The Baikal-GVD neutrino telescope

...

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BAIKAL-GVD

Outline

- Introduction:
  - Neutrinos, cosmic rays, neutrino astronomy.
- Neutrino telescopes:
  - History & present.
- The Baikal-GVD telescope:
  - Physics program, general description, deployment & maintenance.
  - Details: calibration, positioning, trigger.
- Reconstruction of events:
  - Tracks & cascades.
- Background processes:
  - Atmospheric muons.
- Detector simulation:
  - Description of the existing framework and future developments.
- Selected results:
  - High-energy cascades & tracks,
  - Multi-messenger studies.
- Kraków contribution,
- Summary & future plans.

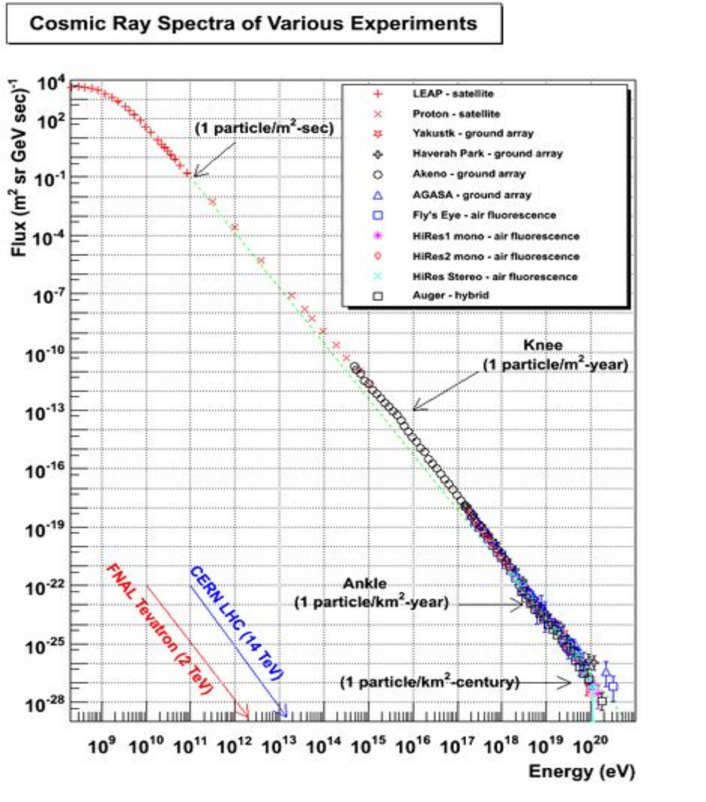
Introduction

Neutrinos

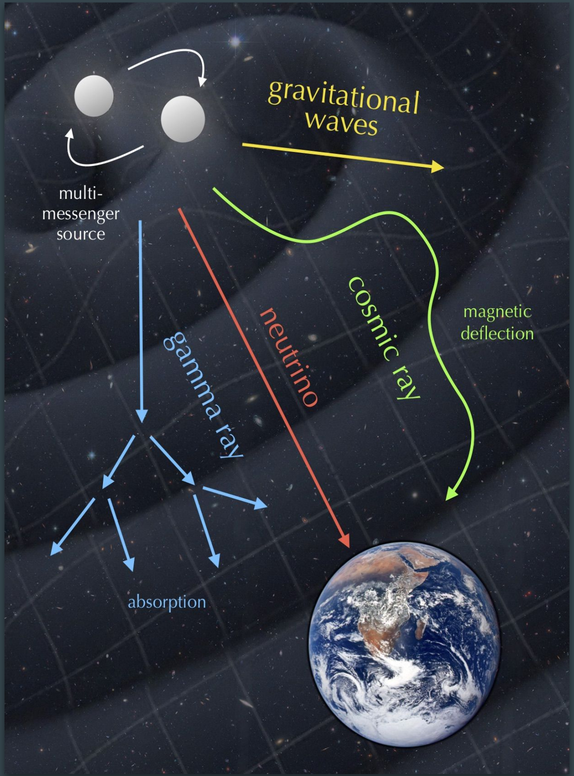
- Proposed by Pauli in 1930 to rescue energy conservation,
- Mysterious elements of the Standard Model,
- Electrically neutral - only weak interaction - very hard to detect.
- Should be massless, but...
  - They oscillate: $P(\nu_i \rightarrow \nu_j)$ is related to $(\Delta m)^2$ between all three flavours.
  - Non-zero $(\Delta m)^2$ -> neutrinos are massive. Neither the mass values nor their hierarchy are not known,
  - $m_\nu < 1.1$ eV.
- Majorana or Dirac particle?
- Why the mass is so small?

Cosmic rays

- Discovered by Hess in 1912,
- Energy range: 14 orders of magnitude, flux range: 32 orders of magnitude,
- The only imaginable source of particles with energies of EeV (10^{18} eV) and above:
  - A collider with such energies would be of the size of Mercury orbit...
- GZK limit: particles with $E > 5 \cdot 10^{19}$ eV should come from inside of our galaxy, yet no sources known so far...



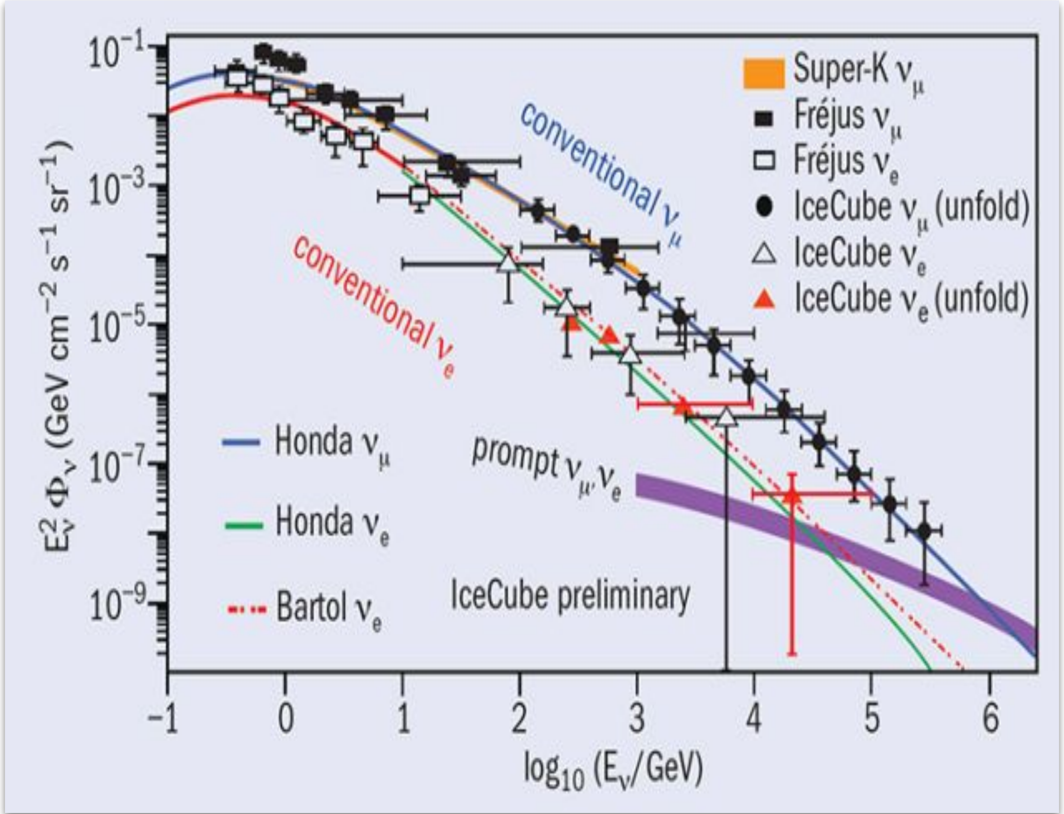
Neutrino astronomy



- While cosmic rays are mostly composed of nuclei, astrophysical neutrinos are also present.
- The universe is transparent to them, no deflection or bending of trajectories happens,
- They can escape very dense environments and provide undistorted picture of their sources.
- Therefore we may speak of *neutrino astronomy* - neutrinos point directly towards their sources!
- Yet the sources are still barely known in detail...

Neutrino flux

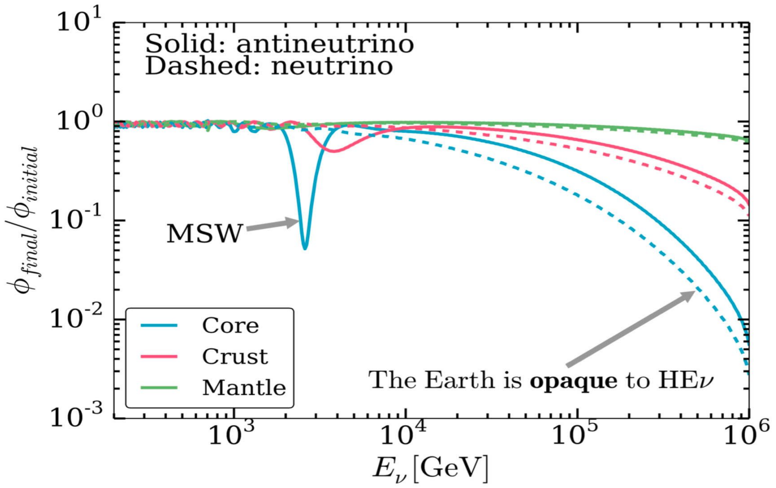
- Born in $p+X \rightarrow \pi^{+}+\ldots$
  ↳$\mu^{+}+\nu_{\mu}$
  ↳$e^{+}+\nu_{e}+\nu_{\mu}$
- Generic spectrum: $\sim E^{-2}$,
- Flavour content: 1:2:0 at the source, 1:1:1 at Earth.
- Direction:
  - From localized sources,
  - Diffuse flux (isotropic).



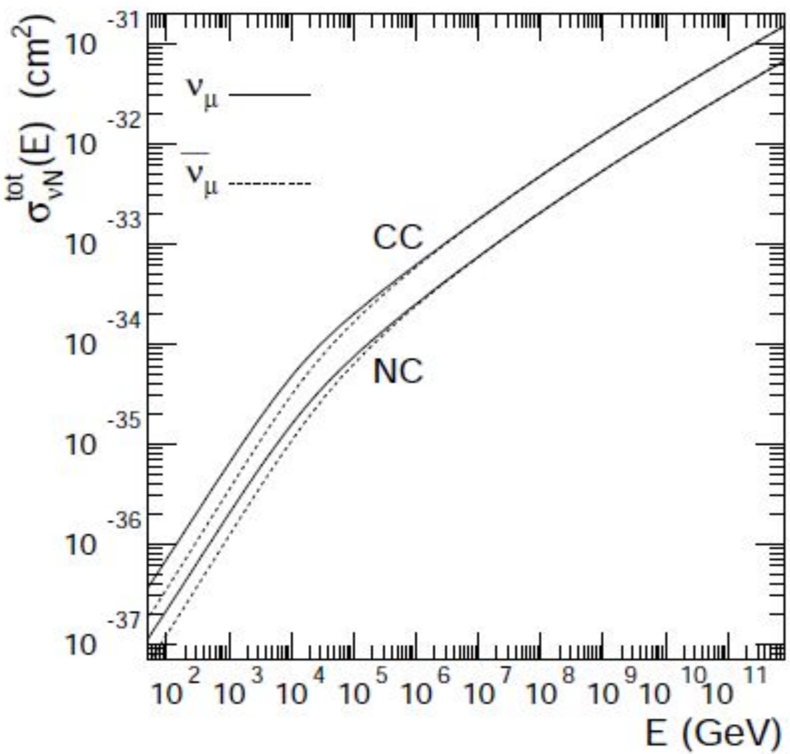
Neutrino cross-sections

Neutrino-nucleon cross-section increases with energy.

The Earth is opaque to the neutrinos above 100 PeV



Delgado, Carlos Alberto Arguelles. "New physics with atmospheric neutrinos." (2015).



Naumov, V.A. et al., Neutrino propagation through dense matter, Astroparticle Physics 10(2-3):239-252

Neutrino telescopes: history

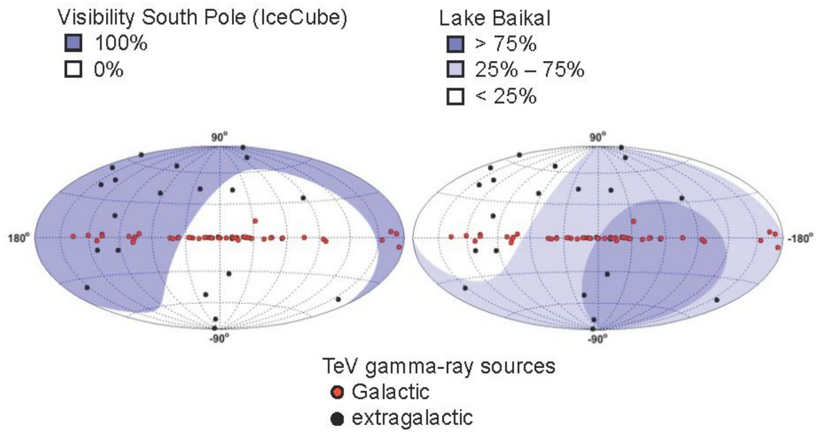
- 1960's - first ideas of using large reservoirs of water or ice as natural detectors (Markov, Greisen, Reines).
- 1970's - conceptual work on DUMAND[1],
- 1987 - deployment of DUMAND at Hawaii,
  - Only one string operational (out of 9) for only 10 hours. However - the work helped understanding the challenges facing neutrino detection in water.
- 1984 - first string of detectors deployed in the Baikal lake (to become NT-200 in 1998),
- 1997 - AMANDA[2] installed at South Pole.
- 2006 - beginning of the ANTARES[3], deployment in the Mediterranean Sea,
- 2004 - 2010 - construction of the IceCube detector in Antarctic ice.
- 2011: construction of Baikal - Gigaton Volume Detector (GVD) starts,
- 2014 - data taking in BGVD starts,
- 2015 - construction of KM3NeT[4] starts.

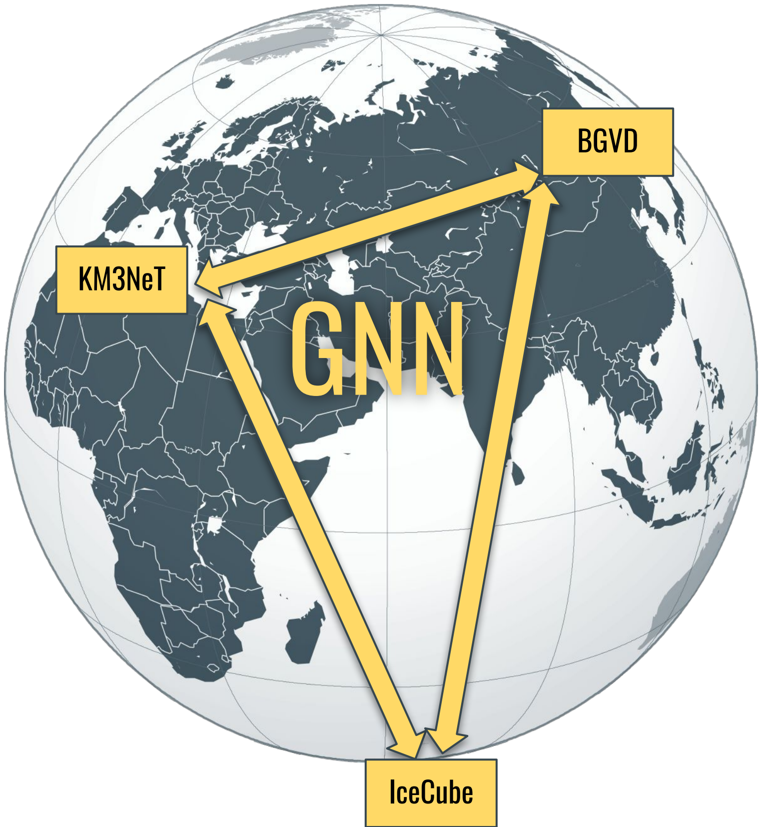
[1]DUMAND: Deep Underwater Muon And Neutrino Detector,
[2]AMANDA: Antarctic Muon And Neutrino Detector Array,
[3]ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch,
[4]KM3Net - Cubic-KiloMeter Neutrino Telescope.

Neutrino telescopes: Global Neutrino Network

The leading telescope is IceCube in South Pole ($1 km^3$ detector, fully operational and mature),

The BGVD is the largest detector in the Northern Hemisphere providing, together with KM3NeT, data complementary to IceCube.





BGVD is looking south

The Earth is a natural shield for overwhelming background of muons. Main characteristic of signal event: upward-going particle.

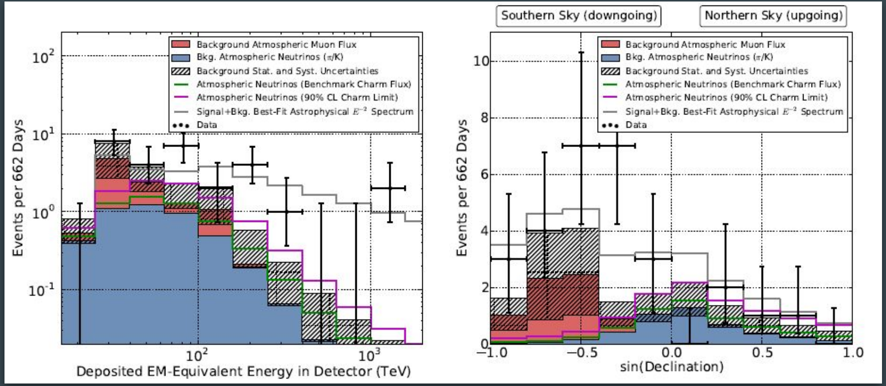
IceCube highlights

High-energy astrophysical neutrinos do exist!

In 2013 a pair of PeV was observed (Phys.Rev.Lett. 111 (2013) 021103) - nicknamed "Bert and Ernie", joined by "Big Bird" soon after (Phys.Rev.Lett. 113 (2014) 10110).

Further 28 events (30 - 1200 TeV) have their atmospheric origin rejected at 4σ level (Science 342 (2013) 1242856).

In 2018, a high-energy neutrino event was found to be in coincidence with a gamma-ray flare from the TXS 0506+056 blazar - first time a source has been identified (Science 361 (2018) 6398, 147-151).



Baikal-GVD telescope

The collaboration

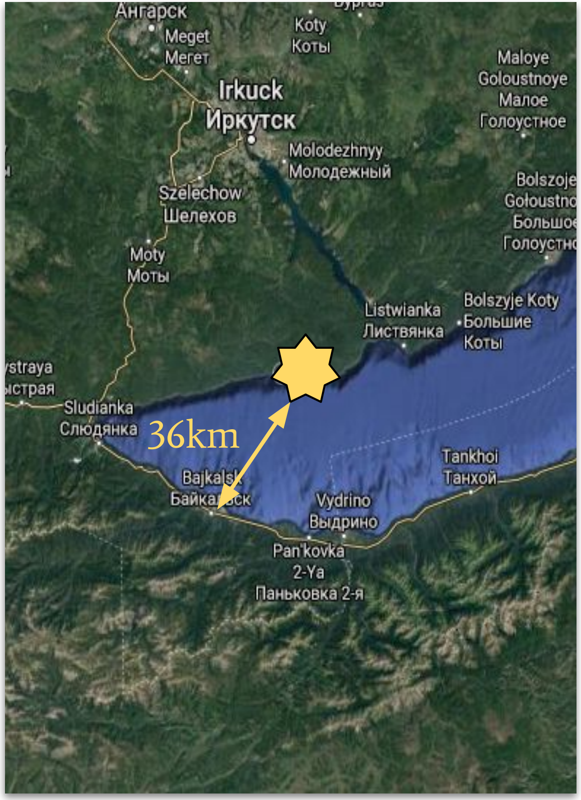
10 institutions from 5 countries,
~60 scientists and engineers.

- Institute of Nuclear Research (Moscow),
- Joint Institute of Nuclear Research (Dubna),
- Moscow State University,
- Irkutsk State University,
- Nizhni Novgorod State Technical University,
- St.Petersburg State Marine Technical University
- EvoLogics GmbH (Berlin),
- Comenius University (Bratislava),
- Czech Technical University (Prague),
- Institute of Nuclear Physics PAS (Kraków).

Physics program

- Search for sources of high-energy phenomena:
  - Extragalactic (10 TeV - 100 PeV): Active Galactic Nuclei (AGN), Gamma-ray bursts (GRB), starburst galaxies, etc.
  - Galactic (up to ~1 PeV): Supernovae, pulsars, the black hole Sgr A*, binary systems, etc...
- Diffuse neutrino flux:
  - Unidentified sources, check energy spectrum, anisotropies, flavor composition...
- Multi-messenger astronomy:
  - Simultaneous observations of the same part of the sky with cosmic rays, neutrinos, photons, gravitational waves...
  - Examples: search for neutrino counterparts of the GW170817A or TXS-0506-056 gamma-ray blazar.
- Search for dark-matter particles, magnetic monopoles, etc...

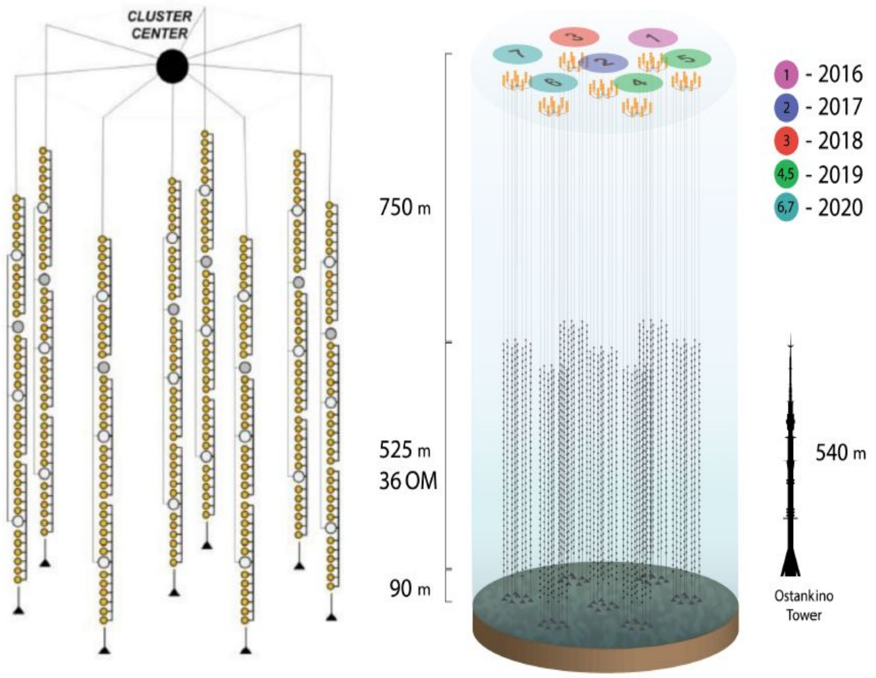
Overview - site location



- The Baikal lake is more than 1 km deep,
- Its water has stable optical properties (absorption, scattering),
- Few bioluminescent life forms,
- Predictable currents,
- Flat lakebed,
- The shore station is located close to railway station, has access to power supply.
- Detectors - 3 km from the shore station.

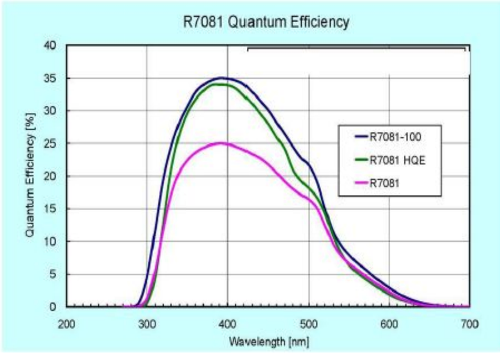
Overview - detector structure

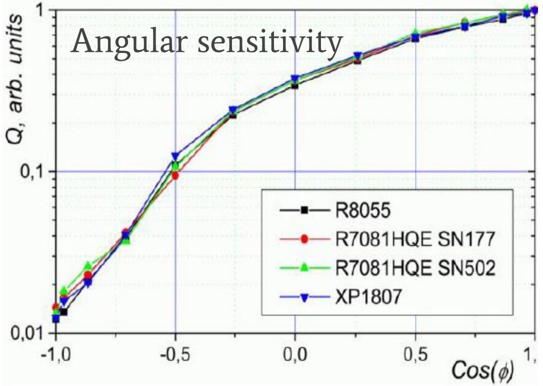
- The telescope is organised in clusters.
- The distance between clusters is 300m.
- Each cluster contains 8 strings,
- Strings are 525m long, separated by 60m,
- Each string is instrumented with 36 Optical Modules (OMs) every 15m. They belong to three sections.
- Currently, there are 7 clusters installed & operational,
- The total active volume of the detector is ~0.4 km^3.

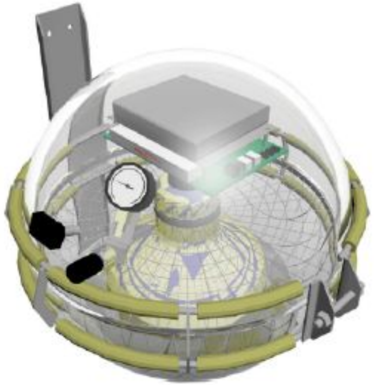


Optical Module & light detection

- Optical Module is the basic detection unit of the BGVD telescope.
- Its heart is a photomultiplier (PMT), Hamamatsu R7081-100 for Cherenkov light detection, looking downwards.
- It contains dedicated electronics and calibration LEDs.
- It is enclosed in 43-cm glass sphere.







Cherenkov radiation

Particle detection in BGVD bases on Cherenkov radiation detection.

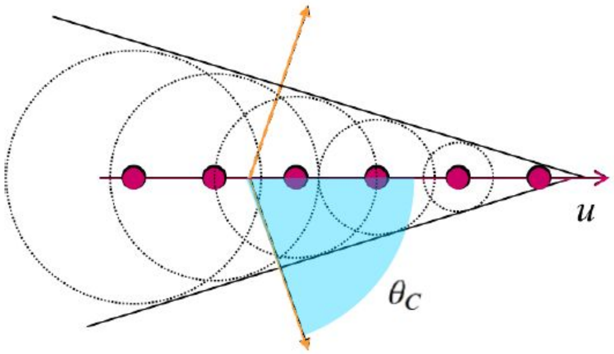
Cherenkov light is emitted when particle velocity exceeds the speed of light in the given medium (~0.75·c in water).

It is emitted by a charged particle: either prompt (like atm. muons) or resulting from neutrino interaction with water or bedrock.

Intensity: $\frac{dN_c}{d\lambda} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2}\right)\frac{1}{\lambda^2},$

$N_c = 230\ \gamma/cm$ (350 – 600 nm, water)

Cherenkov angle: $\cos\theta_c = 1/(\beta n),\ \theta_c = 42^{\circ}\ water$



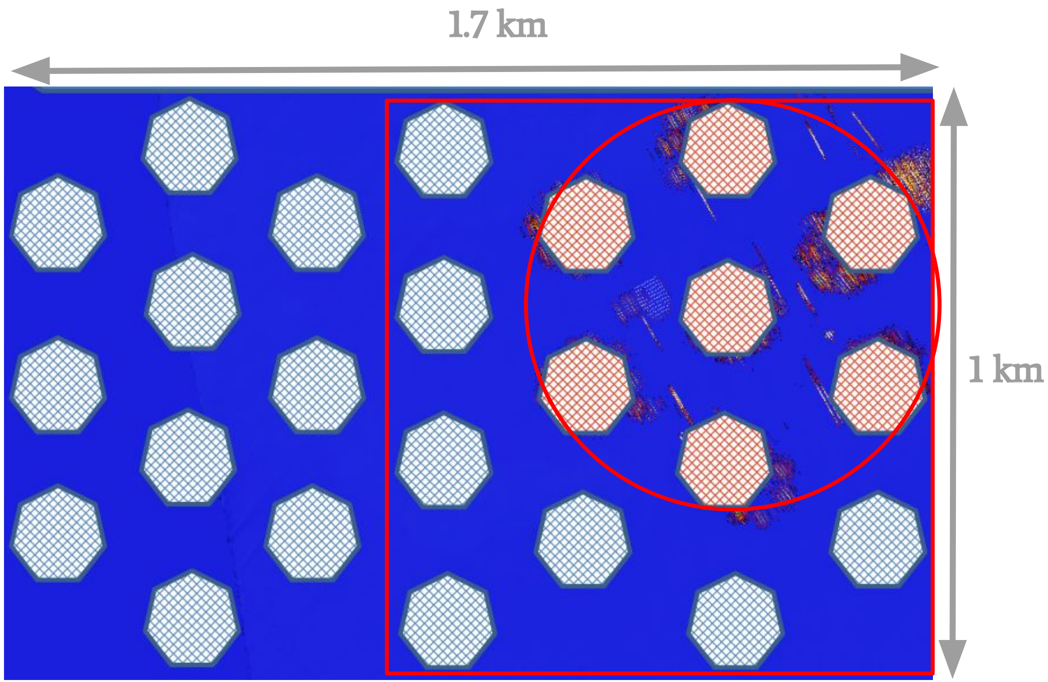
Towards 1 km^3

As of 2020, 7 clusters are installed and operational.

GVD phase-1 will complete in 4 years,

Construction will continue in phase-2.

Expected cluster-deployment rate is 2 clusters/year, however unexpected maintenance issues may occur...



Deployment & maintenance

- The Baikal lake freezes seasonally, in mid-February the thickness of ice cover is about 50-80 cm, allowing for safe use of heavy vehicles.
- This allows for cheap and easy maintenance of existing clusters and deployment of new ones.
- Winter expedition: mid-February until late March. Day temperatures: -3 to +10° C

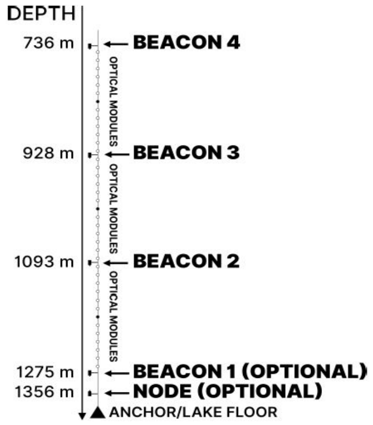
Detector site

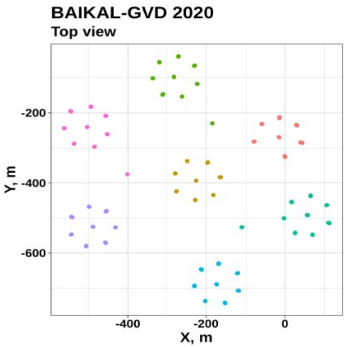
Winter expedition

Detector calibration

Optical Module positioning

- The OMs can drift even beyond 50 m from their median position.
- Spatial positioning of OMs is achieved with Acoustic Positioning System (APS),
- It is built of EvoLogics S2C R42/65 acoustic modems mounted on strings (in 3-4 places).
- The spatial orientation of OMs is determined from accelerometer and compass sensors at each OM.
- Vertical beacon drift is small (below 0.5 m), lateral drift: 5-50 m,
- Precision: 12 cm (less than PMT diameter, similar to that of other telescopes).





Time calibration

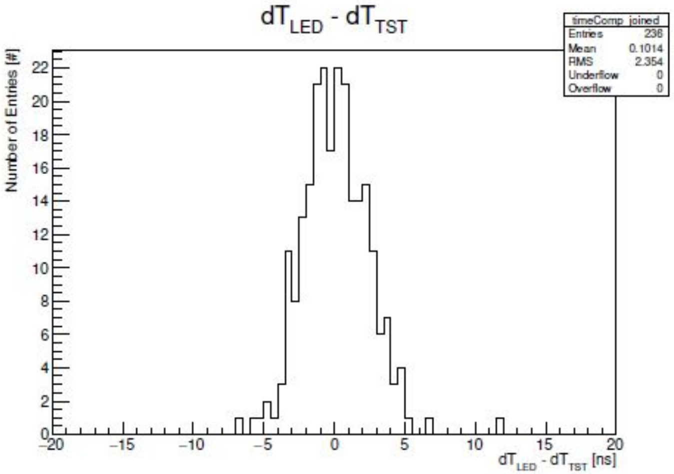
- Time calibration is essential for the rejection of muon background (track direction).
- Each OM has its own time delays:
  - Transit time of the PMT,
  - Different cable lengths,
  - Electronics processing times.
- Several methods exist:
  - Test pulse,
  - Built-in LEDs,
  - LED matrices,
  - Underwater laser.

- Test pulse: a pulse in the OM electronics sent directly to the amplifier (without using PMT) - can serve to measure PMT transit times (TT).
- Built-in LEDs: each OM is equipped with 2 LEDs that can serve for intra- and inter-section calibration.
- LED matrices: several of them are present in each cluster, enclosed in separate glass spheres, can serve for inter-section calibration (up to 100m illumination).
- Underwater laser: can serve for inter-cluster calibration, currently under development and testing.

Time calibration

Intra-section calibration:

- Two methods available, both based on built-in LEDs,
    - dT_{TST}: measure time delay as a sum of cable-delay (measured on-shore) and PMT TT - difference in time between test pulse and led-flash signal arrival.
    - dT_{LED}: difference between the measured and expected light-propagation time with LED flash from neighbouring OM.
- These methods are independent: can estimate precision.



L. Fajt, PoS(ICRC2017)1036

The mean of the residual distribution is 0.1 ns and the RMS is 2.35 ns - this represents the precision of intra-section calibration.

Time calibration

Inter-section calibration:

- Measures the delays between sections mainly due to cable lengths.
- Two methods, based on the trigger system design (see later) are used:
  - Artificial test pulses create trigger request,
  - Triggers from real particles are used.
- Their comparison shows the precision of 2.7 ns.
- This is verified using LED matrices in dedicated runs, with method similar to the dT_{LED}.

Inter-cluster calibration:

- The time-synchronization between clusters is performed with two independent systems, SSBT and White Rabbit (WR).
- They are constructed as networks of nodes with switchboards/hosts connected to an external source of timestamps (GPS time server).
- Verified with laser flashes, precision of 5 ns is achieved.

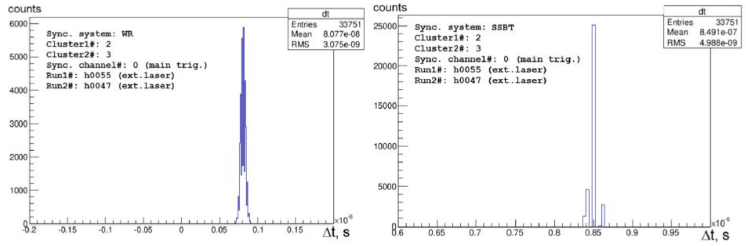


Fig. 3.3 Time differences distribution between laser flash events on Cluster 2 and Cluster 3 measured by WR (left) and SSBT (right)

L. Fajt, K. V. Golukov, PoS(ICRC2019)877

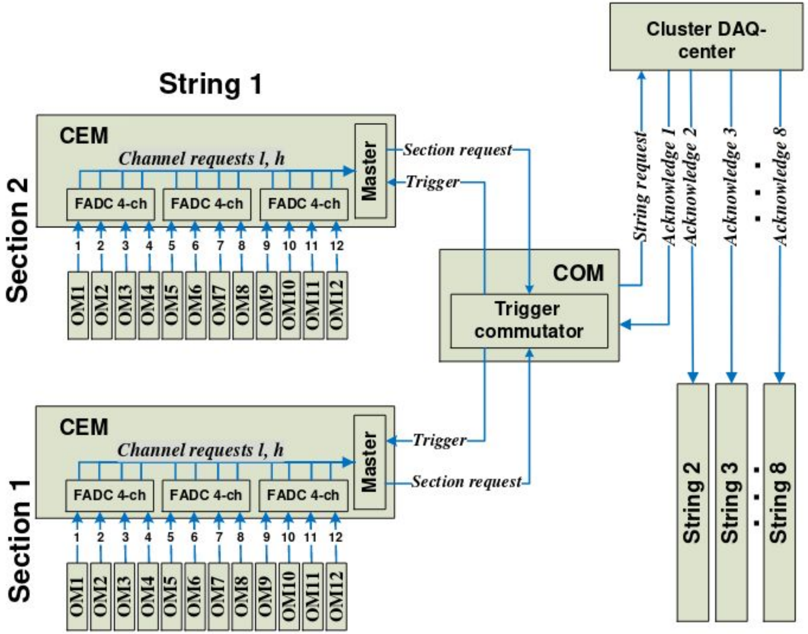
Trigger & data acquisition

The trigger is based on signal from sections Central Modules (CEM) that produce trigger-request signal if a coincidence of pulses from neighbouring OMs (5 p.e. and 2 p.e.) is met.

Request signal is sent to Cluster Center (CC) which generates acknowledge signal to all CMs.

The available time-intervals for signal waveform acquisition in the OMs is 5μs.

This information is then transferred to shore station and stored as raw data. Raw data are transferred to Baikalsk over 5Mbit/s link and then to JINR over high-bandwidth internet. The cluster data rate is 40GB/day.



Baikal-GVD Scientific-Technical Report,
https://baikalgvd.jinr.ru/wp-content/uploads/2019/06/BAIKAL-GVD_En.pdf

Measurement of water properties

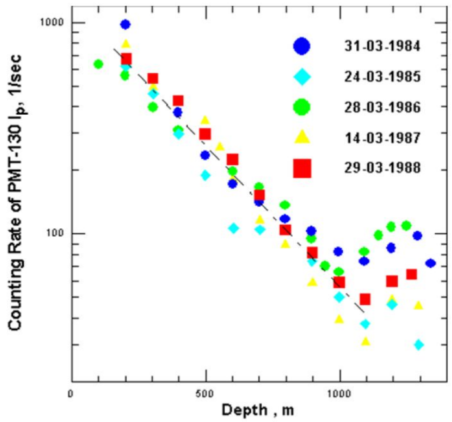
The optical properties of Baikal waters were measured in the past (80's - 90's) using laser light and the NT-200 detector.

They will be verified with the improved laser calibration system exactly at the telescope's location.

- The absorption length was measured to be 20 - 25 m at 488 nm and 8 - 12 m at 400 nm.
- The scattering length is estimated to be 40 - 70 m with <cosθ> = 0.9 ±0.05.
  This is forward scattering at small angles, contrary to that of ice where <cosθ> is far from unity.

The natural light background sources are:

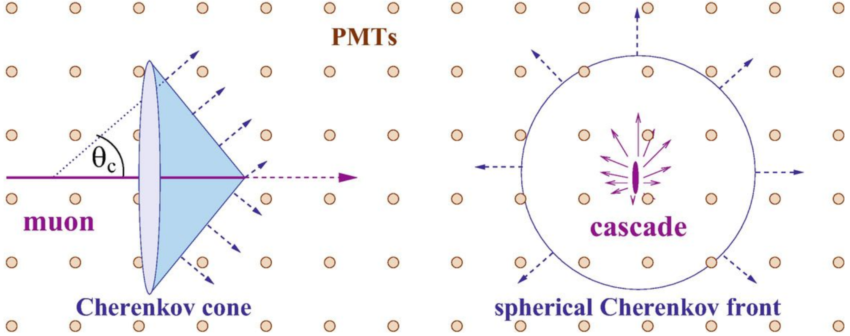
- Sunlight: almost negligible, at 800-m depth it is 1 photon/cm^2 ·s.
- Water luminescence: few hundred photons per cm^2 ·s at 1000-m depth.



EPJ Web of Conferences **2019**, *207*, 09001

Reconstruction & simulations

Two detection modes



Spiering C. (2020) Neutrino Detectors Under Water and Ice. In: Fabjan C., Schopper H. (eds) Particle Physics Reference Library. Springer, Cham. https://doi.org/10.1007/978-3-030-35318-6_17

$$\nu_l + N \xrightarrow{CC} \begin{cases} e^- + X \rightarrow cascades \\ \tau^- + X \rightarrow cascades \\ \mu^- + X \rightarrow track + cascade \end{cases}$$

$$\nu_l + N \xrightarrow{NC} \nu_l + cascade$$

Two ways of detecting particles in neutrino telescopes:

- Tracks (muon neutrinos),
- Cascades (electron, muon and tau neutrinos).

Muon tracks provide very good angular precision and enable for the study of point sources.

Cascades provide good energy-measurement precision, however their directional accuracy is much worse than of muon tracks.

Reconstruction of muon tracks

Noise hits are removed with causality criterion:

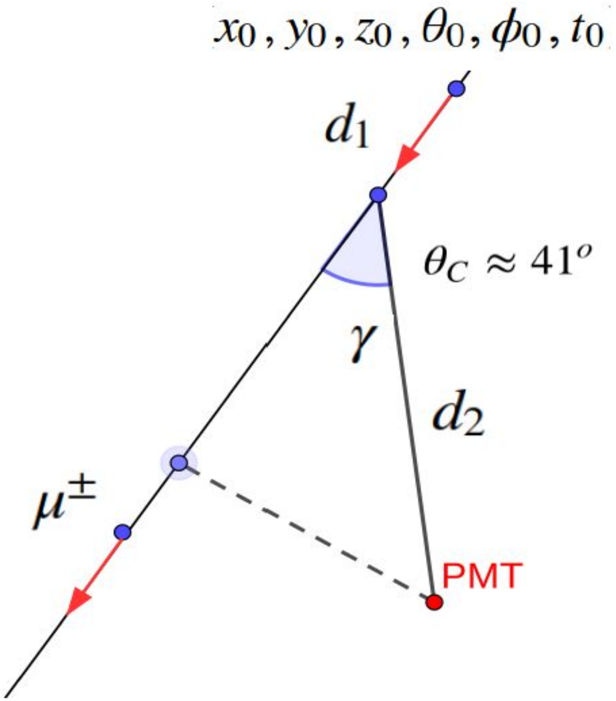
$|t_i - t_j| \leq \frac{\Delta R_{ij}}{c_w} + t_s$ - time difference between pulses should be equal to their distance divided by speed of light in water ± t_s= 10 ns tolerance.

The remaining set of hits is fit by minimizing the function: t_{meas} - t_{exp} where:

$$t_{exp} = t_0 + \frac{d_1}{c} + \frac{d_2}{\frac{c}{n}}$$

and the distance parameters d_i are functions of track parameters.

Track-mismatch angle: 1.35° (determined from MC)

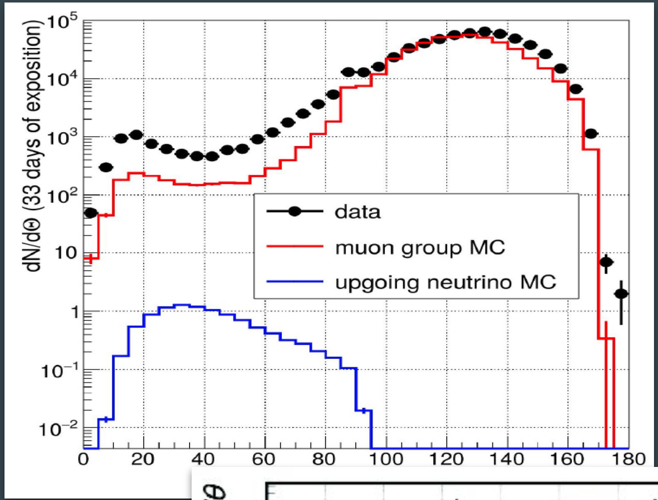


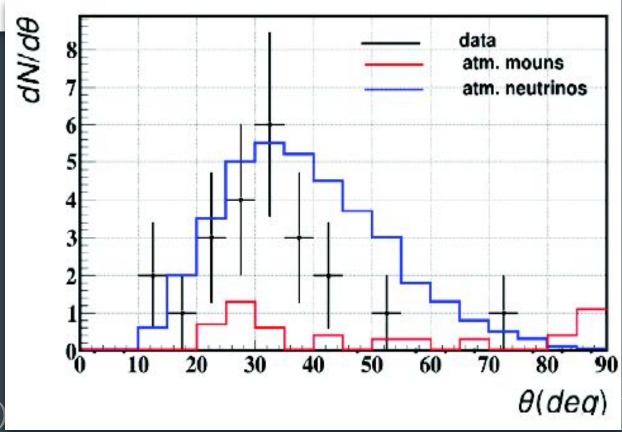
Muon background measurement

With muon-track reconstruction we can measure the main background: atmospheric muon flux.

Good description of down-going muons, shape agreement for up-going tracks. Still, the fraction of mis-reconstructed muon tracks exceed the rate of muon neutrinos by 2 orders of magnitude.

Selection of neutrino events - BDT method, 23 candidates found in 2016 data with 42 expected. Expected number of background events is 6.





EPJ Web of Conferences **191**, 01006 (2018)

Reconstruction of cascades

Two-step method:

- Reconstruct shower vertex coordinates:
  - Assume the source is point-like,
  - Minimize time-χ^2 function.
- Reconstruct shower energy and direction:
  - Maximum-likelihood function using the information on the number of photoelectrons and pulse amplitudes.
- Require large number of hits (N>13) to suppress muon-bundle events.

Preliminary analysis of 2016 and 2018 resulted in 3 cascade events with E > 100 TeV:

	Date	Energy, TeV	Zenith, degree	Azimuth, degree	Distance, m
Cl. #1, 2016	29.04.2016	155	57	249	45
Cl. #1, 2018	21.08.2018	153	49	57	77
Cl. #3, 2018	24.10.2018	107	69	112	89

These are candidates for astrophysical neutrinos.

Obviously, larger statistics is needed for meaningful conclusions, however the results are in agreement with IceCube flux measurements.

R. Dvornicky, PoS (ICRC2019) 873

Simulation - existing framework

The currently-existing simulation framework employs several steps:

- A data bank is created using CORSIKA[1] (muons) or ANIS[2] (neutrinos) generators, a built-in single-muon and basic neutrino-flux generator is also in place.
- The propagation of muons is performed by the MUM[3] (Muons+Medium) package interfaced to simGVD - modeling interactions with Optical Modules. Cascade simulation is also included.
- Detector response (and noise impact) are then modeled by readMC package.
- Afterwards, the output is passed on to the reconstruction software, BARS, just like real data.

[1] CORSIKA: D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, T. Thouw, FZKA 6019, Forschungszentrum Karlsruhe (1998).
[2] ANIS: Comput.Phys.Commun. 172 (2005) 203-213.
[3] MUM: Phys.Rev.D 64 (2001) 074015.

Simulation - developments

The existing framework is old and written in fortran, making it hard to customize and upgrade.
An effort is ongoing to create a new, flexible and CPU-efficient framework.
Planned features:

- Use the calculations by S. Sinegovski[1] for neutrino and muon fluxes at Earth surface,
- Use the works by V. Naumov[2] on neutrino cross-sections for neutrino propagation to detector,
- Use new MUM version (2020),
- Use GEANT4 for particle propagation and Cherenkov light production,
- Use G4-derived light fields for simulating detector response:
    - The BGVD detector is very sparse - direct use of G4 would be inefficient.

[1] Phys. Rev. D 91 (2015) 6, 063011, J. Phys.: Conf. Ser. 1181 012054.
[2] Astroparticle Physics 10(2-3):239-252.

Selected results

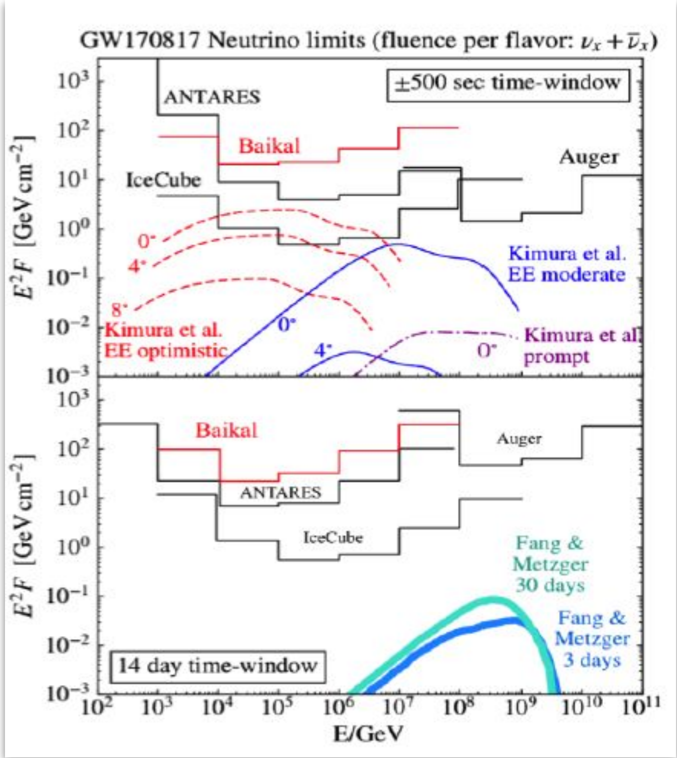
Search for neutrinos around GW170817

Search for neutrinos associated with gravitational wave was performed in 2017 with 2 clusters operational at that time.

Event slightly below BGVD horizon (93°).

No neutrino events found both in prompt emission and in 14-day delayed emission.

Upper limits on neutrino fluence were derived at 90% CL.



JETP Letters volume 108, pages 787–790(2018)

TX-0506-056 blazar and ANTARES alerts

Search for neutrinos associated with TX-0506-056 blazar (the one which IceCube has identified as neutrino source) was performed in 2017 with 2 clusters operational at that time.

Event slightly above BGVD horizon (57°).

No neutrino events associated with this source were identified.

Search for coincidence events with alerts from ANTARES triggers was performed within 6μs, 10s and 1-hour time windows.

No time-direction correlations were found for 6-month observation period.

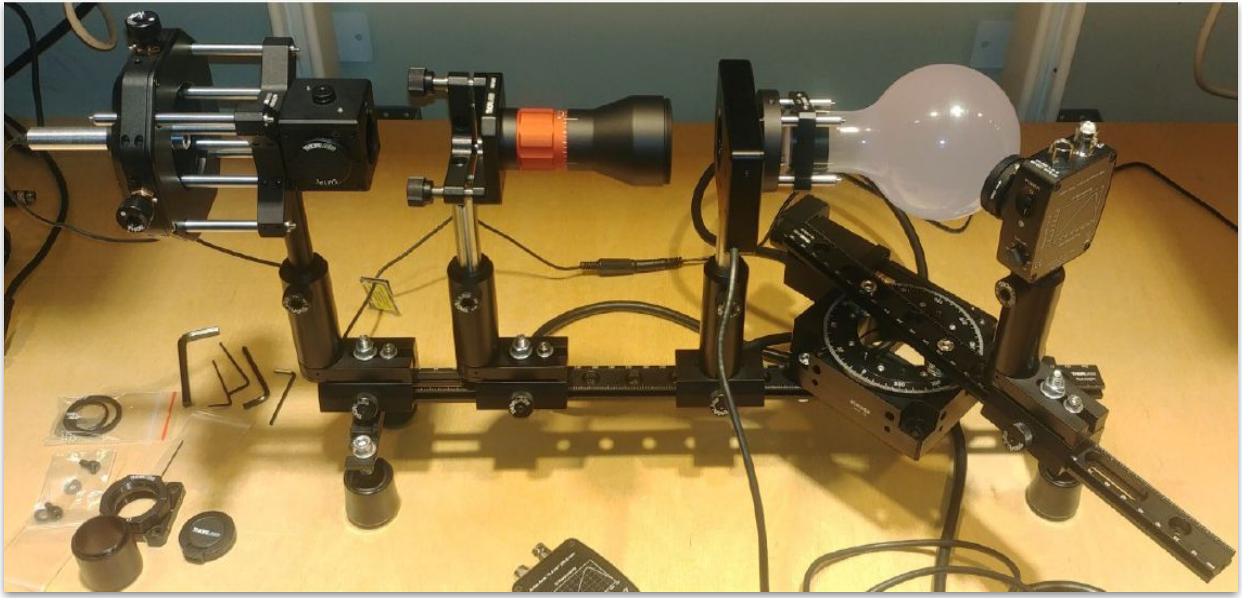
F. Simkovic, PoS ICRC2019 (2020) 1013

Summary & plans

The Kraków group

- The IFJ PAN group has been participating in the BGVD since 2016.
- The group was re-formed in April 2019, our current team is:
  - Paweł Malecki, group leader,
  - Jarosław Stasielak,
  - Konrad Kopański,
  - Wojciech Noga, PhD student,
  - Soon to join: Apoorva Bhatt.
- Our activities cover (so far):
  - Design and construction of the elements of the laser calibration system (K. Kopański),
  - Developments in the detector-simulation framework (W. Noga, Pa. Malecki, J. Stasielak),
  - Time-calibration of Optical Modules with atmospheric muons (Pa. Malecki).

Examples of our work: laser test stand (K. Kopański)

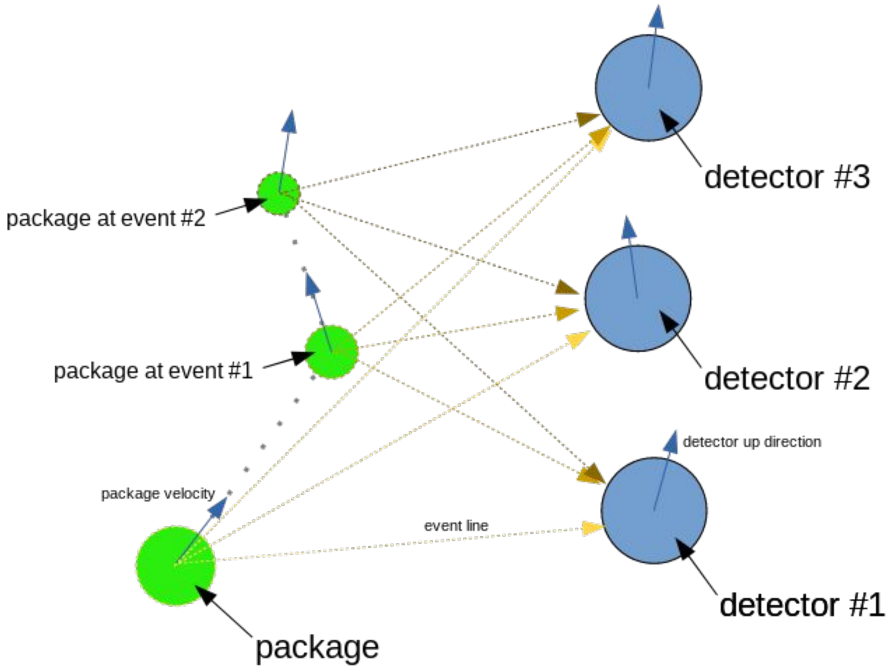


A test stand for various measurements related to laser system was prepared.

It is fully portable and ready to be taken for winter expedition.

It allows for measuring optical properties of elements such as diffusers, also laser characteristics.

Examples of our work: Pretorian package (W. Noga)



Multi-threaded forward ray-tracing MC simulation program:

- Designed for BGVD, optimised for sparse detector structure,
- Propagate photons directly to OMs,
- Propagate photons in packets, that can be fragmented - faster processing.
- Possibility to use various types of sources (laser, diffuser, etc.)

Summary & plans

- The Baikal-GVD detector is growing in a rate of 2 clusters/year increasing its active volume and getting ready for rare events.
- The techniques of reconstruction are evolving allowing for more detailed and robust studies of the registered event candidates, also for better selection efficiencies.
- The Kraków group is gathering experience and becoming more and more visible in the collaboration. We will continue our activities in simulation & reconstruction software and in laser-related hardware studies. An overview BGVD paper is prepared by us and will soon be published in the Symmetry Magazine.

Advertisement

We are hiring!

There is a need for manpower in the Kraków BGVD group:

- Post-docs:
  - Baseline requirements: experience in particle or astroparticle physics, preferably experimental, programming skills (C++, Python), team-working abilities, good knowledge of English.
- PhD students:
  - Baseline requirements: MSc in physics, programming skills (C++, Python), team-working abilities, good knowledge of English.

Please contact me if you are interested:

pawel.malecki@ifj.edu.pl, +48 12 662 8023.

Thank you for your attention!

Contact:
pawel.malecki@ifj.edu.pl

See also: https://baikalgvd.jinr.ru