The BAIKAL Neutrino Telescope: from NT200 to NT200+

Ralf Wischnewski

DESY-Zeuthen

From Colliders to Cosmic Rays, Prague, 12.9.2005

Outline:

- Physics Motivation + Detection Channels
- The Detectors: NT200 and NT200+
- NT200+ .... first light
- Physics Results from NT200: 1998-2002 (selected)
- Summary

For fun, see also
CernCourier 7/8-2005

Telescope takes next step to high-energy frontier

In April, while Lake Baikal in Siberia was iced ovr, the neutrino telescope 1 km below the surface was successfully upgraded with three additionastrings. Renamed NT200+ it is tailored to search for diffuse fluxes of cosmic neutrinos at energies of peta-electron-volts.

Neutrino Telescopes: Physics Motivation

- **High Energy ν-Astronomy --> Catch first astrophysical HE ν's**
  - → **Cosmic ray acceleration sites**
  - → **New observational window to Universe (new objects ?)**

- **Dark Matter** (neutralino annihilation in Earth/Sun/Gal.C.)
- **Prompt lepton production in atmosphere** (ν + μ ; cross sections, ...)
- **Exotic particles:**
  Magnetic Monopoles (relativistic or ultra-slow)

...

- **CR: HE atmospheric muons** (exotic component ?), muon-spectra, composition...

Astro -

- Particle Physics

Astrophysical ν's: Two detection methods

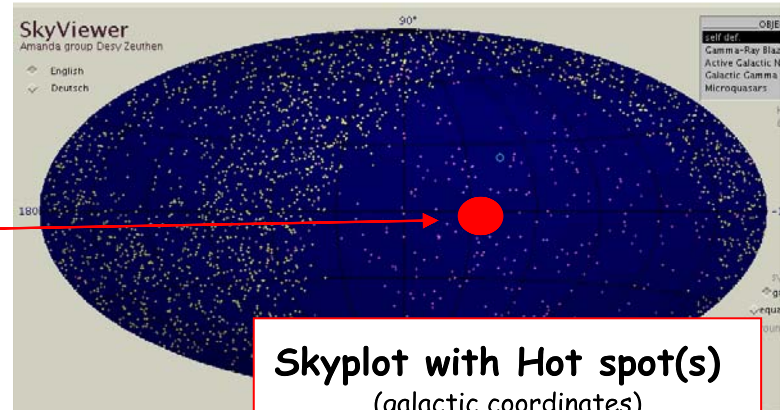
Physics Background: atmospheric neutrinos

A. Point sources

"Find the sources on the sky"

Charged Current (CC) ν_μ N → μ X

+ clean experimental signal
- needs strong enough single sources

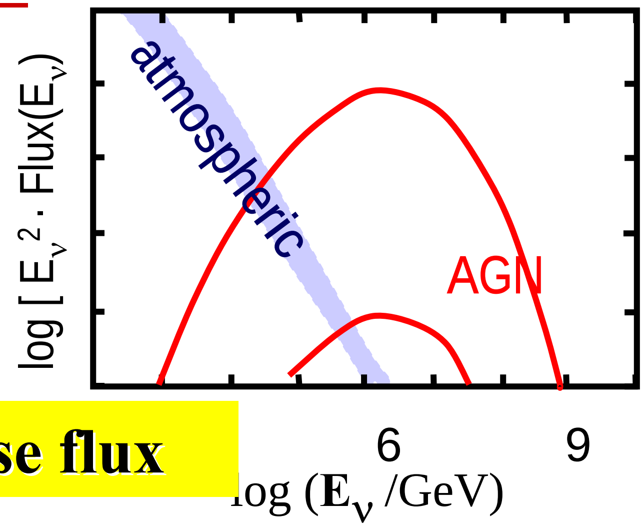


Point source search

B. Anomalies in atmospheric ν-energy spectrum

Electron / hadron cascades from
CC + NC ν_e / ν_τ / (ν_μ)

+ all weak point sources add up; all flavors
+ theoretical predictions ~ exp.sensitivities
- exp. Systematics



Search for a diffuse flux

Baikal Collaboration:
Russia – Germany

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

~45 authors

Milestones:

>1983: site / water studies;
R&D: large area PMT, u-water techn.;
physics small setups (exotics search)

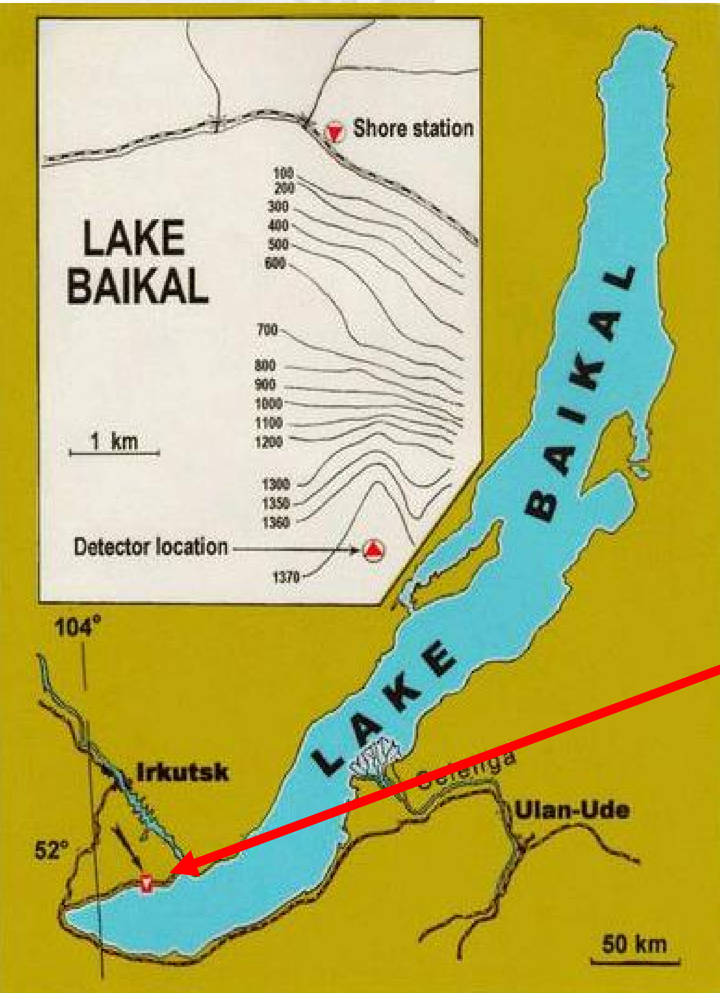
1991: Project NT200

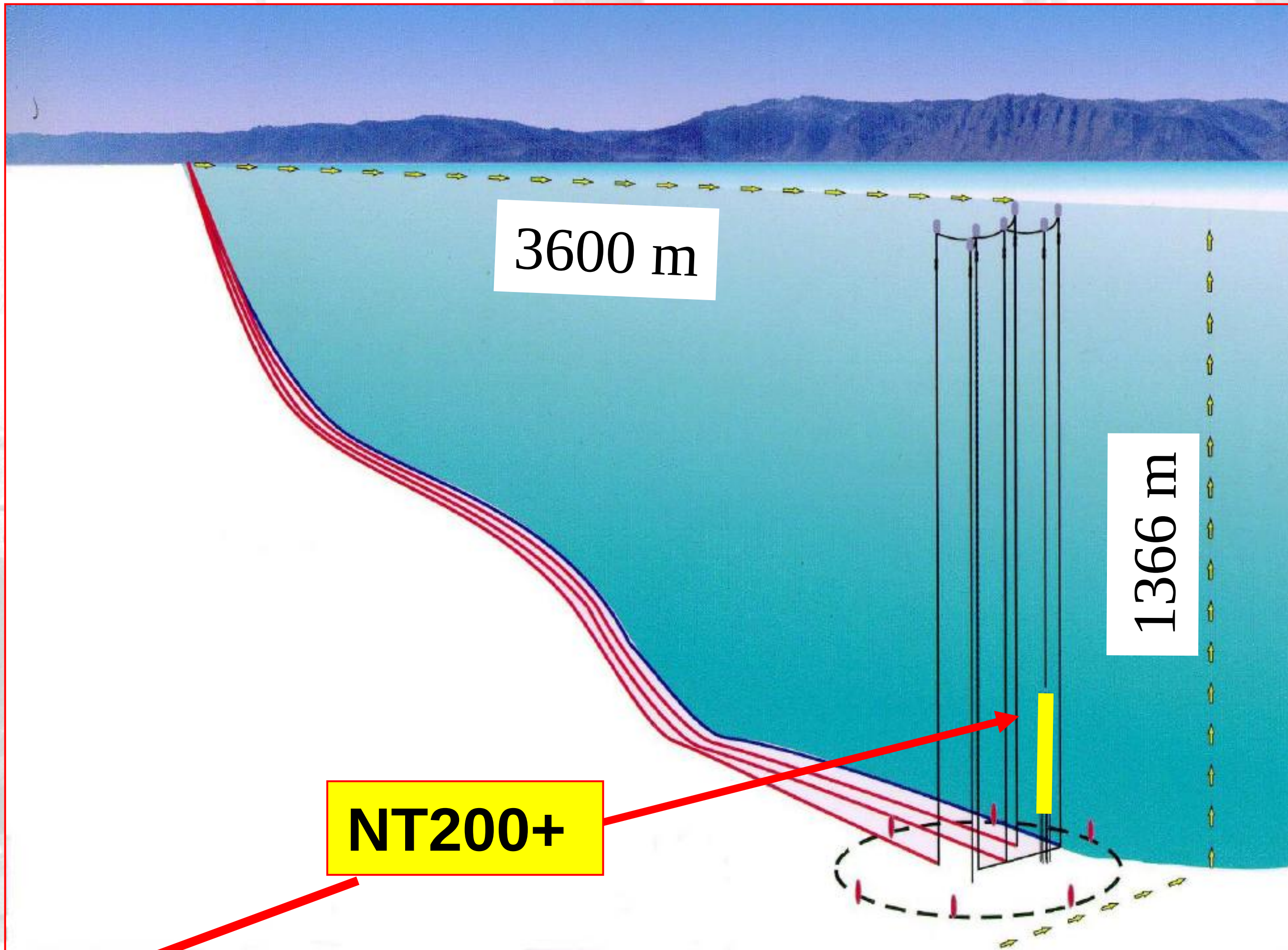
1993: NT36 –
the first underwater array operates

1998: NT200 commissioned

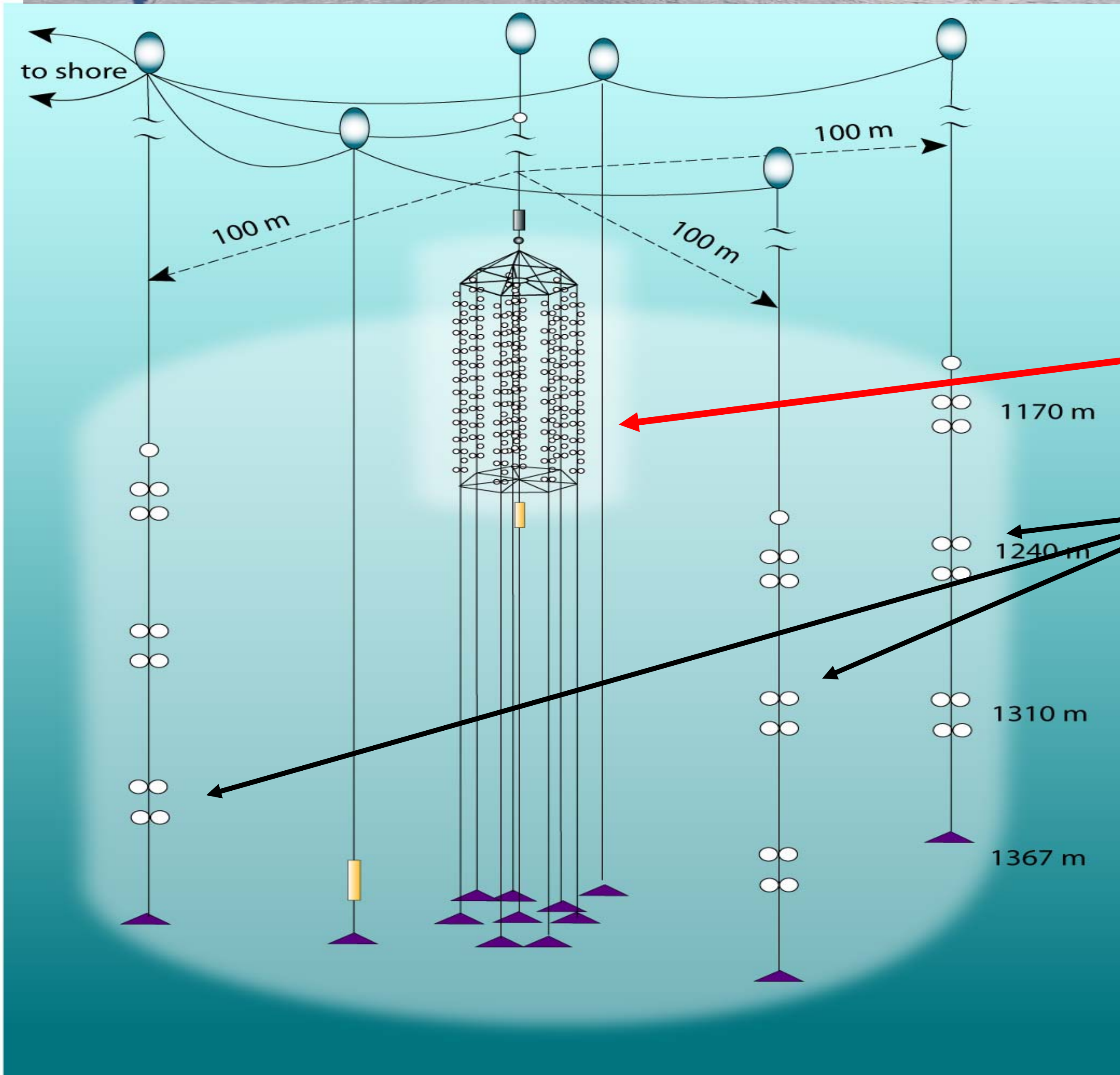
2005: NT200+ completed

The Site





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

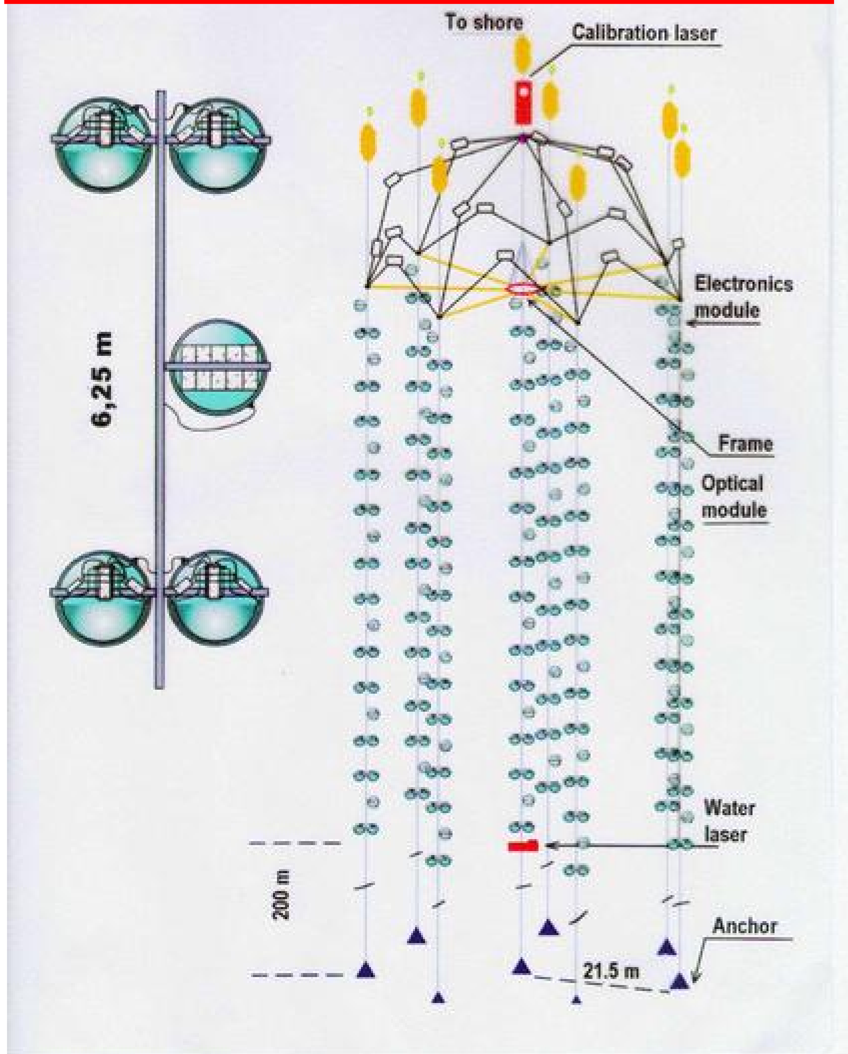


NT200+
=
NT200
+
3 long outer strings

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

R.Wischnewski C2CR, Prague, September 2005

NEUTRINO TELESCOPE NT-200

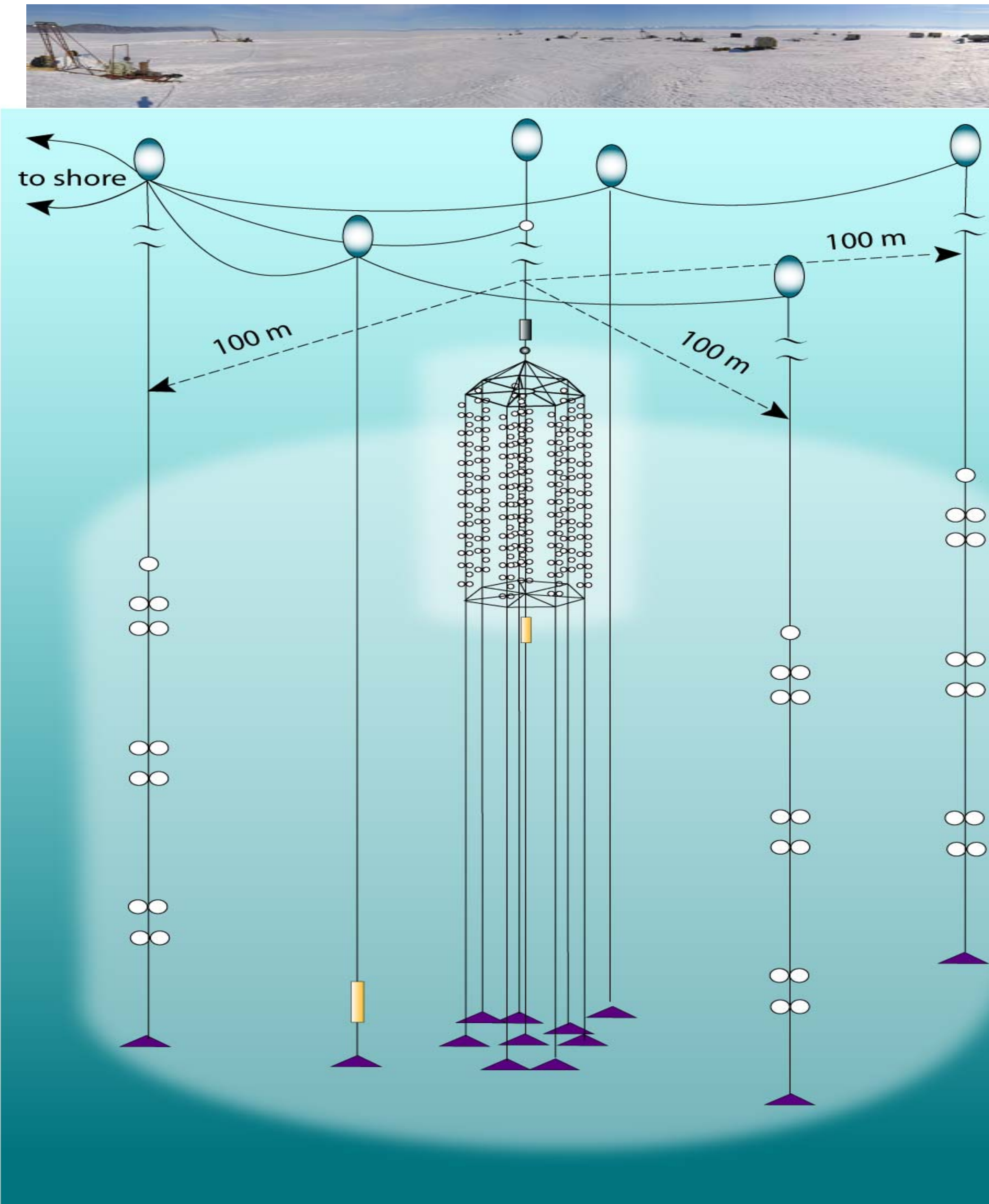


Height x Diameter = 72m x 42m,
$V_{geo} = 10^5 m^3$ = 0.1 Mton

- 8 strings: 72m height
- 192 optical modules
  → 96 pairs (coincidence)
- measure: Time, Charge
  - σ_T ~ 1 ns
  - Dyn. Range ~ 1000 p.e.

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

Quasar PMT: d = 37cm



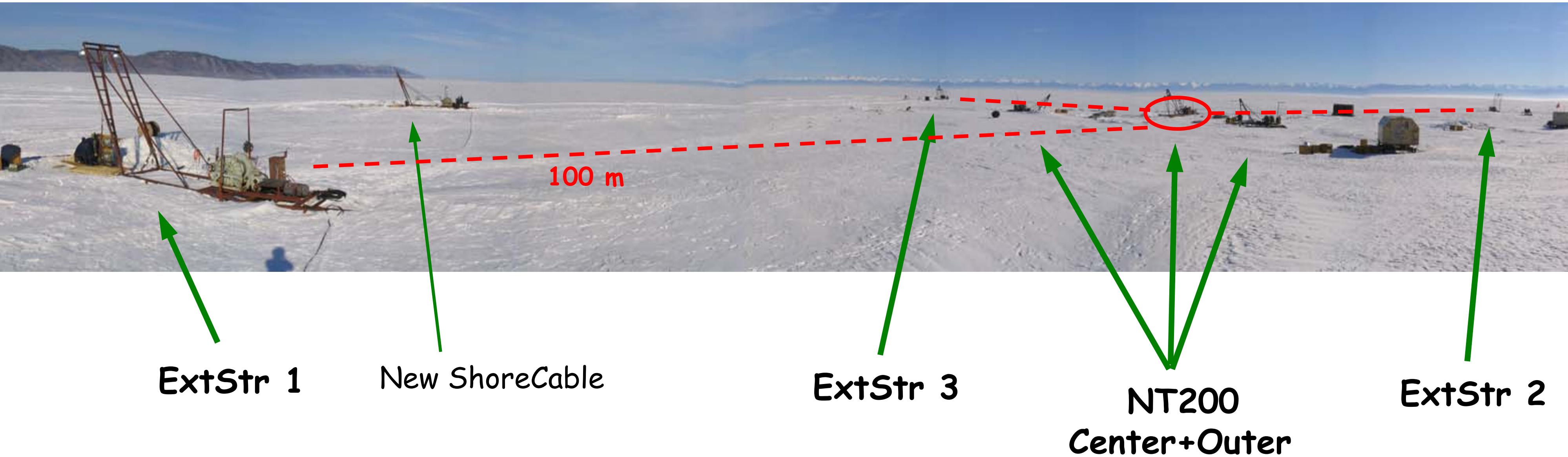
NT200+ commissioned April 9, 2005

Upgrade 2003-2005:

- 3 outer strings were installed
- DAQ – modernization
  - 2 Underwater PC with Flex DSL modem (1 Mbps), full multiplexing, Underwater Ethernet
  - Synchronization unit
    - * time synchronization (~ ns) NT200 <-> outer strings
    - * event building
  - Transition to Linux, RemoteCntrl.
- Calibration - New bright Laser
- 2 new cables to shore (2x4 km)

Ice – A perfect natural deployment platform

March, 2005, 4km off-shore:
NT200+ deployment from ice.

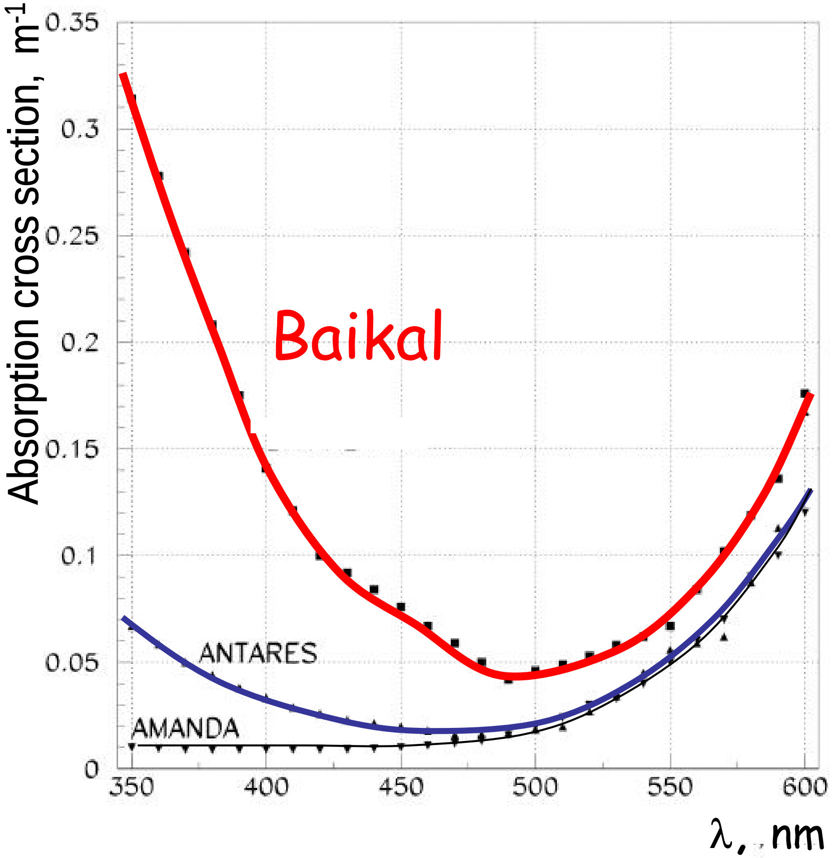


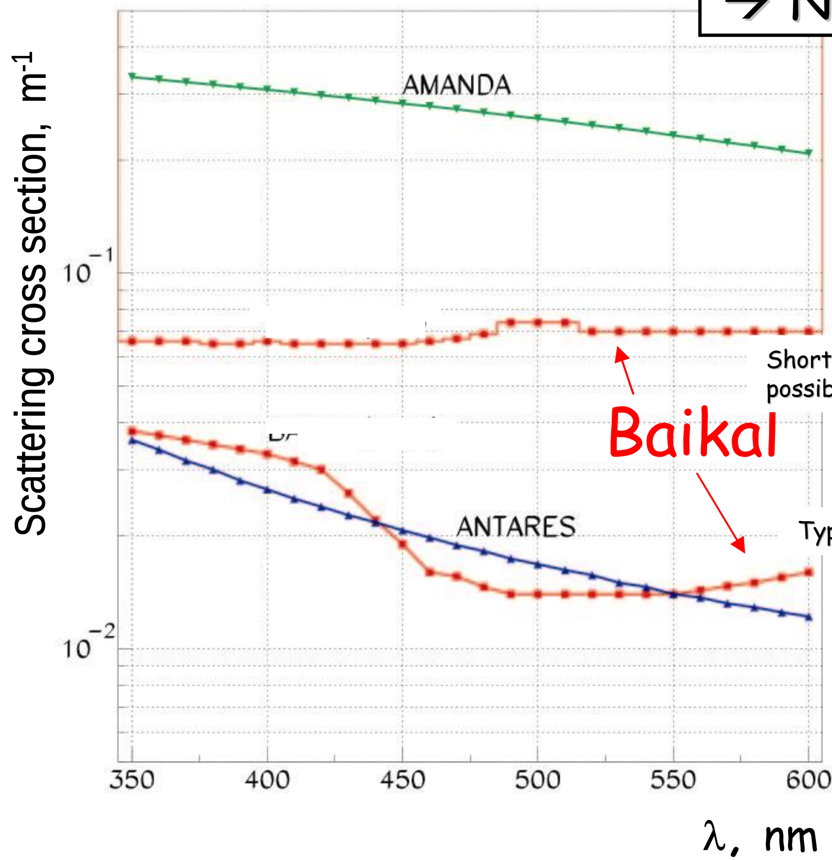
- Ice is stable for 6-8 winter-weeks/year :
  - Upgrades & maintenance
  - Test & installation of new equipment
  - Operation of surface detectors (EAS, acoustics,…)
  - Electrical winches used for deployment operations (all connections done dry)

R.Wischnewski

Water: Optical Properties

Baikal:
Fresh water
→ No K40 BG





Abs. Length: 22 ± 2 m

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

In-situ measurements over many years

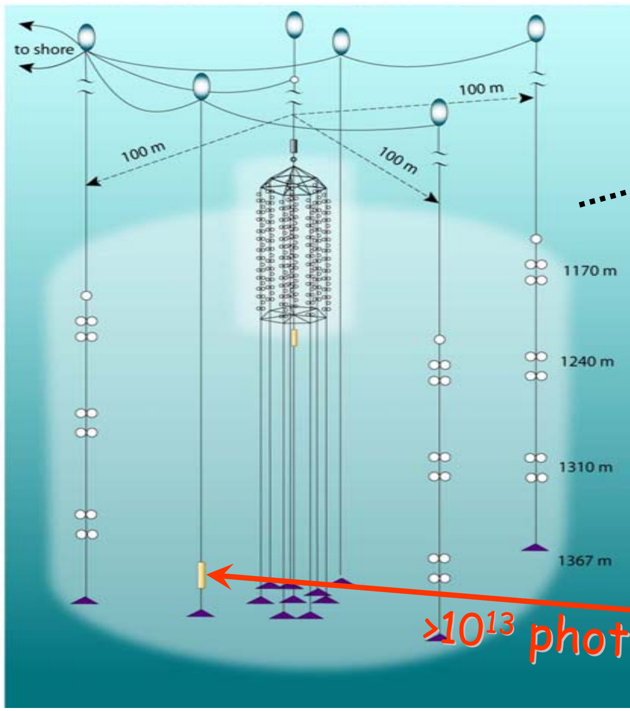
2001: Cross calibration with NEMO/ANTARES L_{att}-device

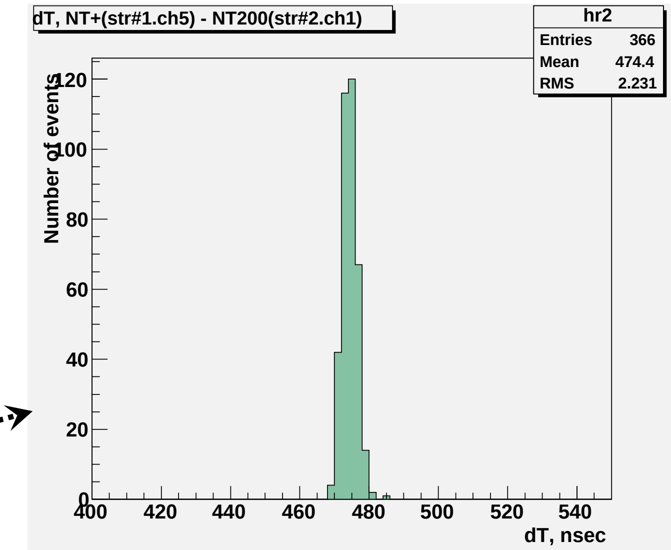
NT200+ Time Synchronization (new laser)

Laser: (400kW / 1 ns)

- **Time calibration**
- **Imitation of <10^3PeV cascades**

>10^13 photons/pulse isotropically w/ diffusor, up to ~200m for full NT200+





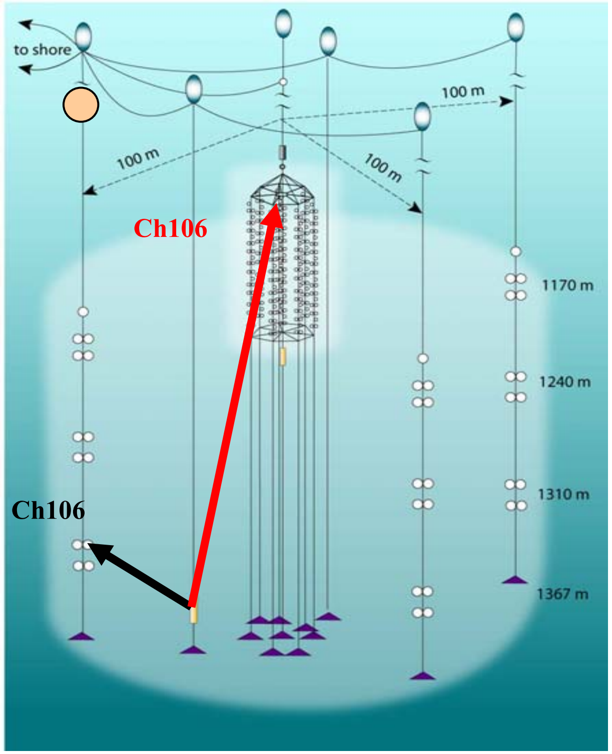
Time differences NT200 - outer string:
Jitter is **< 3ns rms** for NT+/NT200.

$>10^{13}$ photons/pulse

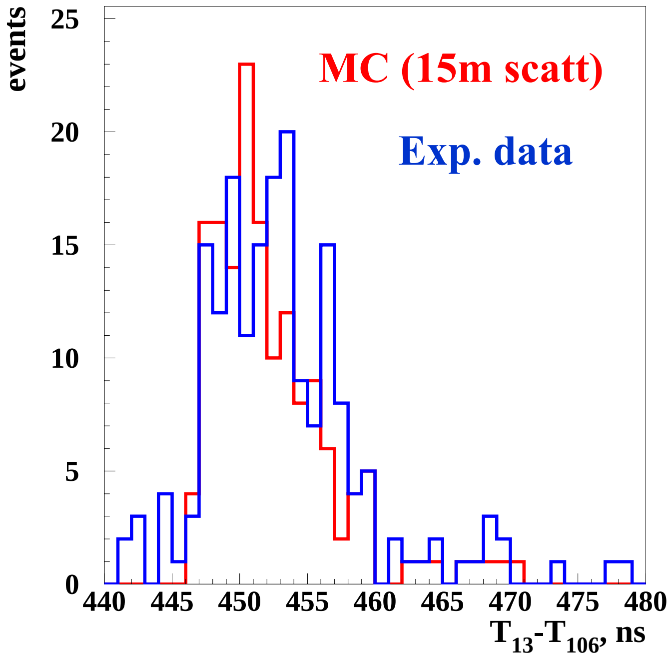
NT200+ Laser: Scattering jitter ~few nsec @ 180m

Arrival time difference Ch106 and 13:

- DT = $T_{106} - T_{13}$
- L_{106} ~60m, L_{13} ~180m to Laser
- Electronics jitter 2-3ns



Arrival time distribution @ 180m



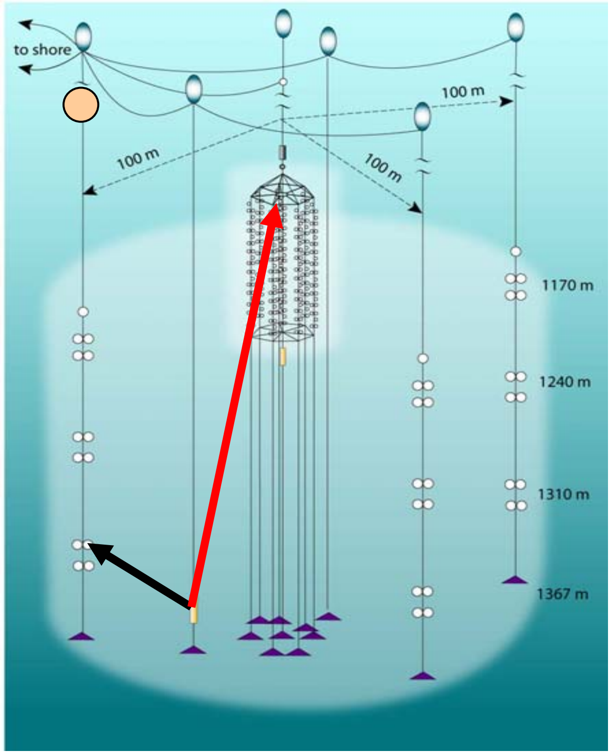
Amplitude(13) ~ 3-5 p.e.

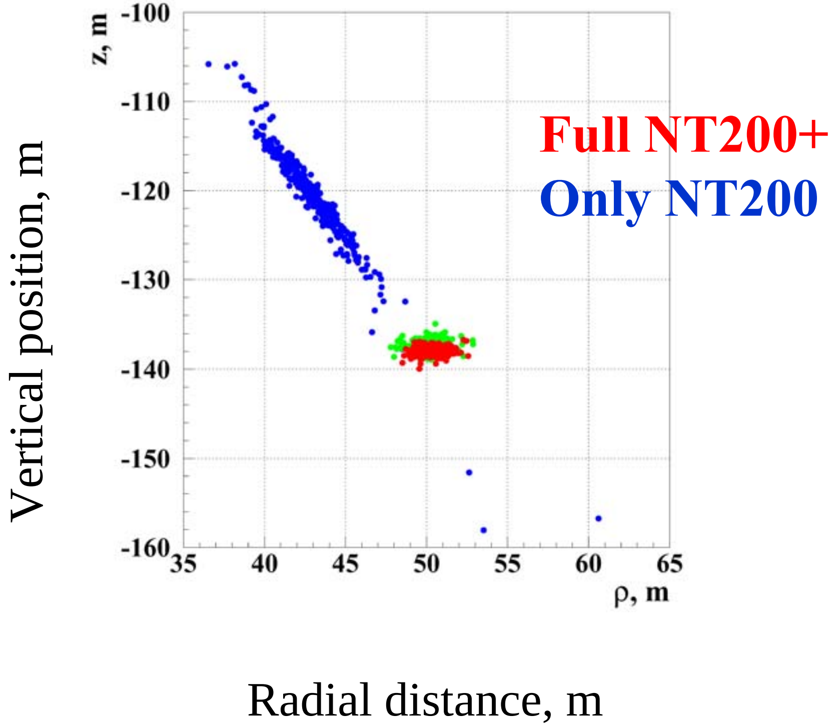
→ Scattering contribution to jitter above 20p.e. is < 1ns

→ L_scatt is > 15m; independent measurement (prelim.)

NT200+ Laser (3)

Laser position reconstruction for ~10PeV Cascades





→ L_scatt > 15m, independent measurement (prelim.)

NT200 - Selected Results

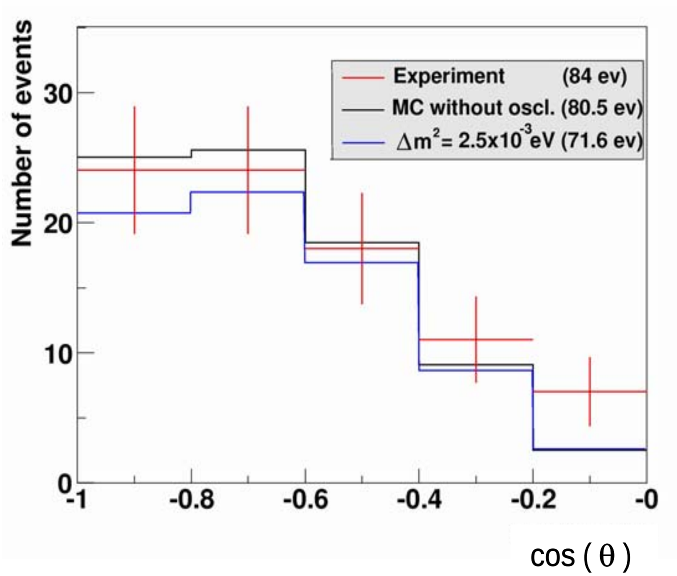
- **Low energy phenomena**
  - Atmospheric neutrinos ⇐
  - WIMP Neutrinos ⇐
- **High energy phenomena**
  - Diffuse neutrino flux ⇐
  - Neutrinos from GRB
  - Prompt muons and neutrinos
  - Exotic HE muons ⇐
- **Search for exotic particles**
  - Relativistic Magnetic monopoles ⇐

Data sample

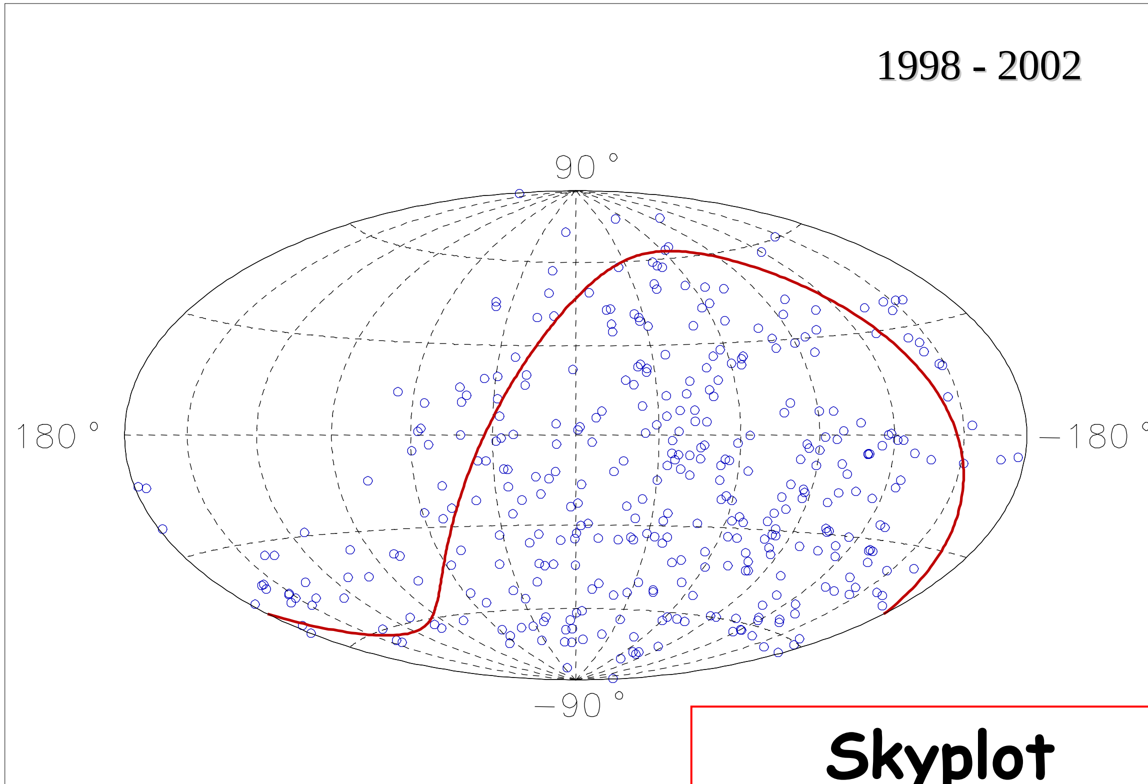
- 1998-2002:
  1038 days
  (Apr.98-Feb.03)
- 1998-1999:
  502 livetime days earlier results

Recent reports
- 4x ICRC2005 (& astro-ph)
- Neutrino2004, ECSR2004, …
- APP (Diffuse search)

Atmospheric Muon-Neutrinos



Zenith distribution 84 evts (1998/99)
→ Atmospheric calibration beam



Skyplot
(galactic coordinates)

- With looser cuts, 1998-2002: 372 events.
  → A higher statistics neutrino sample for Point-Source Search.
- MC: 385 ev. Expected (15%BG).
- No indication for Point Sources found.

E_thr ~ 15GeV

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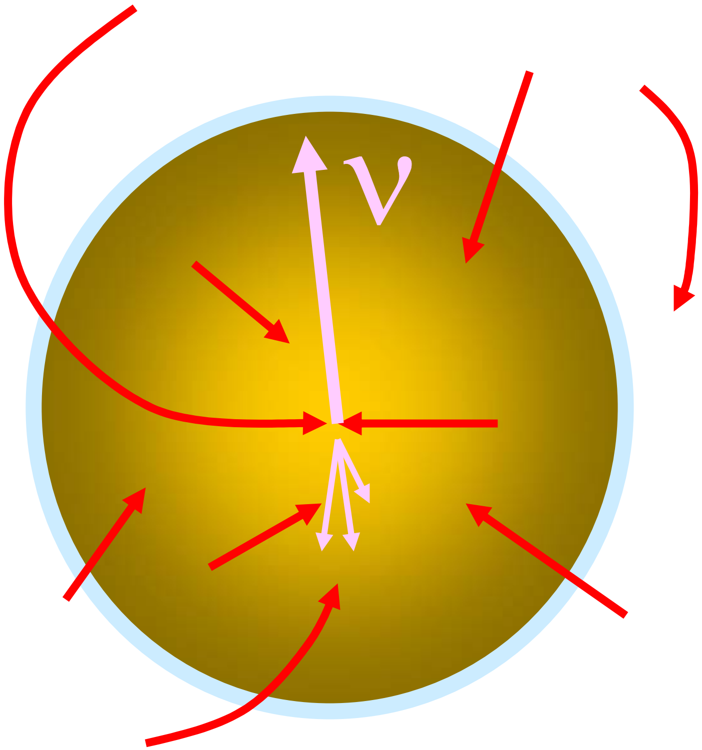
WIMP Search

Neutrinos from WIMP Annihilation in the Center of the Earth



$$\chi + \chi \to b + b$$

$$\to c + \mu + \nu_{\mu}$$

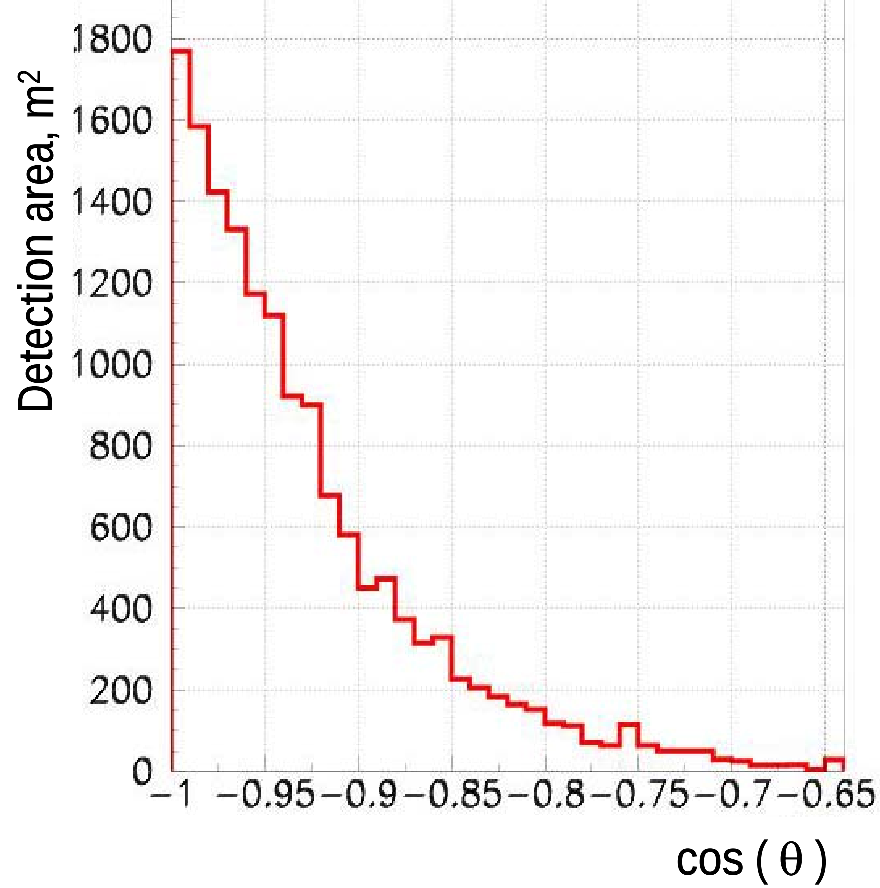
$$\to W^{+} + W^{-}$$

Tailored Vertical Track Reconstruction (single string)

→Effective Area > 10^3 m²

(after all cuts)

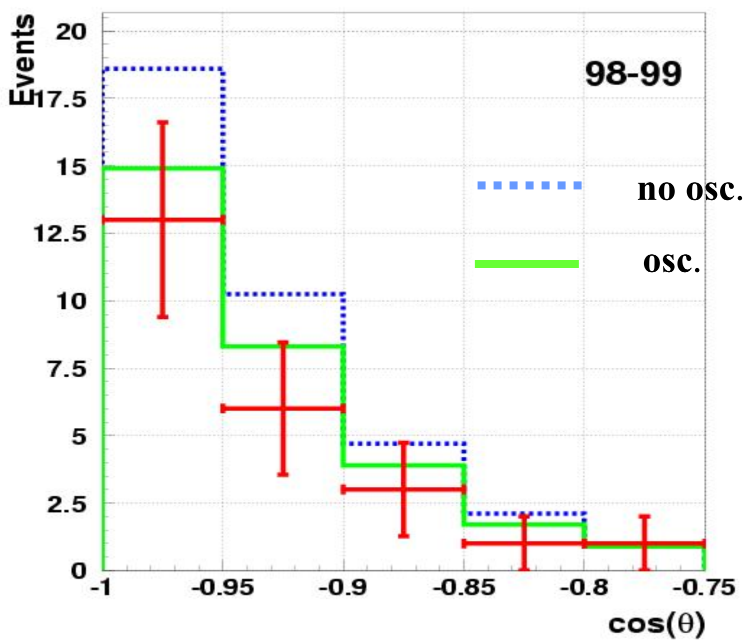
r 2005



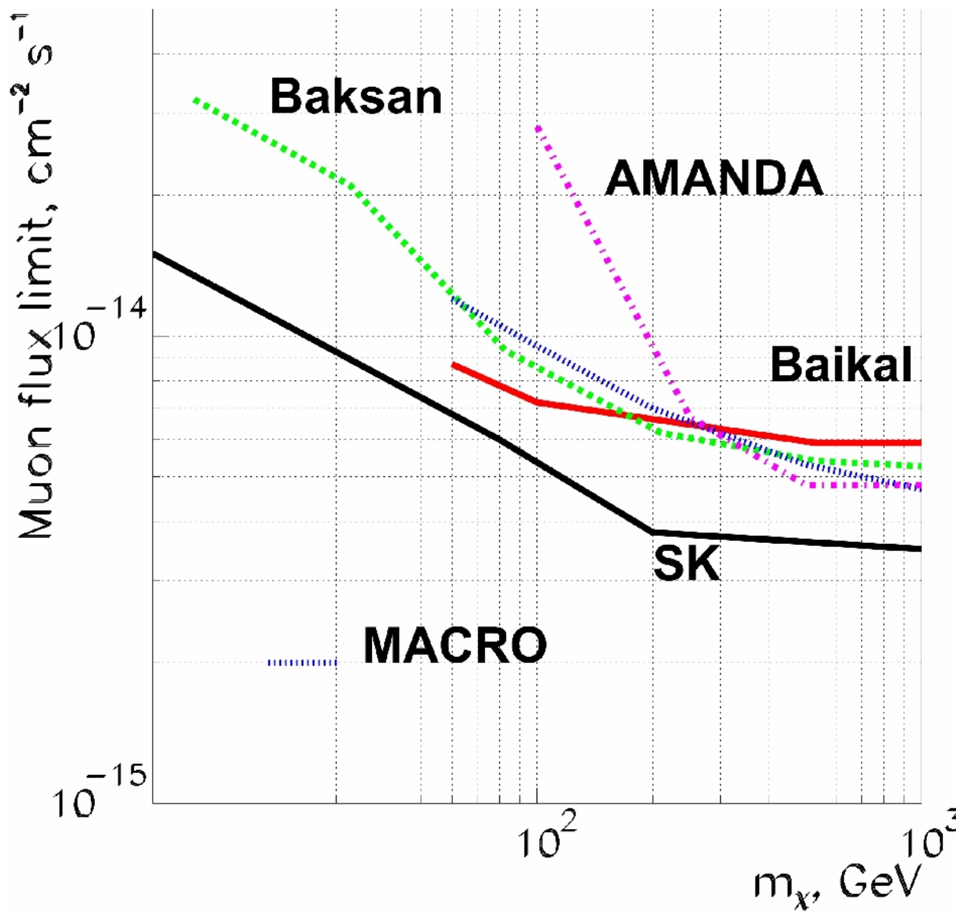
WIMP Search

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)



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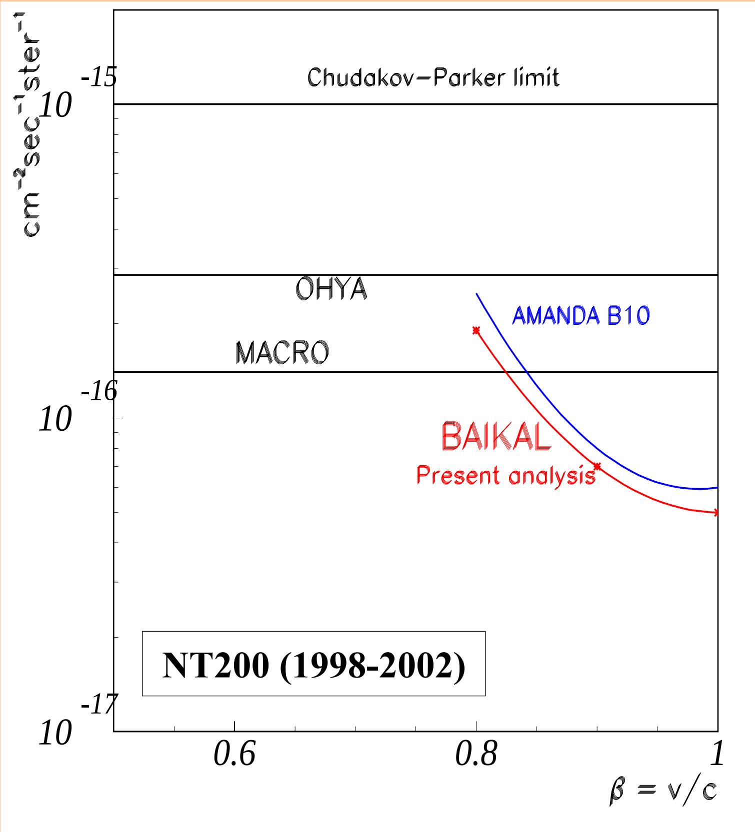
Search for fast Monopoles ($\beta > 0.75$)



90% C.L. upper limit on the flux of fast monopole and experimental limits from [4,6,7]

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

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

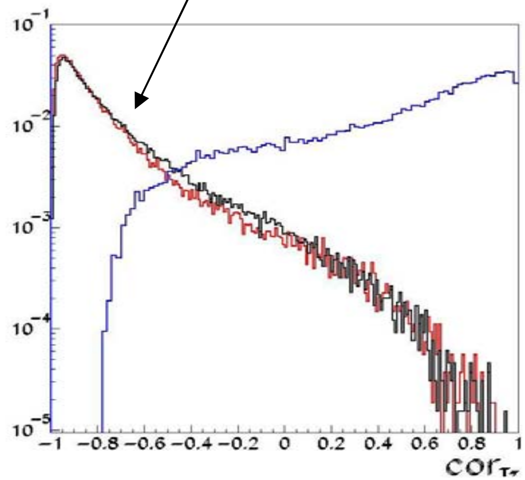
Bright light source: 8300 x muon

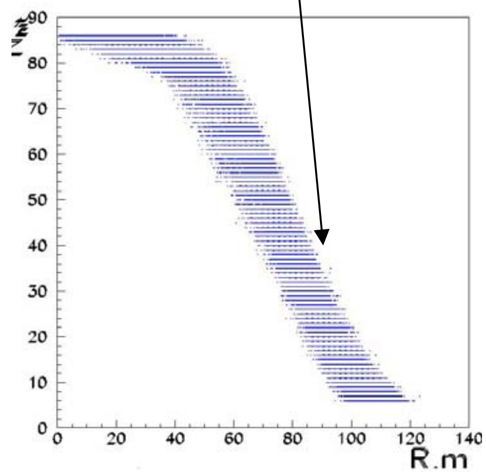
Monopole selection criteria:

- **large hit channel multiplicity: $N_{hit} > 35$ ch**
- **well reconstructed upward going track:**

corTz = $\Sigma(z_i\text{-}z)(t_i\text{-}t)/(\sigma_t\sigma_z) > 0.45$, $\theta > 100^o$

Background : atmospheric muons (downward)





N_{hit} vs distance

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

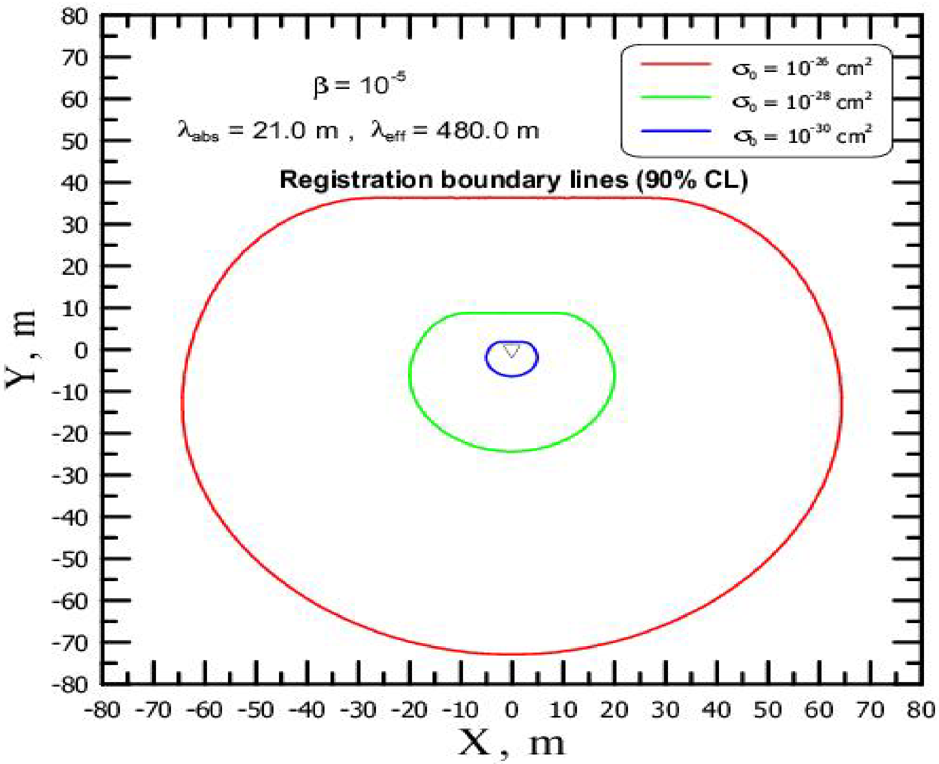
$\sigma_{cat} = 0.17\sigma_0/\beta^2, \; 10^{-5} < \beta < 10^{-3}$

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

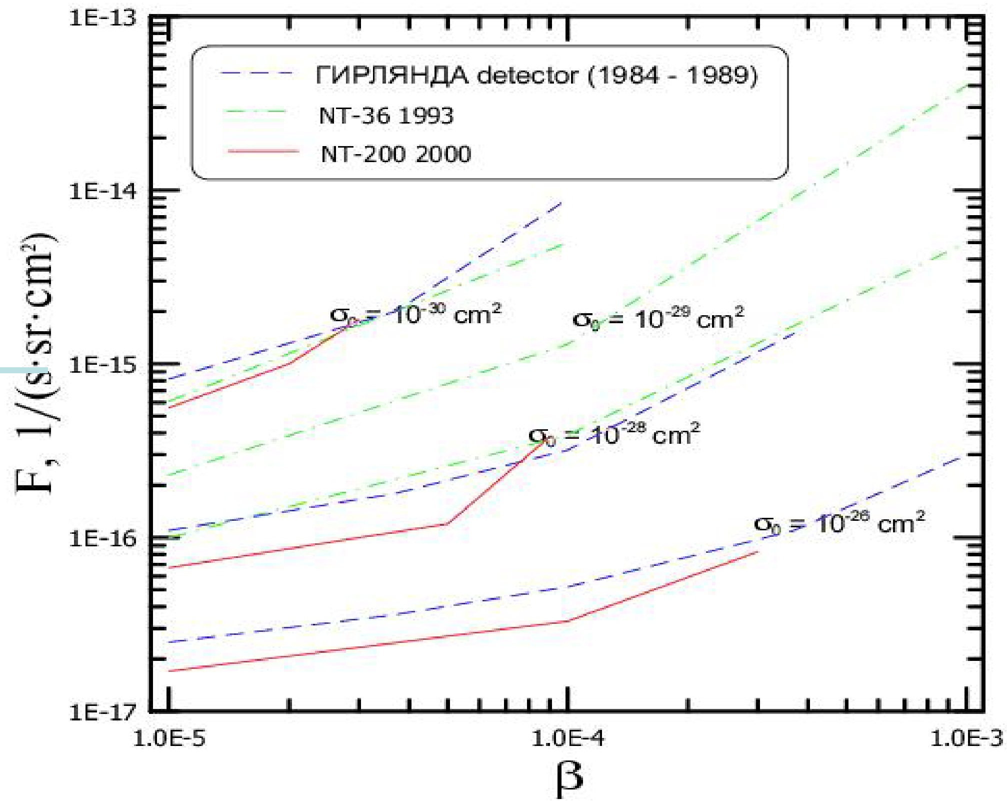
NT200 – capable to detect massive bright objects (GUT-monopoles, nuclearites, Q-balls …):

Monopole Trigger: $N_{local} > 4$ within $dt = 500 \mu sec$

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



Magnetic monopole visibility boundaries

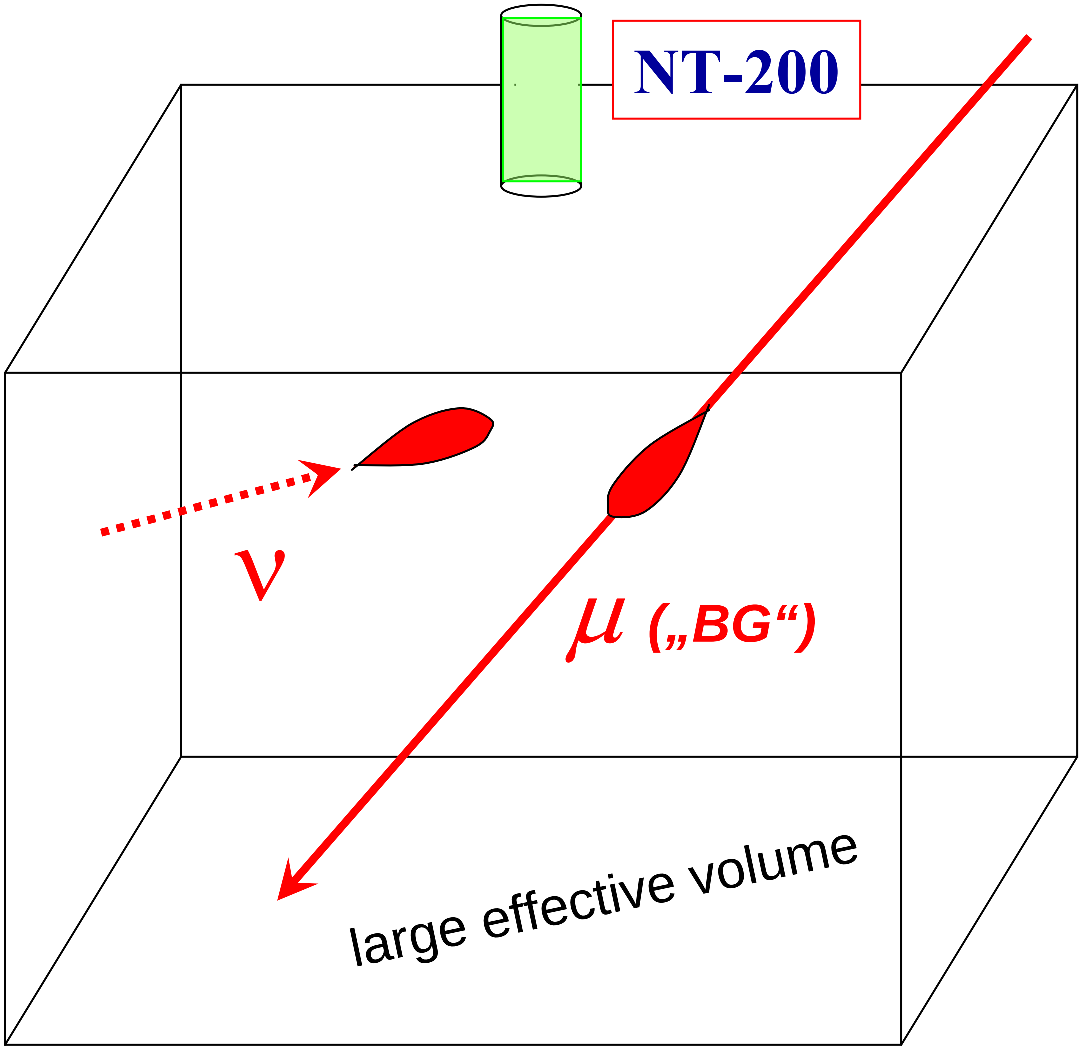


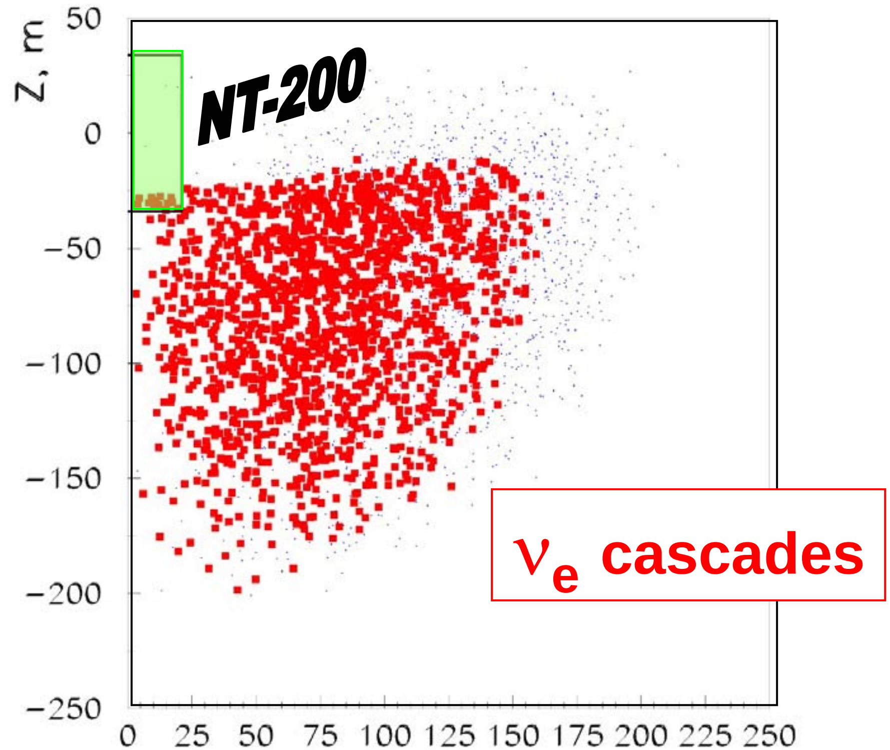
Magnetic monople Flux limit

Search for High Energy Cascades

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

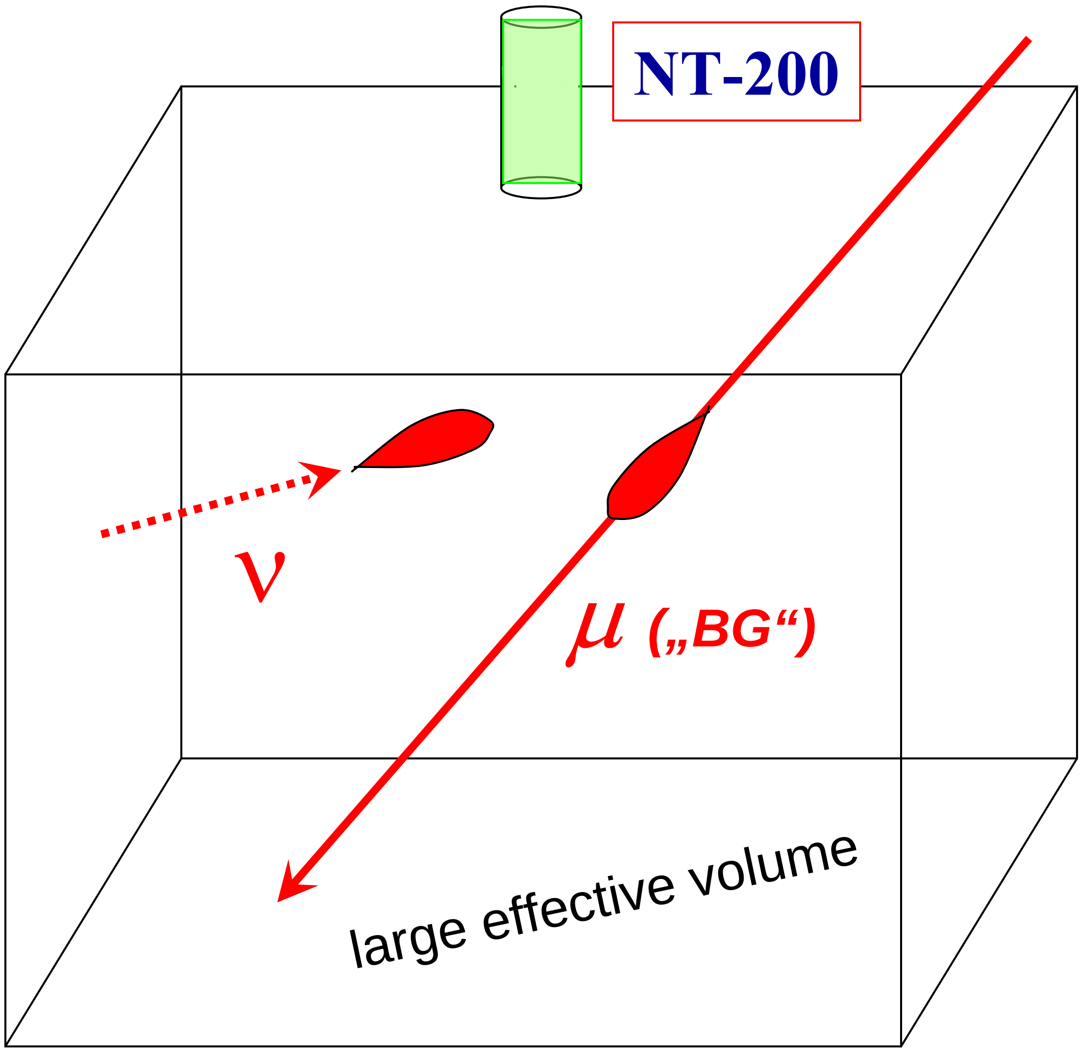
Look for upward moving light fronts.





Excellent scattering length Λ_{scat}=30-50m!

Search for High Energy Cascades



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

Physics topics:

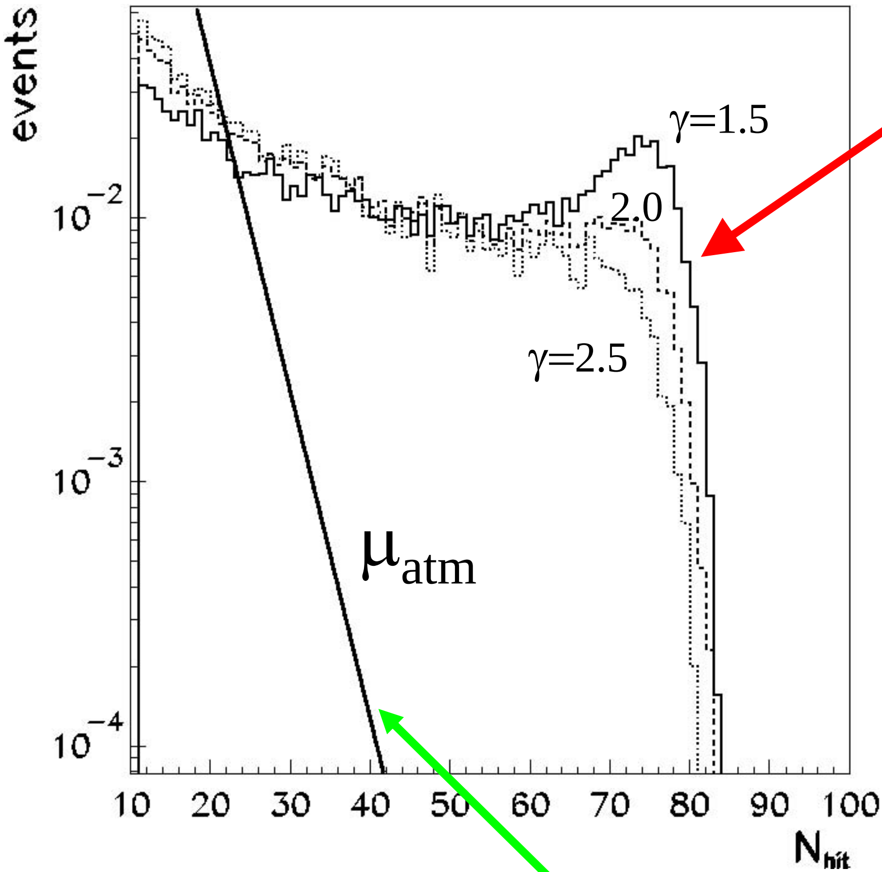
- HE cascades from ν_e ν_μ ν_τ - NC/CC
  - ❑ <u>Diffuse astroph.flux</u>
  - ❑ GRB correlated flux
- HE atmospheric muons (the „BG" to ν's)
  - ❑ Prompt μ
  - ❑ Exotic μ
- ...

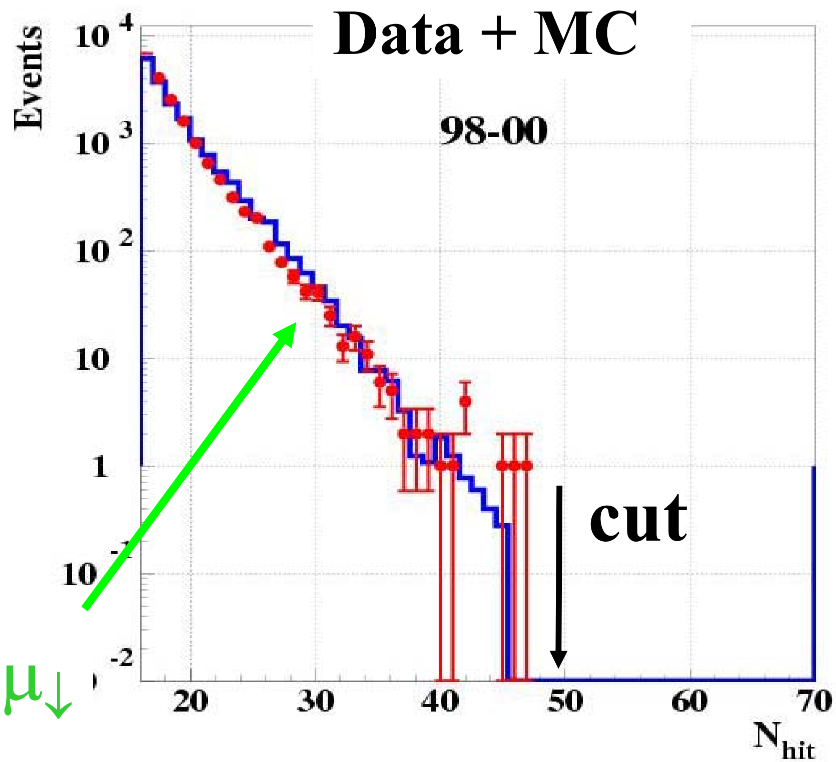
Selecting HE Cascades

Hard signal spectra would pile up in the "energy parameter"

N_{hit} = Number of Channels hit

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

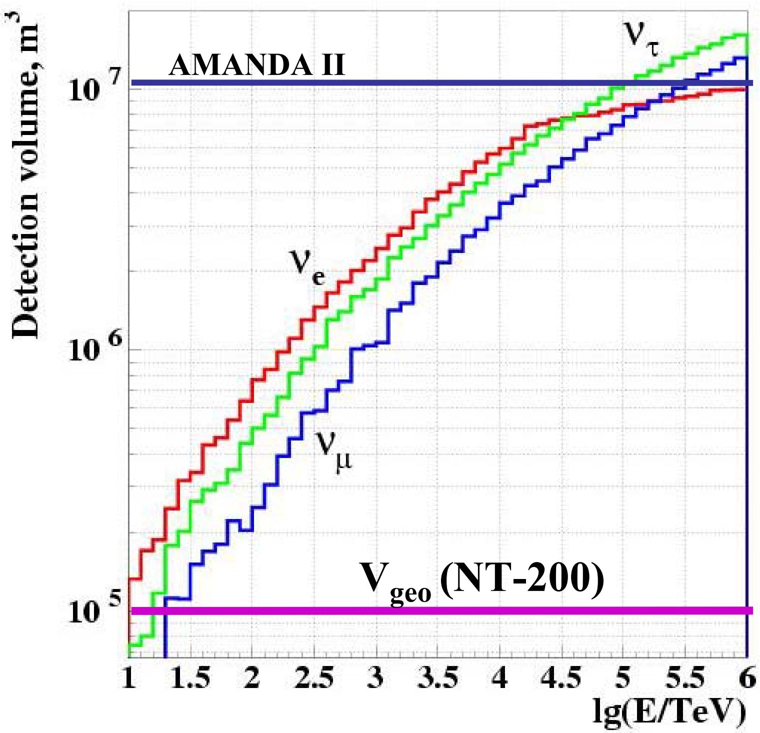




Showers along $\mu_\downarrow$

Limit on Diffuse Flux of Astrophysical ν_e, ν_τ, ν_μ

Effective Volume vs. Energy



V_{eff} > 1 Mton at 1 PeV

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

The 90% C.L. "all flavor" cascade limit (1038 days)
for a <u>γ=2 spectrum $\Phi_\nu \sim E^{-2}$ (20 TeV < E < 50 PeV)</u>,
and $\nu_e:\nu_\mu:\nu_\tau$ = 1 : 1 : 1 at Earth (1 : 2 : 0 at source) is

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

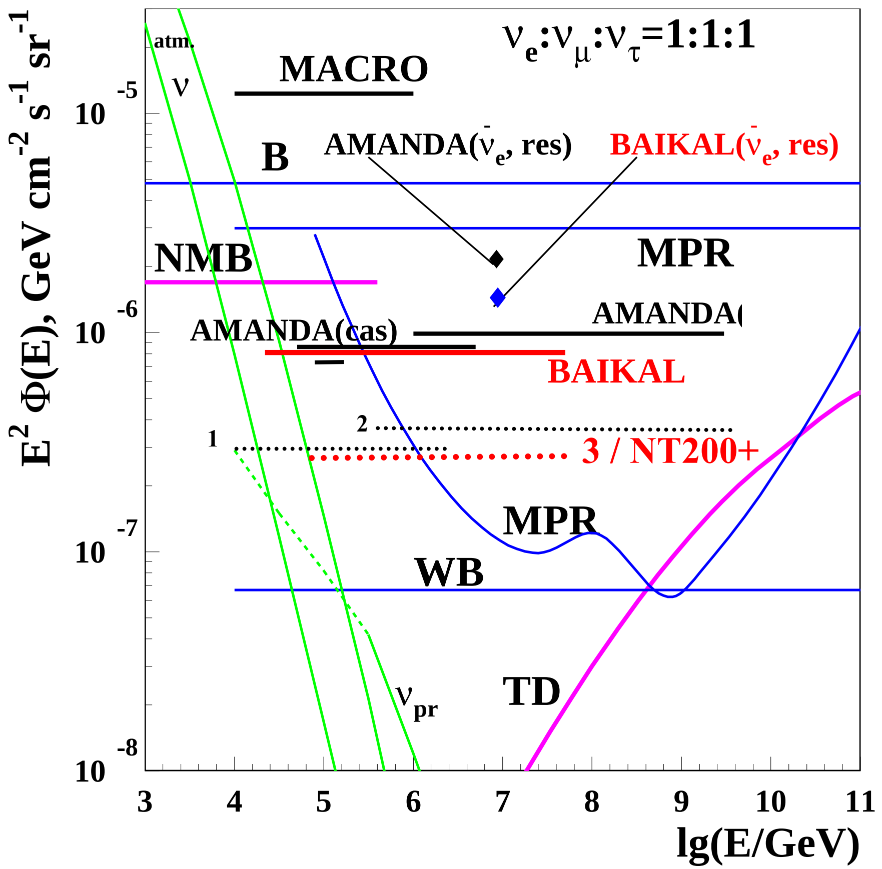
The 90% C.L. Limit for W-RESONANCE production
(E = 6.3 PeV, $\sigma = 5.3 \cdot 10^{-31}$ cm^2) is

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

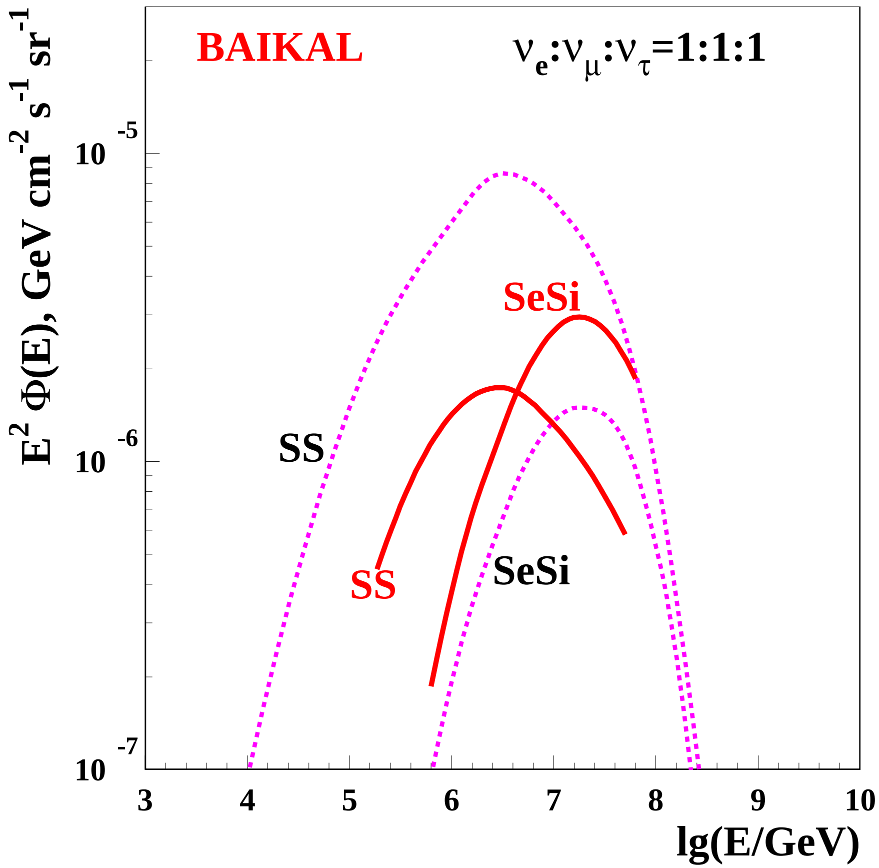
Subm. to APP; astro-ph/0508675

Diffuse Astrophysical Flux Limits + Models

Experimental limits + bounds / predictions



1,2: AMANDA sensitivties for 4 yr / 1 yr
3 : NT200+ sensitivity for 3 yr



Models already ruled out by the experiments:
SDSS - Stecker et al.92
SS - Stecker, Salamon96 (Quasar)
SP - Szabo, Protheroe92
(Models/Expts. are rescaled for 3 flavours)

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

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

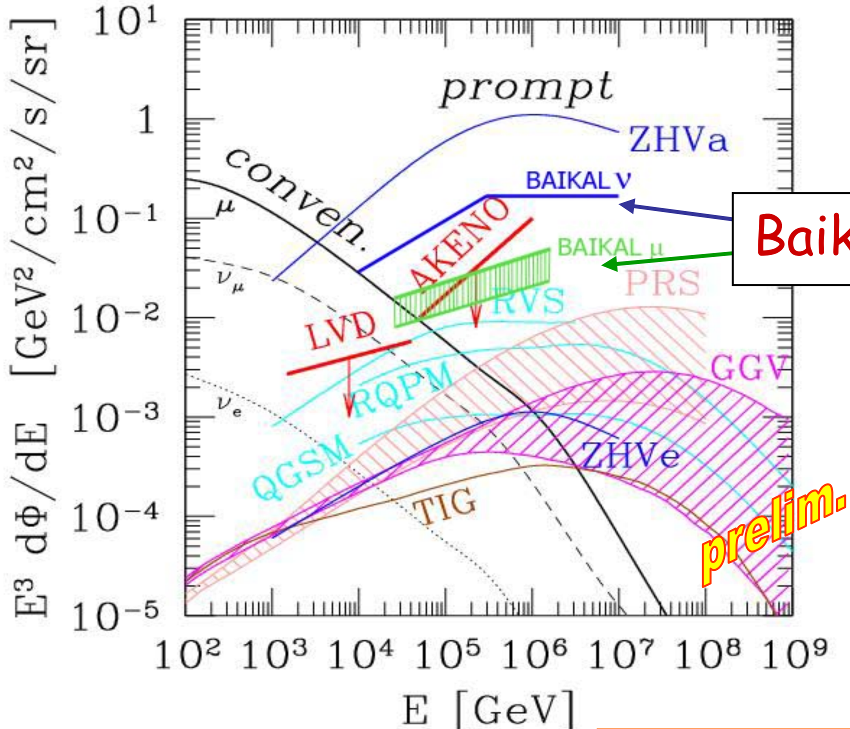
$\Phi_\mu \sim \Phi_\nu$ – isotropic for $E < 10^7$ GeV

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

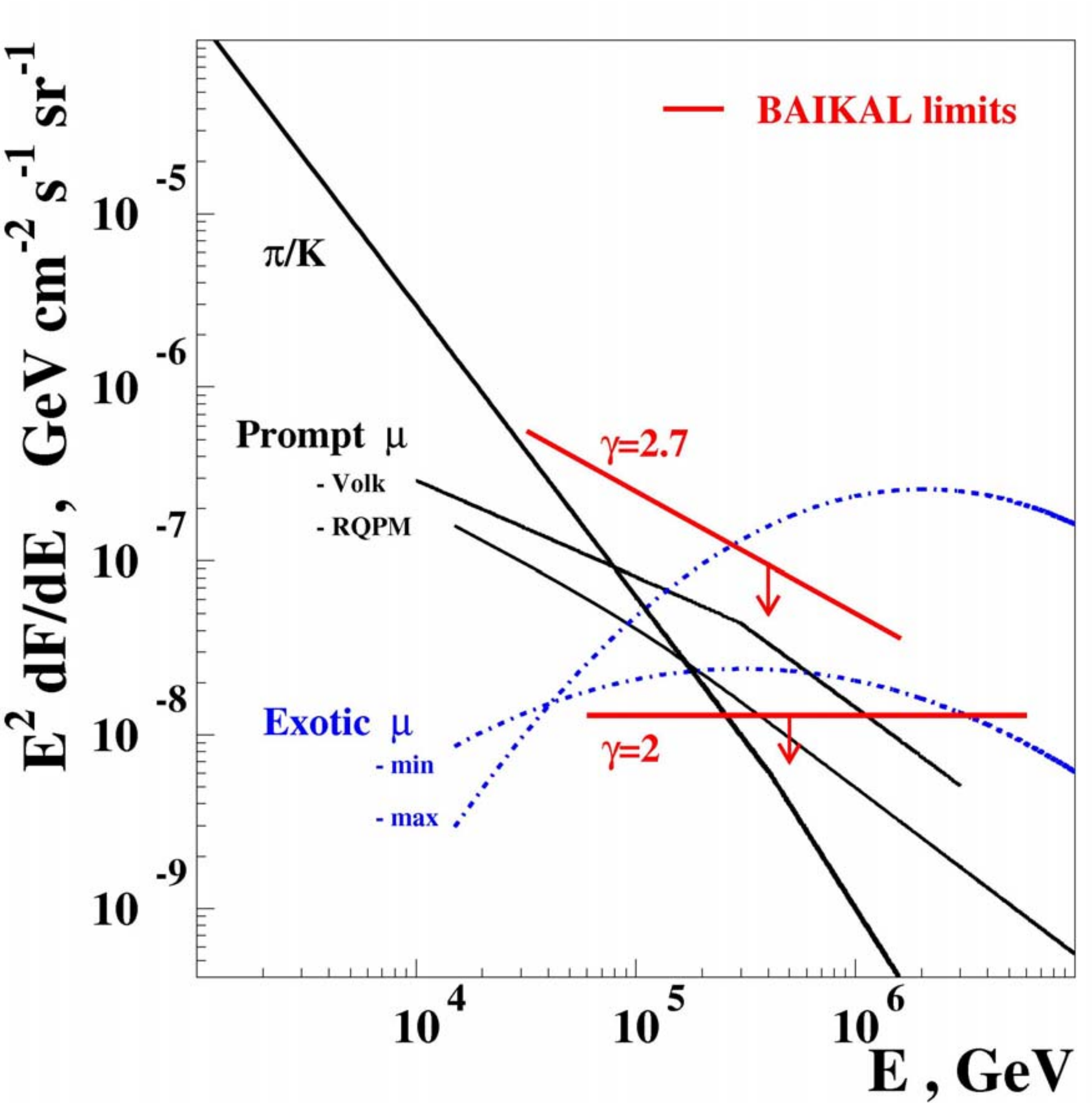
preliminary

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 : Exotic Muons

Flux prediction and flux limits



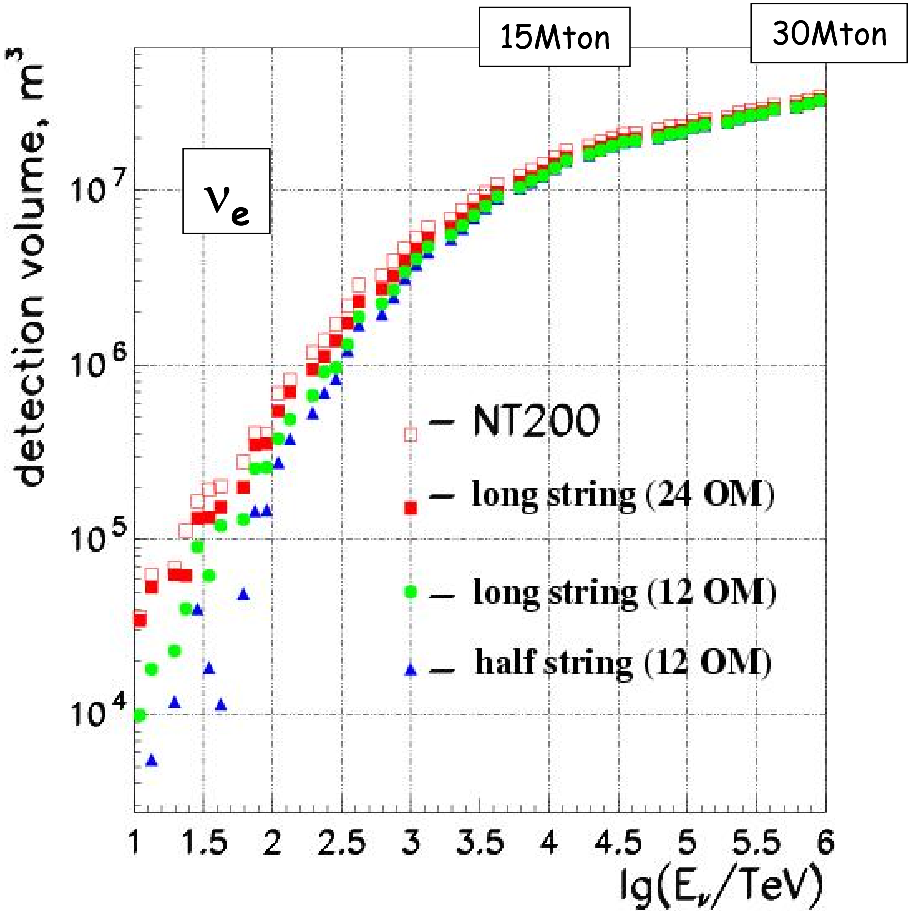
Use the *high energy cascade sample* to test various HE muon and/or neutrino signal spectra.

Testing the predicted "Exotic Muon Component" (Petrukhin 1999, 2002) , postulated to explain the CR-knee by the onset of "new physics" at E_{thr}~1 PeV, that pumps EAS energy to exotic muons.

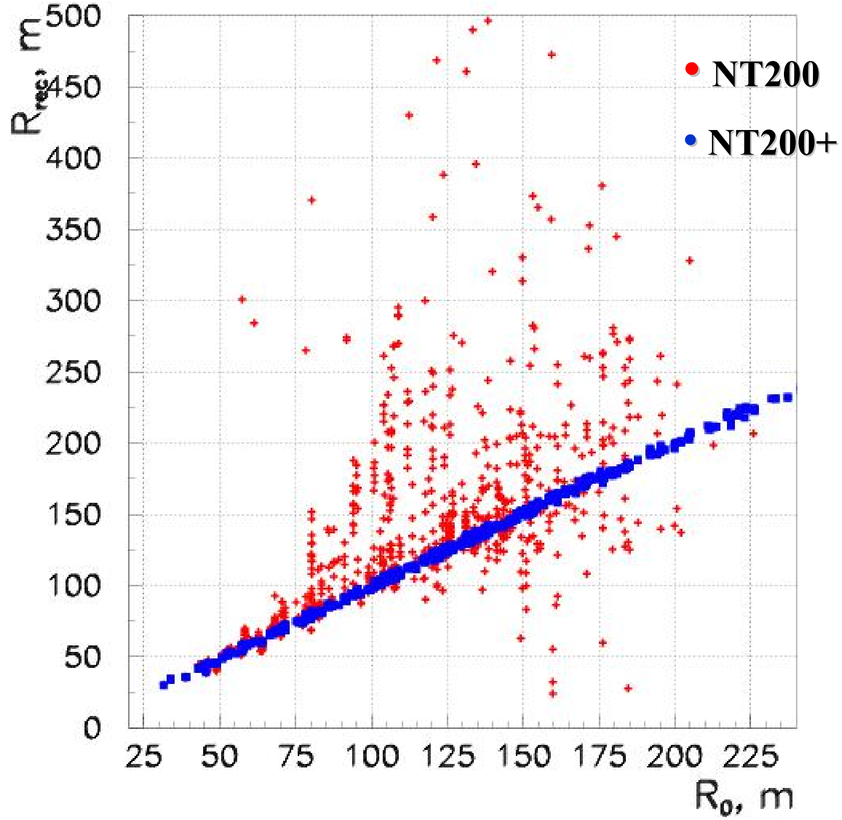
The limit for E^{-2} spectrum (γ=2) shows the model rejection power !

A detailed limit calculation for exotic μ "predictions" is in progress.

Expectation for NT200+



Much improved reconstruction of cascade coordinates + energy



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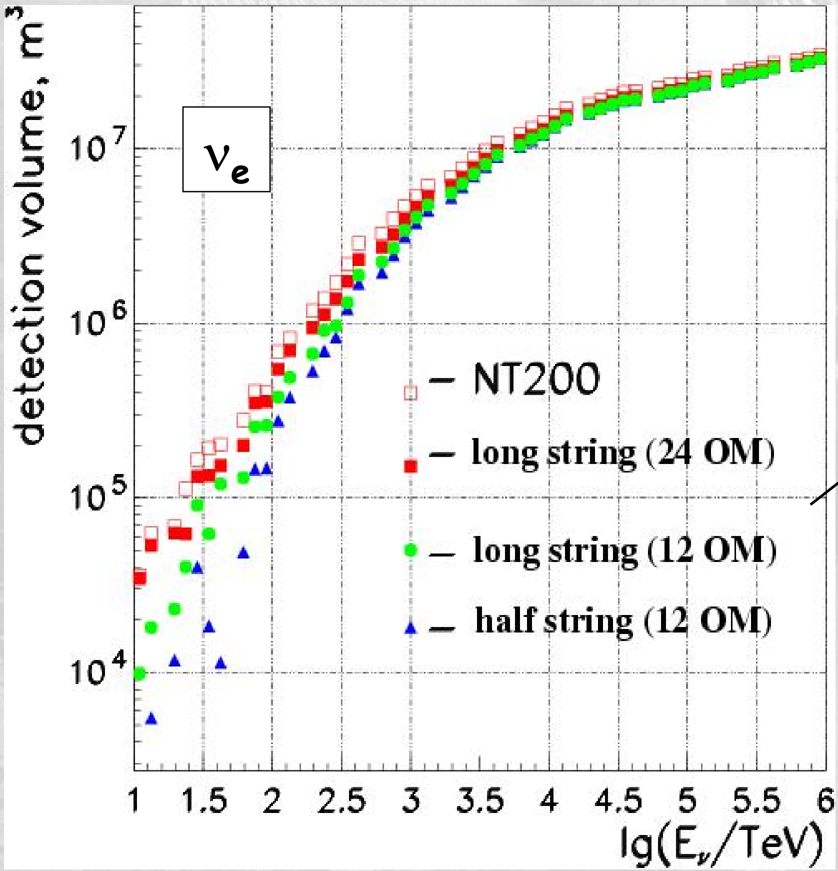
Predicted all-flavor-sensitivity for astrophysical ν's :
$E^2 \Phi_\nu < 2.7 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} **(3 yr)**
→ 3-4 fold improvement over NT200.

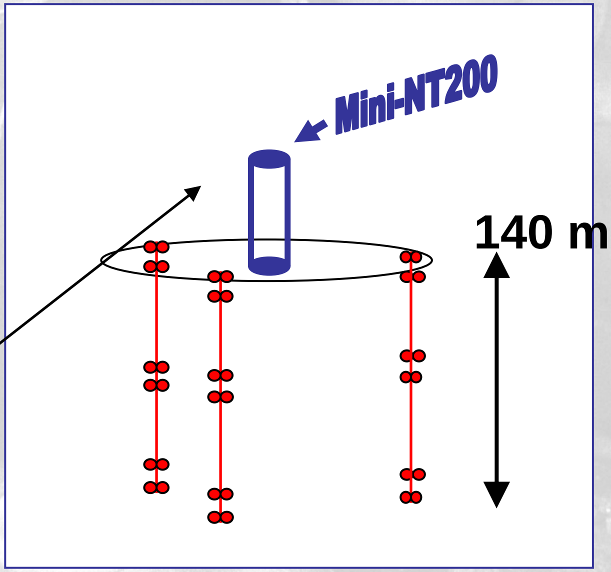
(vertex + energy reconstruction not yet used: will improve sensitivity !)

NT200+ - A step towards a Baikal-km3

NT200+ as a subunit of a km3 scale detector ?

Effective volume for simplified NT200's.





For High Energy Cascades:
A single small string replacing the NT200 central core reduces V_{eff} less than x3 for E>100TeV.
→ A short string instead NT200 as a subunit for a Gton scale detector = ok.

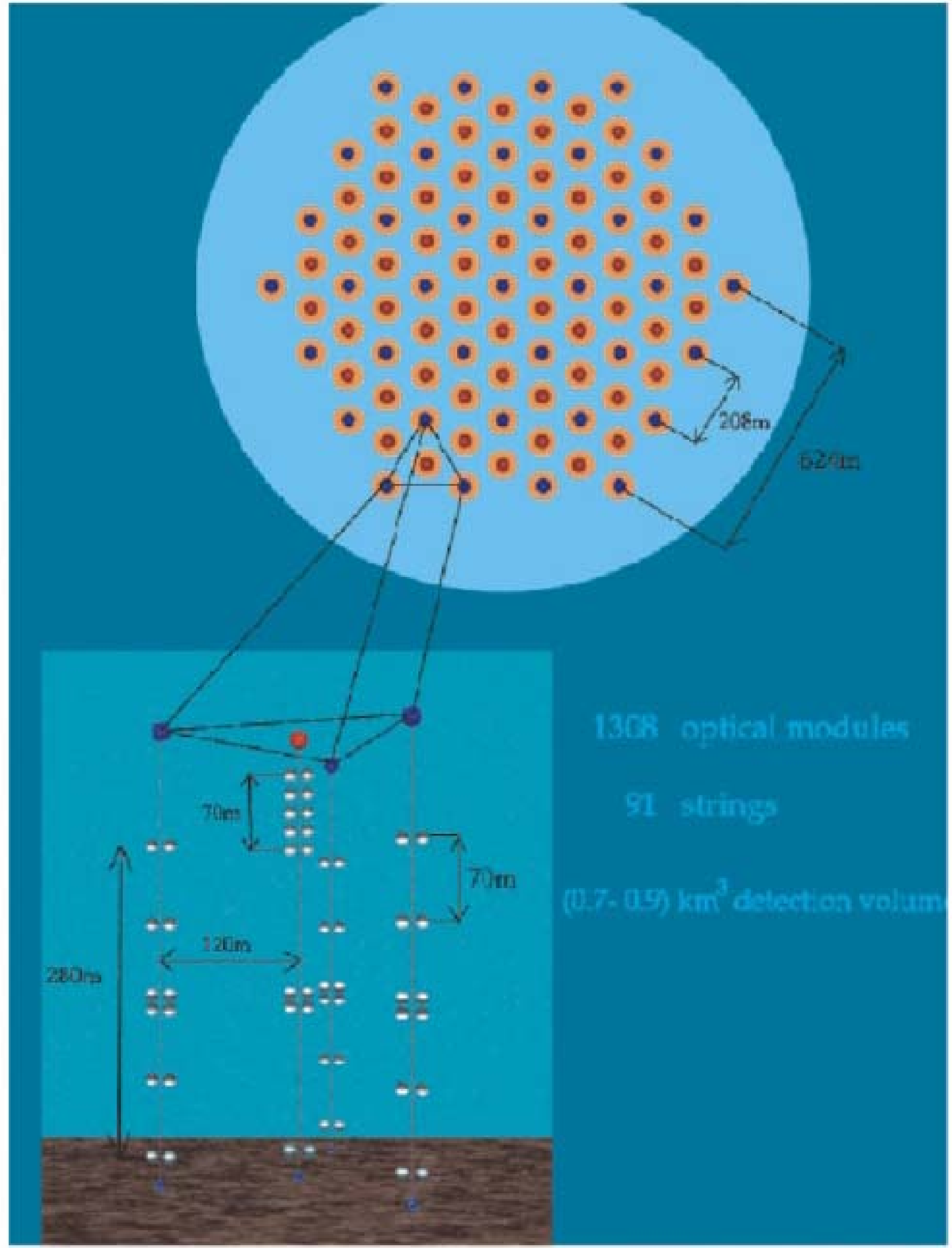
A future Gigaton (km3) Detector in Lake Baikal.

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



Summary

- The Baikal Telescope is successfully running since 10 years

NT200

- Strong in HE-diffuse search (cascades): "Mton-detector"
- Good GRB-sensitivity
- Relevant other results: Magnetic Monopoles, WIMPs, atm. μ

NT200+

- Upgrade to NT200+ … Tailored to diffuse cosmic nu's: >10Mton at 10PeV
  3-4fold improved HE cascade sensitivity with "prototype ultra-thin array"

Future: Ideas on a Gigaton Volume Detector (km3) in Baikal

Complementarity to Amanda/Ice3: S-Sky, GalCenter; Scattering;
Pattern_recognition,
Sensitivities to diffuse flux are quite similar .

A exciting time in HE-Neutrino Astrophysics.

BAIKAL NT200+ will for a while be the largest Northern hemisphere HE-nu Cherenkov Telescope.