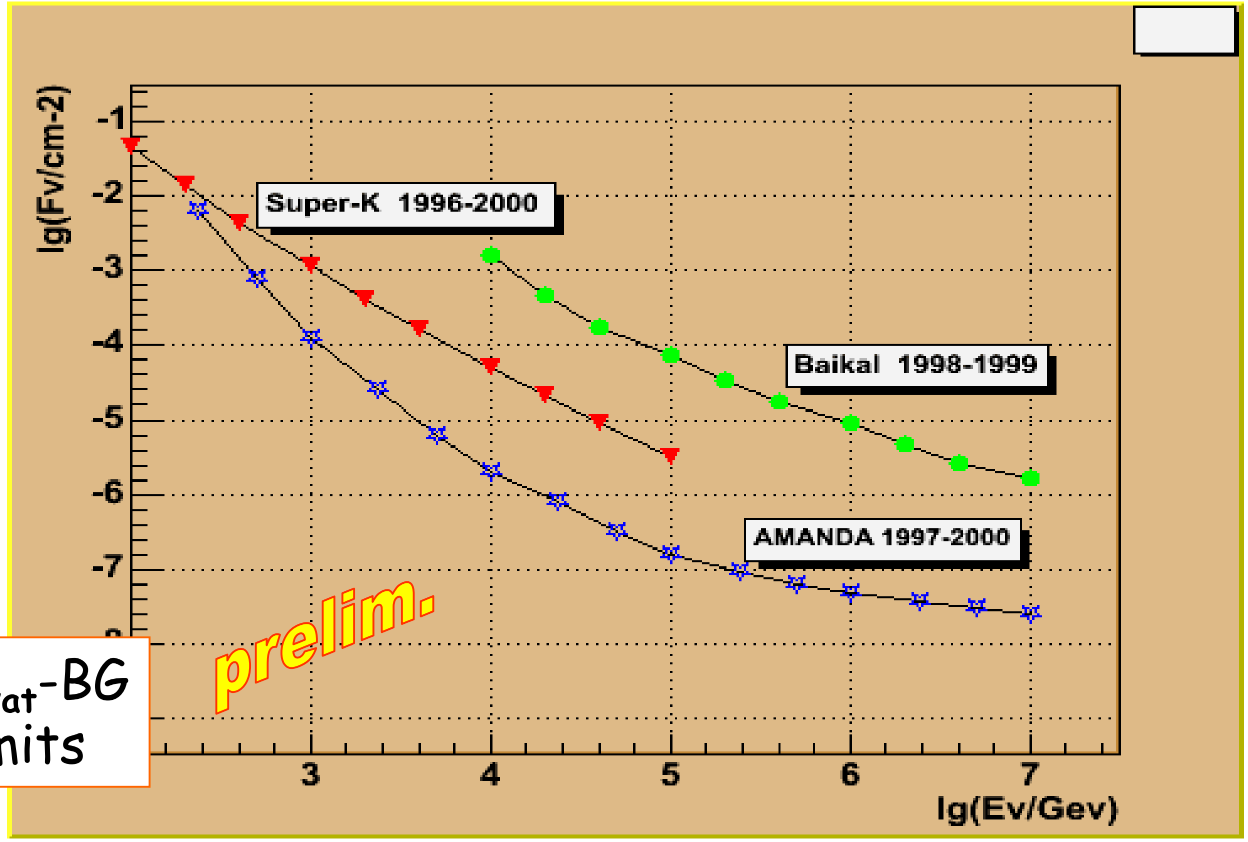
BATSE-GRBs vs. HE-Cascades event sample.

GRB - Prospects:
We expect better sensitivity for the <u>muon event sample</u>. Analysis in progress.

April 1998 - February 2000: N_{tot}= 722 BATSE evts
NT-200: CascadeCuts (N_{hit}>10 & t_{min}>-10 ns)

& t_{BATSE} - 100 s < t < t_{BATSE} + 100 s

	Triggered GRB		All GRB	
N_{Hit}	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 μ_{at}-BG
→ 90% C.L. differential flux limits

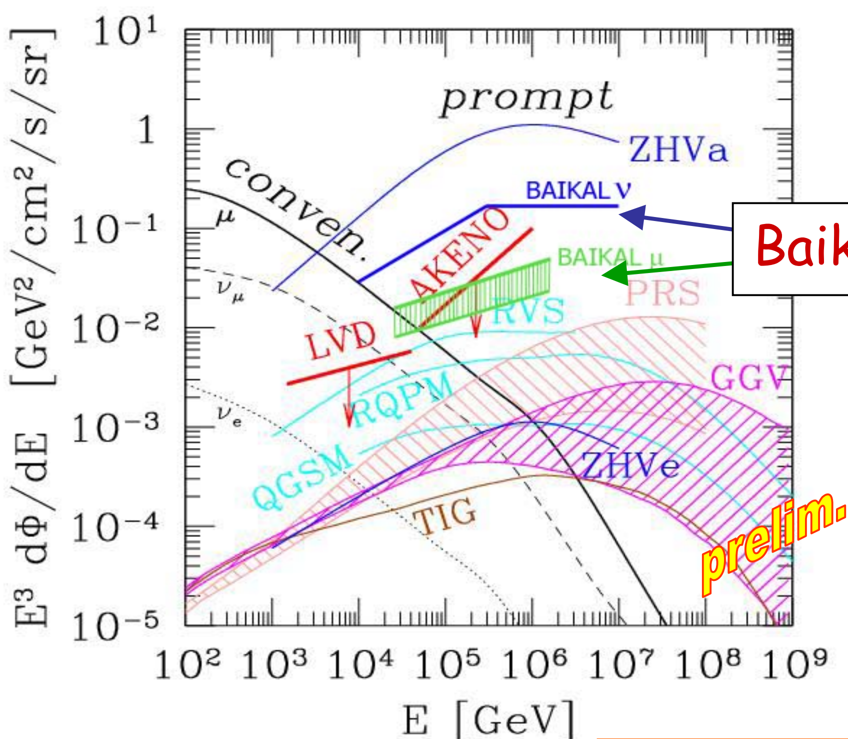
Prompt atmospheric ν's and muons
BG source for neutrino telescopes

Source – decays of short-lived particles (Λ, D, …)
$\Phi_\mu \sim \Phi_\nu$ – isotropic for $E < 10^7$ GeV

Neutrinos $-\nu_\mu, \nu_e$: 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.)
$\Phi_\mu = A_\mu E^{-2.6}$



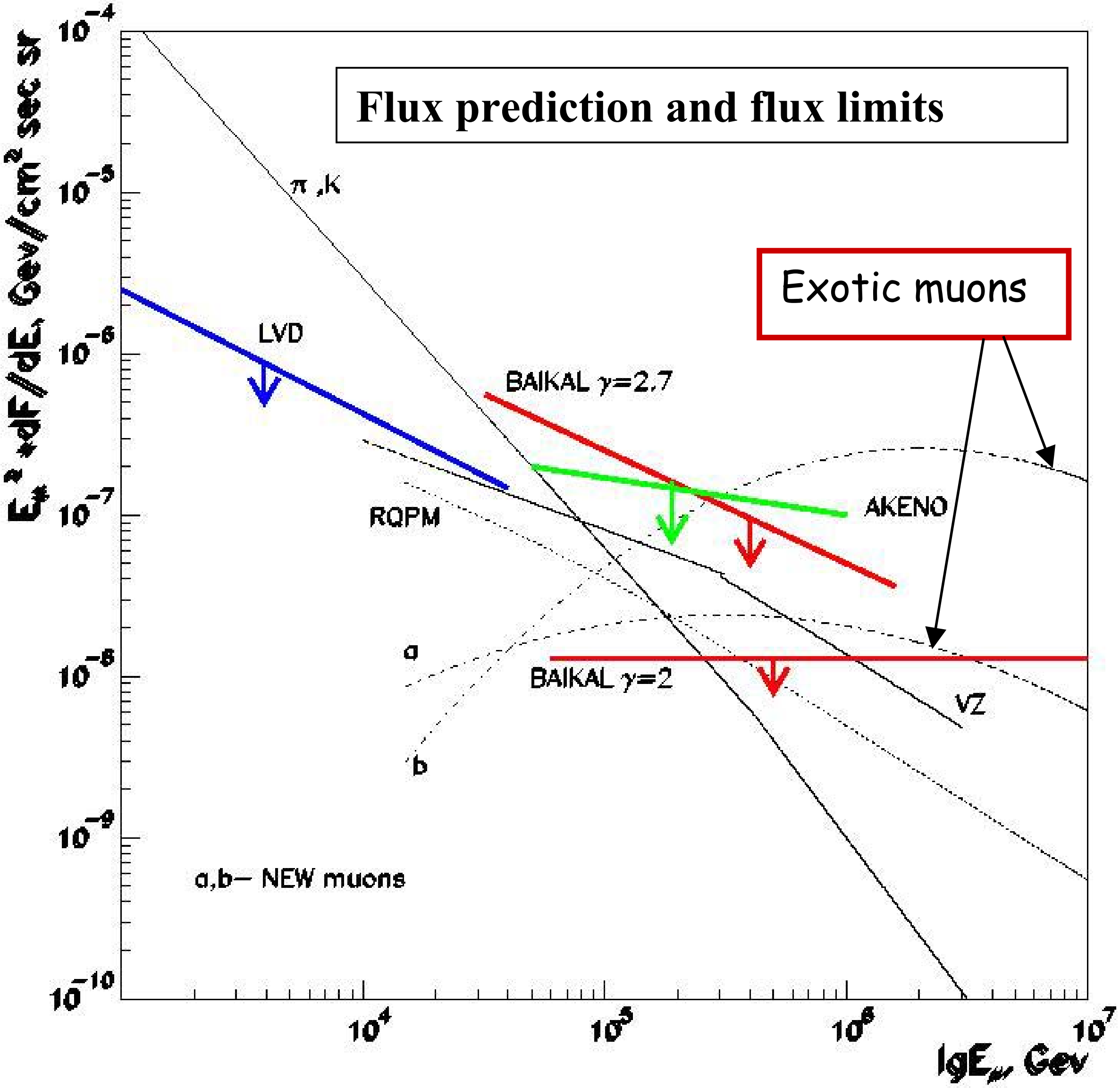
Baikal limit: ν μ

preliminary

Predictions:

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

Limits to HE Muon Flux: Exotics



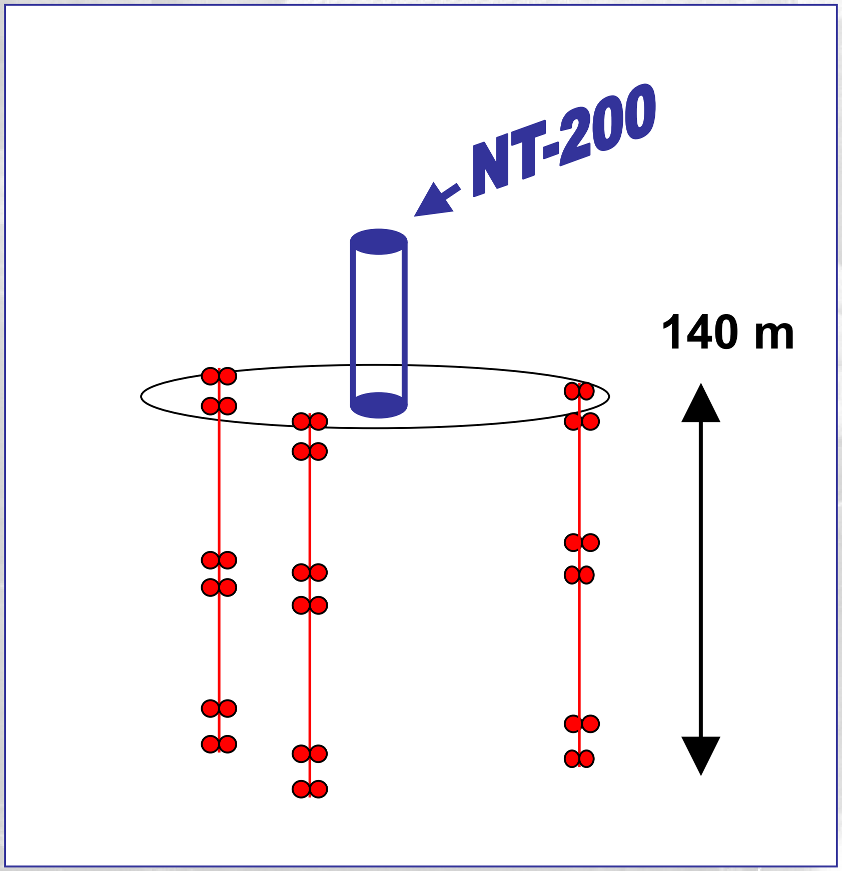
With the *HE Cascade Cuts*:
Any HE muon model spectrum can be tested.

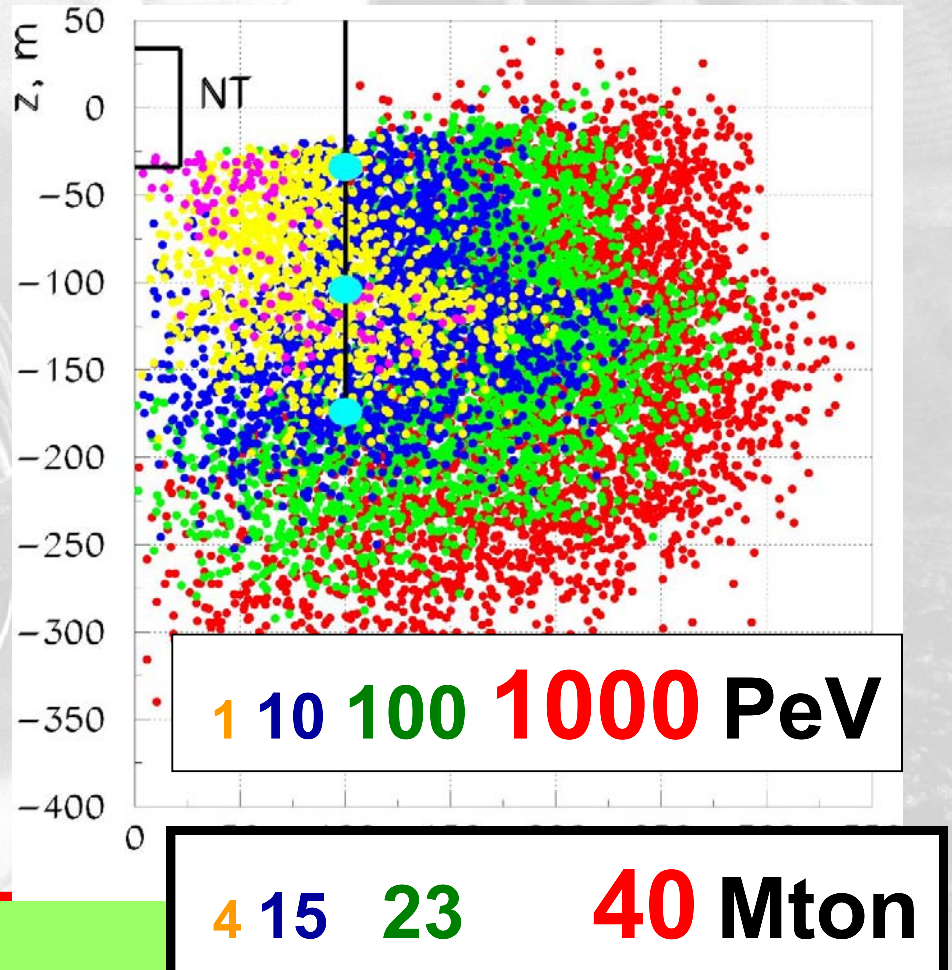
Trying to rule out:
"Exotic Muon Component",
as postulated to explain the CR-knee by "new physics" at E_{thr}~1 PeV that pump EAS energy E_0 to exotic muons (Petrukhin99, curves a and b).

A detailed limit calculation for exotic μ "predictions" is in progress.
The prel. limit for E^{-2} spectrum shows the model rejection power.

Upgrade to NT200+

Aim: Improve sensitivity to cascades with sparse instrumentation.

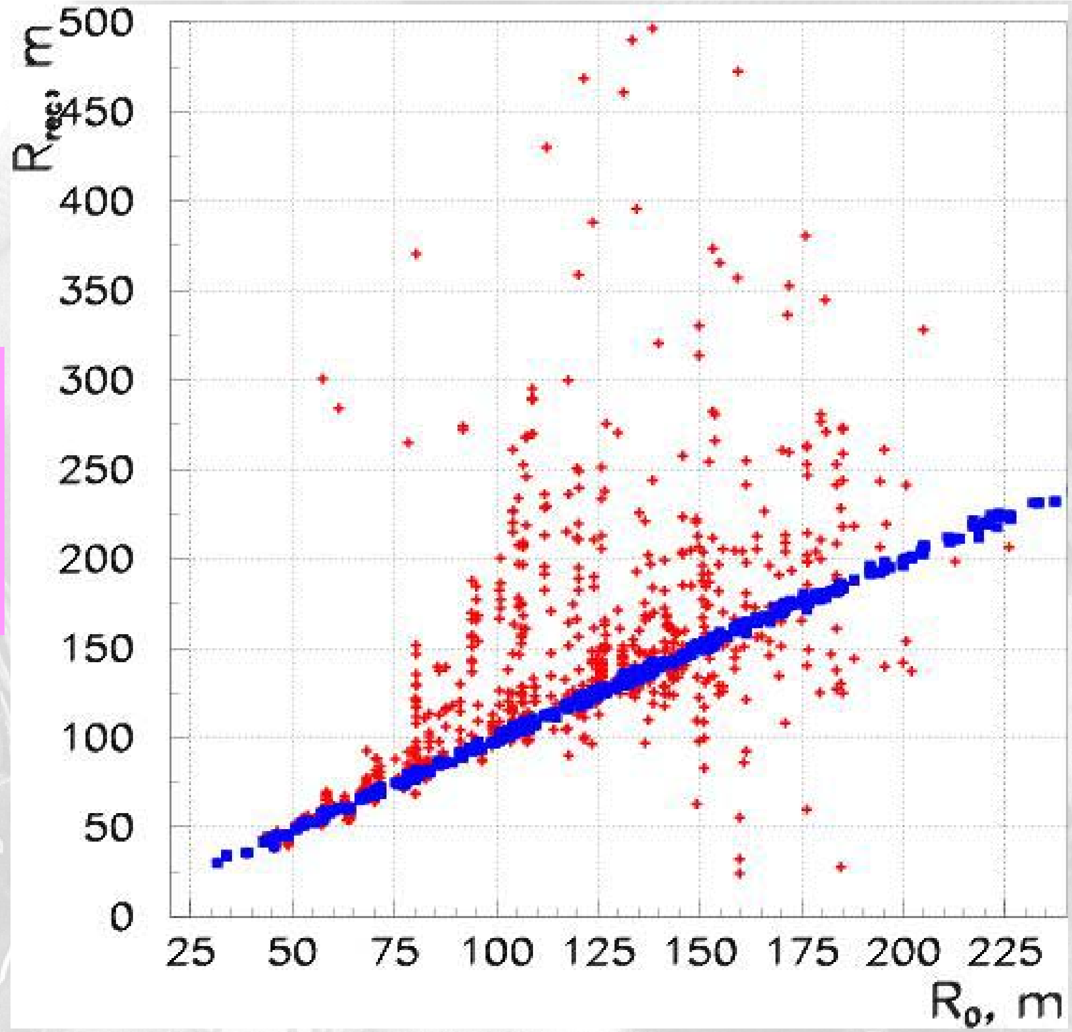




36 additional PMTs on 3 far 'strings' → 4 times larger V_{eff} !

NT200+

Much improved cascade coordinates (+ energy) reconstruction.



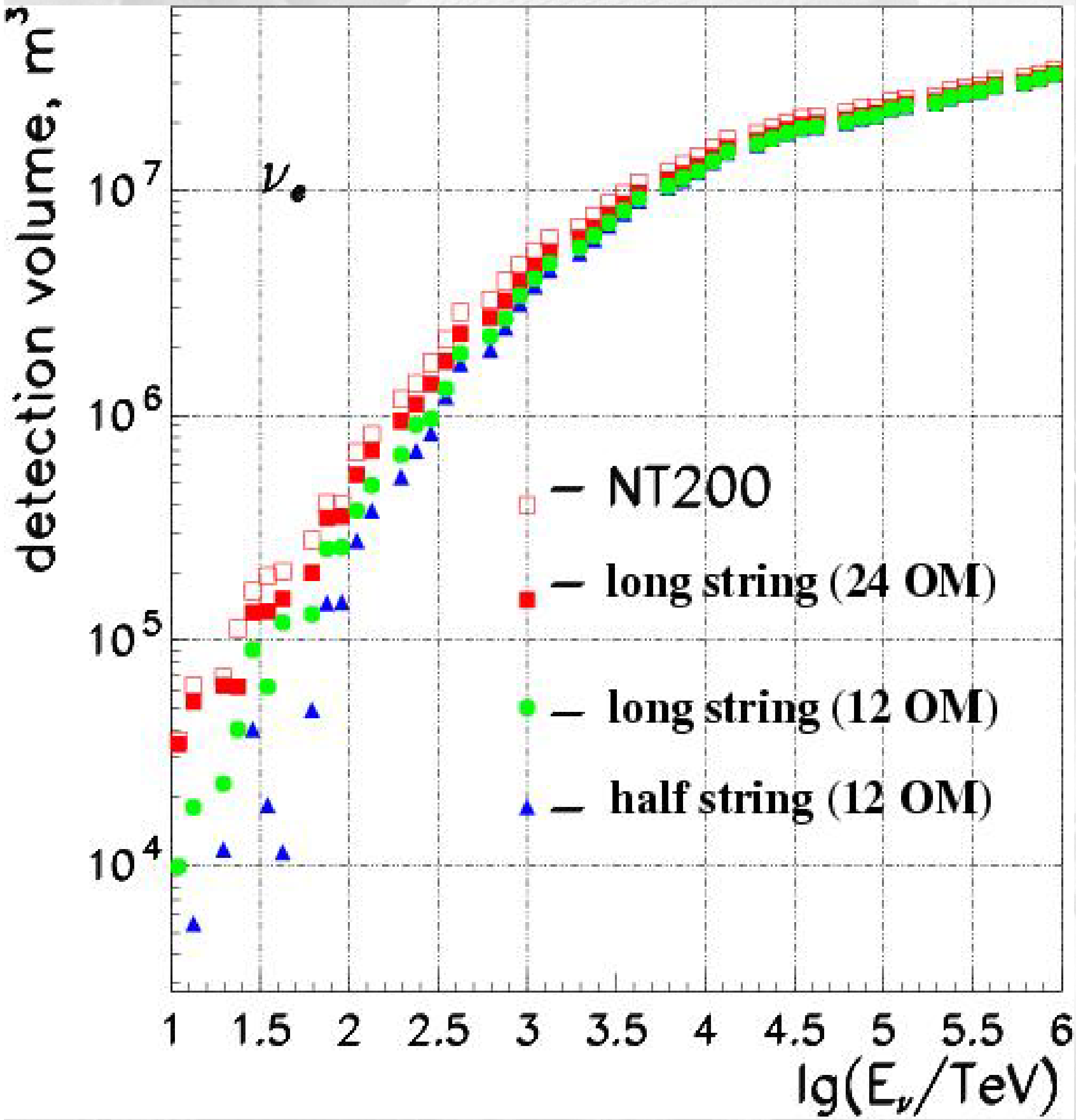
Expected ν_μ - sensitivity (3 yrs NT200+) :

$E^2 \Phi_\nu < 0.8 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

for "classical HE cuts" (vertex + energy reco will improve !!)

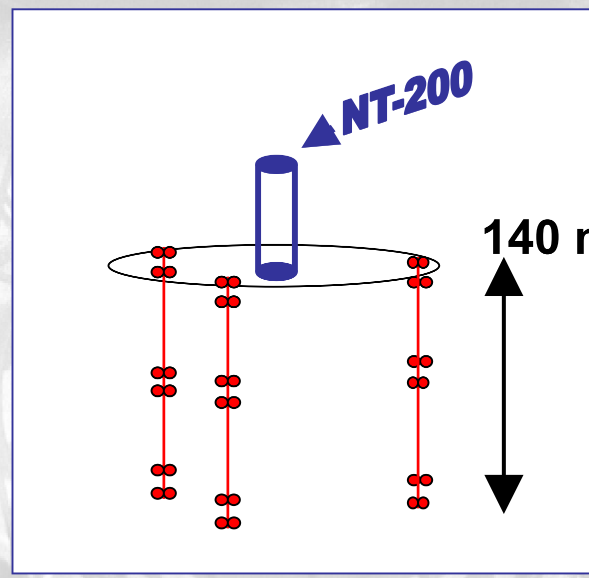
NT200+

NT - 200+ as subunit for a Gton scale detector ?



For High Energy Cascades:
A single small string replacing the NT-200 central core reduces V_{eff} less than x3 for E>100TeV.

→ Short strings as a subunit for a Gton scale detector



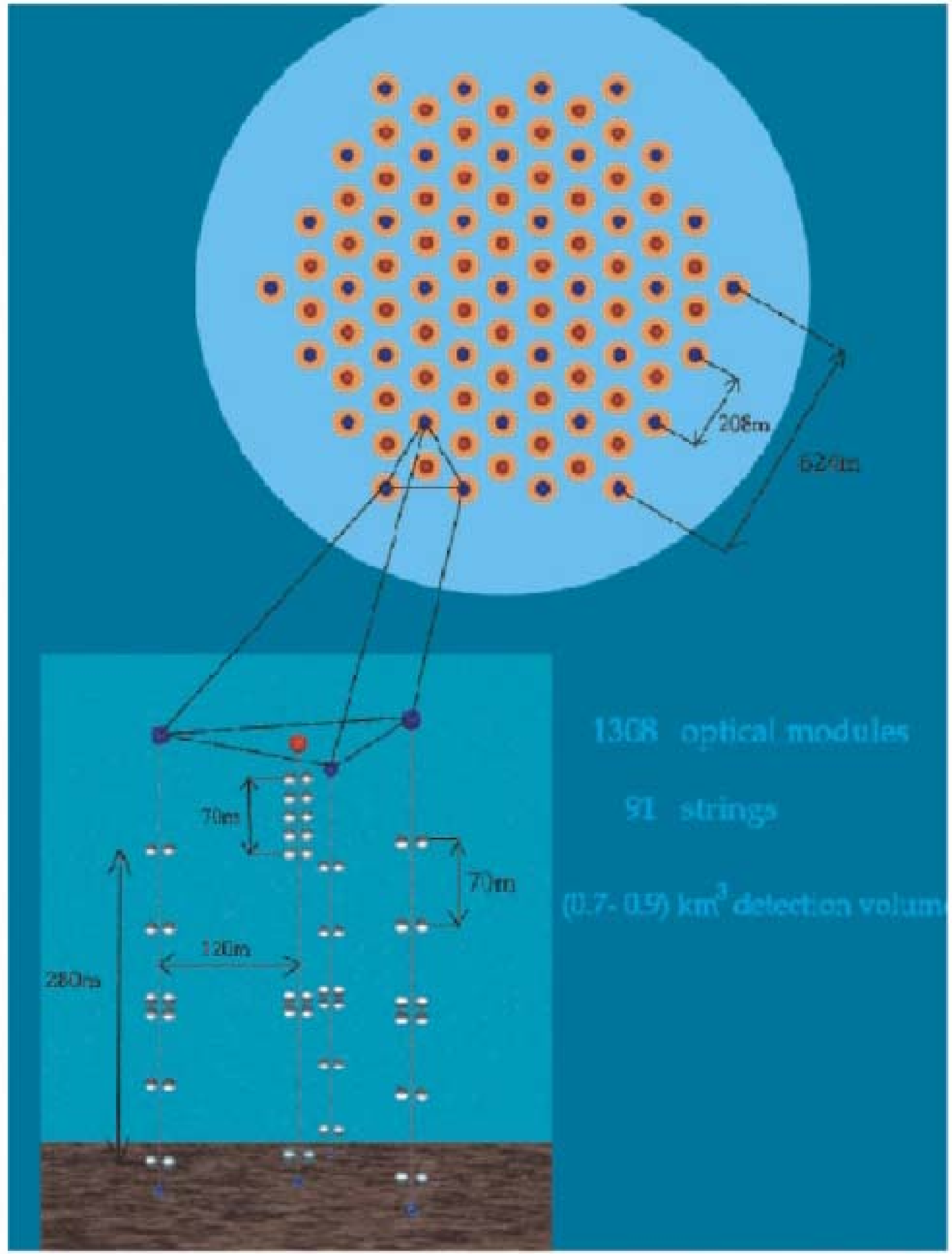
A future Gigaton (km3) Detector in Lake Baikal (?)

Sparse instrumentation:

91 strings with 12/16 OM
= 1308 OMs

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

→ muon threshold
between 10 and 100 TeV

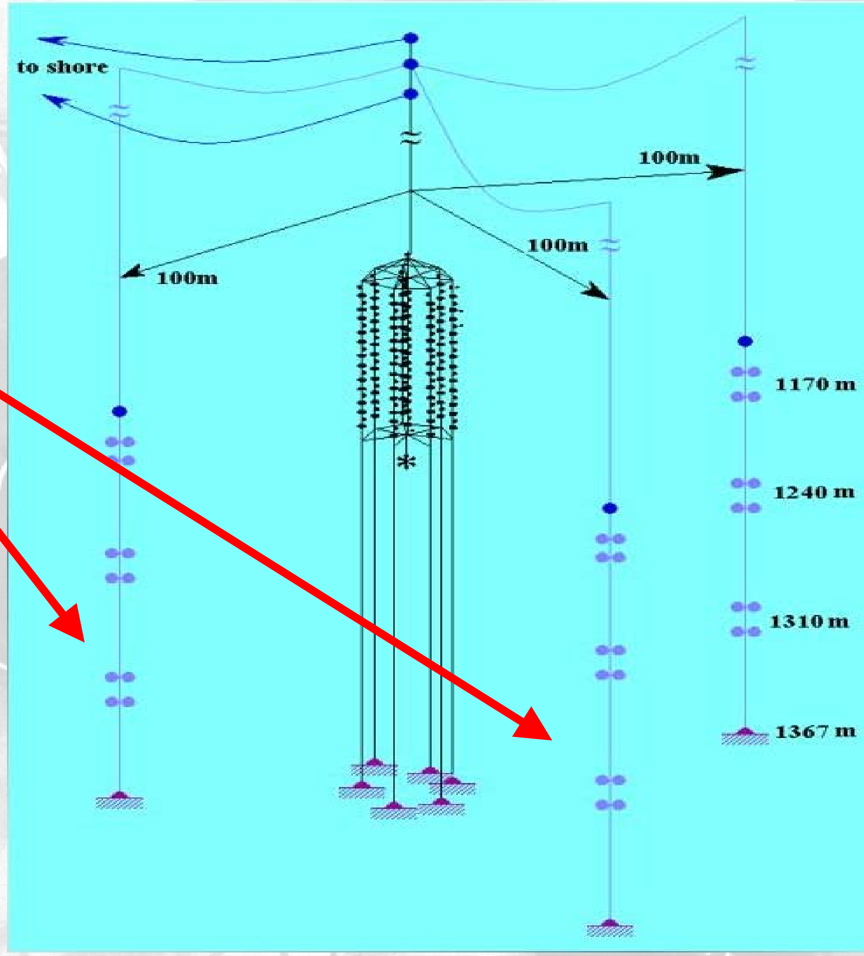


NT200+ Status

2004:

- **Two outer strings** are installed
  $2.3\ 10^4$ common events taken during
  364 h life time (0.017 Hz)

- **New cable** to shore (4km underwater)
- **Synchronize:** Time + Location Laser,Ac
- **DAQ system redesigned**
  - MBit-DSL shore connection: x100 bandwidth
  - Embedded Linux PC's and Ethernet underwater
    (fast trigger Level 0 possible)
  - Remote Experiment Control from Moscow/...



2005:

- NT200+ will be completed

DAQ Layout

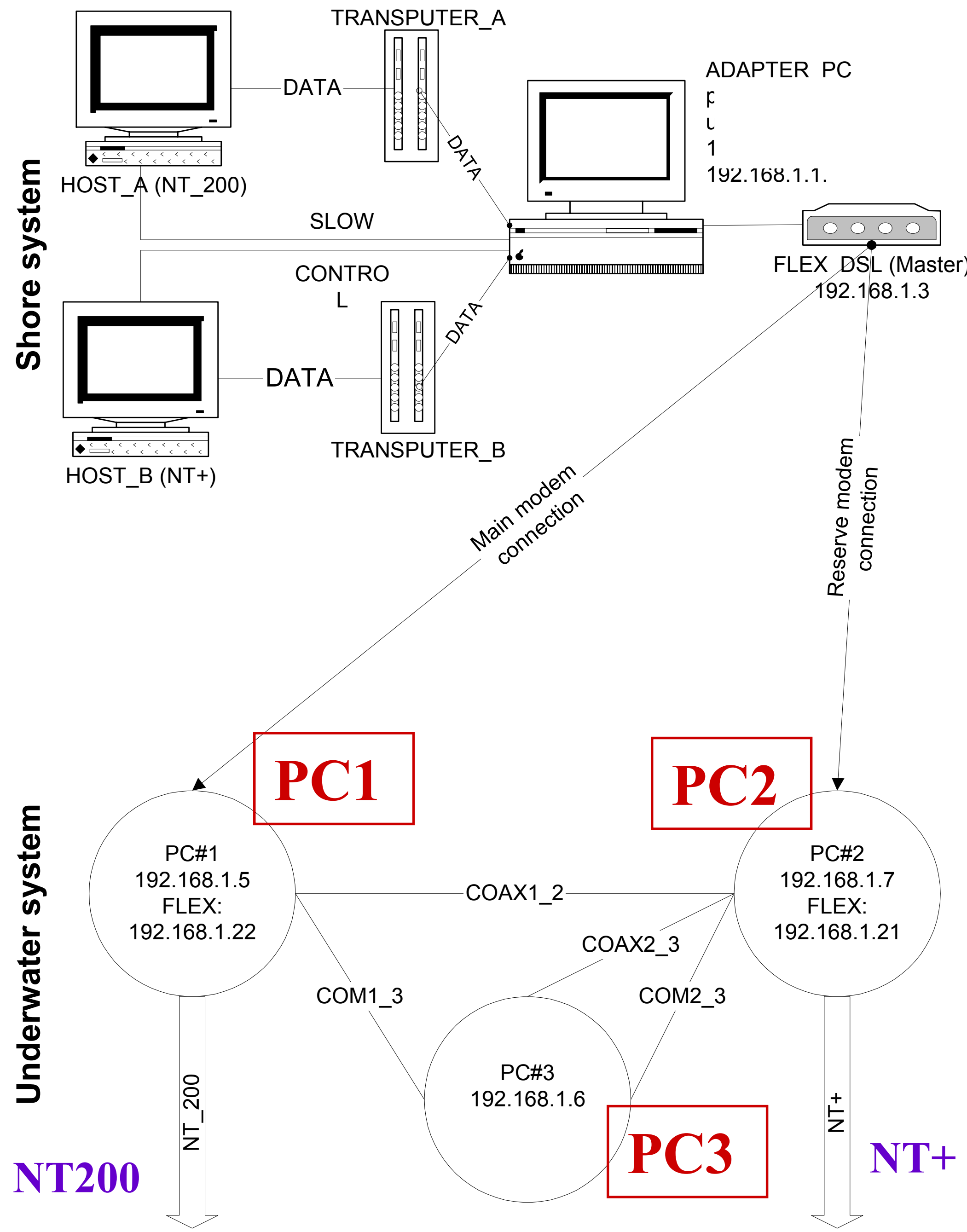
Shore:

2 parallel systems for NT200 and NT+

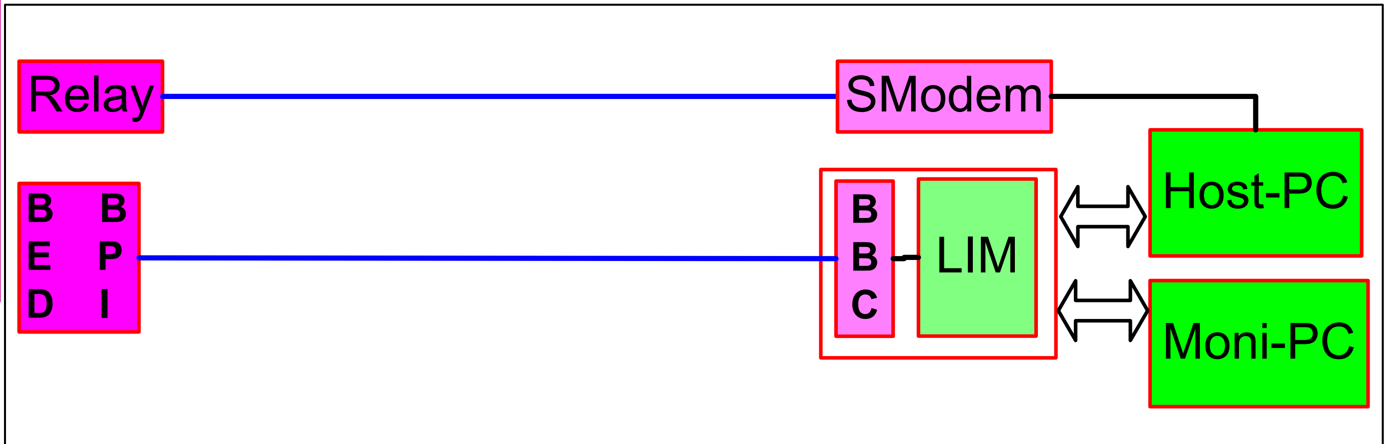
UnderWater:

3 additional spheres

- PC1 – NT200; PC2 – NT+
  PC3 – fallback TermServ
- DSL shore connection:
  main + spare

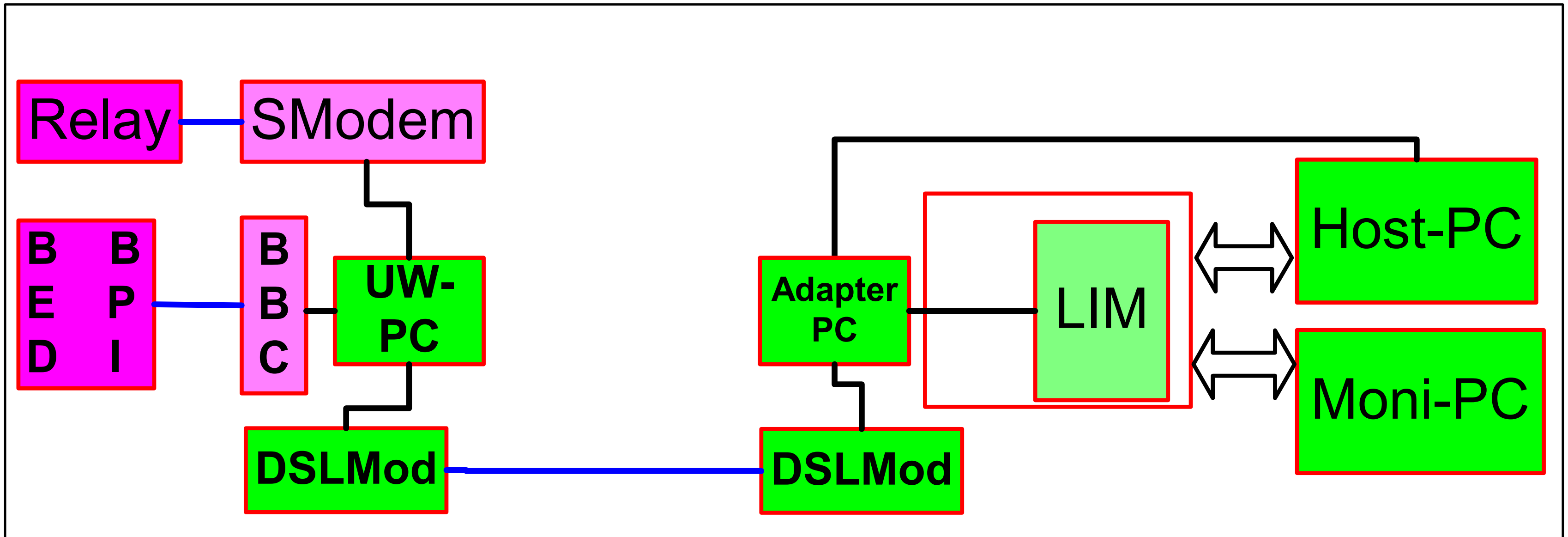


Baikal-DAQ: 1993-2003



Desgin (1990-92):
- Underwater ←→ Shore: proprietary slow & data „modems"
- Shore-Computing: DOS-PC + Transputer farm, Moni-PC FTN

2004



- Underwater ←→ Shore: ‚Standard' DSL Line (Ethernet)
- Shore-Computing: DOS-PC + Transputer, Moni-PC FTN

Adapter-PC allows to keep teempor. old shore SW/HW.

NT200+ DAQ-Upgrade, March 2004

- Linux and Ethernet "go underwater" for the new Baikal-DAQ:
  - 3 Baikal-spheres with first PCs ready for deployment (left)
  - Mounting the central trigger/DAQ underwater system (right)

Summary

- The Baikal Telescope is operating since 1993
- Strong in HE-diffuse search: "Mton-detector"

- News (+ larger data sample) from NT200:

  Magnetic Monopoles, WIMPs, HE atm. μ (prompt; exotic), GRB-limits

- Sensitivity comparable to Amanda-II
- Complementary to Amanda (northern sky, optical prop., pattern-reco, …)

- Aggressive upgrade to NT200+ in 2004/5:
  - improve the HE cascade sensitivity by 2…4 for PeV…EeV
  - serious improvement: Mbit + Ethernet/CPU now underwater + RemoteC

- Ideas for future: Gigaton Volume Detector (km3)

BAIKAL will for a few years remain the largest (and only) Northern hemisphere Underwater Cerenkov Telescope . . .