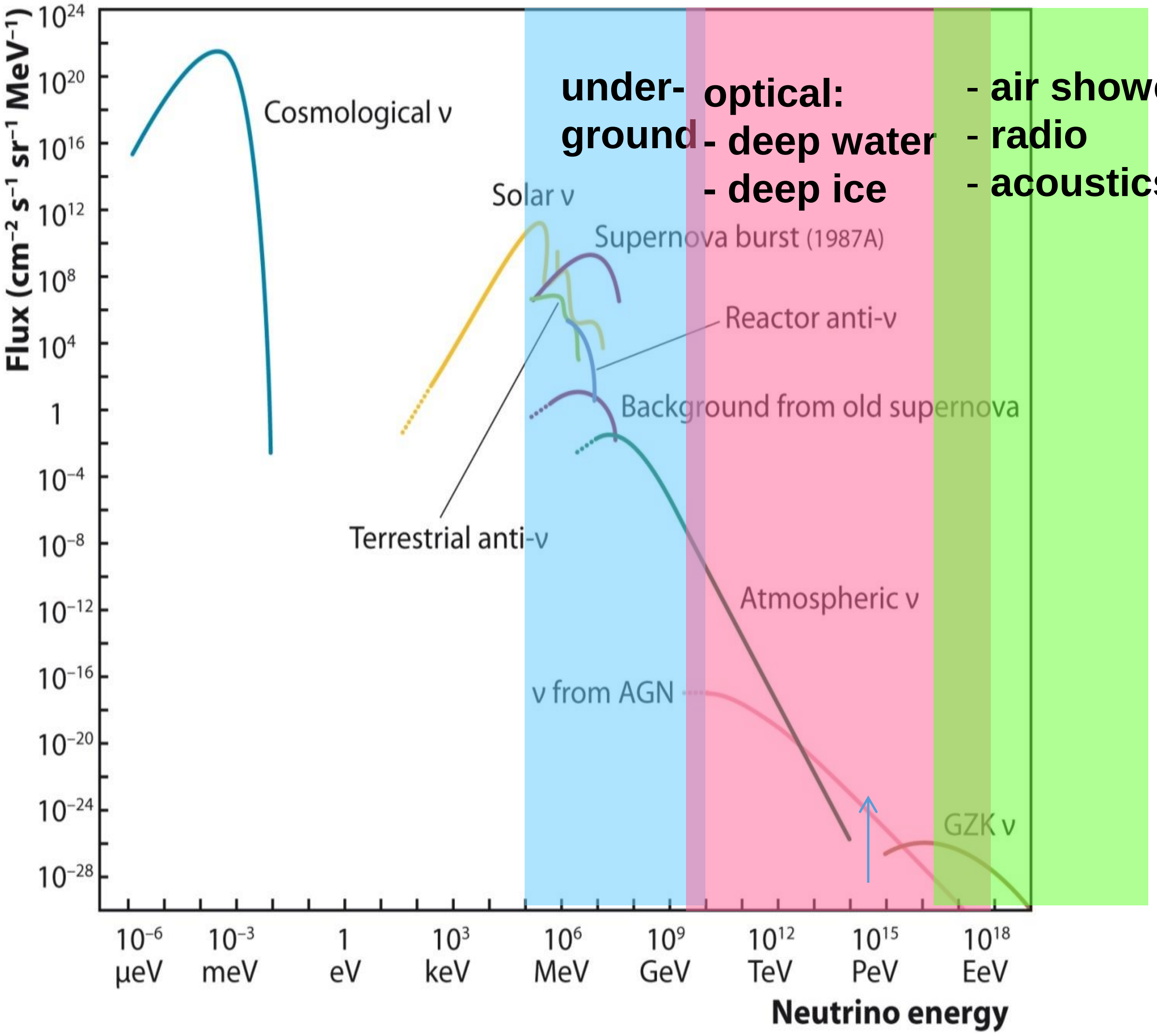
Байкальский нейтринный эксперимент

Г.В.Домогацкий (ИЯИ РАН)
за коллаборацию Baikal-GVD

We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charge particle directions by Cerenkov radiation. Markov M.A., 1960, In: Proc. 10th ICHEP, Rochester, p. 578

Природные потоки нейтрино

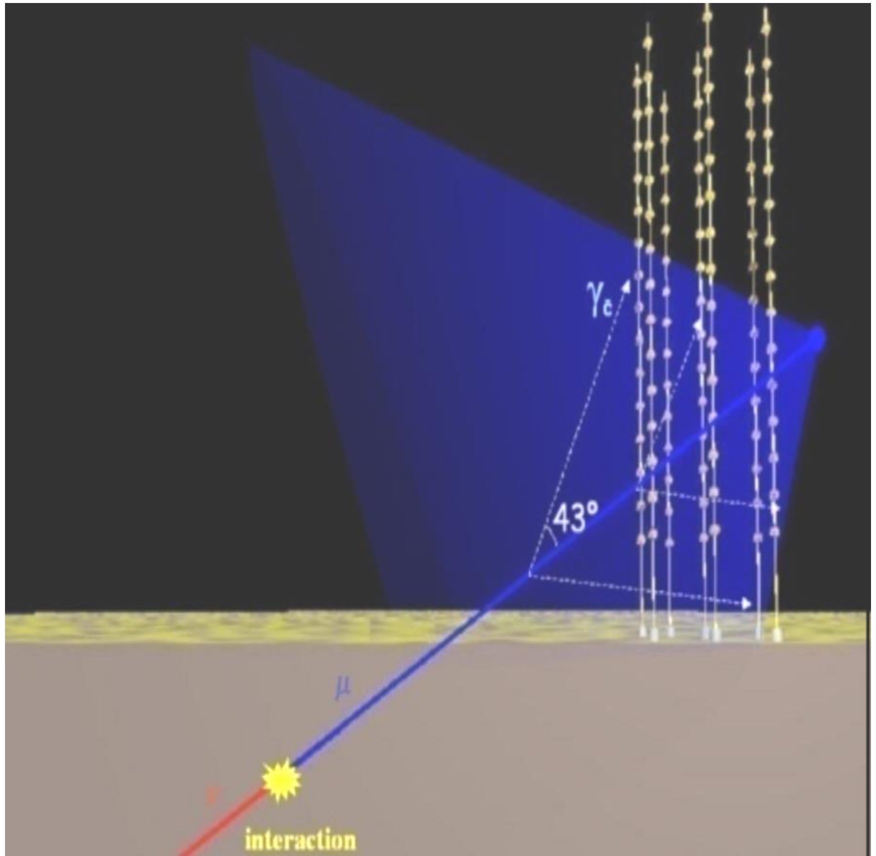


Detection Modes – cascads&muons

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

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

μ/casc. ≈ 1/4 for 1:1:1



Detection principle

Sparse array of photodetectors in natural water(ice) reservoir

Cerenkov light from charged particle produced in neutrino interaction is detected

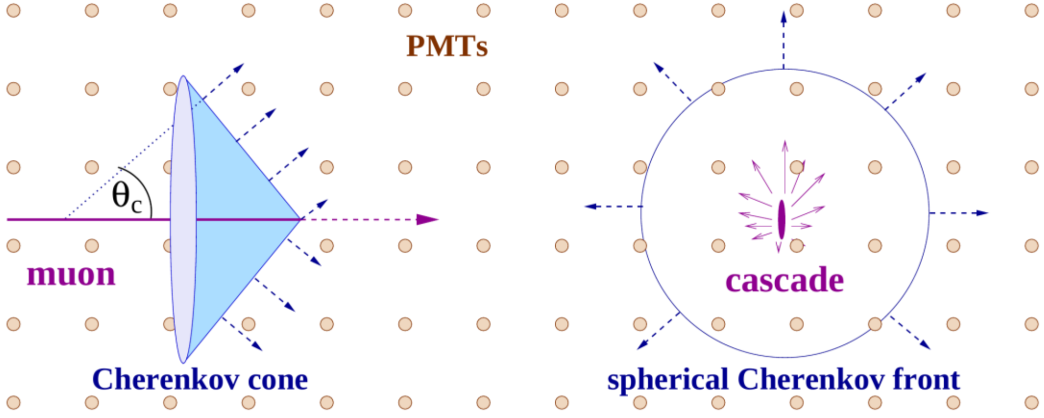
Neutrino event types:

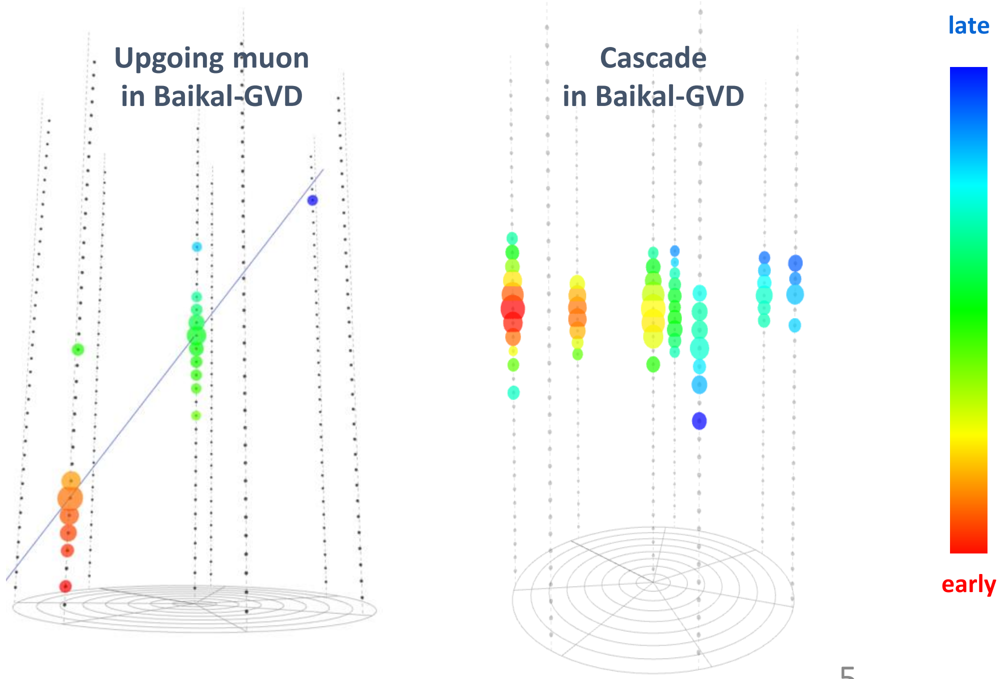
Tracks (CC, ν_μ ν_τ):

- Good angular resolution: ~0.3° - 0.5°
- Poor energy resolution: 200-300%
- Increased sensitive volume due to muon propagation range

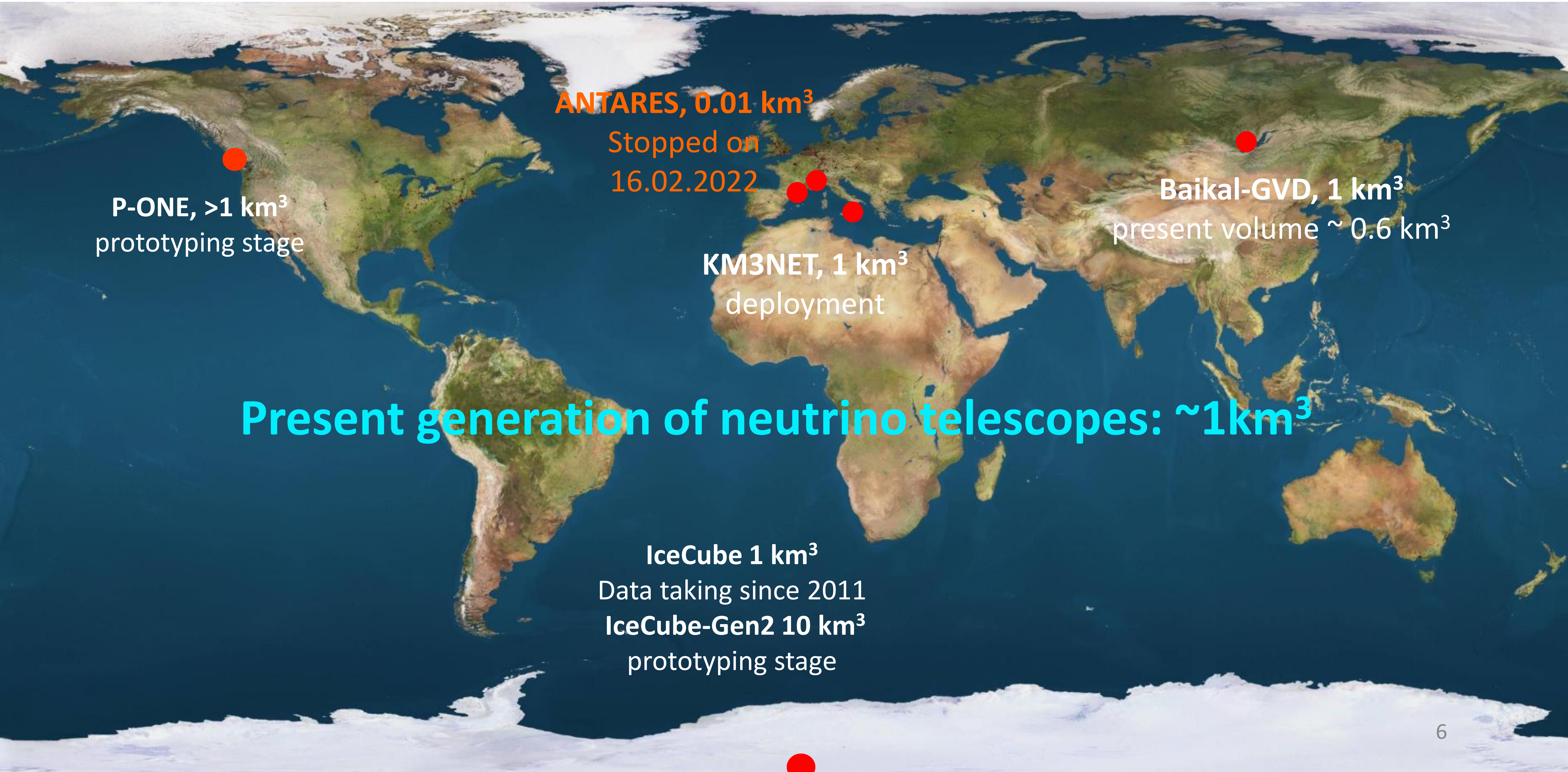
Cascades (CC ν_e ν_τ, NC):

- Moderate angular resolution 3°-10°
- Good energy resolution: 5-30%





Neutrino telescope network



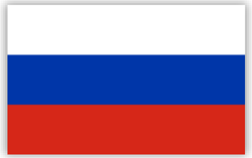
Этапы развития Байкальского проекта

- 1980 – 1990. От решения Ученого совета ИЯИ РАН от 1 октября 1980г. о создании лаборатории Нейтринной Астрофизики Высоких Энергий до создания проекта детектора НТ-200 - *изучение водной среды, создание больщого высоковольтного фотоэлектронного умножителя «Квазар-370», испытания прототипов детектора.*
- 1990 – 2000. Создание и запуск первого нейтринного телескопа НТ-200, выделение первых событий от нейтрино в водной среде, исследование диффузного потока нейтрино высоких энергий.
- 2000 – 2010. Разработка проекта детектора Baikal-GVD масштаба 1куб км. Создание и запуск детектора НТ-200+ как прототипа детектора Baikal-GVD.
- 2010 – 2030. Создание детектора Baikal-GVD. Физические исследования. Разработка проекта детектора масштаба до 10 куб. км. Испытания прототипа и начало работ.

Нейтринный телескоп Baikal-GVD

Baikal-GVD (Gigaton Volume Detector) представляет собой глубоководный нейтринный телескоп объемом порядка кубический км, создаваемый в оз.Байкал.

11 организаций из 4 стран, ~ 60 членов коллаборации



- Институт ядерных исследований РАН (Москва)
- Объединенный институт ядерных исследований (Дубна)
- Иркутский Государственный Университет (Иркутск)
- НИИ ядерной физики им.Д.В.Скобельцина, МГУ (Москва)
- Нижегородский Государственный Технический Университет (Нижний Новгород)
- Санкт-Петербургский Морской Технический Университет (Санкт-Петербург)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- LATENA (Санкт-Петербург)
- INFRAD (Дубна)
- Comenius University (Bratislava, Slovakia)
- Institute of Nuclear Physics ME RK (Almaty, Kazakhstan)

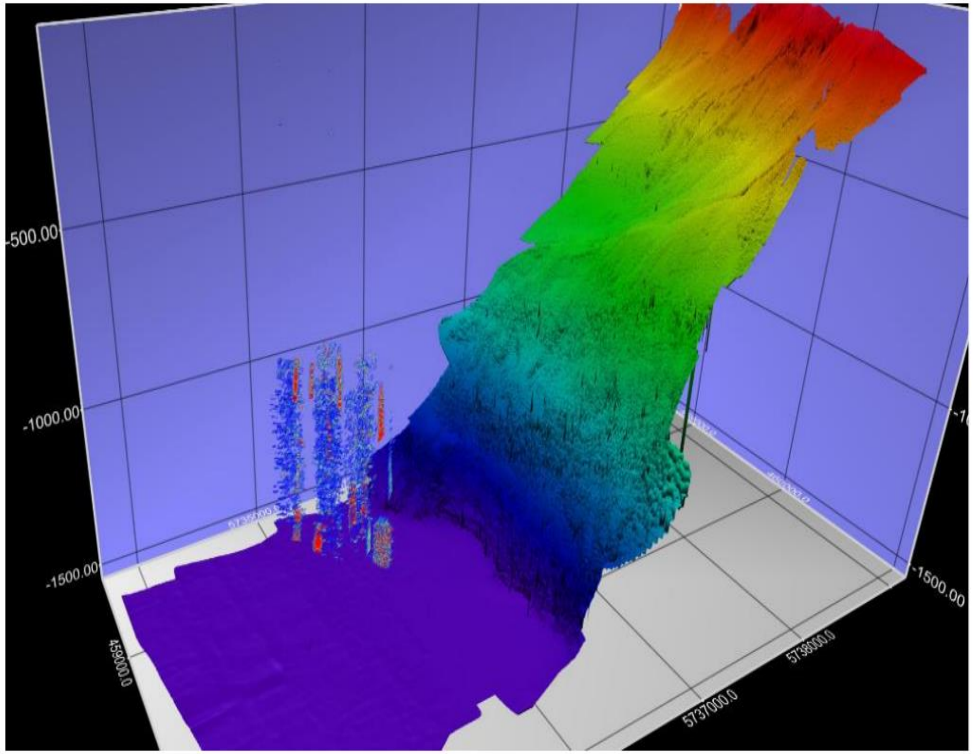
Месторасположение телескопа

Платформа 106км КБЖД
Телескоп находится на расстоянии 4км от берега.
Глубина составляет 1366 - 1367 m

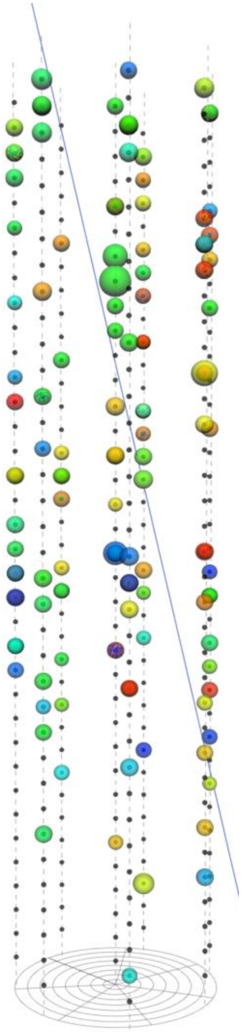
Характеристики воды:

- Длина поглощения: 21 - 23 m
- Длина рассеяния: 60 - 80 m

Стабильный ледовый покров 7 – 8 недель в феврале-марте-апреле.



Event reconstruction



track-like event before the noise cleaning, data 2019

Cluster event is read-out if coincident signal is found on neighbouring OM
An event frame is 5 μs

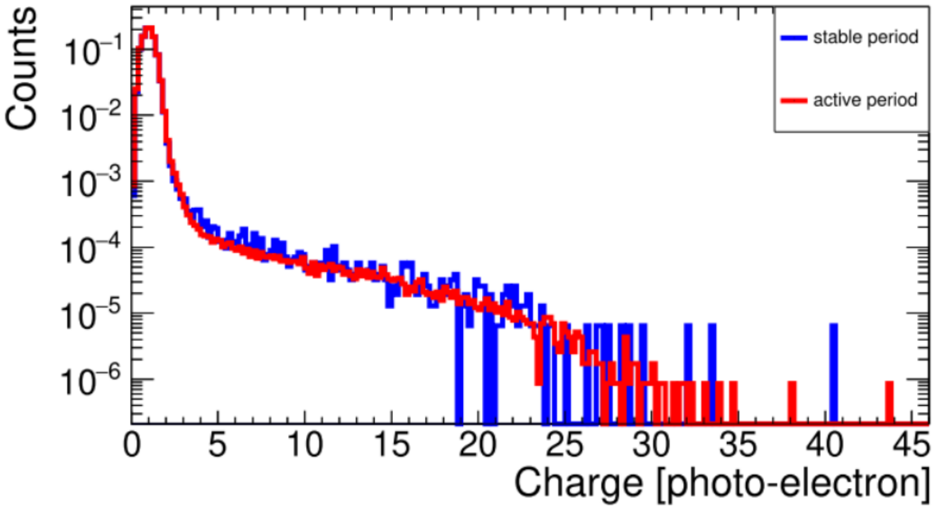
Most of pulses (or hits) in the event frame are noise from lake water luminiscence:

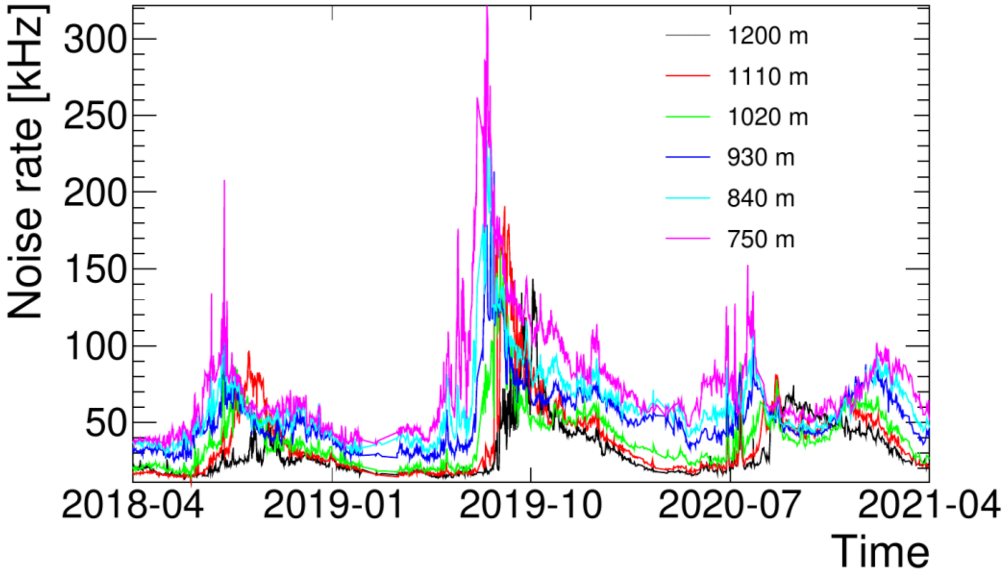
- Typical pulse rate 20-100 kHz
- ~1 photoelectron (p.e.) charge deposition
- Substantial seasonal variations
- Rate is larger on top layers

Challenge for our MC simulation

Variety of algorithms for noise suppression

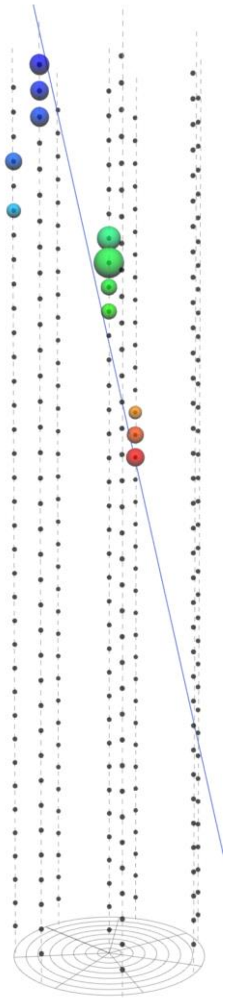
Machine learning -based algorithm in development:
[arXiv:2210.04653]





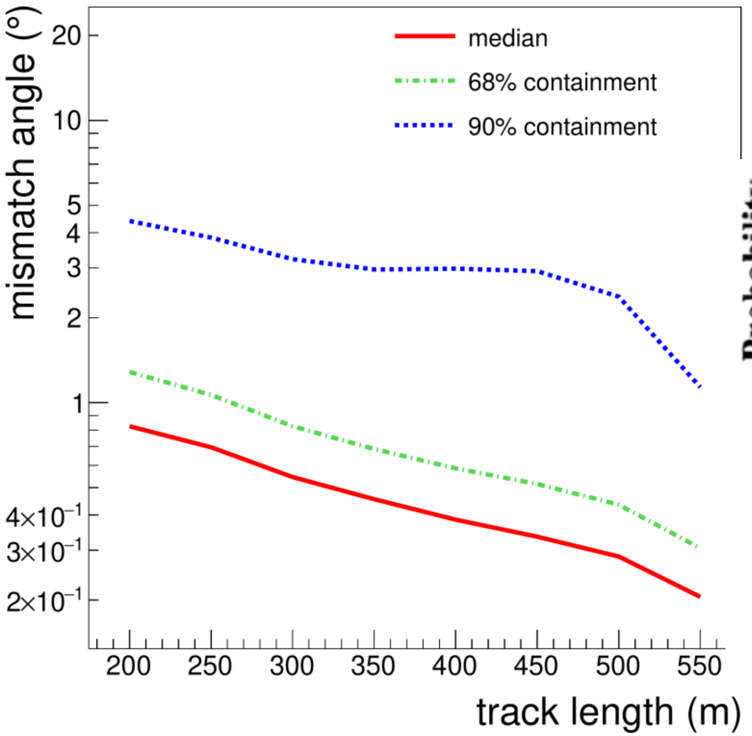
Event reconstruction

Time, location and deposited charge of each pulse
are used for the reconstruction

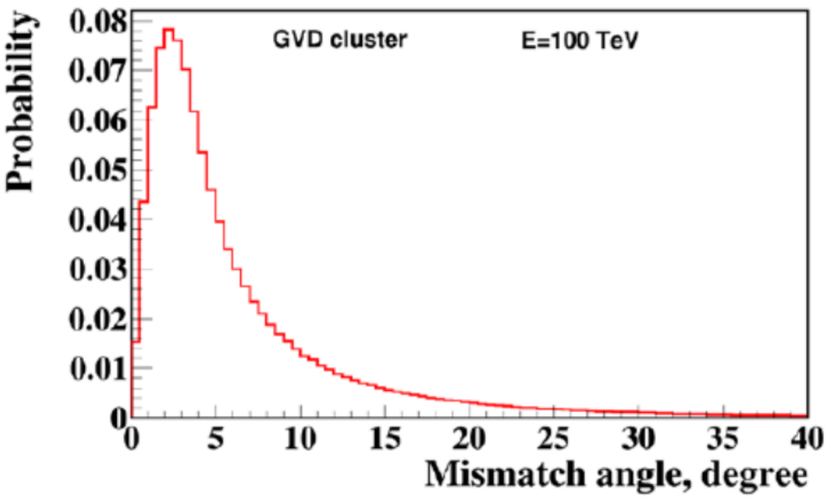


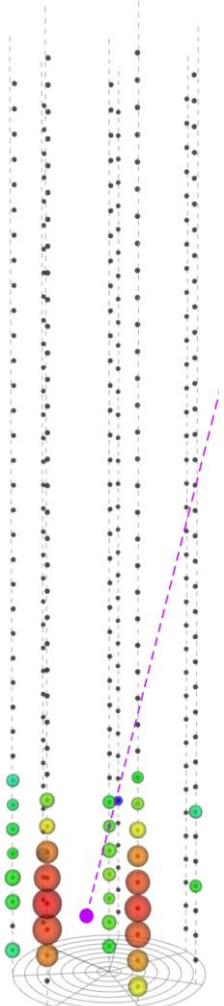
track-like,
data 2019

Track angular resolution:
~0.8° - ~0.2° for tracks longer
than 200 m



Cascade angular resolution:
2-4° depending on energy and
cascade location

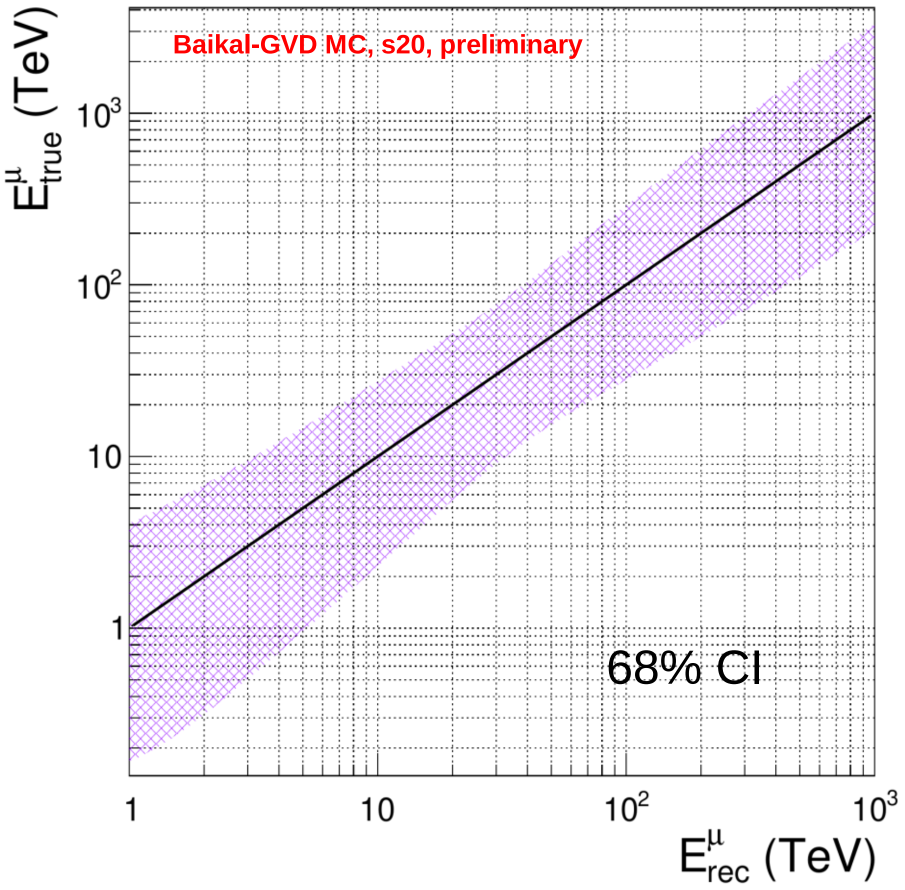




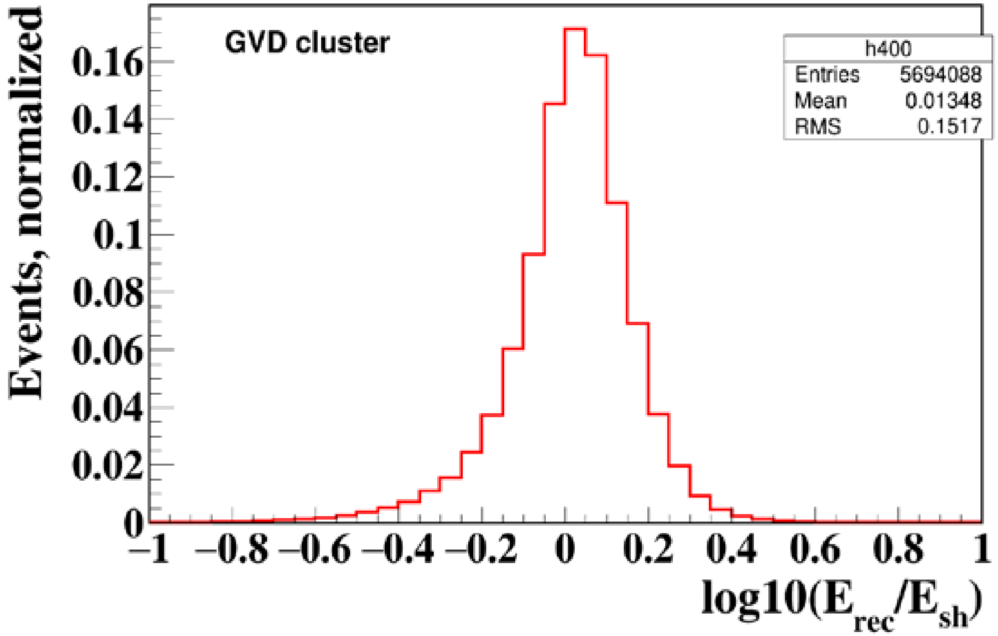
cascade-like,
data 2022

Event reconstruction

Track energy resolution:
Factor 3 for 100 TeV muon

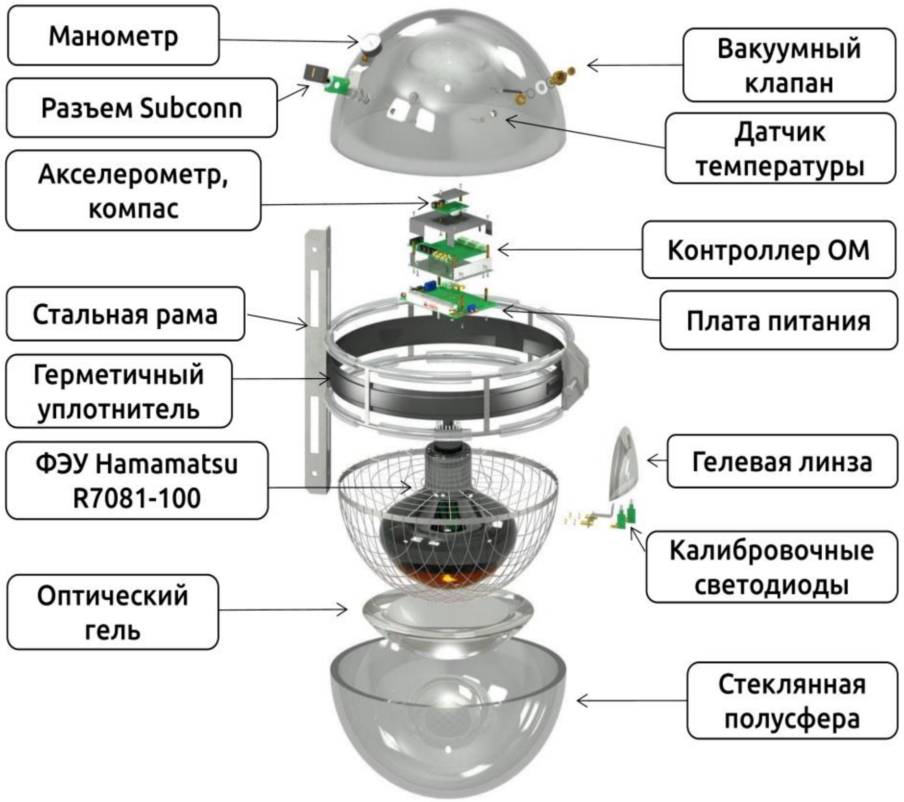


Cascade energy resolution:
δE/E ~10-30%



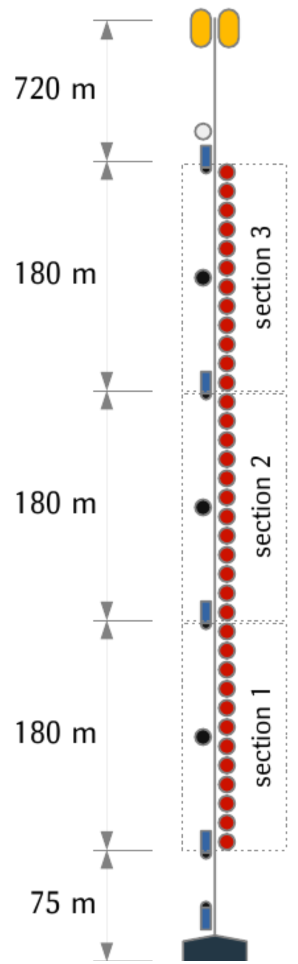
Детектор Baikal-GVD I

Регистрирующий элемент телескопа: оптический модуль.
По состоянию на 2024 год установлено 3960.



Basic components

String:



buoy
string master module
section master module
optical module
acoustic modem
anchor

Each string carries 36 optical modules (OMs)

- 10-inch high Q eff. PMT
- 15 m vertical spacing
- OM facing the lake bottom

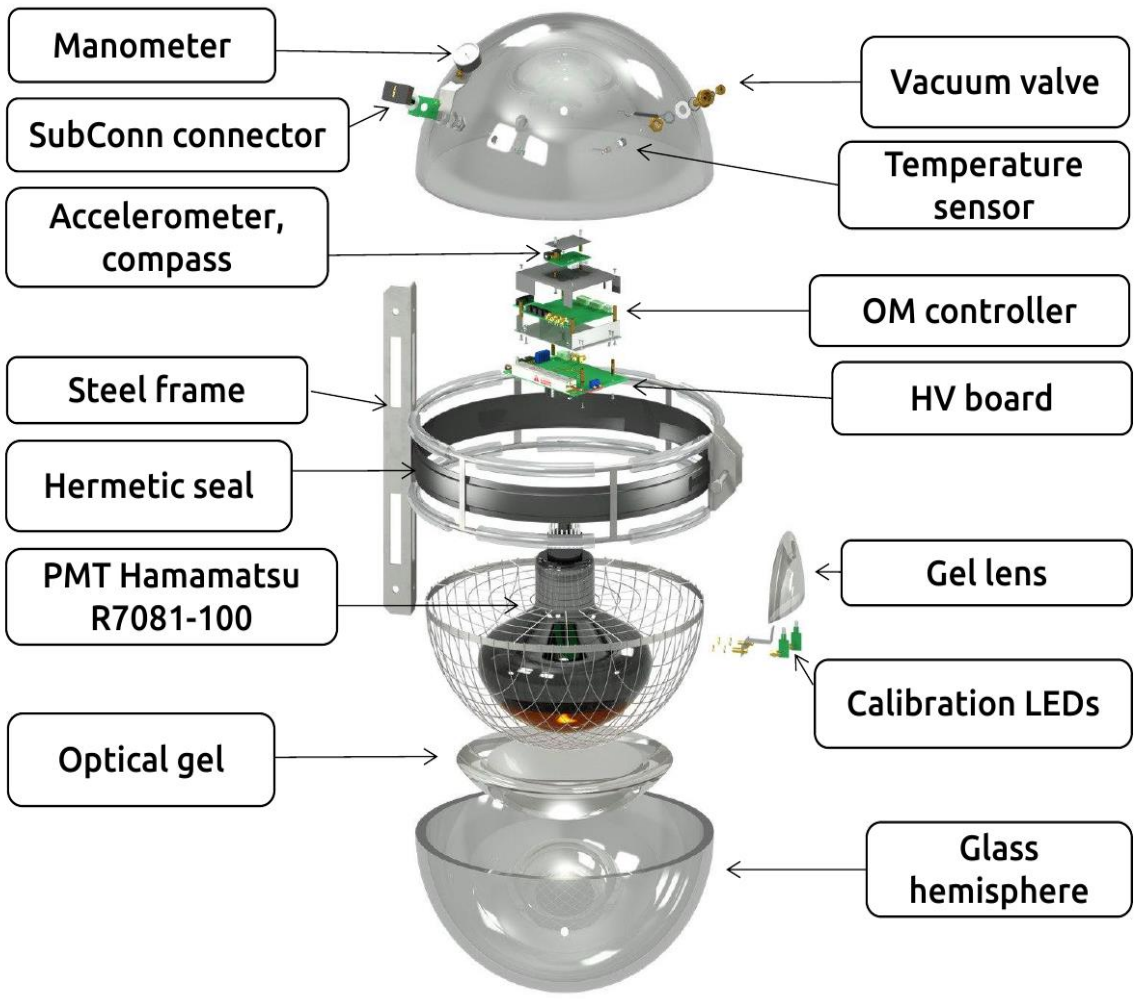
Time calibration systems

- LED in each OM
- LED beacons
- Isotropic lasers between clusters
- Calibration precision ~2 ns

Geometry calibration system

- Acoustic modems on each string
- OM positioning precision ~ 20cm

Optical module (OM):



Detector status

Presently detector consists of 110 strings arranged into 14 independent detectors - **clusters**

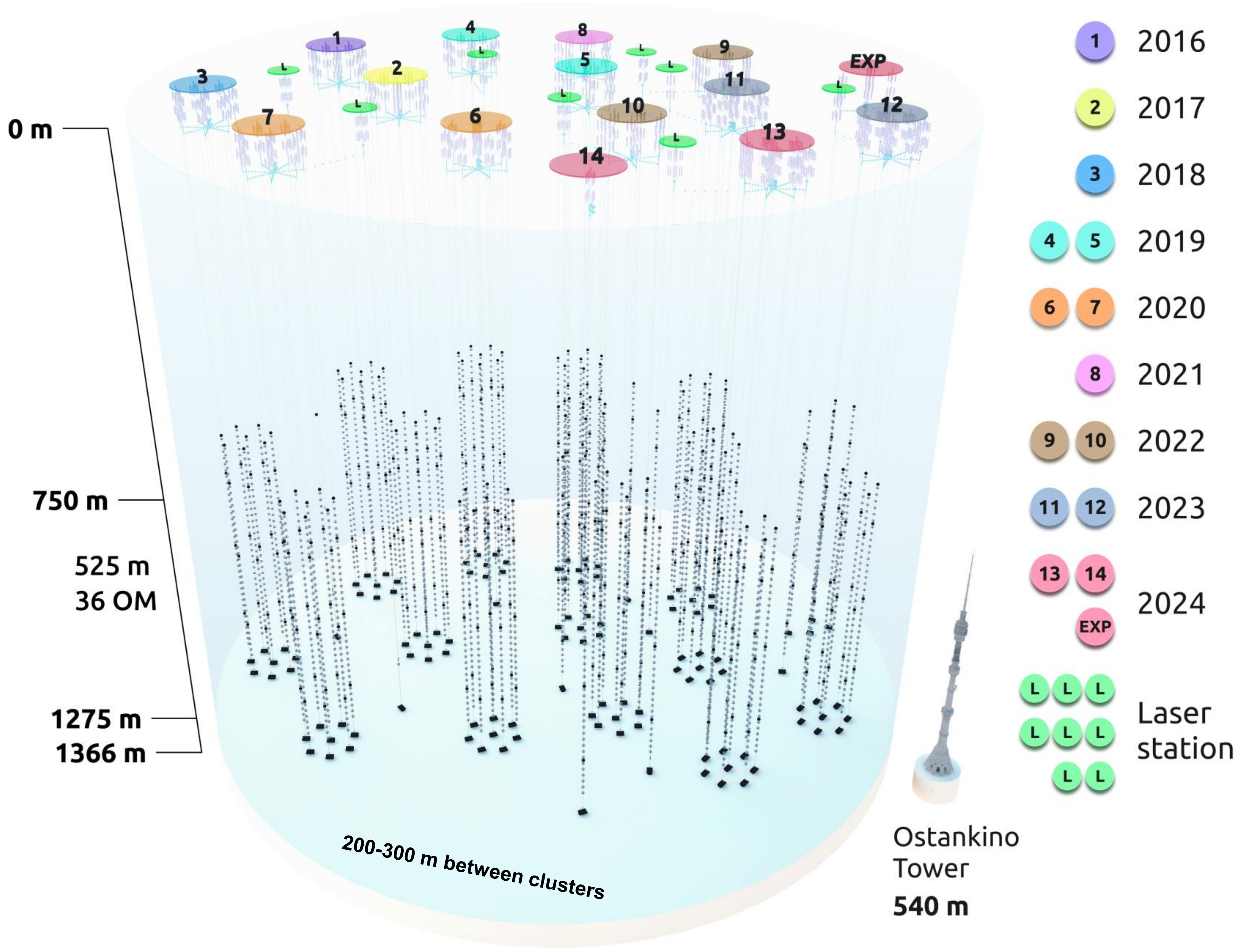
- 3960 OMs in total

Baikal-GVD cluster:

- 8 regular strings, 525 m is instrumented with optical modules (OM)
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs
- Has its own control, trigger and readout systems

Additional cluster “EXP”:

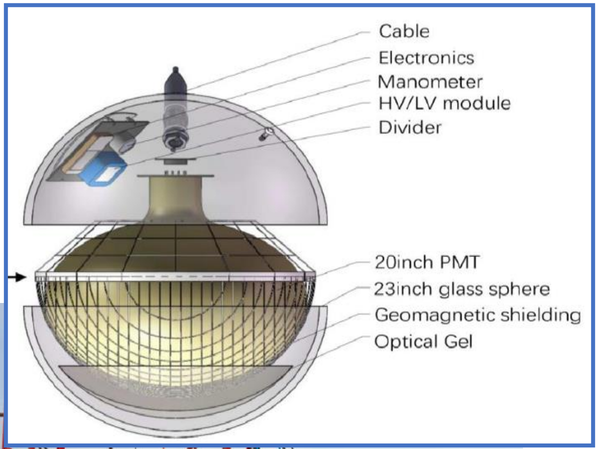
- 4 strings with experimental high-speed DAQ



Expedition 2024

Succesfull 2024 deployment campaign 16/02 - 07/04

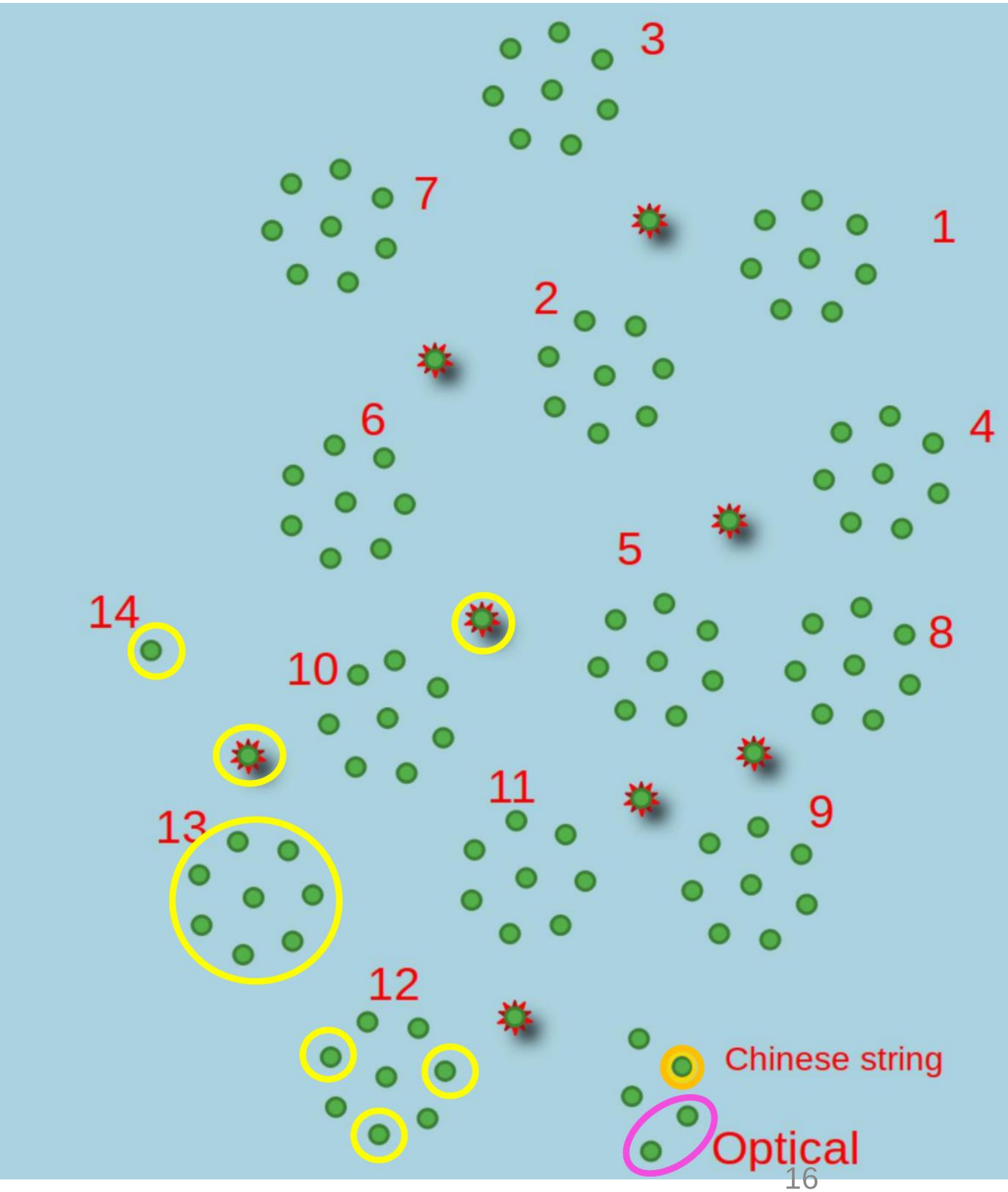
- 14 regular strings carrying 36 OMs installed
- 2 strins added to experimental ("optical") cluster
- Pilot string for HUNT project



HUNT - next generation neutrino telescope project [PoS(ICRC2023)1080]

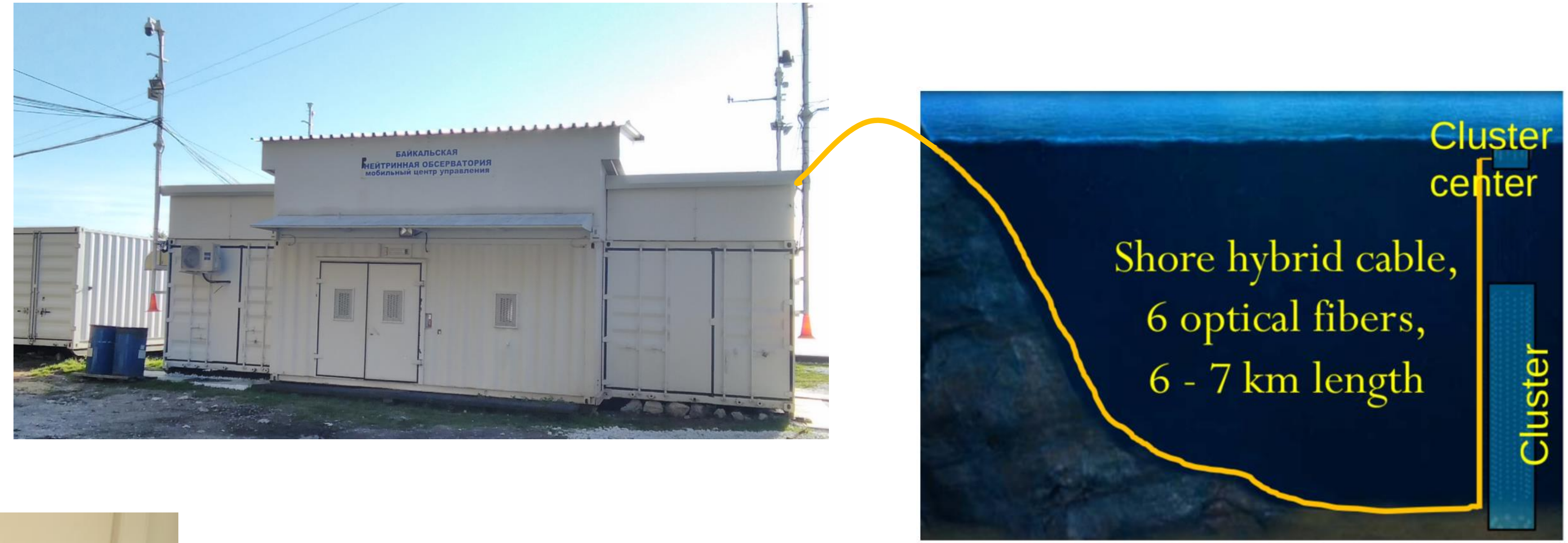
OMs based on 20-inch PMT

Pilot string with 12 OMs deployed as a part of experimental cluster in joint IHEP (Bejing) and Baikal-GVD effort



Data flow

Each cluster is connected to the **shore center** with opto-electric cable
- Power distribution
- Data transmission

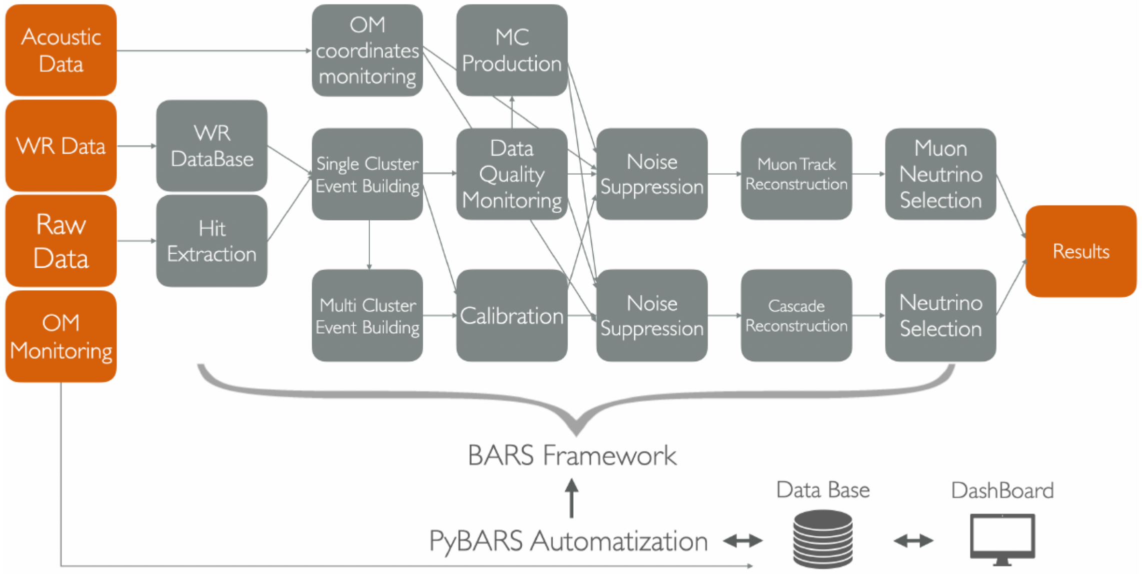


Baikal shore center:
- Power distrubution
- Data readout hardware/software
- Data-taking management (shifter)
- Data quality control
- Long-term storage of raw data
- Alert system (to be deployed)

Data flow

Raw data are transferred from the Shore center to JINR

- Shore center ➞ Baikalsk: 300 Mbit/s radiochannel
- Baikalsk ➞ JINR: Ethernet
- Compressed data volume ~10-40 GB per day per cluster
- Full-scale reconstruction at JINR
- Delay due to shore ➞ JINR data tranfer: < 1 min



JINR computing farm:

- Long-term storage of raw data
- Event reconstruction, storage
- Databases
- Alert workflow
- User analysis

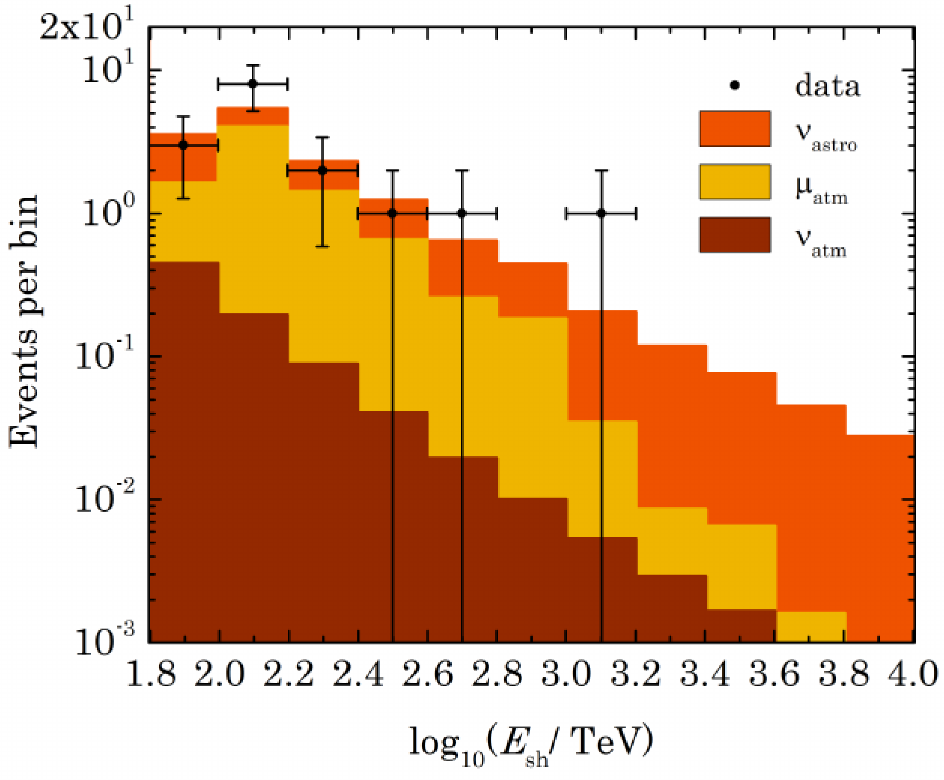
Results in cascade channel

Search for diffuse astrophysical neutrino flux

Most of the Baikal-GVD data were processed with HE cascade analysis algorithms

Four years dataset: 04.2018 - 03.2022

14328 events E_{sh}>10 TeV, N_{hit} > 11 after quality cuts



All-sky analysis:

- E_{sh} > 70 TeV, N_{hit} > 19
- 16 events were selected
- 8.2 background ev. expected
  - 7.4 μ_{atm}, 0.8 ν_{atm}
- 5.8 ν_{astro} ev. expected
- Largest energy event: ~1.2 PeV

All-sky diffuse flux significance: 2.22σ

[Phys.Rev. D 107, 042005 (2023)]

Search for diffuse astrophysical neutrino flux

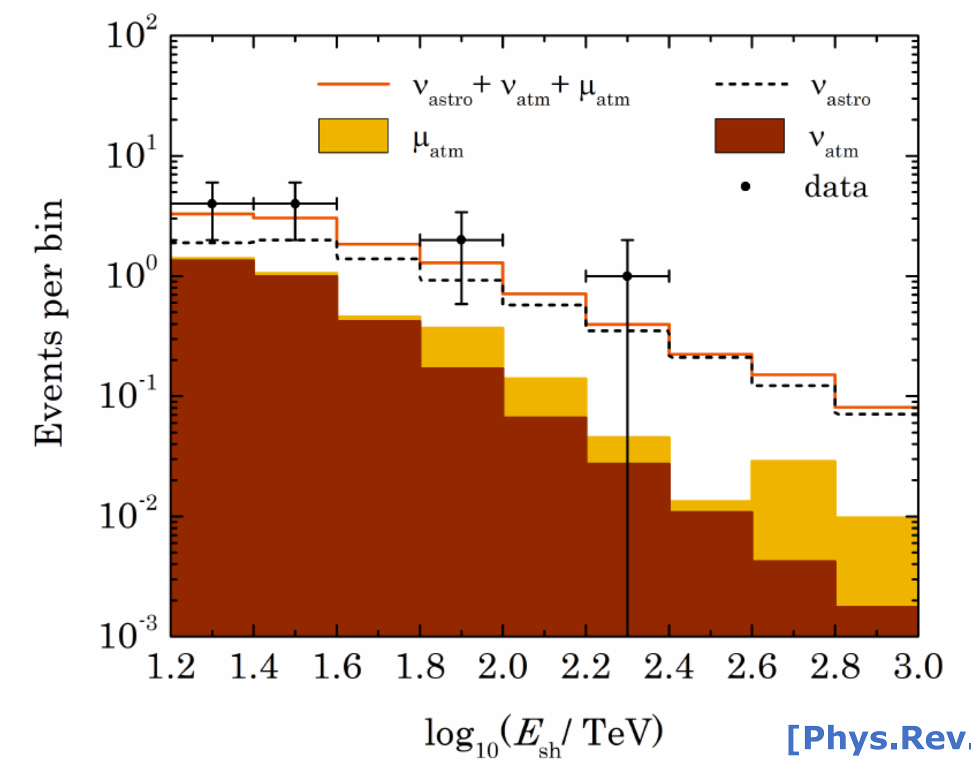
Analysis of upward-going events

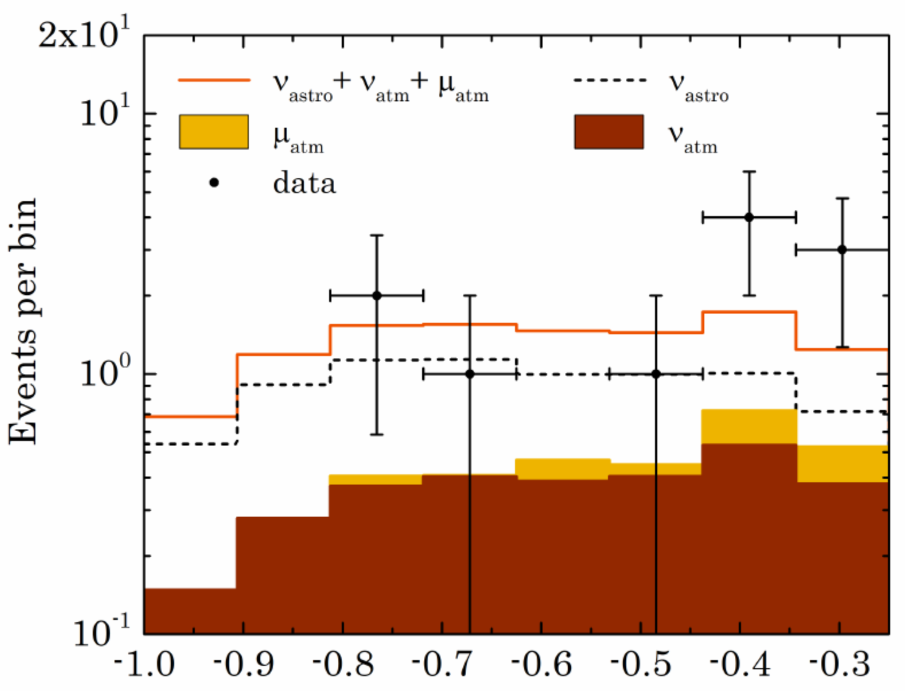
- Zenith angle cut: cos(θ) < - 0.25
- Loosened cuts: E_{sh} > 15 TeV, N_{hit} > 11
- 11 events selected
- 3.2±1.0 atm. background ev. are expected
  - 0.5 μ_{atm}, 2.7 ν_{atm}
- Highest energy: 224 TeV

Significance of diffuse flux in upward-going events: 3.05σ !

Main uncertainties

- Absorption length ±5%
- OM sensitivity ±10%
- ν_{atm} flux normalisation ±15%

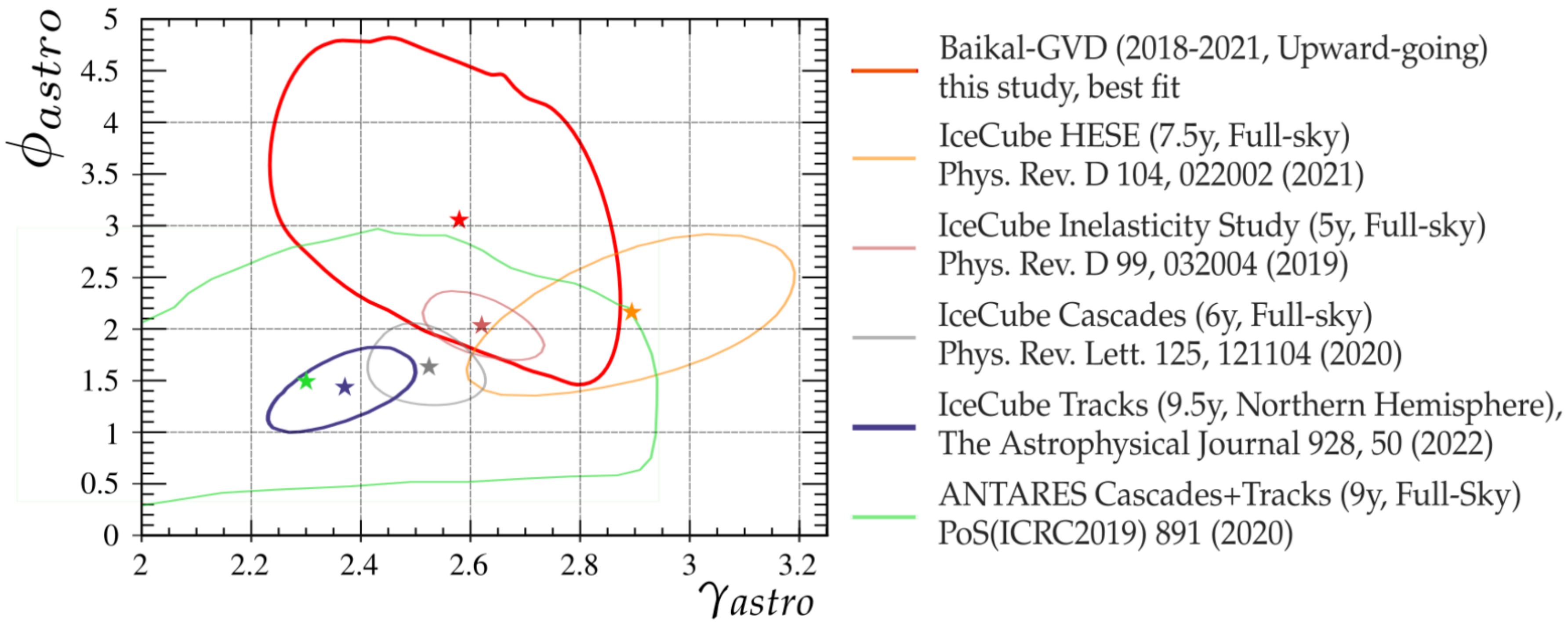




[Phys.Rev. D 107, 042005 (2023)]

Diffuse spectrum

Extraction of spectrum power and flux normalisation: $\Phi^{\nu+\bar{\nu}}_{astro} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0} \right)^{-\gamma_{astro}}$



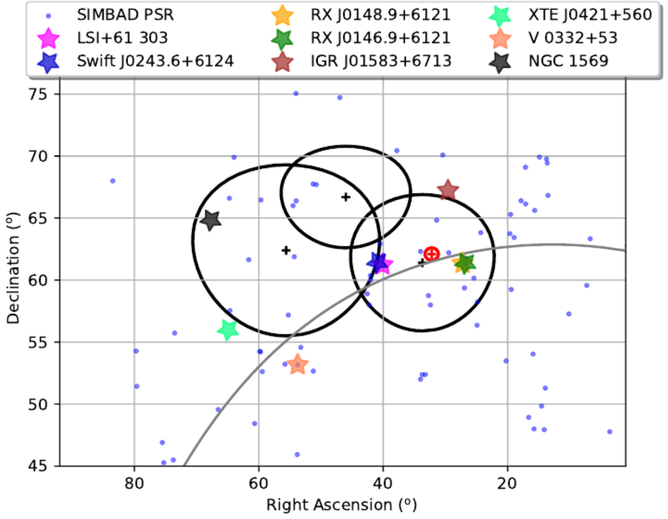
Results are in agreement with previous measurements by IceCube and ANTARES

First “non-IceCube” evidence for diffuse ν_{astro} flux at above 3σ !

[Phys.Rev. D 107, 042005 (2023)]

HE cascade sky map

[MNRAS 526 (2023) 942]

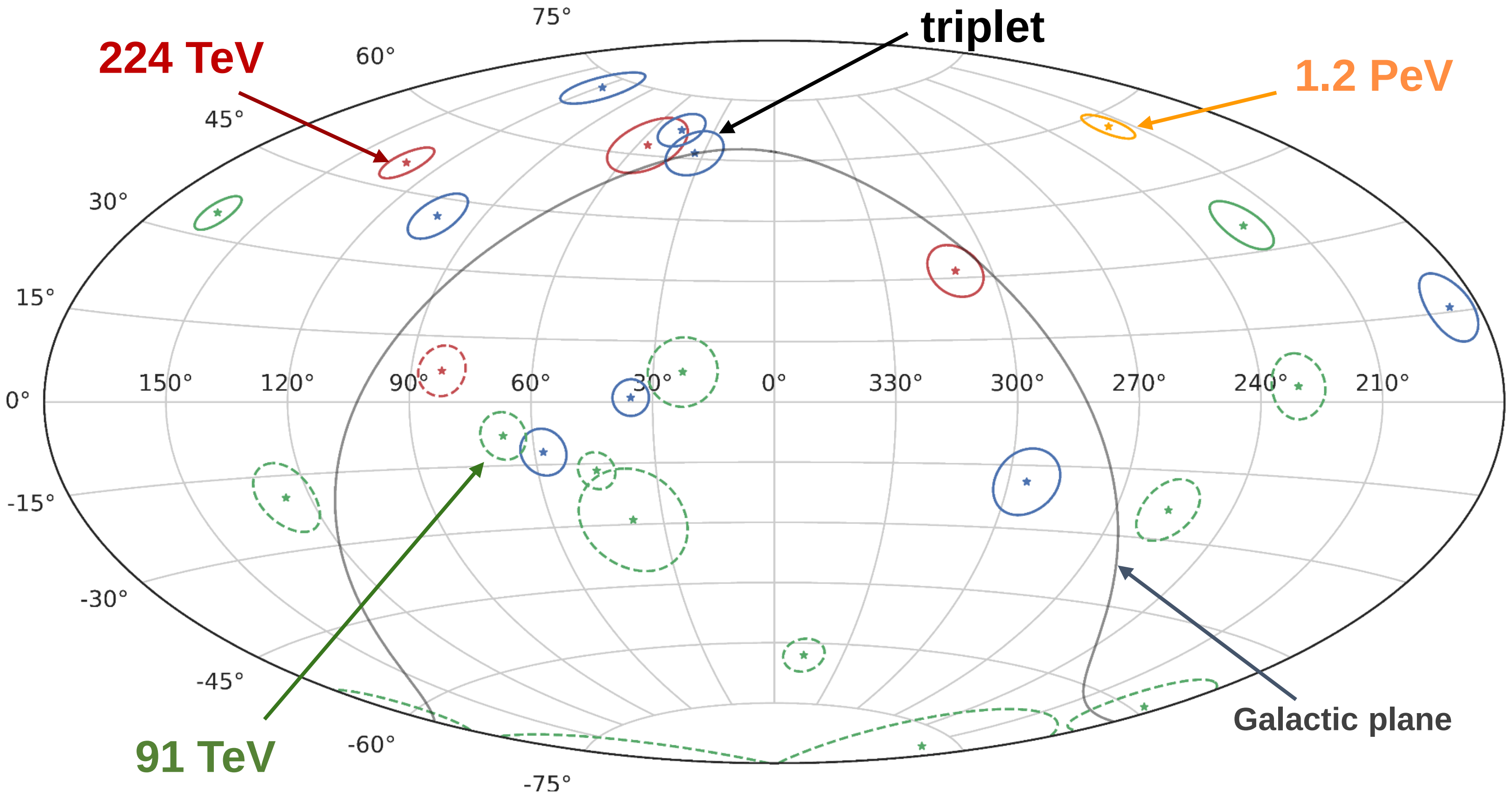


Three events close to the Galactic plane (grey line)

The red plus and circle – IC hotspot
[Aartsen & et al. ApJ, 835,151 (2017)]

Intriguing coincidence in view of recent IC statement on diffuse flux from galactic plane [Science 380, 6652, 1338-1343 (2023)]

Best fit positions and 90% angular uncertainty regions



color represents energy:

E_{rec} < 100 TeV
100 TeV < E_{rec} < 200 TeV
200 < E_{reco} < 1000 TeV
E_{rec} > 1 PeV

Cascade diffuse flux update

Preliminary: An update of analysis adding data from 04.2022 - 03.2023 (10 cluster detector)

Comparison of statistical significances for old and new samples

All-sky analysis

Seasons	N_{data}	N_{bckg}	P-value	σ(stat.)
18-21	16	8.2	2.09×10^{-2}	2.31
18-22	28	14.5	1.06×10^{-3}	3.07

Upgoing analysis

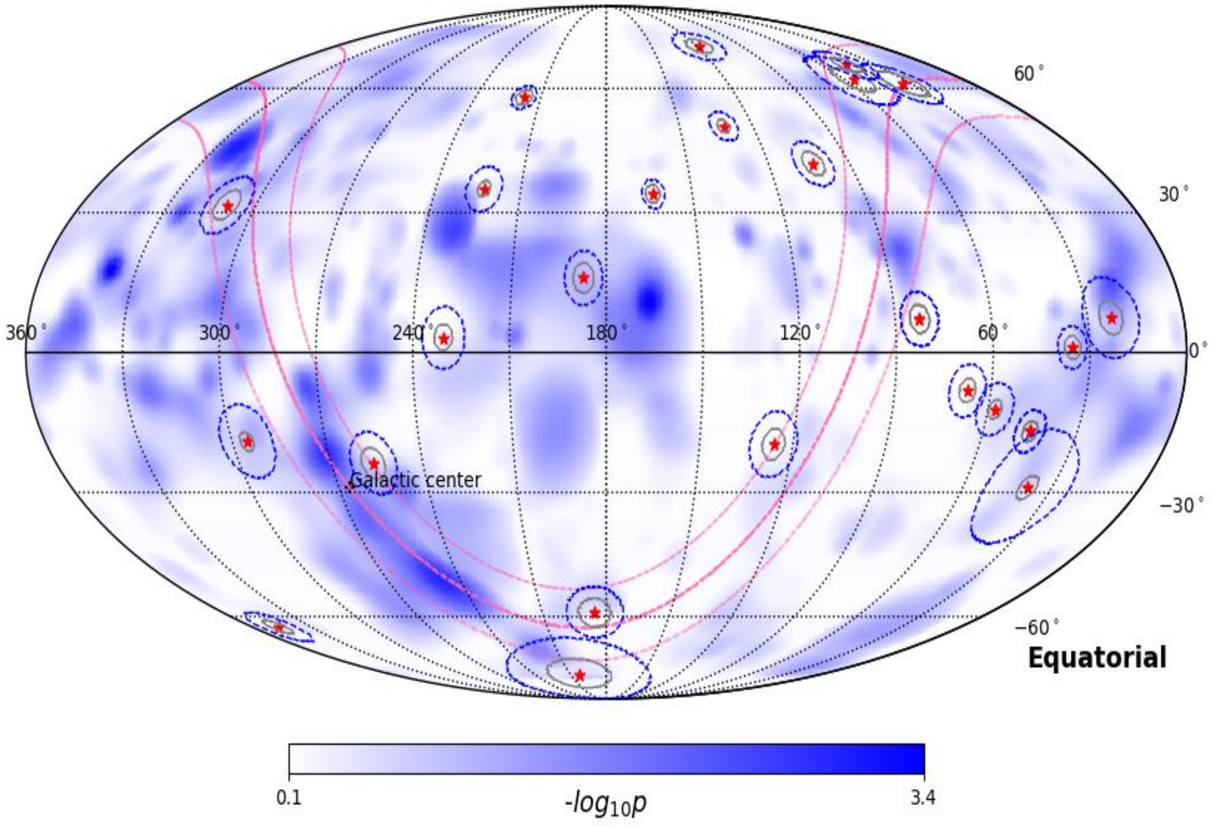
Seasons	N_{data}	N_{bckg}	P-value	σ(stat.)
18-21	11	3.2	1.7×10^{-3}	3.13
18-22	19	5.7	1.11×10^{-5}	4.24

Significance of excess over atmospheric background increases

HE cascades and the galaxy plane

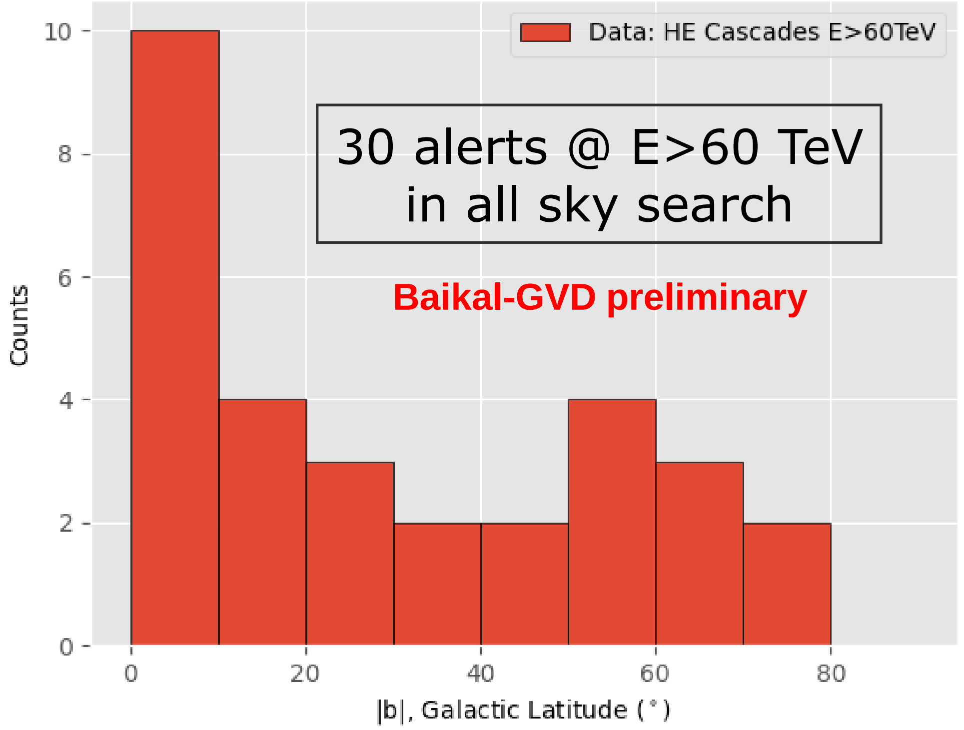
Hint on alert events concentration near galactic plane

Baikal-GVD: 25 all sky alerts for **04/2018-03/2022**



Baikal-GVD alerts compared to IC galaxy plane analysis

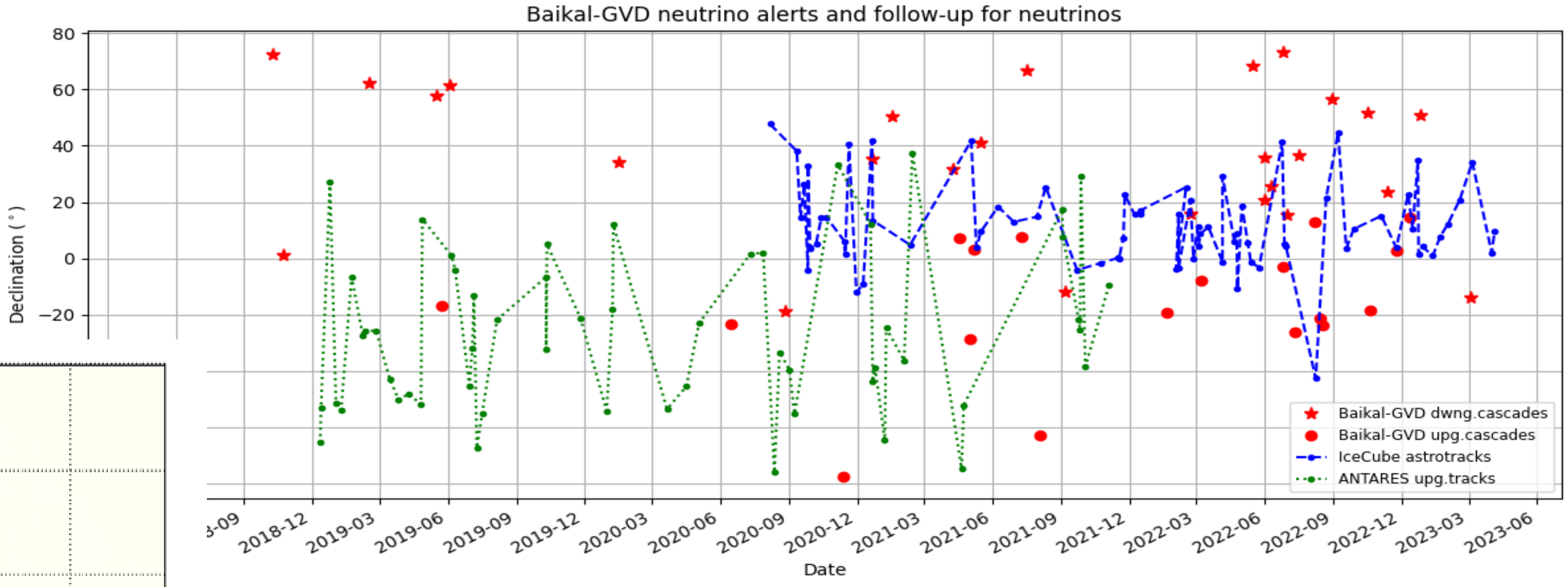
Extended dataset of
45 all-sky alerts **04/2018 - 03/2023**

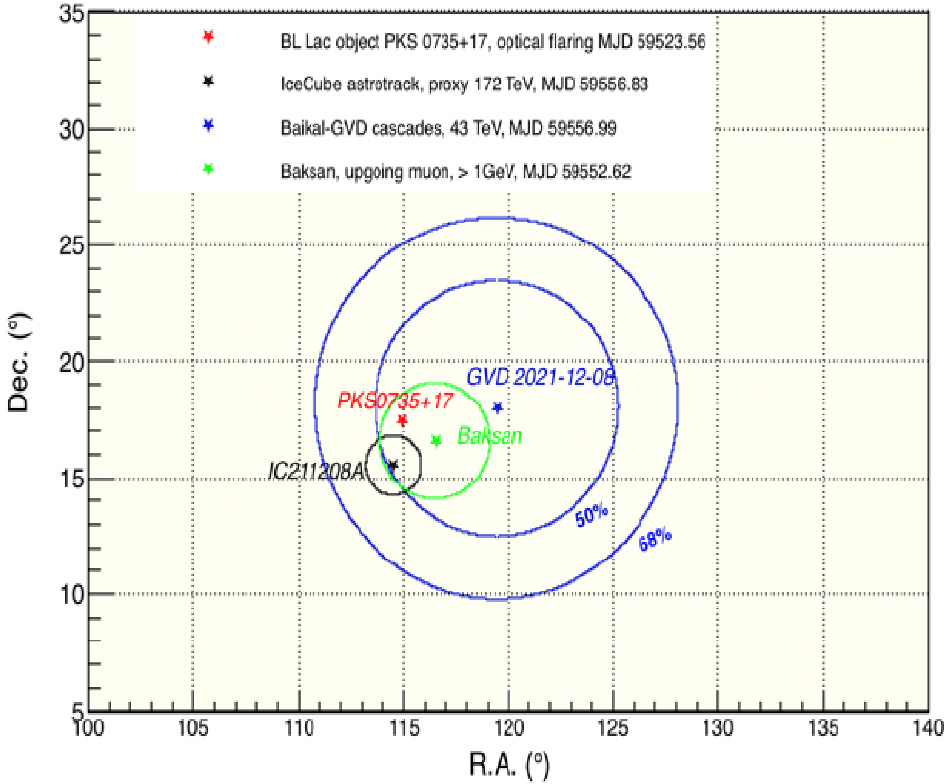


Analysis continues

Follow-up of IceCube and ANTARES alerts

60 ANTARES alerts followed,
3 correlated cascades
[PoS(ICRC2021)1121]





[PoS(ECRS2022)096]

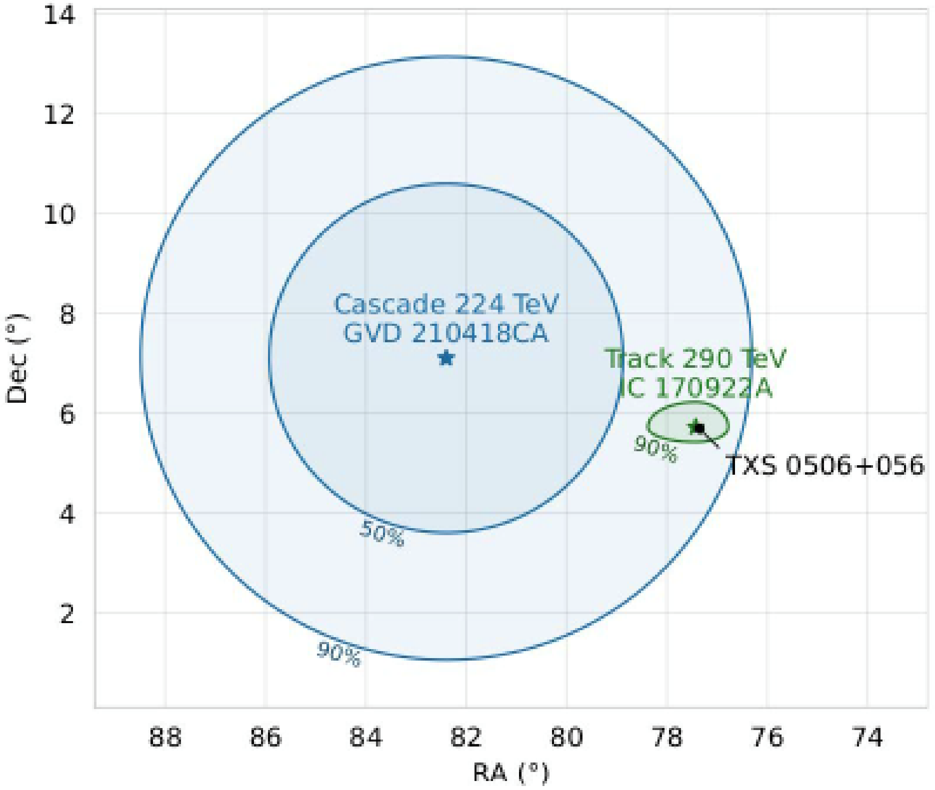
Follow-up of IceCube "astrotracks" events (~20 per year)

- On 8.12.2021 detected cascade from the direction of blazar PKS0735+17 in coincidence with IC211208A
- Delay wrt. IC: 3.95 hrs., E ~ 43 TeV
- Pre-trial significance: 2.85σ, later reduced to 1.13σ
- Astrotelegram published:

https://www.astronomerstelegram.org/?read=15112

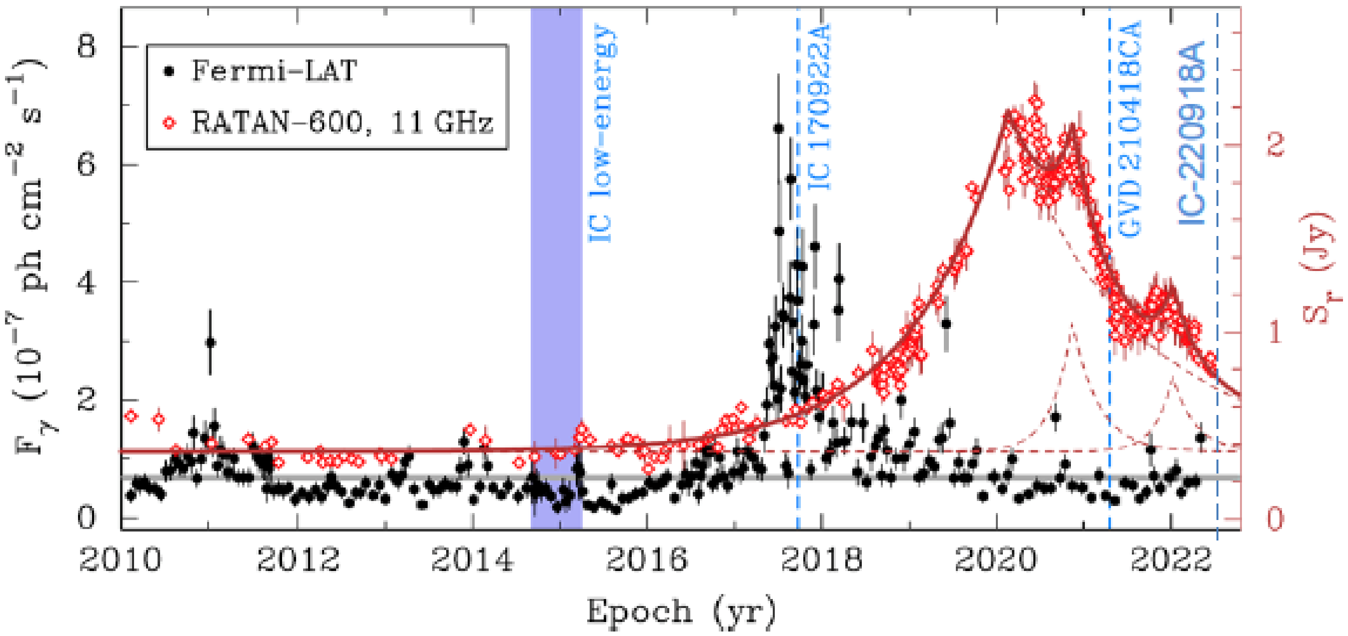
A high energy neutrino from the direction of TXS 0506+056

GVD210418CA (97% signalness) lies within 90% error circle from TXS 0506+056



The chance probability for such an association to occur randomly due to the background is p = 0.0074

Radio and gamma-ray light curves of TXS 0506+056.



Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

- IC event registered during γ flare and radio activity
- Baikal-GVD event during radio activity
- Probability of IC non-observation: 11%

MNRAS 527, 8784–8792 (2024)

Заключение

Эффективный объем детектора Baikal-GVD превысил в 2024г. значение 0.6 km^3

В составе детектора содержится 3960 ОМ, размещенных на 110 гирляндах.

- Установлены для испытаний также 4 гирлянды с оптоволоконной системой внутреннего управления и передачи данных.

Baikal-GVD включился в совместные с Ice Cube и KM3NeT исследования природного потока нейтрино высоких энергий:

- На уровне достоверности 3σ подтверждены результаты первого наблюдения потока астрофизических нейтрино высоких энергий на антарктическом детекторе IceCube.
- В рамках международной практики многоканальных оповещений получены первые результаты поиска событий от нейтрино на детекторе Baikal-GVD, ассоциированные с оповещениями антарктического детектора IceCube.


Спасибо за внимание

BACKUP

Summary

Baikal-GVD has reached ~0.6 km^3 detector volume:
110 strings carrying 3960 OMs

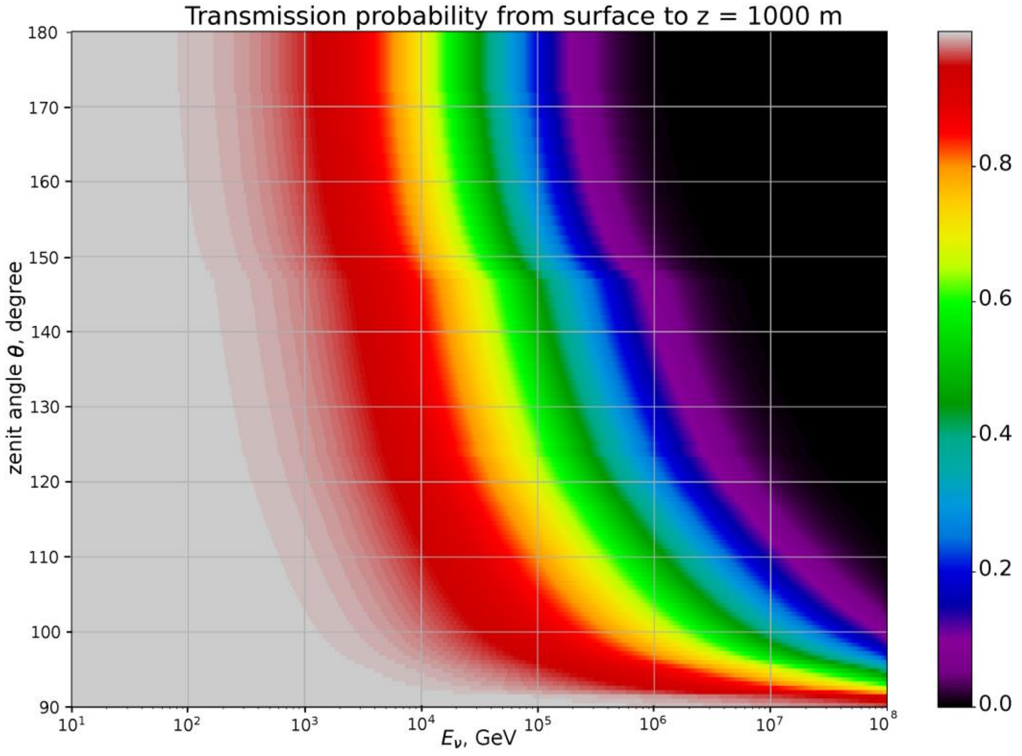
- Also: 4 strings with experimental high-bandwidth DAQ

Baikal-GVD is joining the astrophysical neutrino origin quest

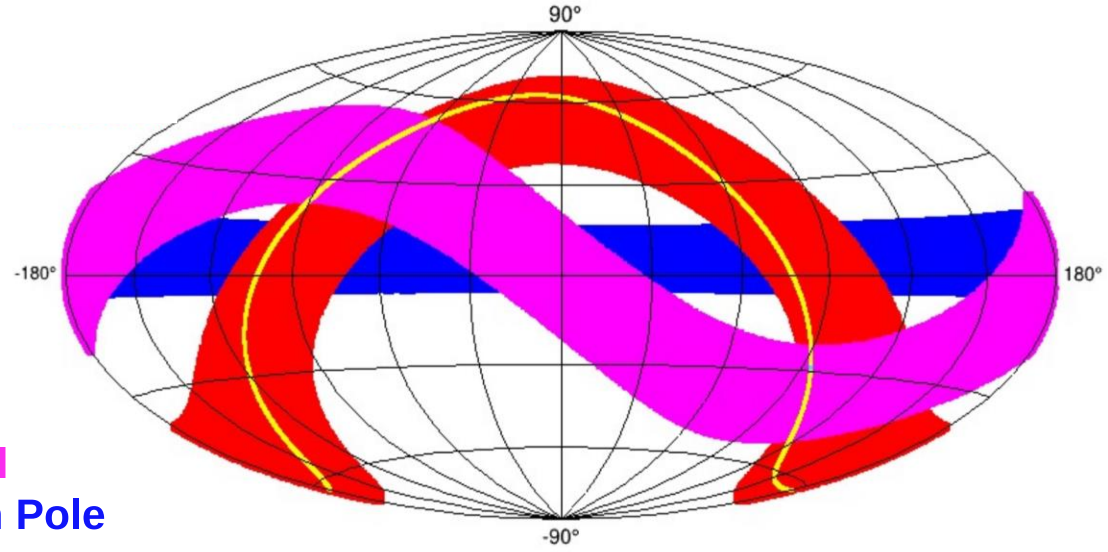
- Telescope performance was validated with the atmospheric neutrino flux observation
- First high-energy events are selected in track-like event analysis
- HE cascade event analysis confirms the diffuse flux observation at the level above 3σ
- Experiment participates in high-energy alert follow-up and alert exchange

Neutrino detection principle

Earth opaqueness increases with increasing energy



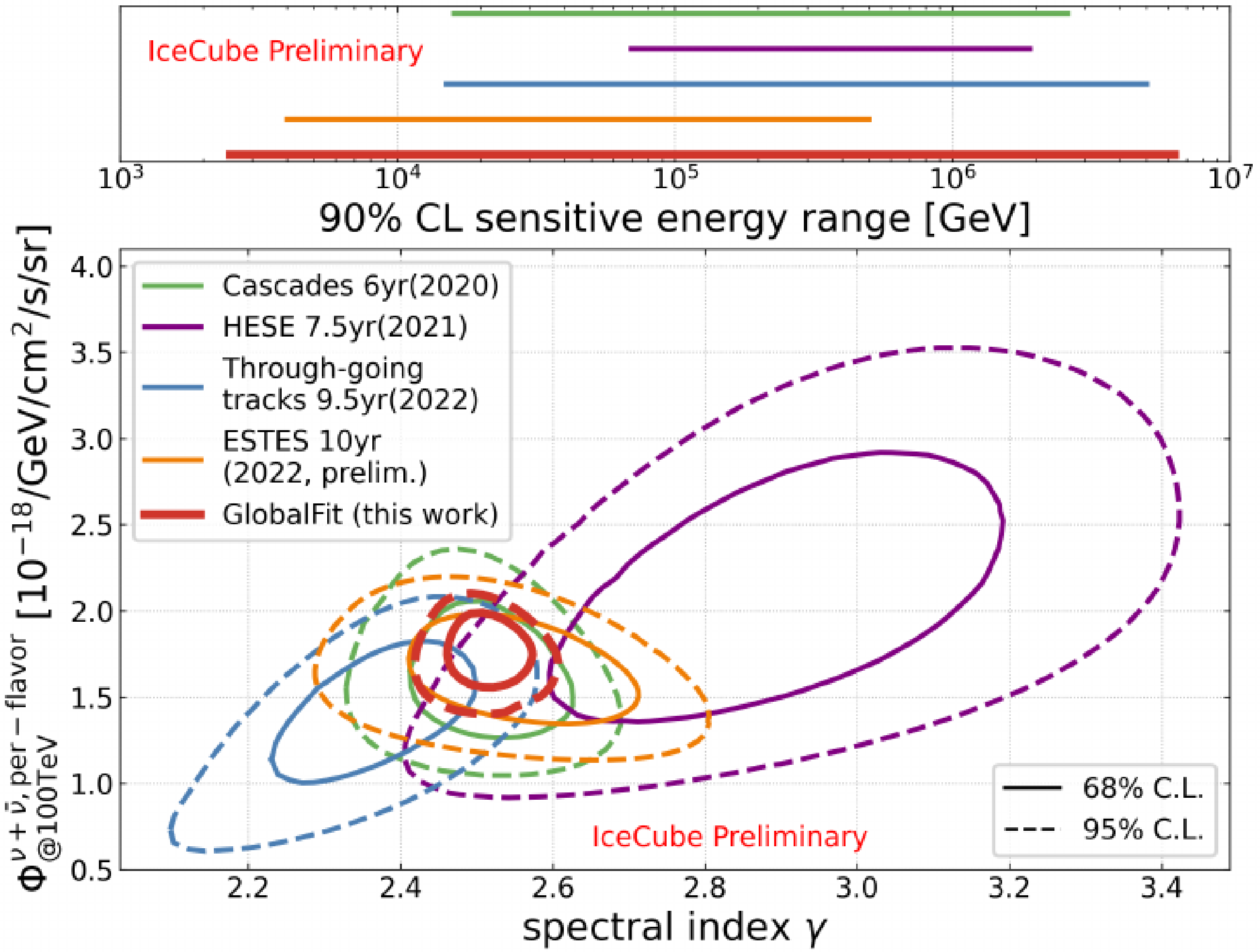
Complimentary maximum sensitivity areas for different telescopes



Baikal
South Pole
Mediterranean

P. Coyle, ICRC2021

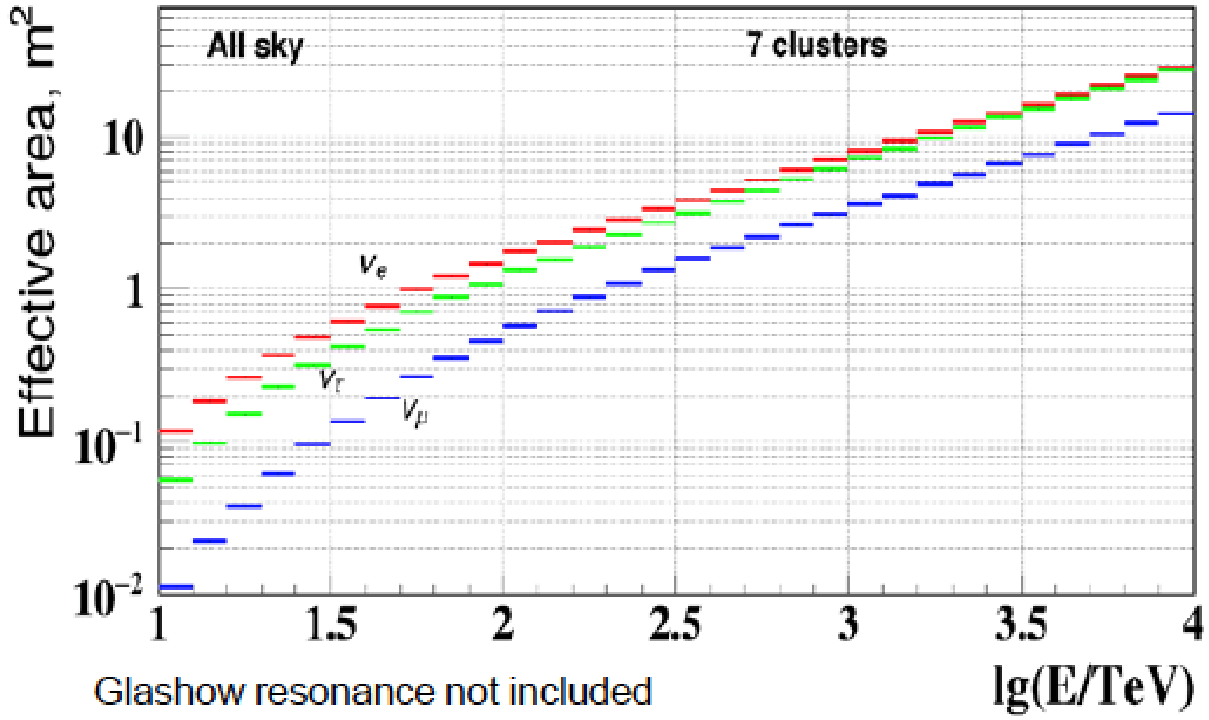
IC global fit
PoS-ICRC2023-1064



Cascade analysis : effective area and rates

Analysis sensitive to all-flavour CC and NC interactions over the whole sky

neutrino effective area for cascade detection

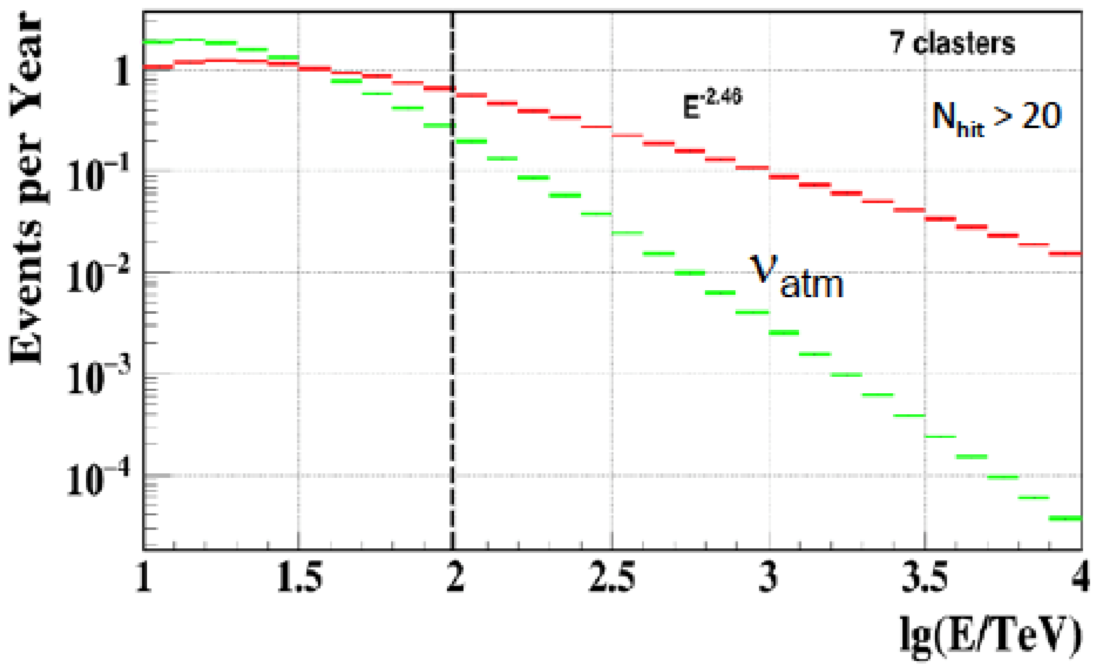


Glashow resonance not included

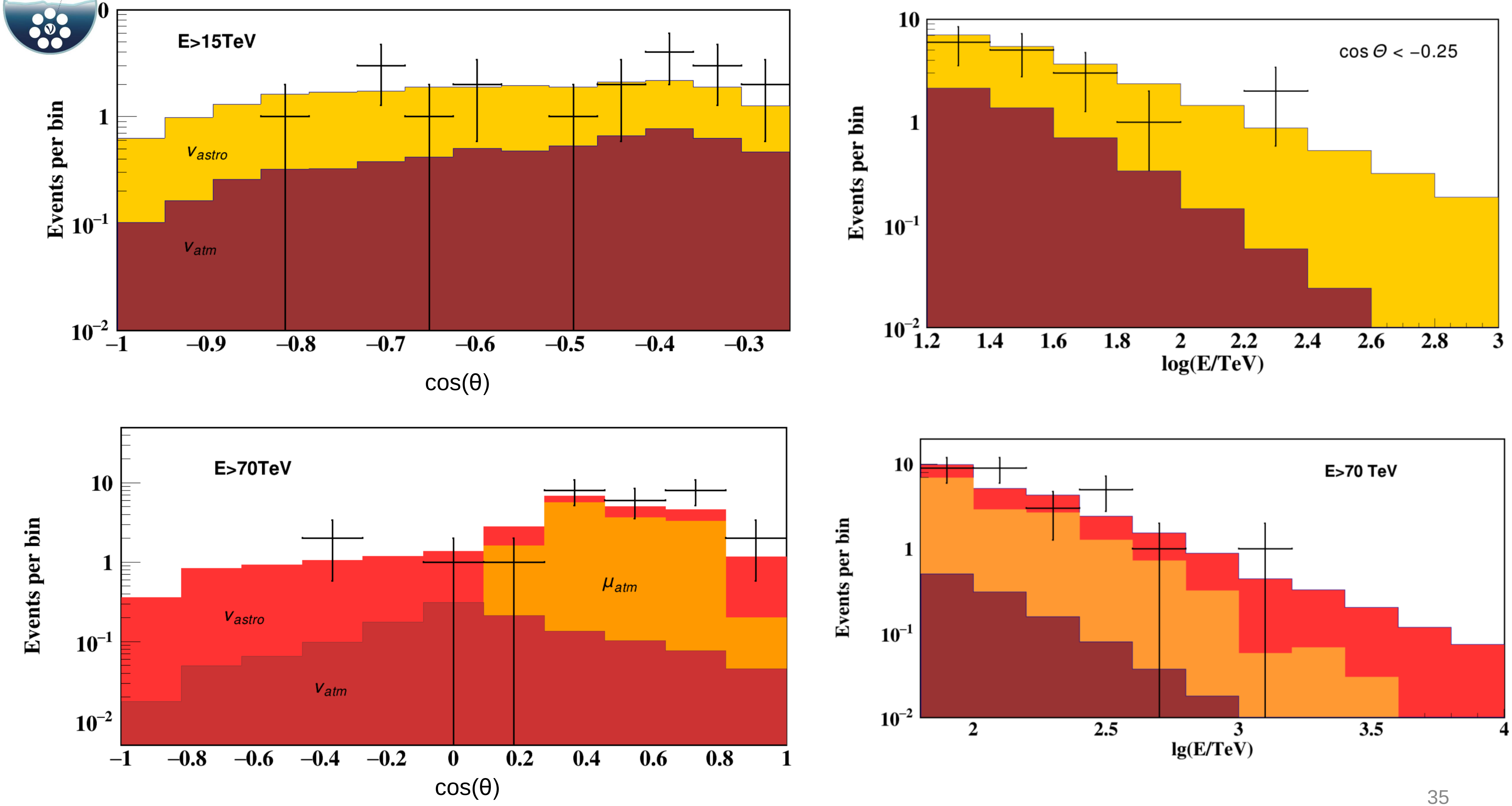
Assumption for astrophysical neutrino energy spectrum (IceCube fit):

$4.1\cdot10^{-6}\ E^{-2.46}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

Expected number of cascade events per year



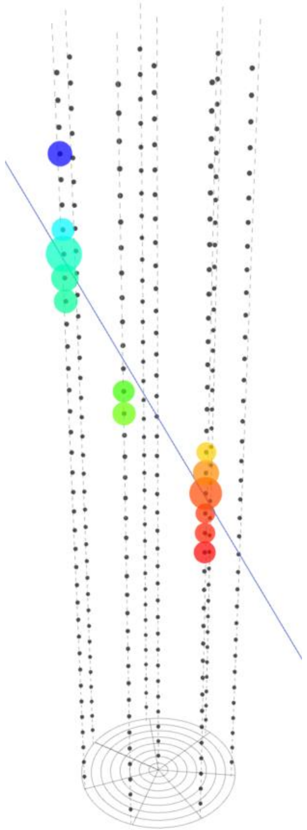
- 3–4 ev/yr with E_{sh} >100 TeV for 7 clusters


E>15TeV
ν_{astro}
ν_{atm}
Events per bin
cos(θ)
cos Θ < −0.25
Events per bin
log(E/TeV)
E>70TeV
ν_{astro}
ν_{atm}
μ_{atm}
Events per bin
cos(θ)
E>70 TeV
Events per bin
lg(E/TeV)

Track-like events

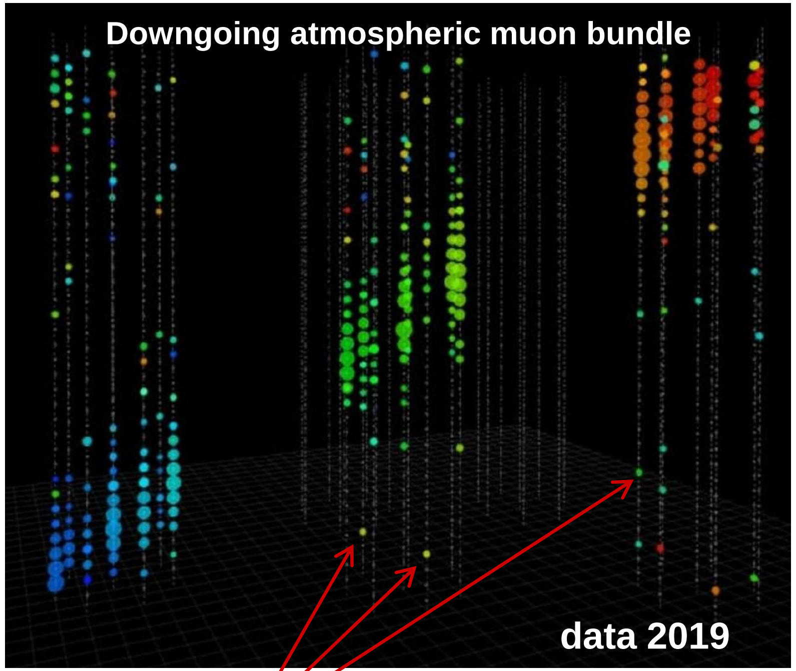
Two modes of analysis
- Single-cluster: each cluster is treated as an independent detector
- Multi-cluster: common reconstruction for simultateously triggered single-cluster events

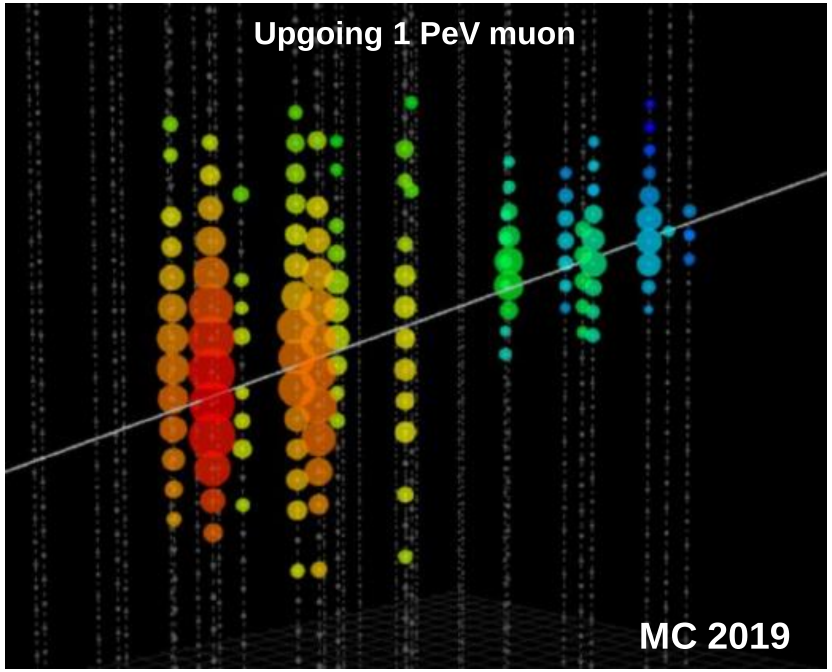
Single-cluster upgoing event:



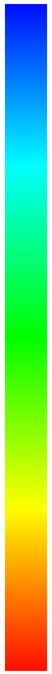
data 2019

Multi-cluster events:





late

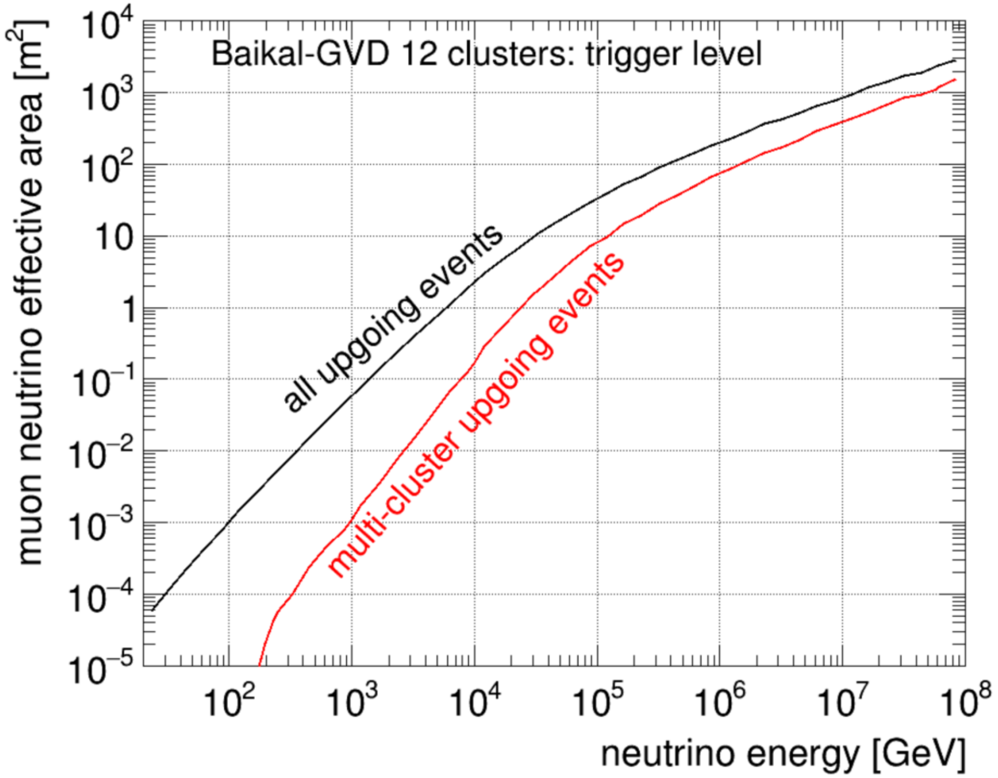


early

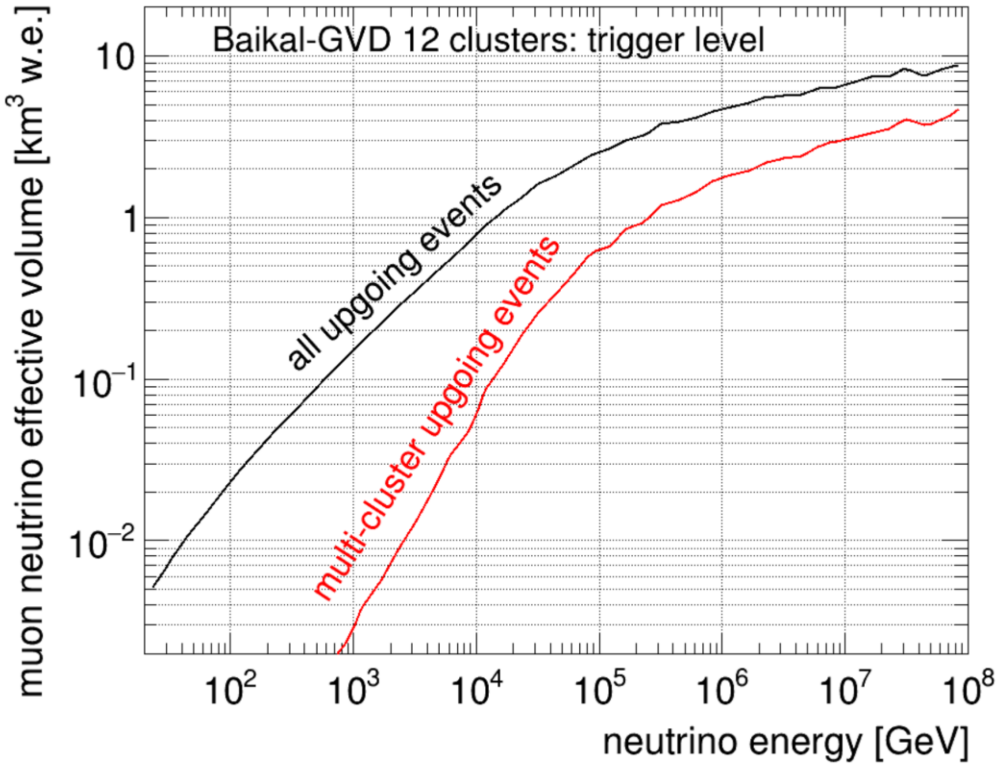
Lake and PMT noise hits

Track trigger-level sensitivity, 12 clusters

Effective area



Effective volume:
measure of sensitive volume



Absorption in Earth is not taken into account

At the reconstruction level sensitivity will be lower (estimation is in progress)

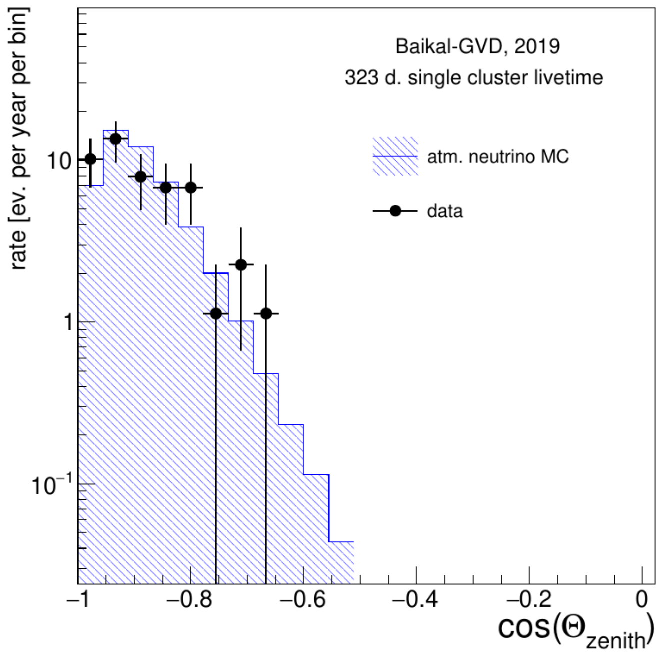
First track-like neutrino candidate event sample

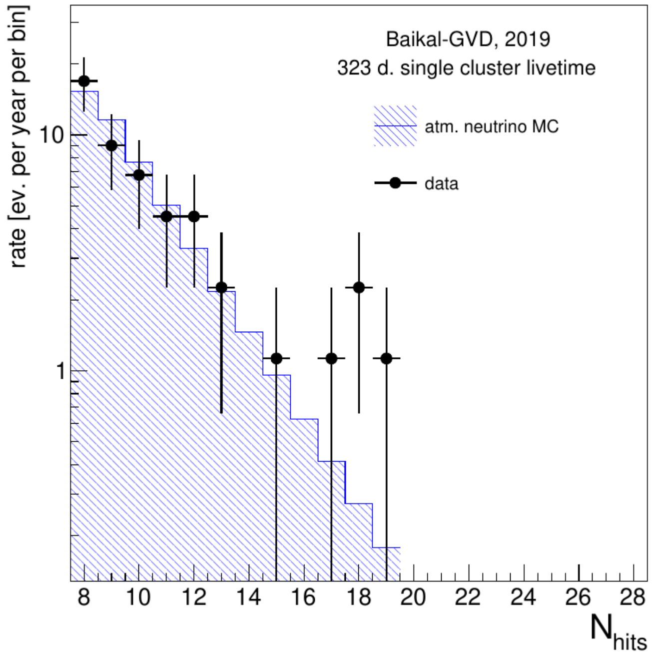
First set of single-cluster muon neutrino candidates based on 2019 data

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, $\langle E_\nu \rangle$ ~ 500 GeV
- Runs from April 1st until June 30th 2019
- Results are compared to atmospheric neutrino simulation

MC expected: 43.6
- atm. neutrino :43.6
- atm. muon: 0

Observed: 44





Excellent agreement of MC expectation and data

[Eur. Phys. J. C 81, 1025 (2021)]

Sucessful Baikal-GVD performance validation

Progress in single-cluster track-like analysis

Large-scale data and MC track channel reprocessing campaign is ongoing

Improved track MC with more detailed detector description
- Switch to CORSIKA 7.741 for muon bundle simulation
- Realistic time-dependent detector configuration

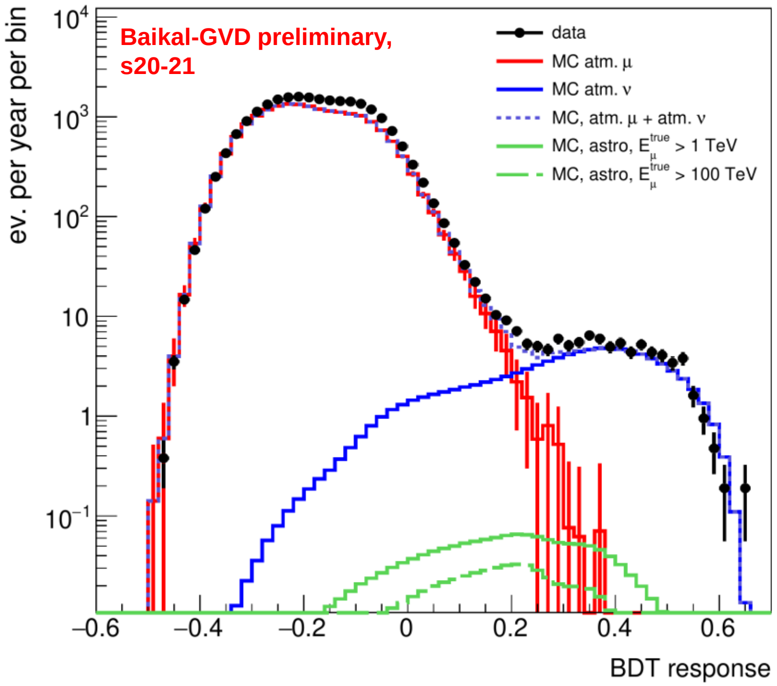
Improved muon reconstruction
- New noise suppression algorithm
- More precise track fit algorithm
- Improved neutrino selection capabilities

Improvement in tools for muon background suppression

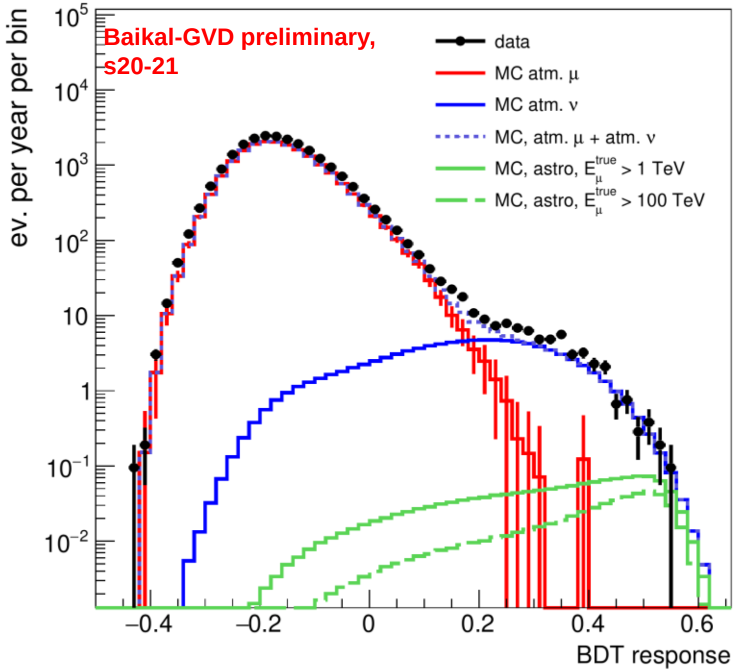
BDT discriminant as a main variable for neutrino selection

Good data-MC agreement
→ background is under control

Low-E BDT



High-E BDT



Increasing ν_μ candidate dataset

Seasons 2020-2021 were reprocessed in single-cluster regime

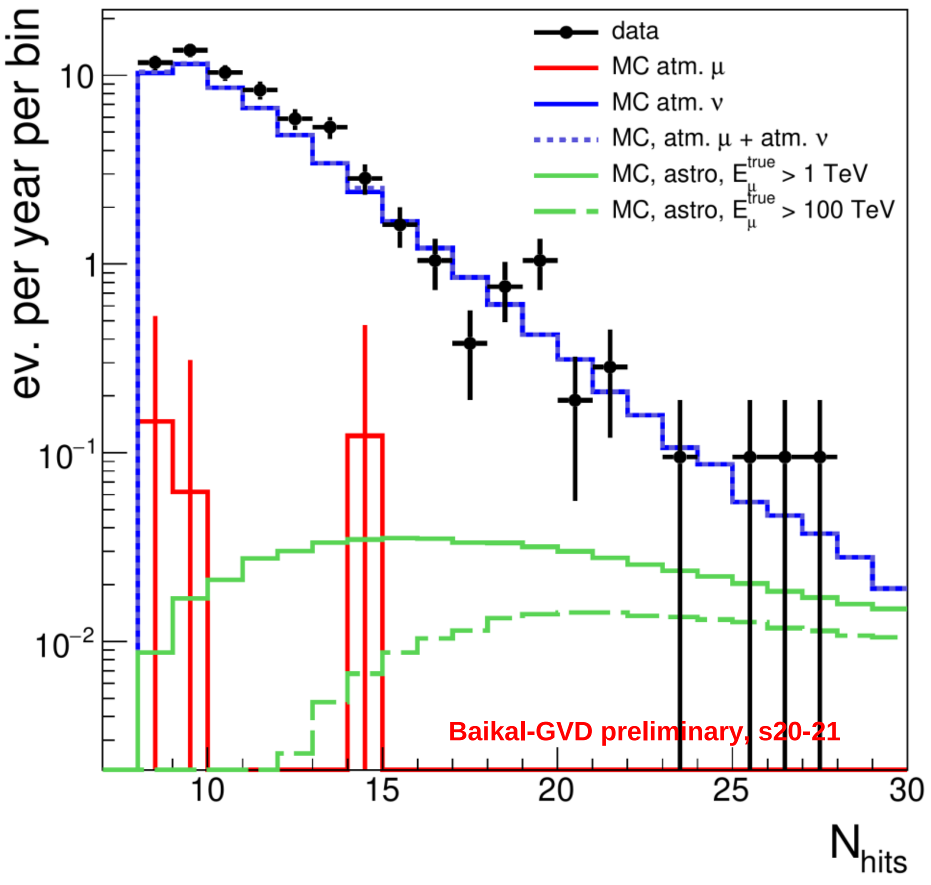
- 3845 days single-cluster livetime equivalent
- Validation of reconstruction results is ongoing
- Optimisation of high-energy ν selection is ongoing

Demonstration sample of ν_μ candidates dominated by atmospheric neutrino

671 neutrino candidates selected in 3845 days

- atm. μ: 3.5
- atm. ν: 565.1
- **data: 671**

Total rate is 15% larger than MC expectation

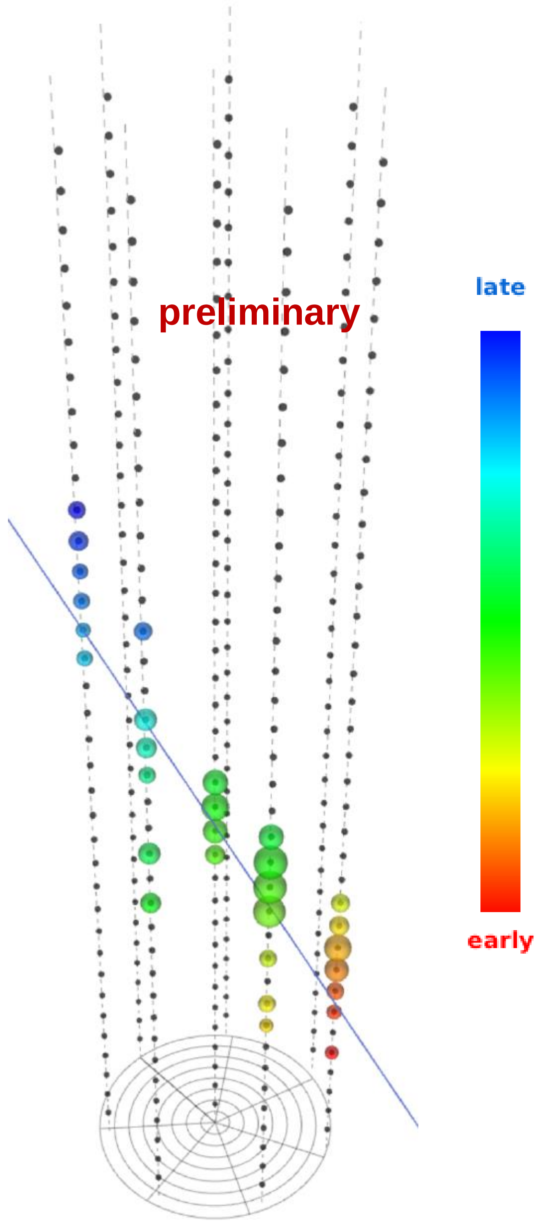


High-energy track event candidate

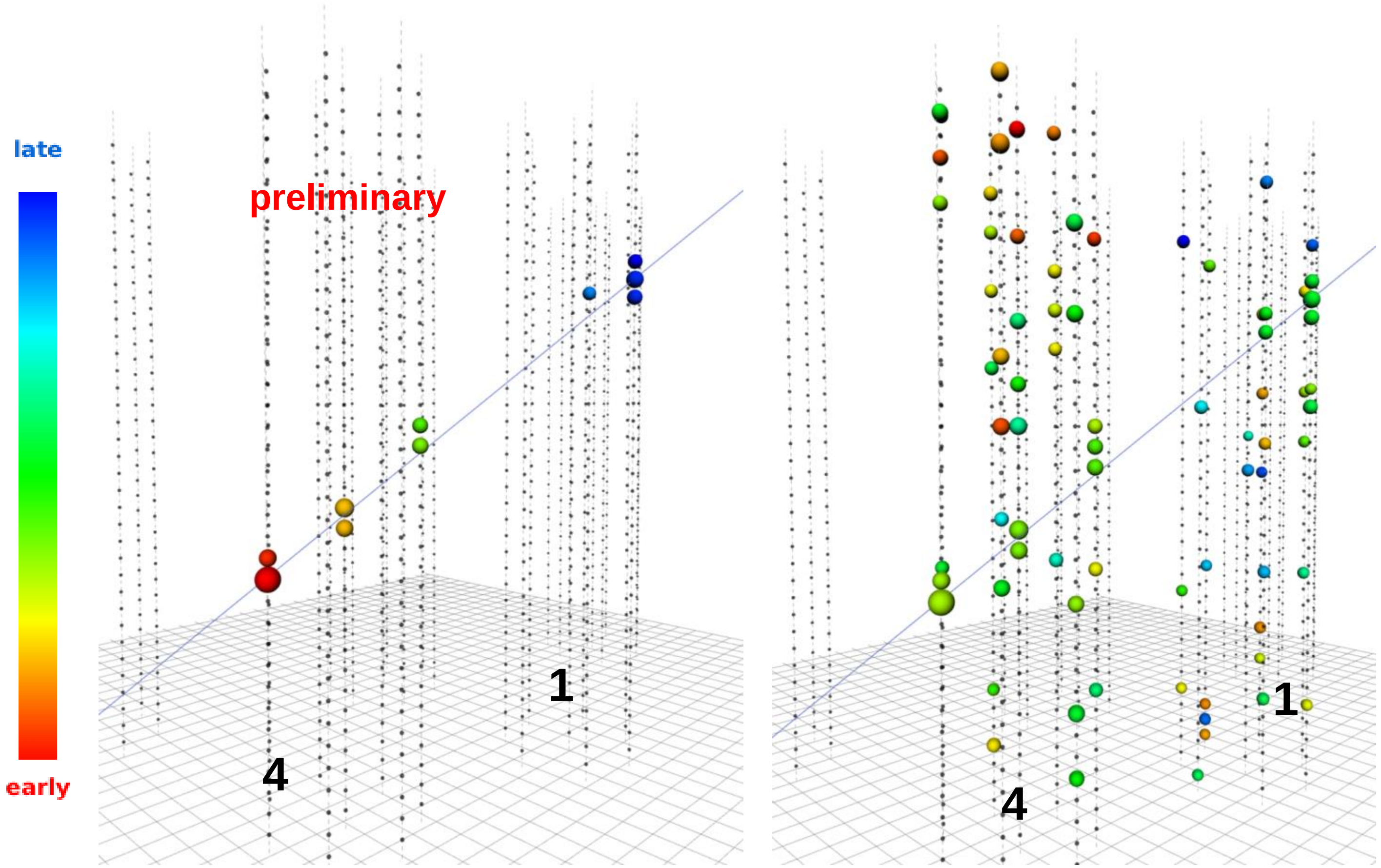
Preliminary: spectacular single-cluster event
with high probability of astrophysical origin

Season 2019, Cluster 3, run 590
θ_z = 153.4°
N_{hits} = 30
E_{rec} = 103.4 TeV
[68% CI: 24.9<E<266.3 TeV]
Track length: 332.4 m

Angular resolution: 0.45° (50%)
0.67° (68%)



Track-like multi-cluster analysis



selected hits | all hits in the event

Track-like multi-cluster analysis unlocks the full Baikal-GVD potential in angular resolution

First multi-cluster neutrino candidate events start to appear

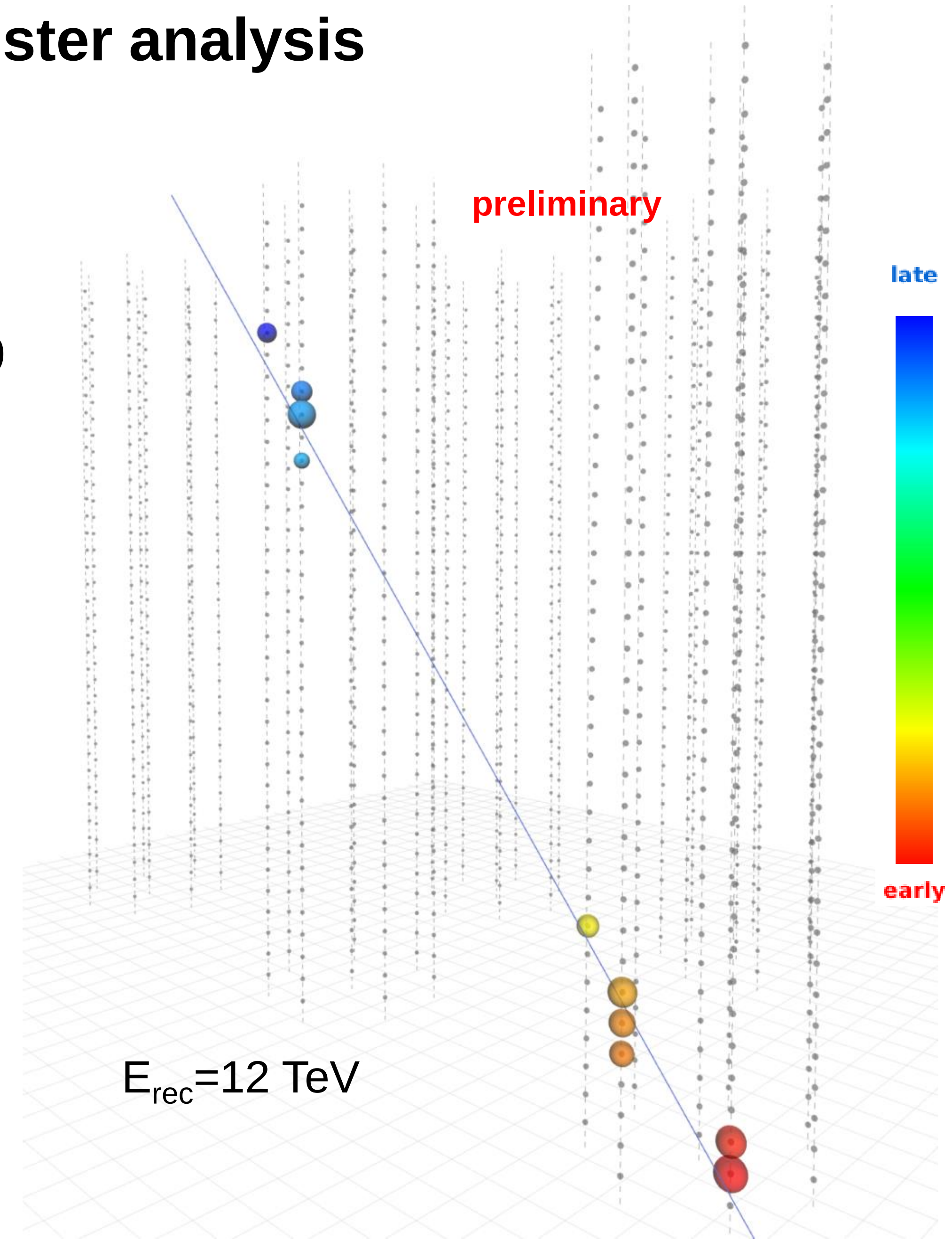
Example of ν candidate event:

Summer 2019
Clusters 1 & 4
θ_z = 125.6°
N_{hits} = 10
track length = 399 m
E_{rec} < 1TeV

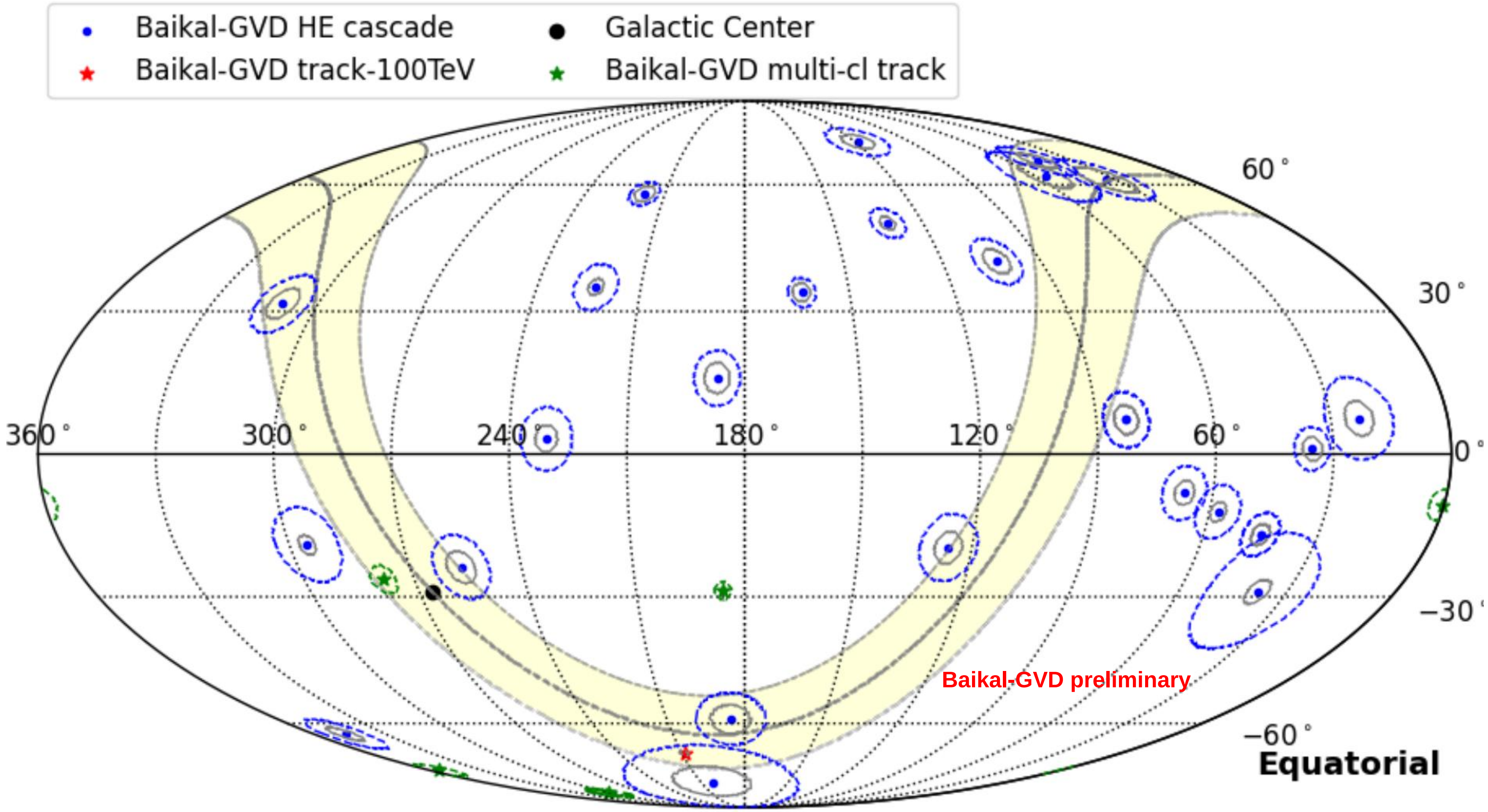
Track-like event multi-cluster analysis

In total 5 ν candidates selected from 150 days of 2019
(5-cluster detector)
Dominated by atmospheric neutrino

Multi-cluster analysis is in the development phase



Track-like events skymap



Multi-cluster neutrino candidate events, very preliminary, **dominated by atmospheric events**

Single cluster 100 TeV event - high probability of astrophysical origin

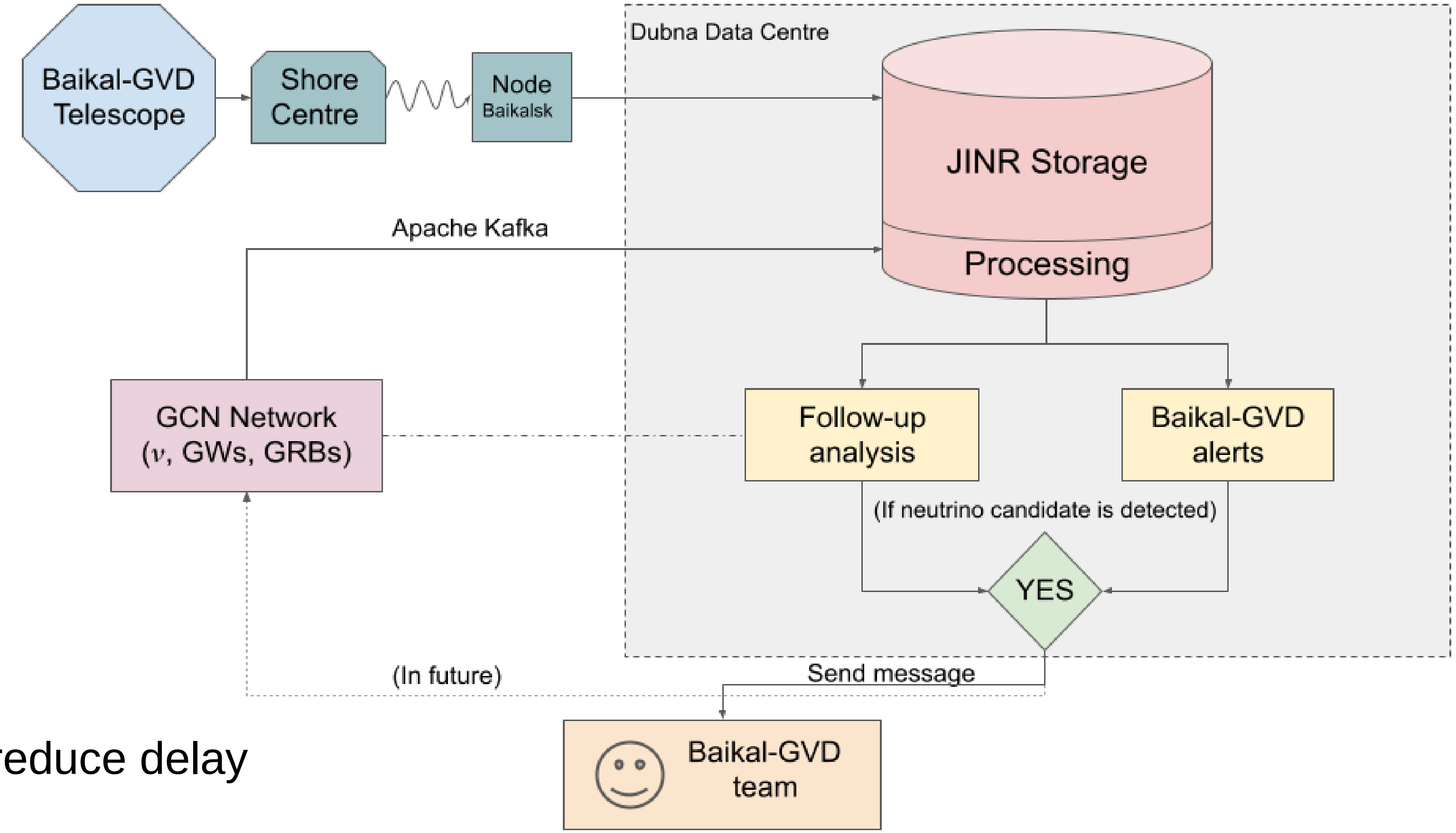
Alert program

Alert workflow

Getting ready to full-scale participation in real-time multi-messenger alert exchange

Automated alert generation and follow-up system

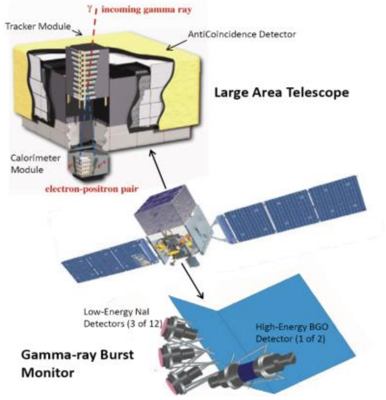
- Baikal-GVD alerts: distribution of our own alerts for events with high probability of astro origin
- Follow-up: follow-up analysis of external alert events



Baikal-GVD alert generation

- Simplified extrapolated calibrations
- Processing delay 3-10 minutes
- Planned to be deployed at the shore to reduce delay
- Presently internal distribution of alerts

Global Coordinate Network (GCN) alert follow-up



Fermi-GBM/LAT:

[T0 - 1 day,T0],
[T0 - 1 day, T0 + 12 hours],
[T0 - 1 day, T0 + 1 day]

LIGO-Virgo-KAGRA:

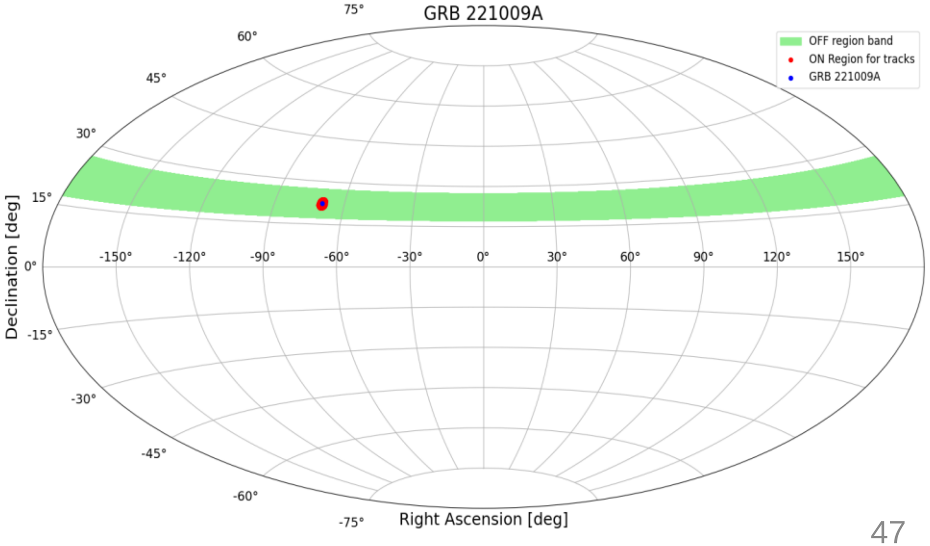
IGWN reception: “significant” = 1
[T0 - 1000 s, T0 + 1000 s],
[T0 - 1000s, T0 + 14 days]

IceCube:

[T0 - 1 h, T0 +1 h]
[T0 - 1 day, T0 +1 day]

Search for online coincidences:

- ON/OFF method
- ON includes 90% localization error and Baikal-GVD median angular resolution
- OFF is extended within a ± 5 declination band
- OFF is evaluated using real data from previous seasons

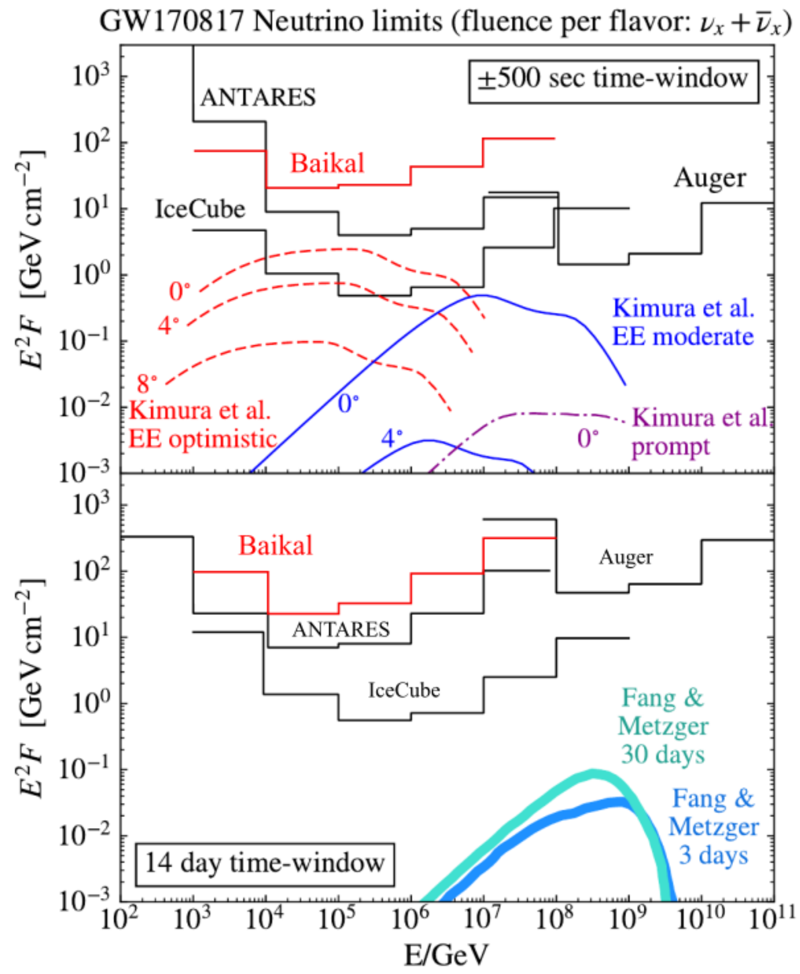


Multi-messenger follow-ups

Baikal-GVD follows reported multimessenger high-energy events, e.g.:

GW170817 (LIGO/VIRGO) - neutron star merger, first gravitational waves detection associated with γ/optical/radio signal: time-integrated flux (fluence) limit is set

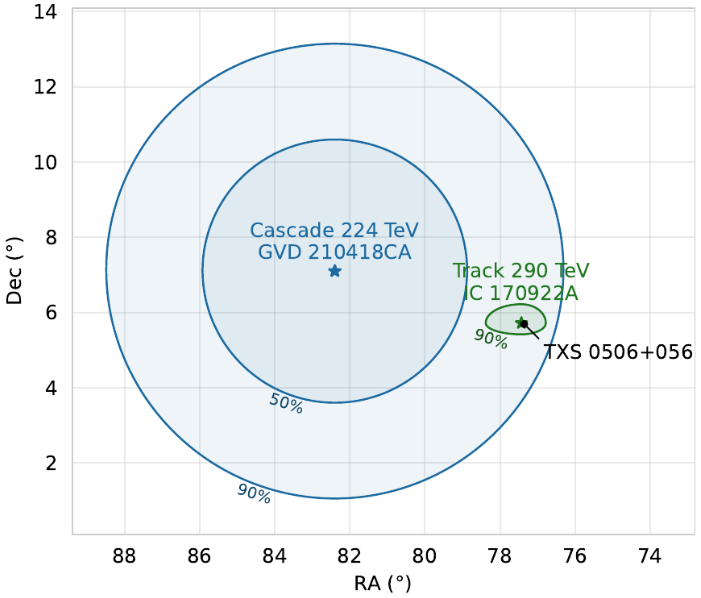
[Phys. ReV. Lett. 119, 161101]
[JETP Letters, v.108, issue 12]



Radio-burst from magnetar **SGR 1935+2154** (28.04.20)

- IceCube fluence limit: 5.2*10^{-2} GeV*cm^{-2}
- ANTARES fluence limit: 14 GeV*cm^{-2}
- Baikal-GVD fluence limit: 2 GeV*cm^{-2} [PoS(ICRC2021)946]

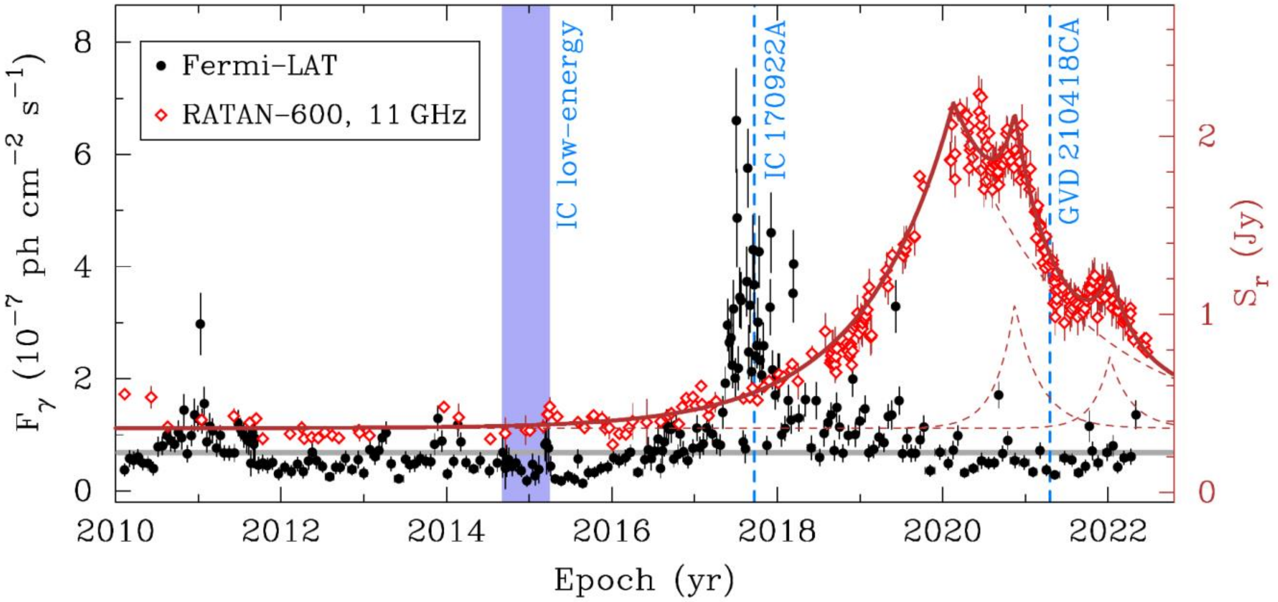
Cascades: TXS0506 coincidence



[MNRAS 527 (2024) 8784]

Upgoing cascade analysis, highest energy event (18.04.2021):

- 224 TeV, 24 hits
- Neutrino source candidate TXS 0506+056 is within 90% containment circle
- Signalness: 97.1% (probability of astro origin)
- Chance coincidence probability (E>200 TeV): 0.0074



Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

- IC event registered during γ flare
- Baikal event during radio flare
- Consistency with IC observations: 8% or 13% depending on ν spectrum assumption