Baikal-GVD neutrino telescope: status and results

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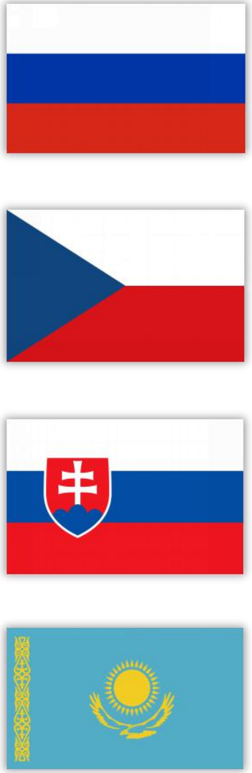
for the Baikal-GVD collaboration

QUARKS 2024, Peryaslavl-Zalessky, May 19-24 2024

Baikal-GVD neutrino telescope

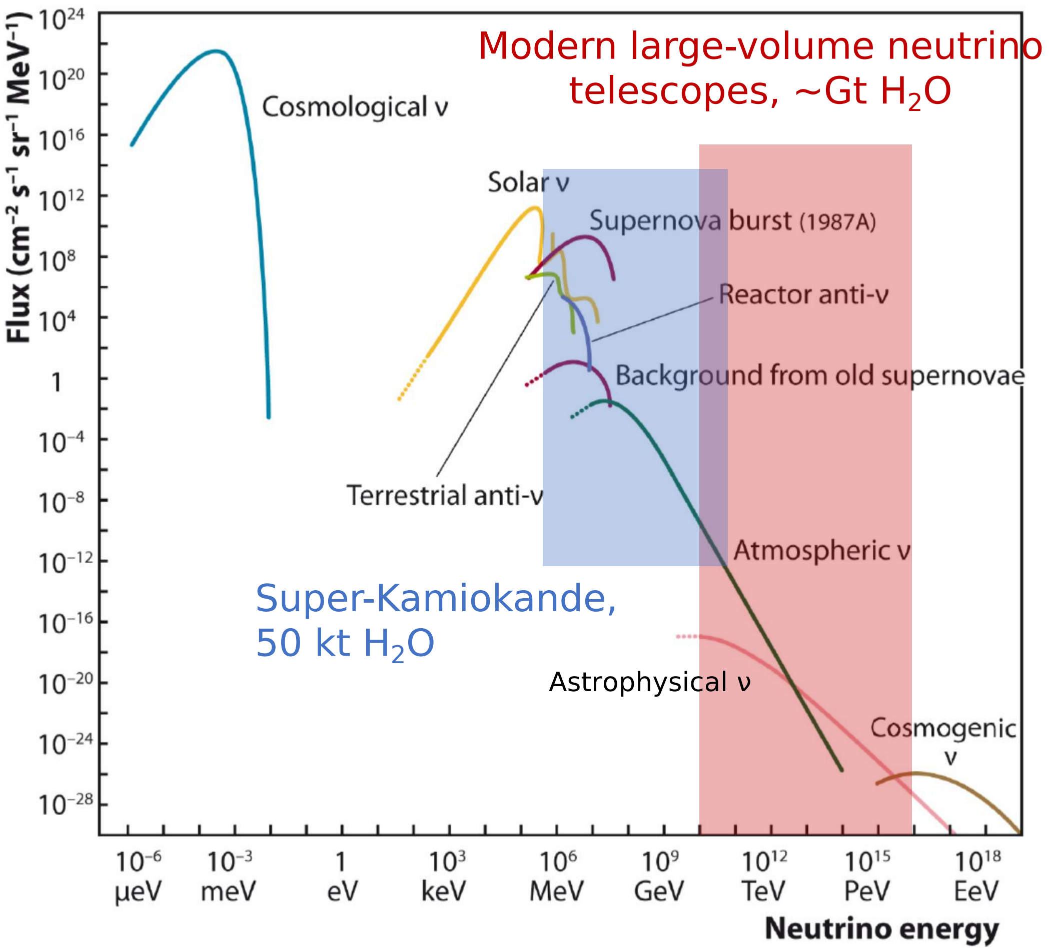
The Baikal-GVD (Gigaton Volume Detector) is a cubic-kilometer scale underwater neutrino detector being constructed in Lake Baikal

11 organisations from 4 countries, ~60 collaboration members



- Institute for Nuclear Research RAS (Moscow)
- Joint Institute for Nuclear Research (Dubna)
- Irkutsk State University (Irkutsk)
- Skobeltsyn Institute for Nuclear Physics MSU (Moscow)
- Nizhny Novgorod State Technical University (Nizhny Novgorod)
- Saint-Petersburg State Marine Technical University (Saint-Petersburg)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- LATENA (St. Petersburg)
- INFRAD (Dubna)
- Comenius University (Bratislava, Slovakia)
- Institute of Nuclear Physics ME RK (Almaty, Kazakhstan)

Physics motivation



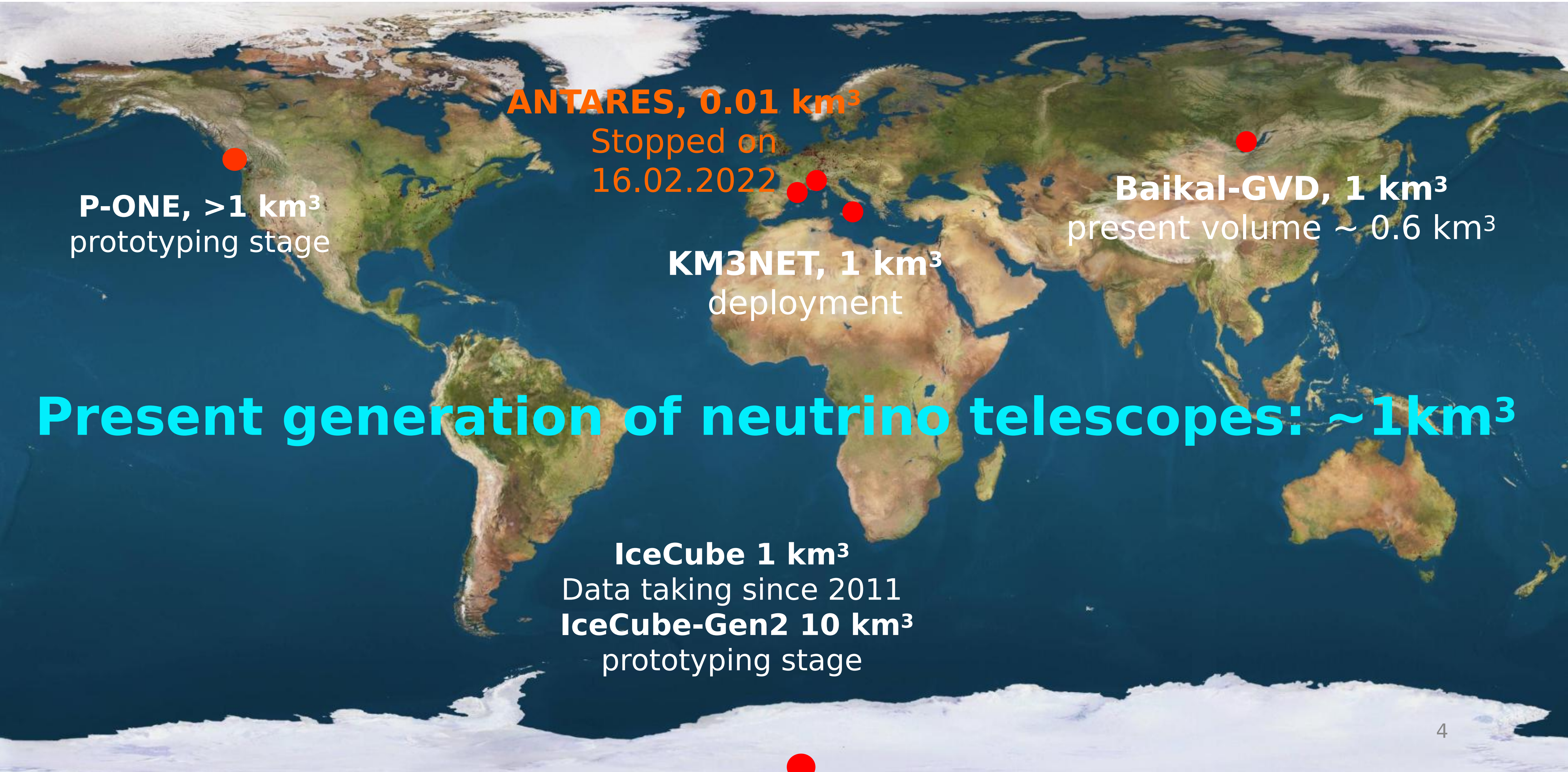
The primary goal of large-volume neutrino telescopes like Baikal-GVD if the study of high-energy (TeV - PeV) neutrino flux

High-energy (HE) neutrinos are produced in cosmic-ray pp or pγ interactions

- In Earth atmosphere
- In the vicinity of the remote powerful acceleration sites
- Along the CR path

Astrophysical HE neutrinos do not loose energy or deviate and can provide direct probe of particle energy scale near identified remote source

Neutrino telescope network



Detection principle

Sparse array of photodetectors in natural water(ice) reservoir

Cerenkov light from charged particle produced in neutrino interaction is detected

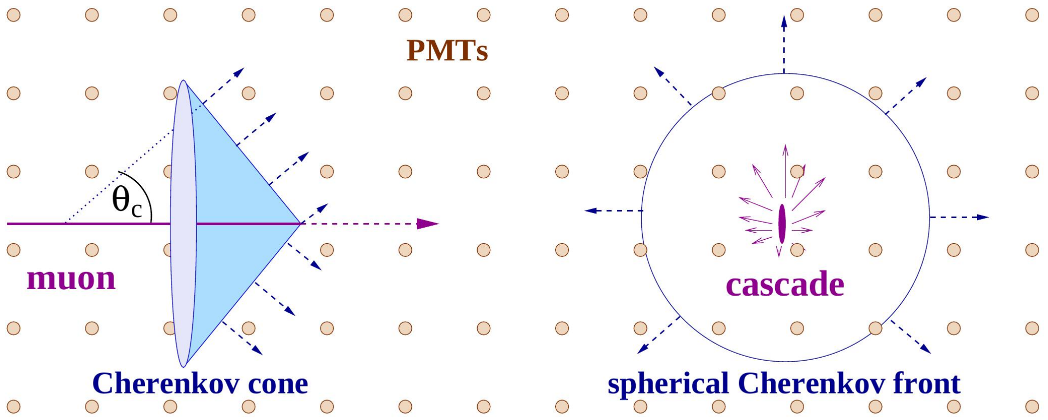
Neutrino event types:

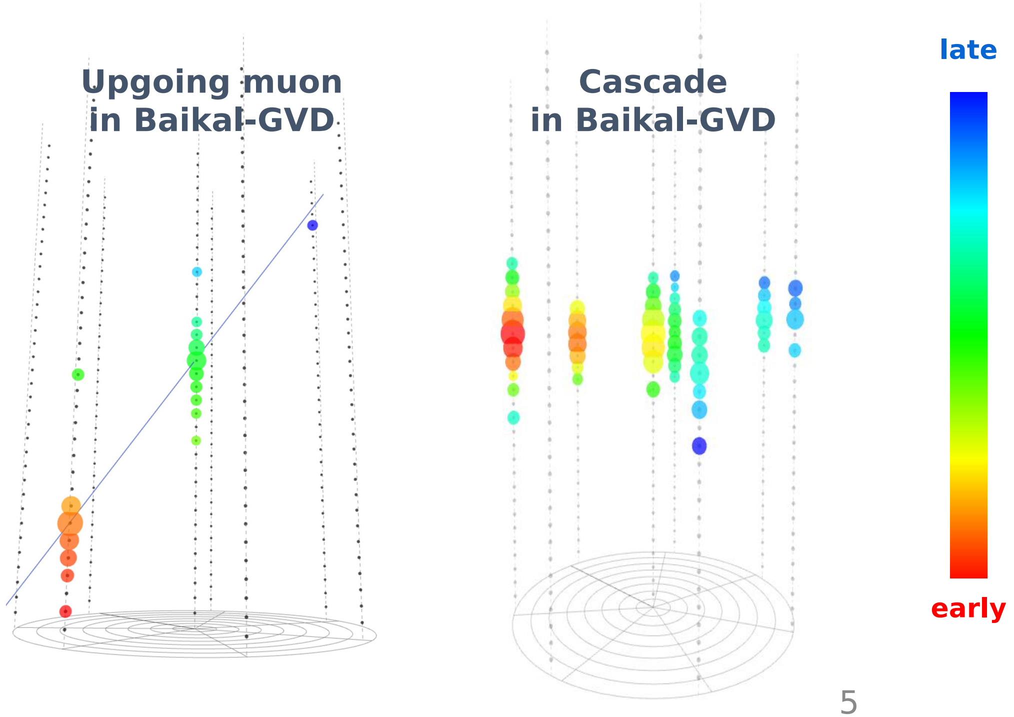
Tracks (CC, ν_μ ν_τ):

- 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%

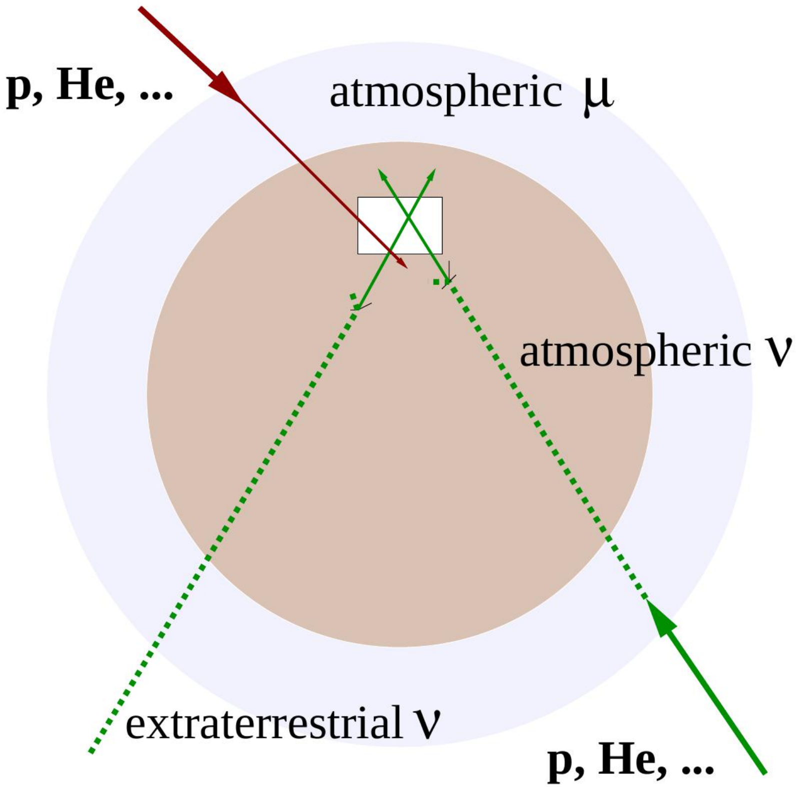


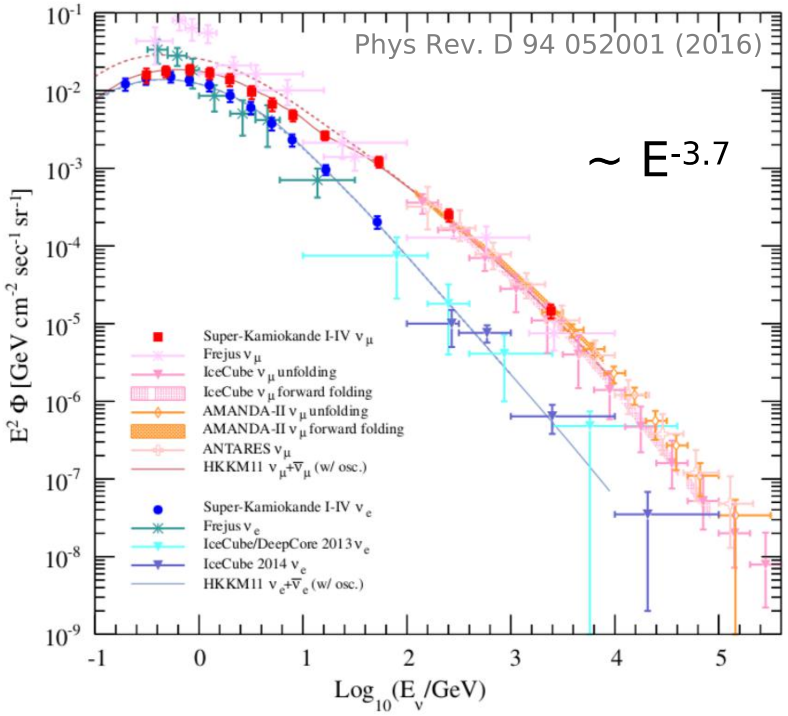


Backgrounds

Atmospheric muons: bundle of downgoing muons from CR interaction
- Background to all neutrino events
- Upgoing events have orders of magnitude less background

Atmospheric neutrino: neutrino from CR interaction
- “Standard candle” for neutrino telescope performance
- Background to astrophysical searches



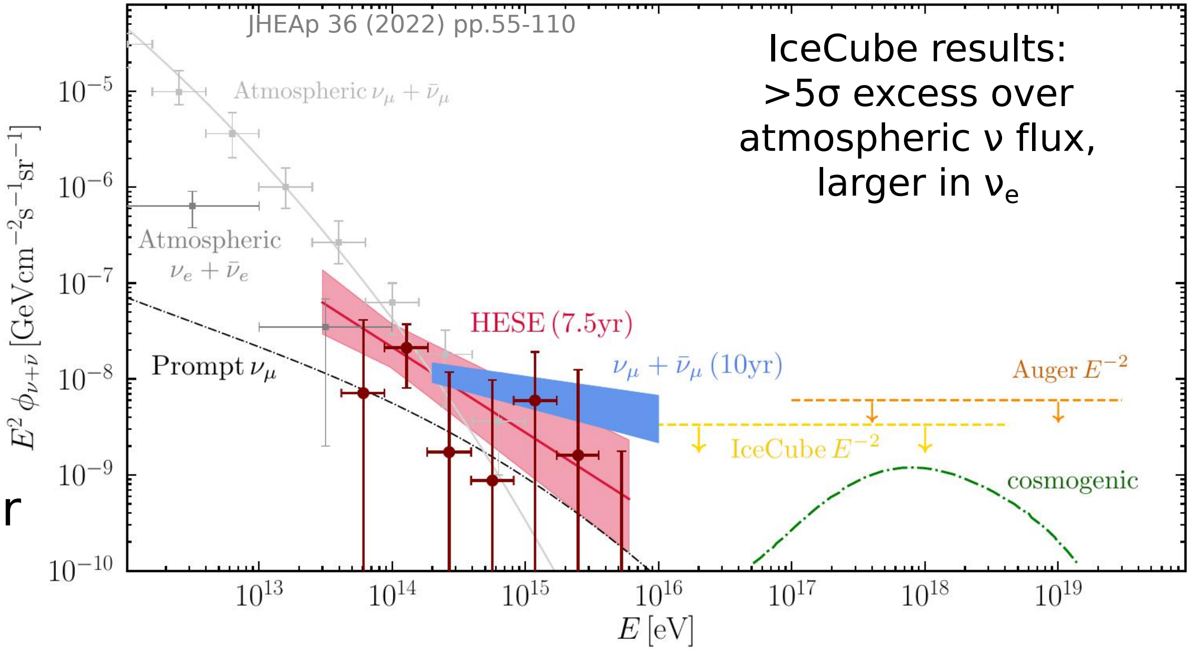


Atmospheric neutrino
are dominated by ν_μ for E_ν > ~10 GeV

Astrophysical neutrino diffuse flux:
- An excess in neutrino events over the atmospheric neutrino spectrum
- Usually larger significance in cascade channel

HE neutrino astrophysics key experimental results

The presence of TeV - PeV diffuse astrophysical neutrino flux is established by the IceCube telescope with significance well above 5σ (e.g. **[Astrophys.J. 928 (2022) 50]**)



ANTARES diffuse flux significance 1.8σ
[PoS(ICRC2019)891]

No neutrino source is established above 5σ so far

However:

- Blazar TXS 0506: **3.5σ** **[Science 361, 147-151 (2018)]**
- Seyfert II galaxy NGC 1068: **4.1σ** **[Science 378, 6619, 538-543 (2022)]**
- Diffuse flux from galactic plane: **4.5σ** **[Science 380, 6652, 1338-1343 (2023)]**

>90% of astrophysical neutrino flux remains unexplained

Deployment of new telescopes is crucial to resolve the diffuse flux origin problem
Complimentary field of view for projects at different locations

The Baikal-GVD detector

Location

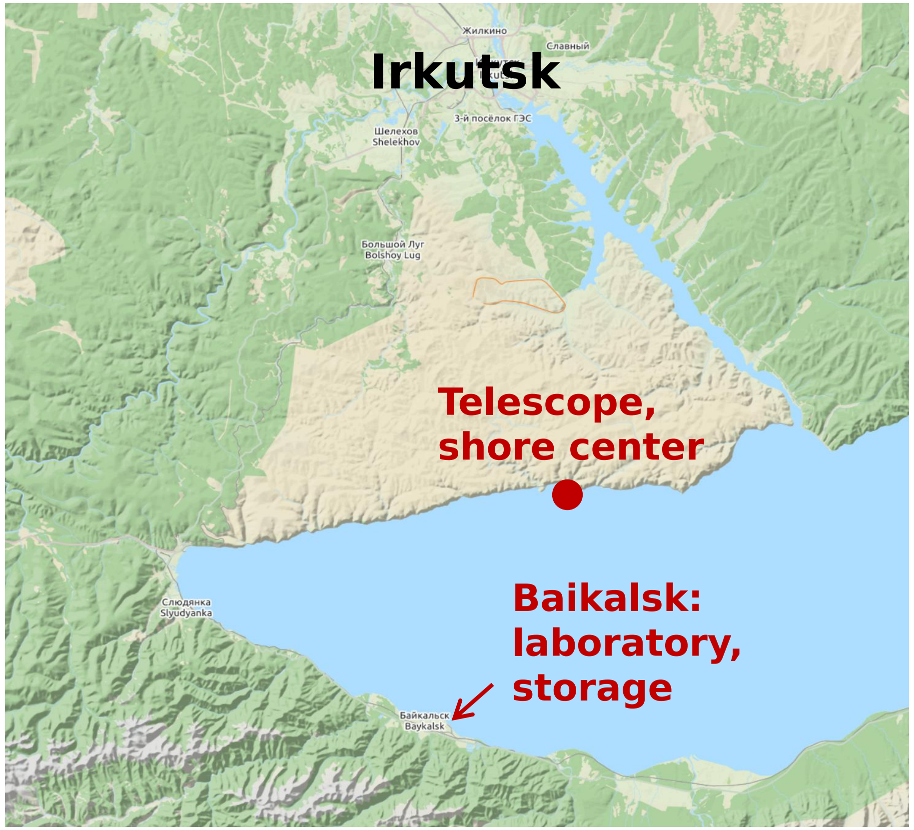
Platform “Ivanovskaya” of Circum-Baikal railway

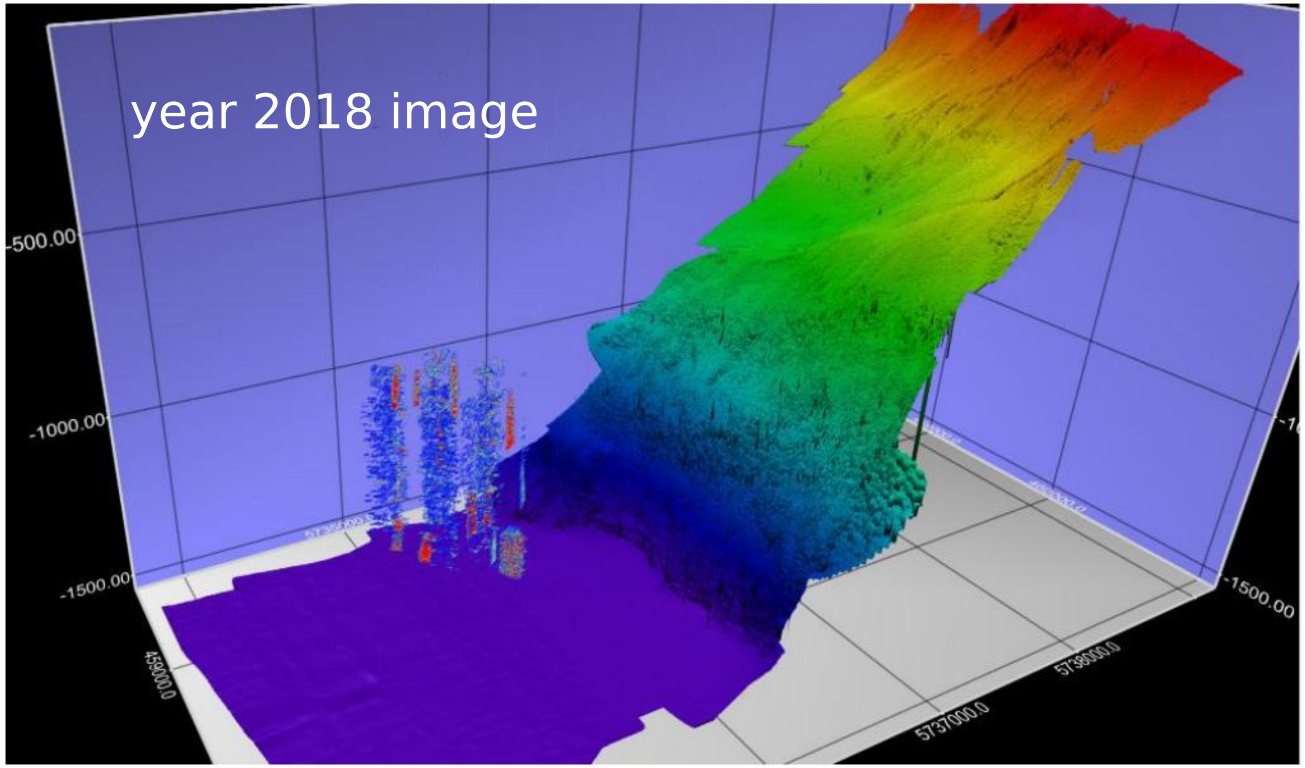
Telescope is located 3.6 km away from shore

Constant lake depth: 1366 - 1367 m

Water transparency:
- Absorption length: 21 - 23 m
- Scattering length: 60 - 80 m

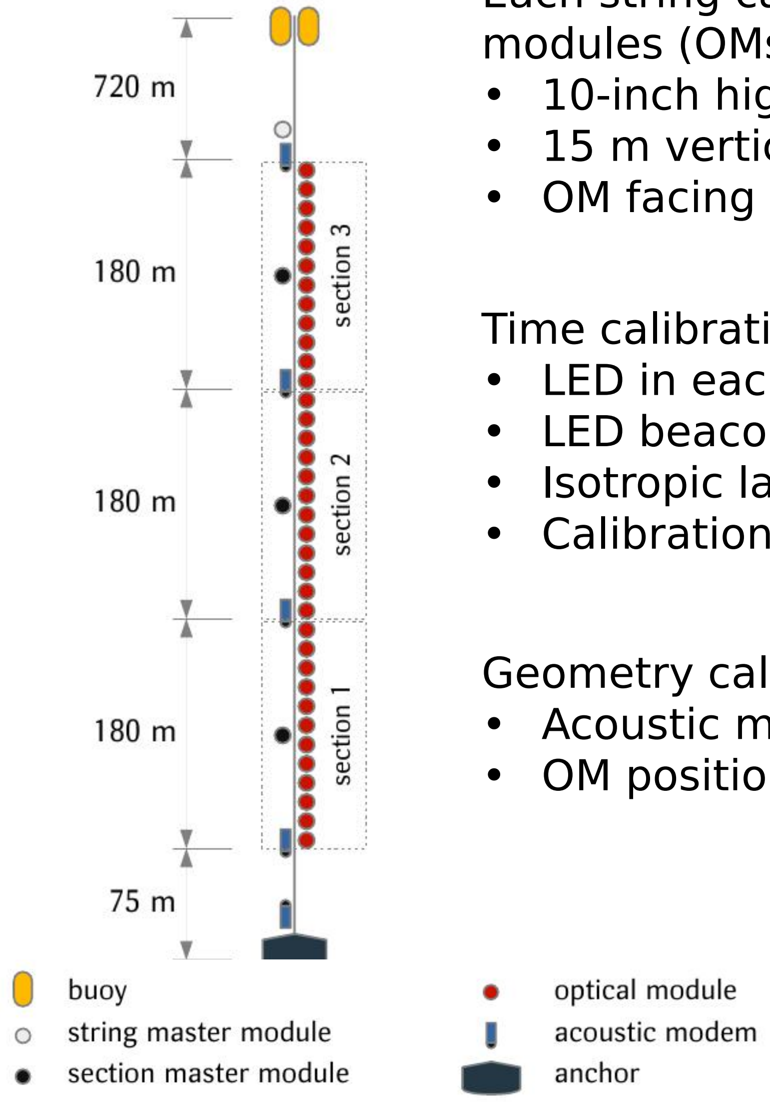
Stable ice cover over 7 - 8 weeks in February - April: detector deployment and maintenance





Basic components

String:

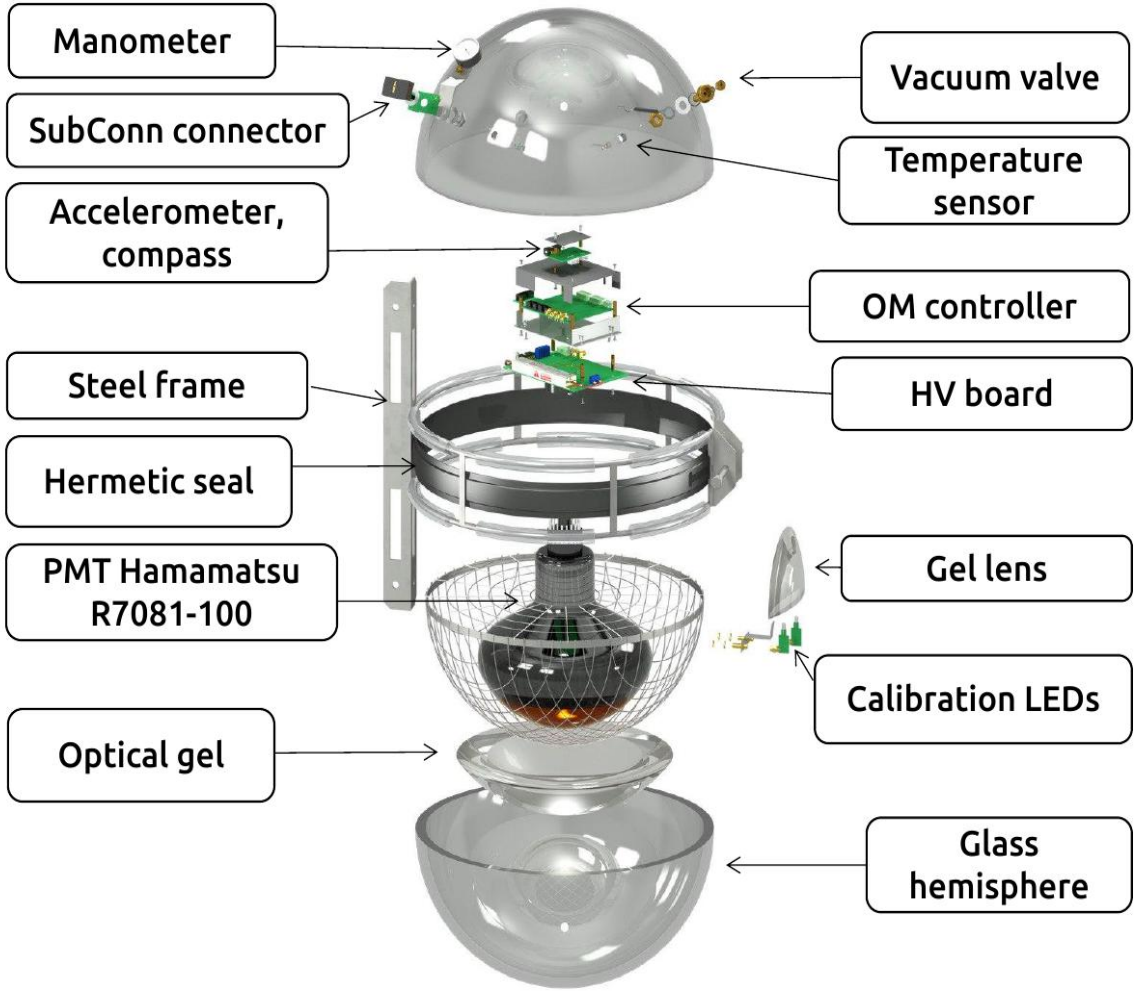


Each string carries 36 optical modules (OMs)
- 10-inch high Q eff. PMT
- 15 m vertical spacing
- OM facing the lake bottom

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):

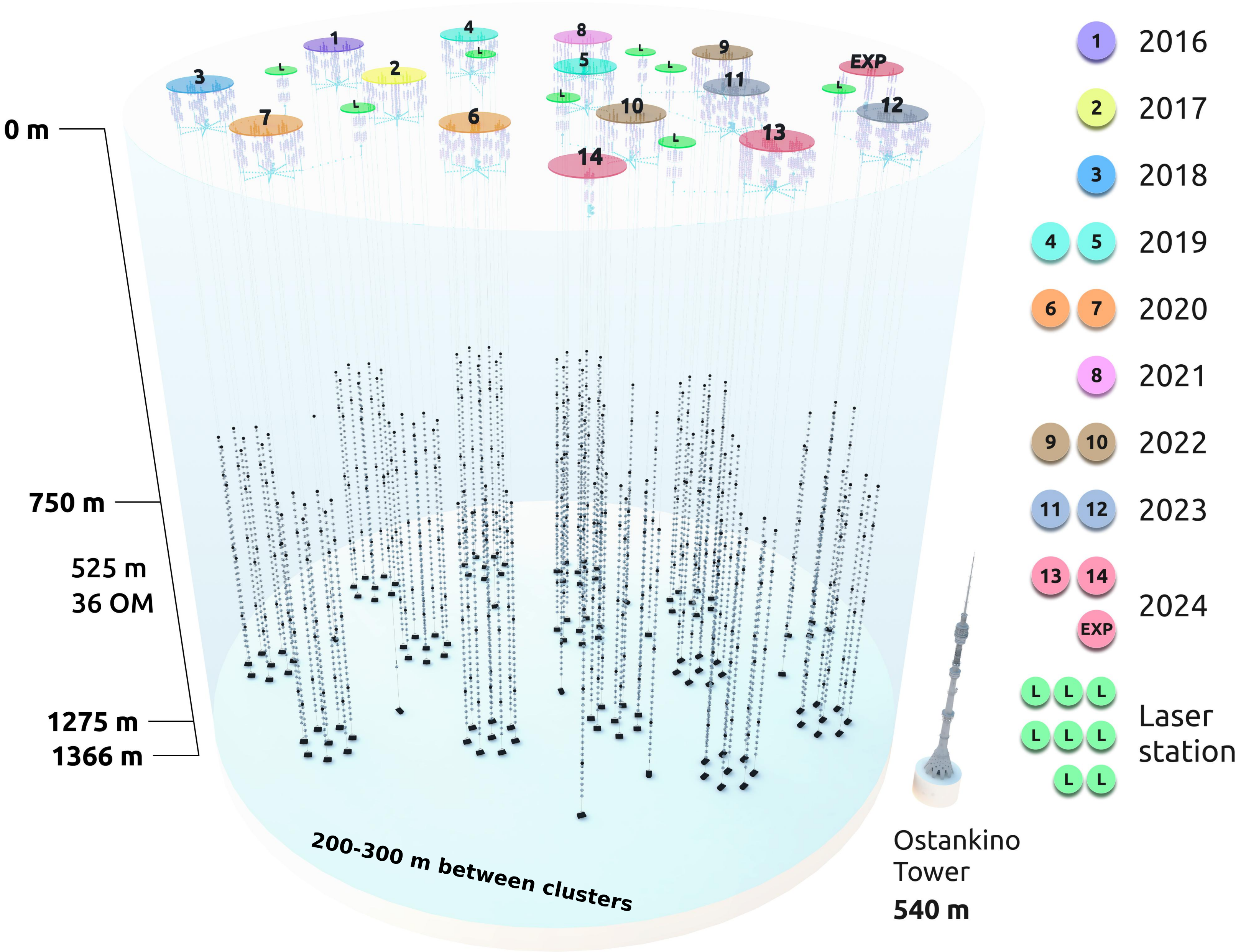


Detector status

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

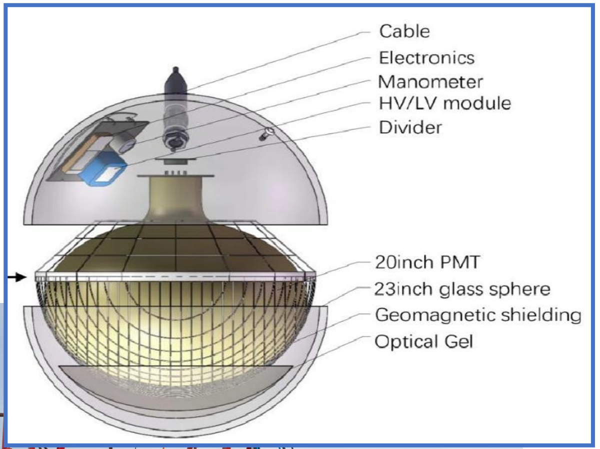
Additional cluster “EXP”:
- 4 strings with experimental high-speed DAQ



Expedition 2024

Succesfull 2024 deployment campaign 16/02 - 07/04

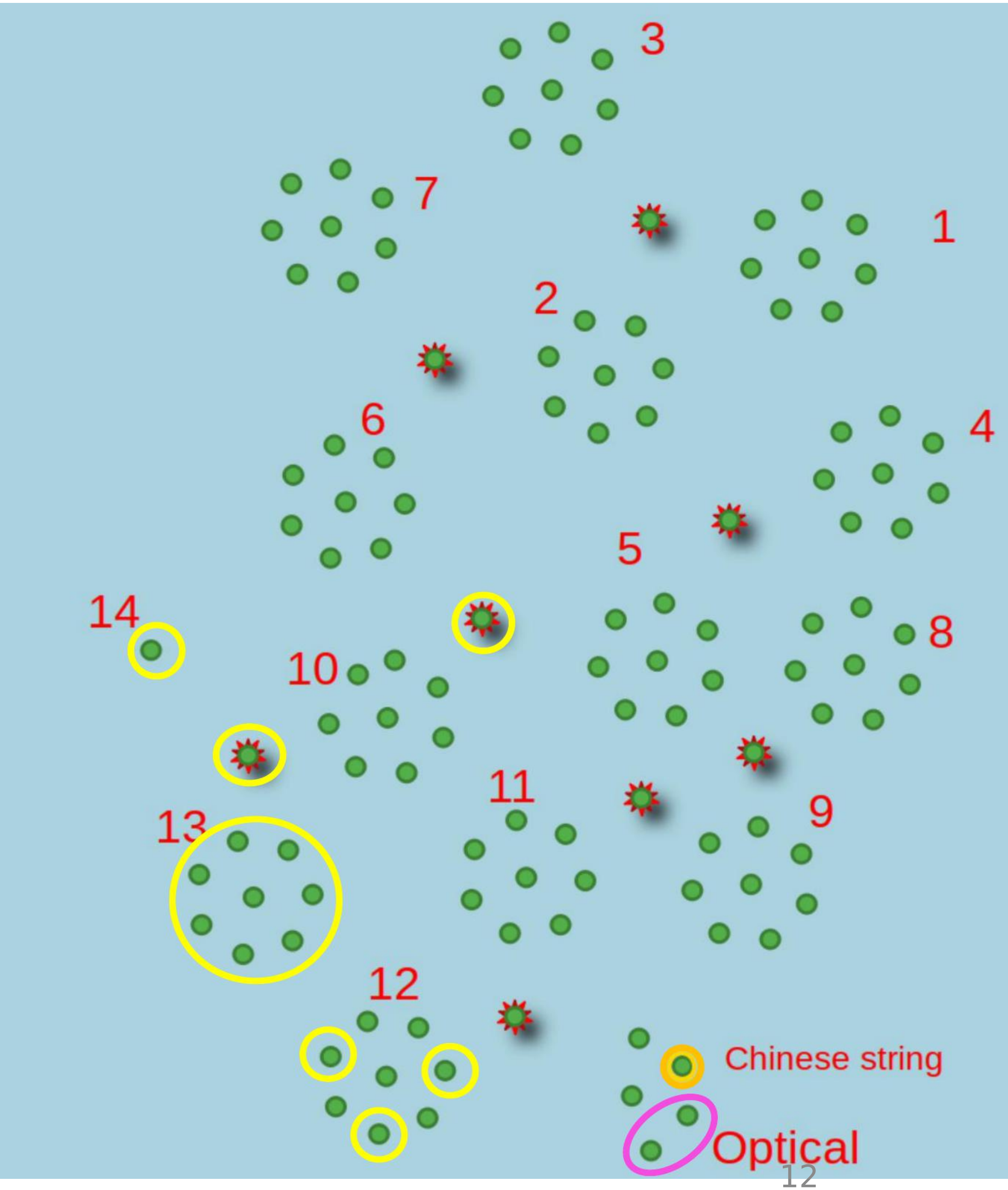
- 14 regular strings carrying 36 OMs installed
- 2 strins added to experimental ("optical") cluster
- Pilot string for HUNT project



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

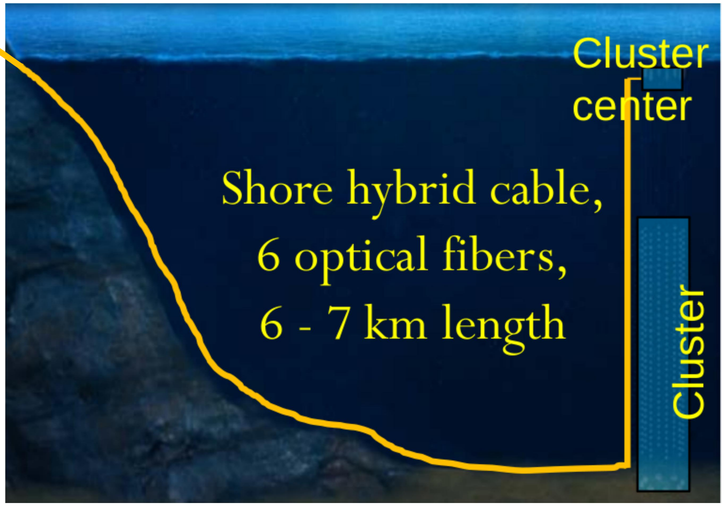
OMs based on 20-inch PMT

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

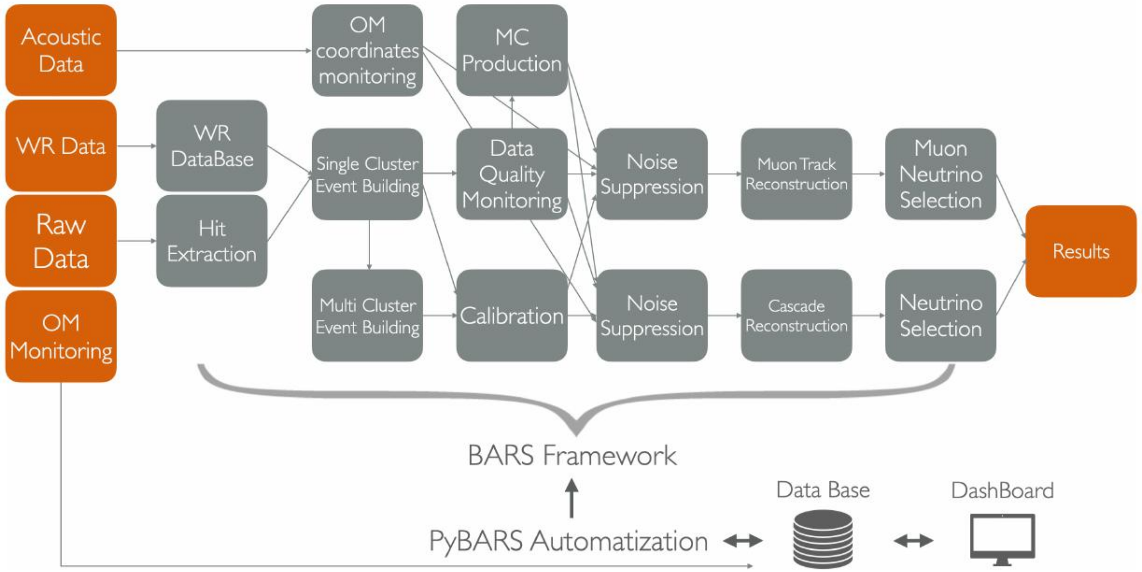


Baikal shore center:
- Power distrubution
- Data readout hardware/software
- Data-taking management (shifter)
- Data quality control
- Long-term storage of raw data
- Alert system (to be deployed)

Data flow

Raw data are transferred from the Shore center to JINR

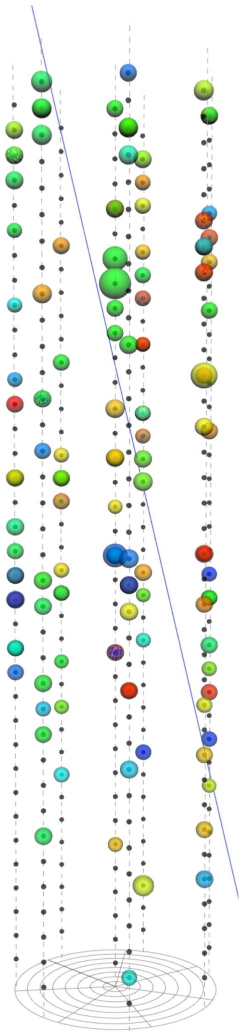
- Shore center → Baikalsk: 300 Mbit/s radiochannel
- Baikalsk → JINR: Ethernet
- Compressed data volume ~10-40 GB per day per cluster
- Full-scale reconstruction at JINR
- Delay due to shore → JINR data tranfer: < 1 min



JINR computing farm:

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

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 mks

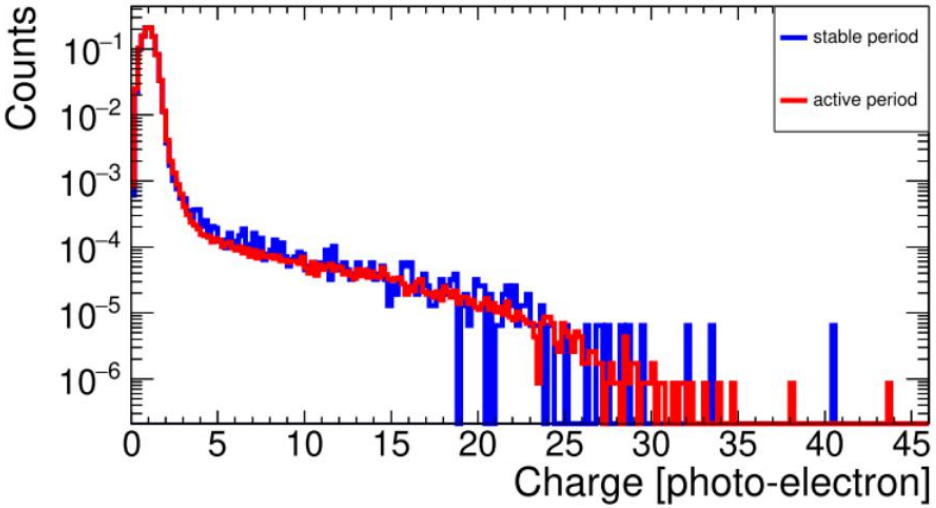
Most of pulses (or hits) in the event frame are noise from lake water luminiscence:

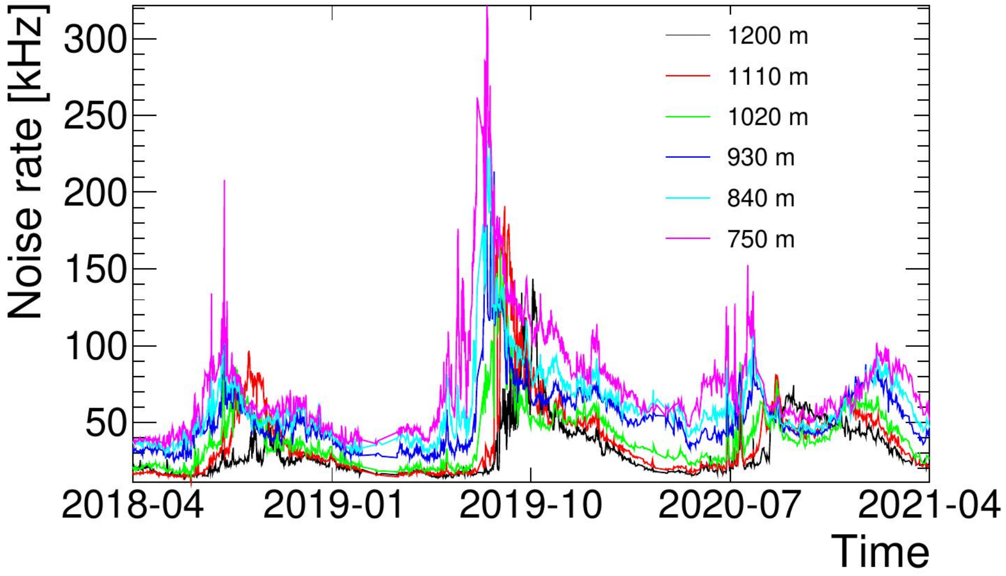
- Typical pulse rate 20-100 kHz
- ~1 photoelectron (p.e.) charge deposition
- Substantial seasonal variations
- Rate is larger on top layers

Challenge for our MC simulation

Variety of algorithms for noise suppression

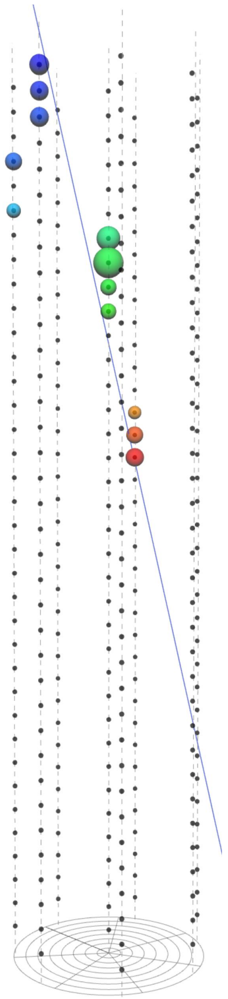
Machine learning -based algorithm in development: **[arXiv:2210.04653]**





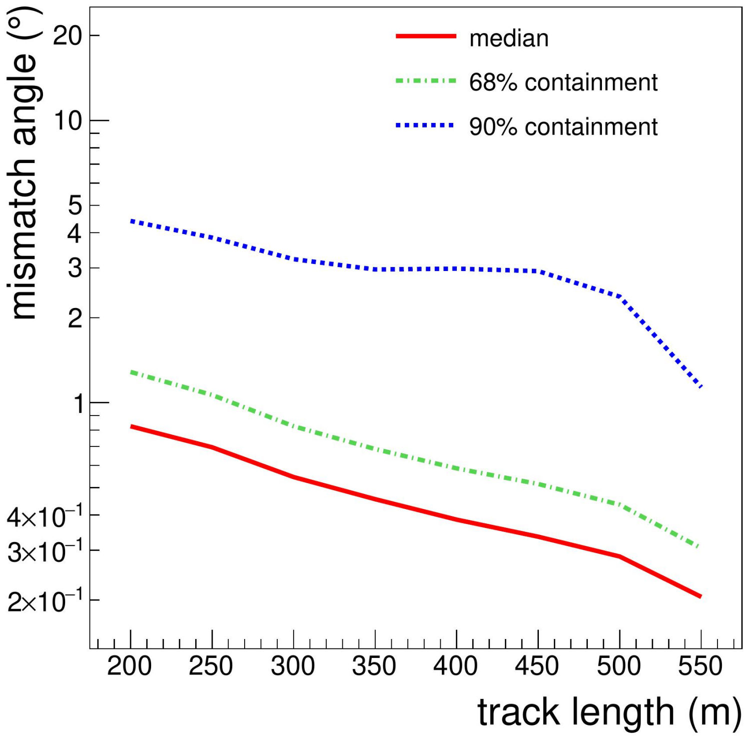
Event reconstruction

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

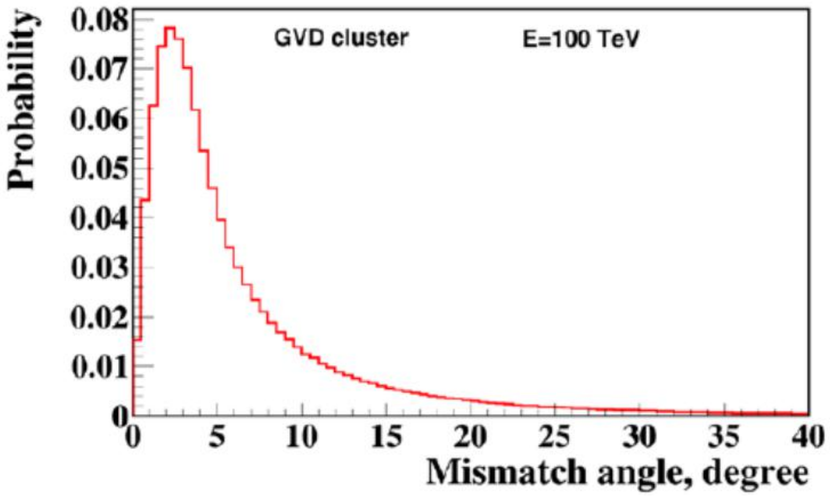


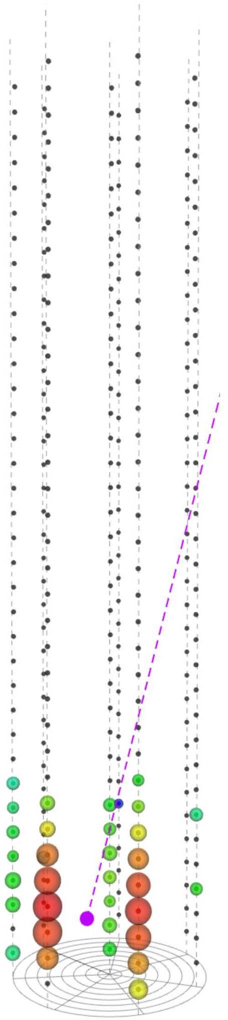
track-like,
data 2019

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



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

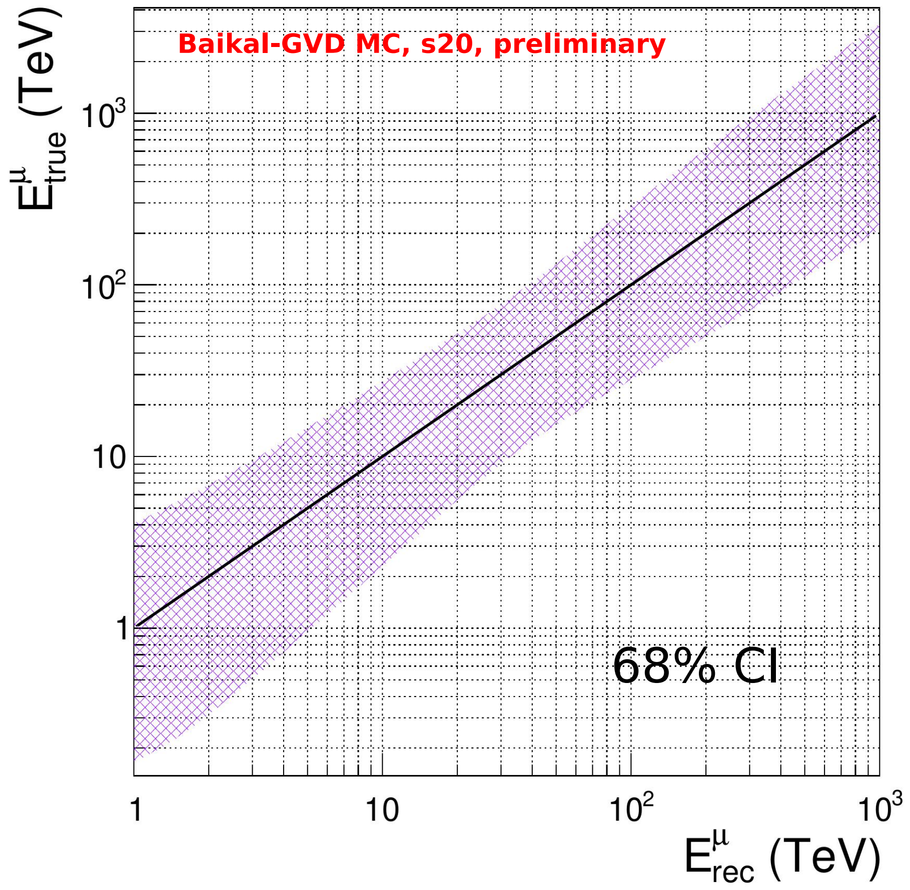




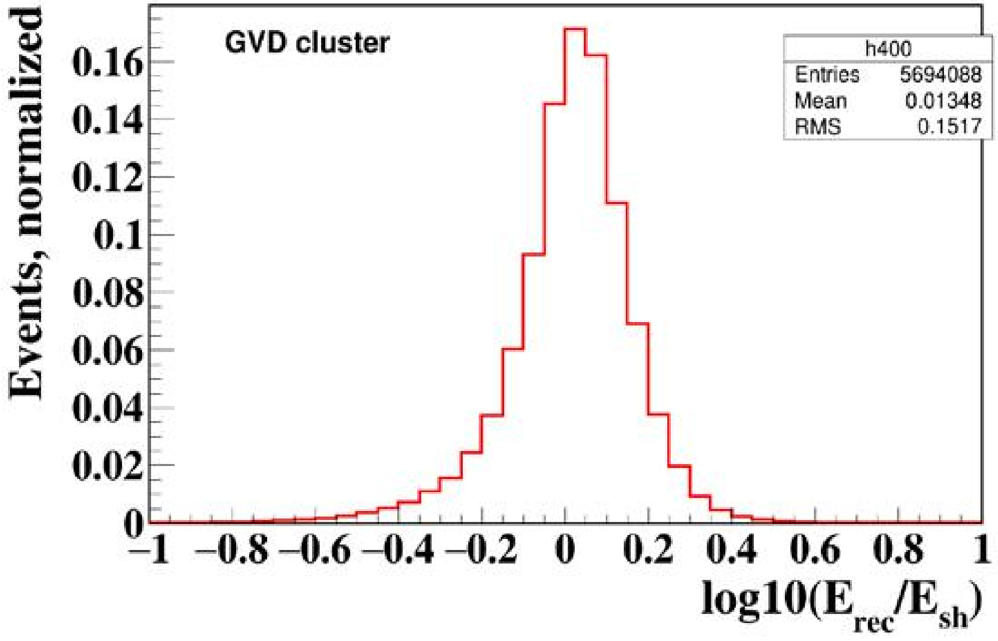
cascade-like,
data 2022

Event reconstruction

Track energy resolution:
Factor 3 for 100 TeV muon



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



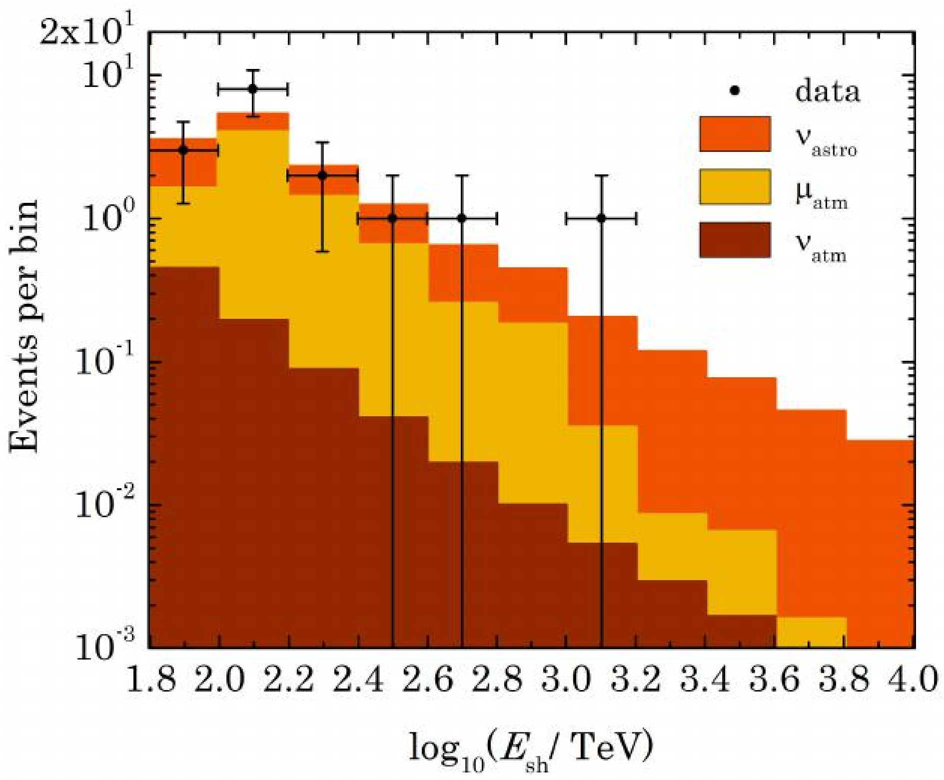
Results in cascade channel

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

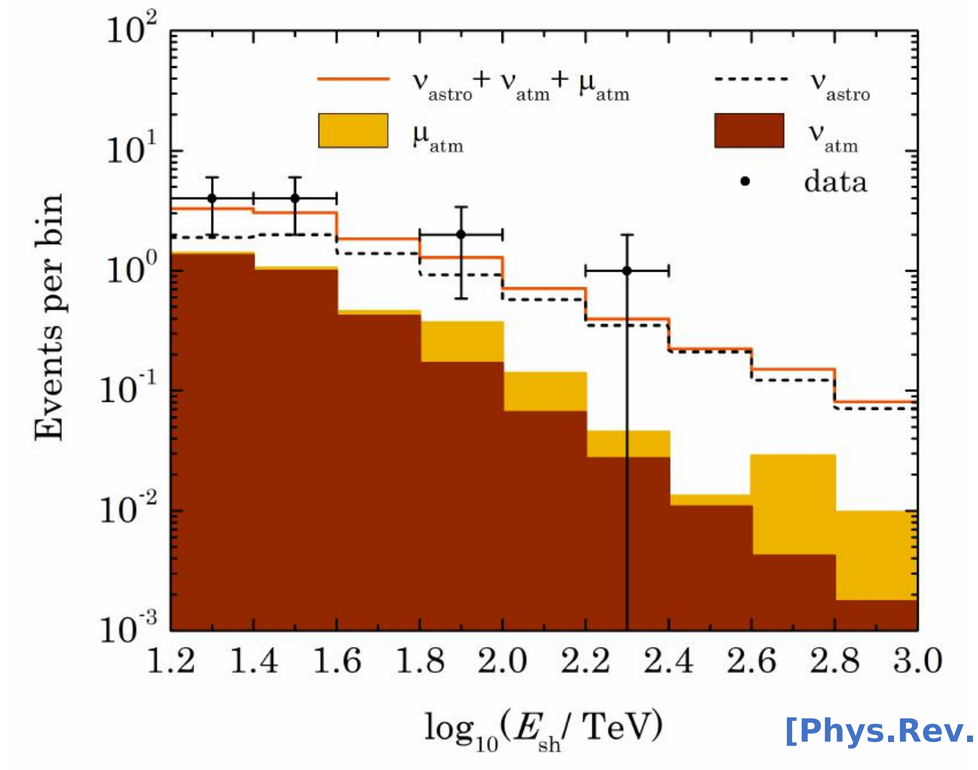
Analysis of upward-going events

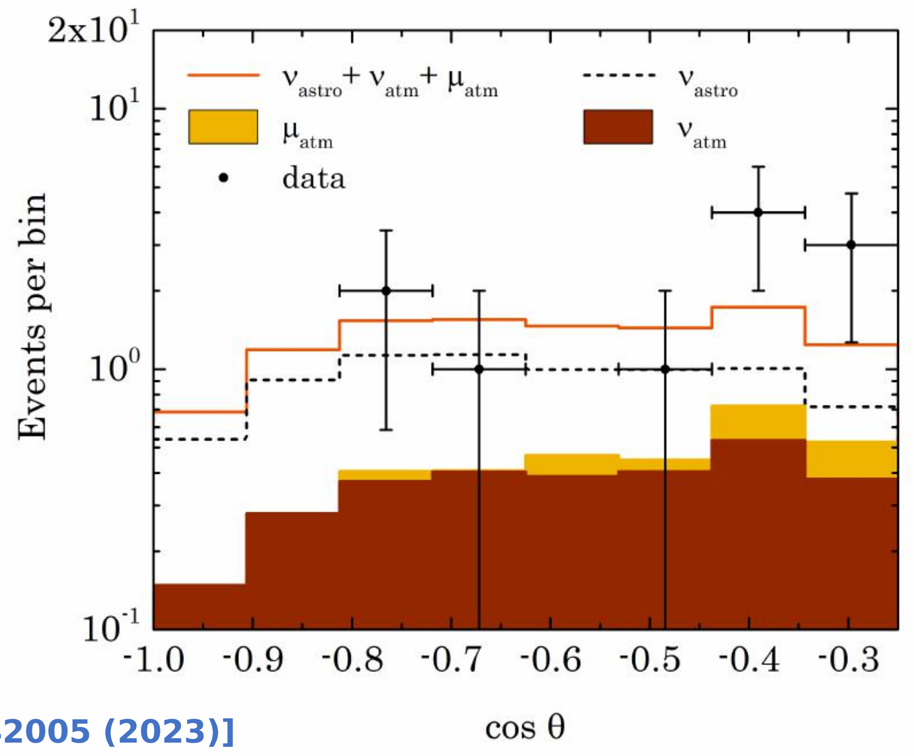
- Zenith angle cut: cos(θ) < - 0.25
- Loosened cuts: E_{sh} > 15 TeV, N_{hit} > 11
- 11 events selected
- 3.2±1.0 atm. background ev. are expected
  - 0.5 μ_{atm}, 2.7 ν_{atm}
- Highest energy: 224 TeV

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

Main uncertainties

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



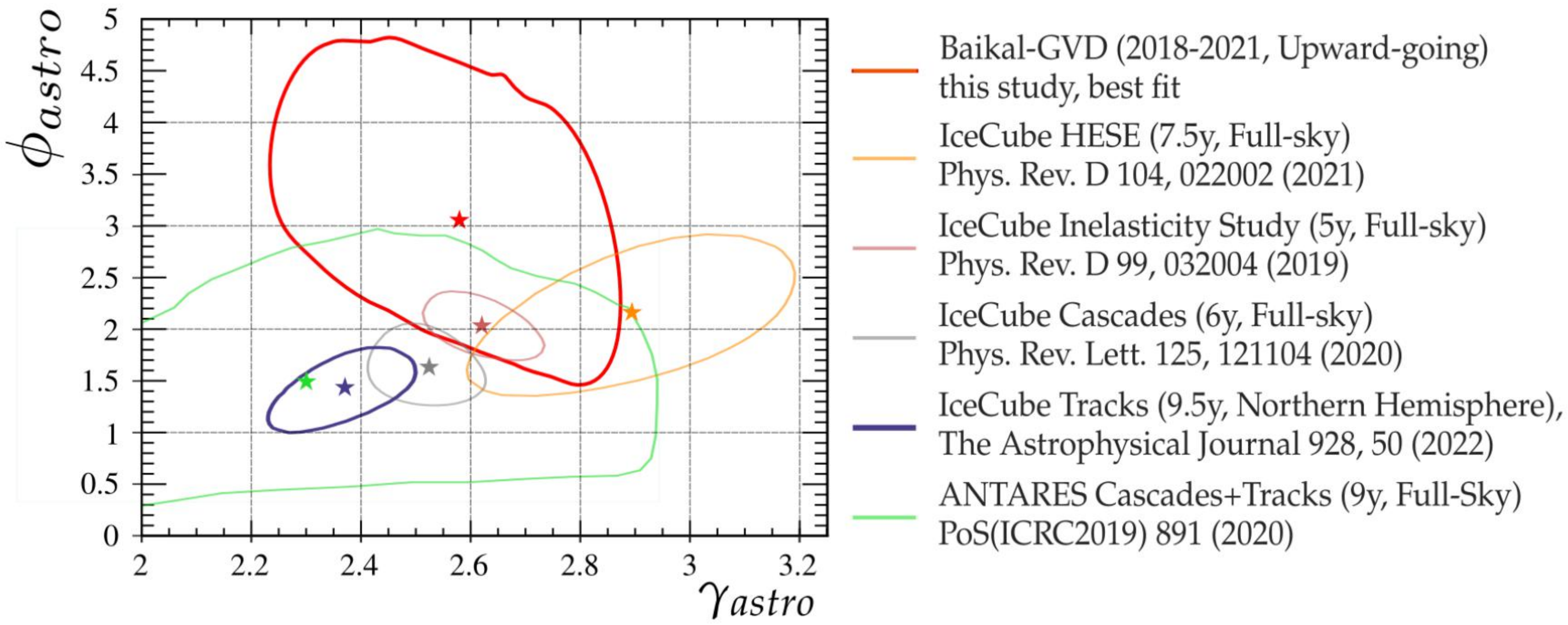


[Phys.Rev. D 107, 042005 (2023)]

Diffuse spectrum

Extraction of spectrum power and flux normalisation:

$$\Phi^{\nu+\bar{\nu}}_{astro} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0}\right)^{-\gamma_{astro}}$$



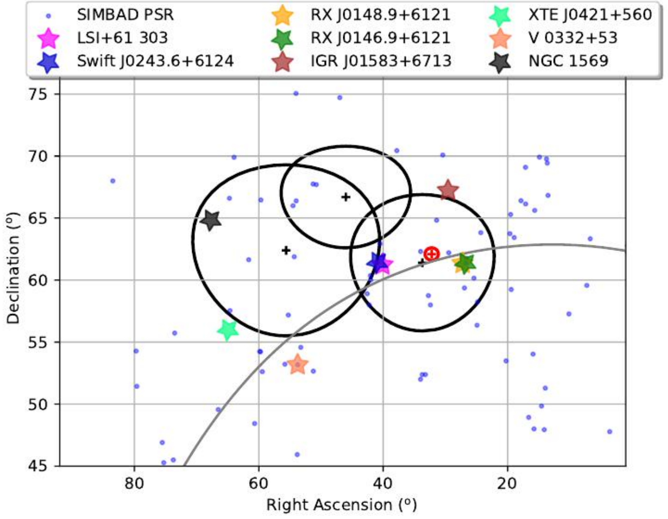
Results are in agreement with previous measurements by IceCube and ANTARES

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]

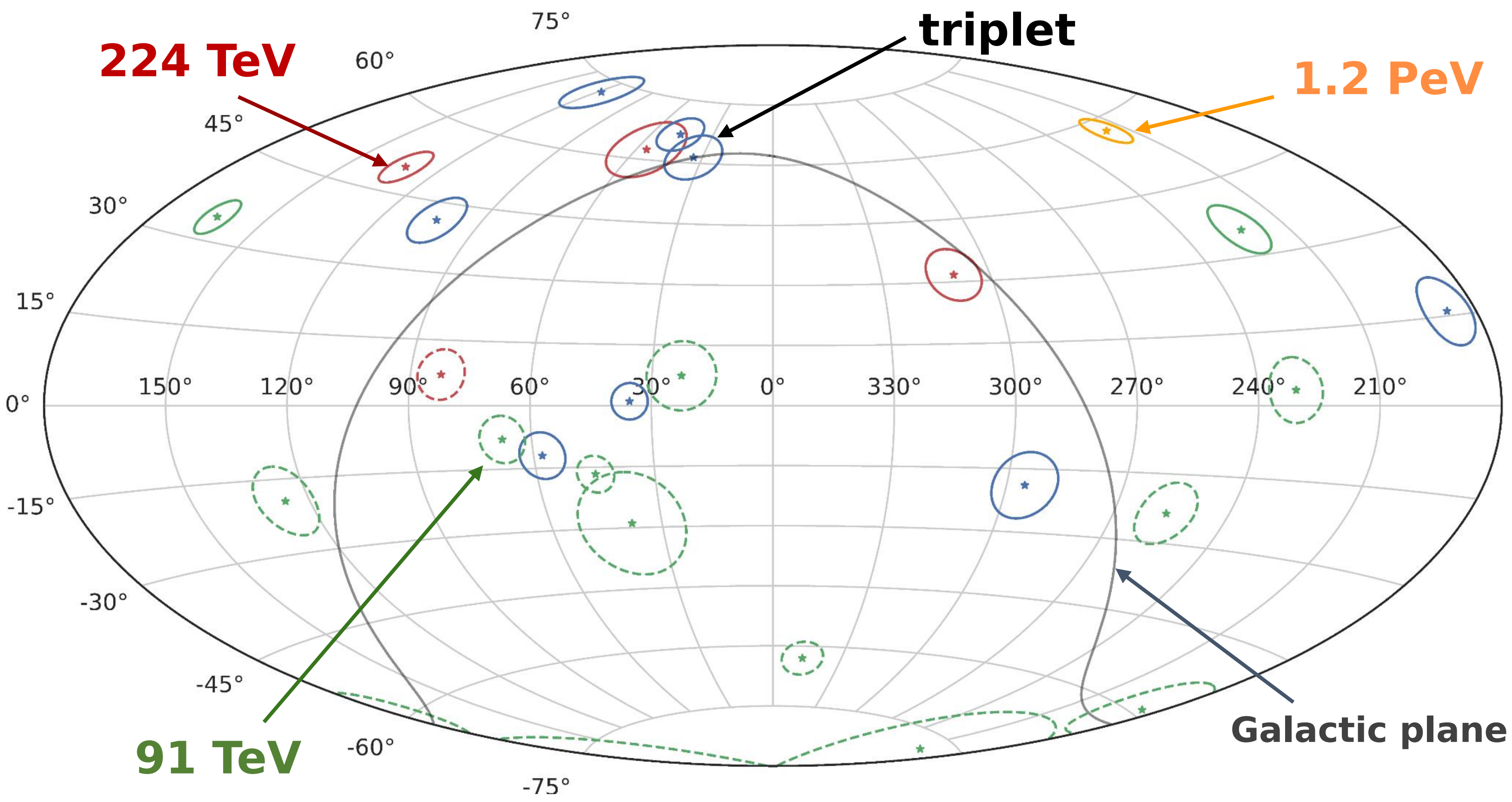


Three events close to
the Galactic plane (grey line)

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

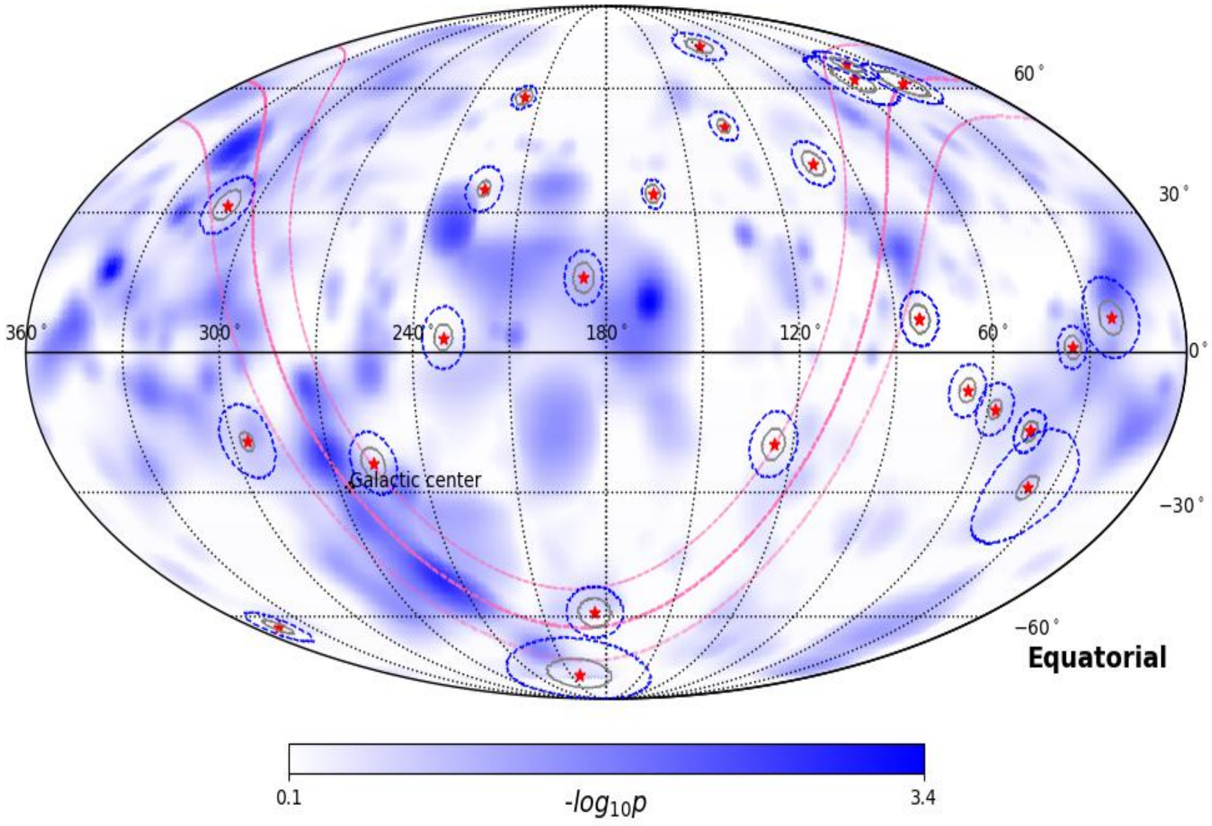
Seasons	N_{data}	N_{bckg}	P-value	σ(stat.)
18-21	11	3.2	1.7×10^{-3}	3.13
18-22	19	5.7	1.11×10^{-5}	4.24

Significance of excess over atmospheric background increases

HE cascades and the galaxy plane

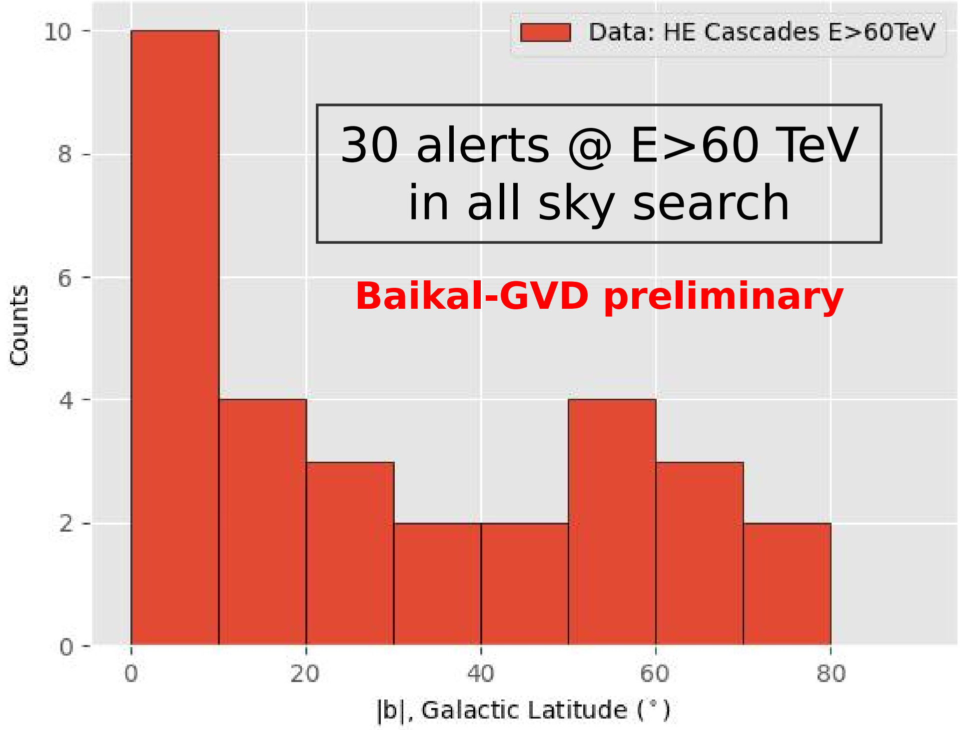
Hint on alert events concentration near galactic plane

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



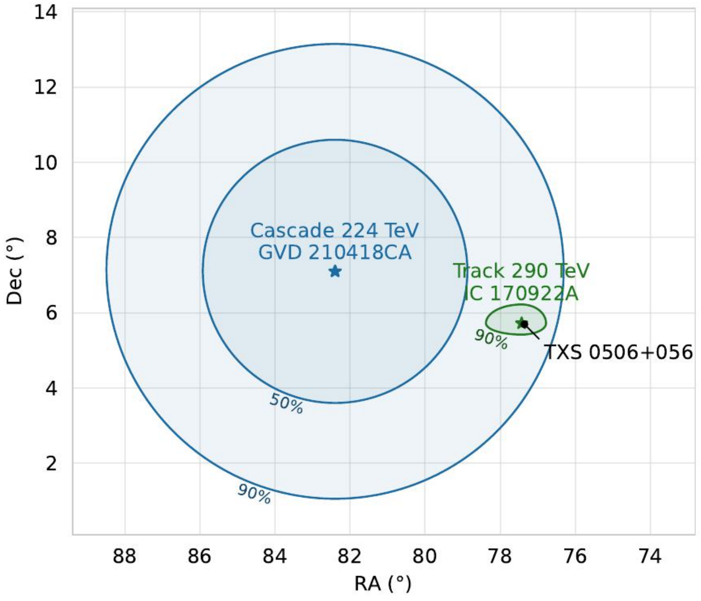
Baikal-GVD alerts compared to IC galaxy plane analysis

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



Analysis continues

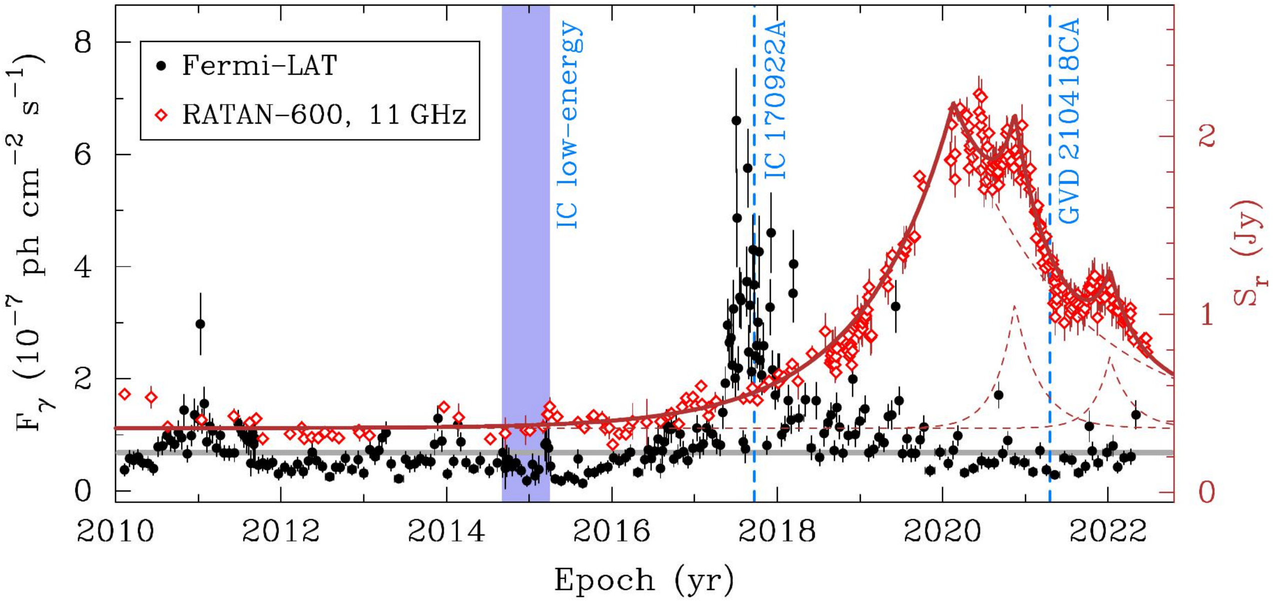
Cascades: TXS0506 coincidence



[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

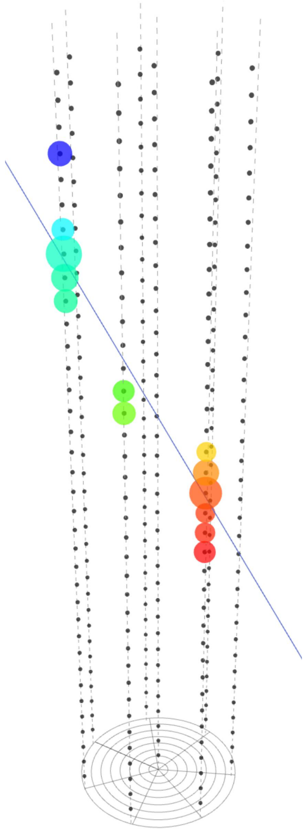
- IC event registered during γ flare
- Baikal event during radio flare
- Consistency with IC observations: 8% or 13% depending on ν spectrum assumption

Track-like channel

Track-like events

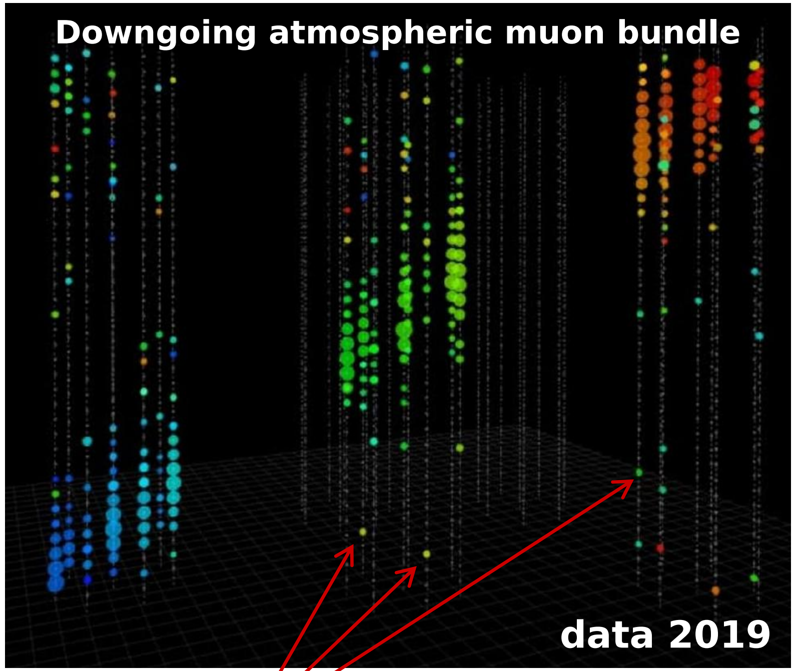
Two modes of analysis
- Single-cluster: each cluster is treated as an independent detector
- Multi-cluster: common reconstruction for simultateously triggered single-cluster events

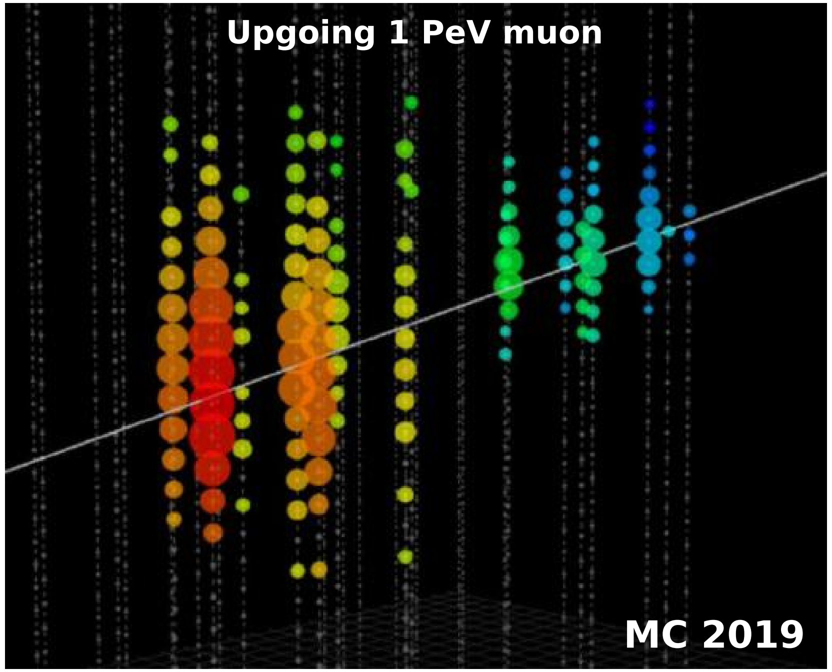
Single-cluster upgoing event:

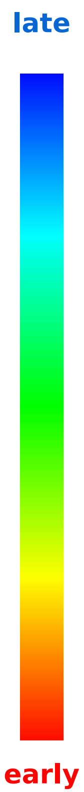


data 2019

Multi-cluster events:



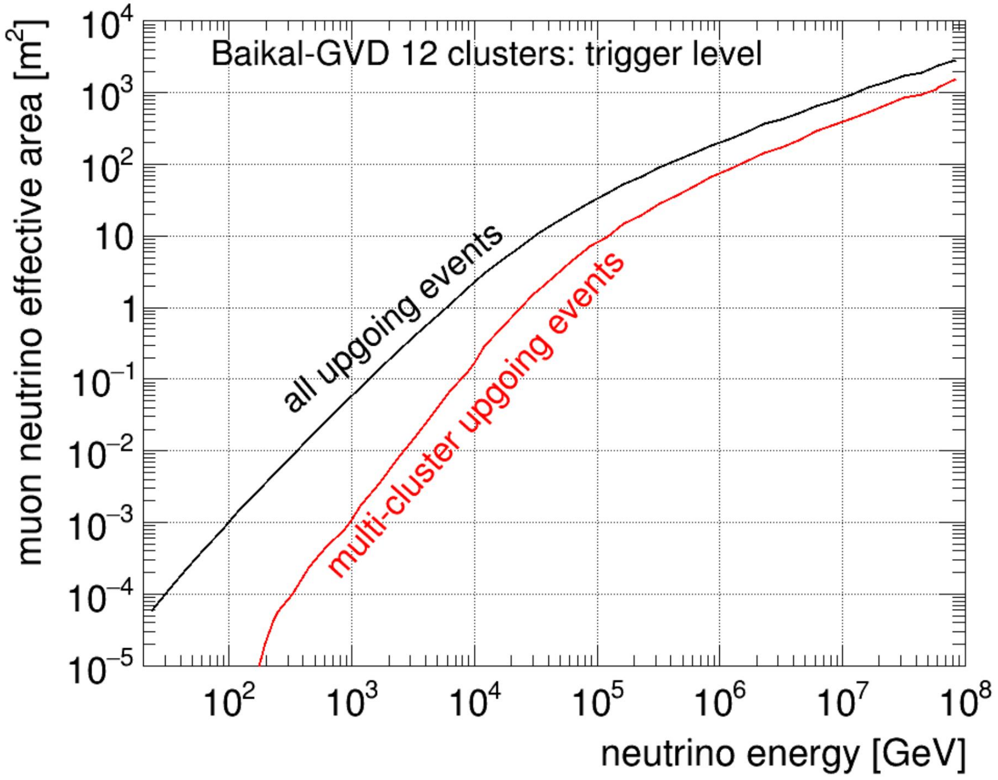




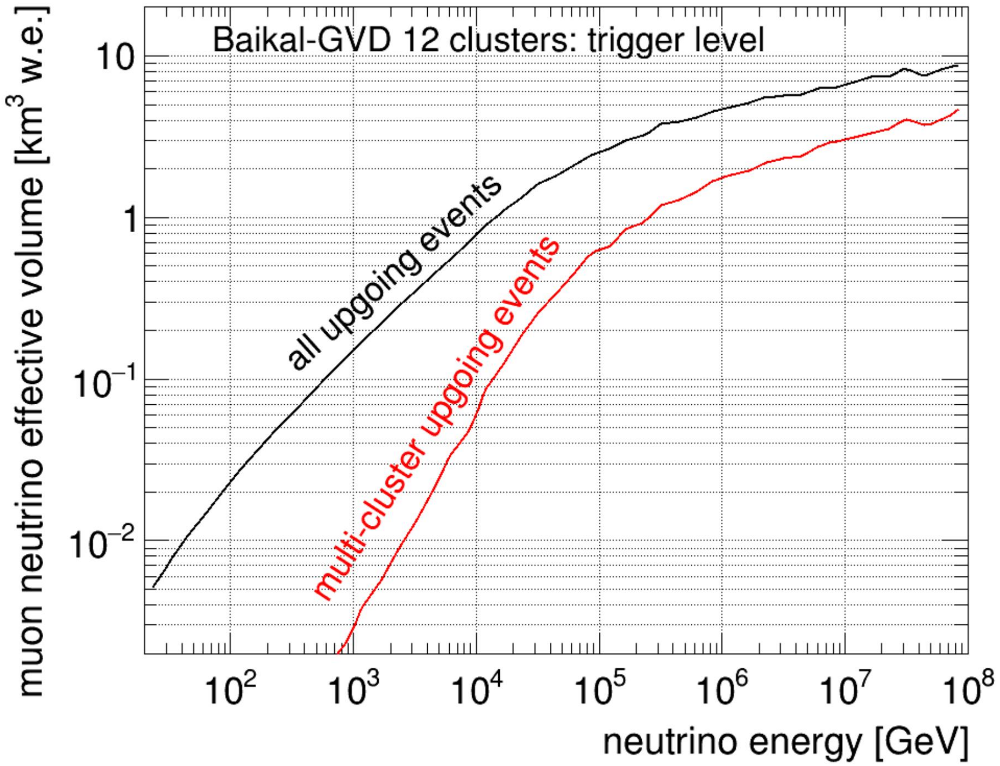
Lake and PMT noise hits

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)

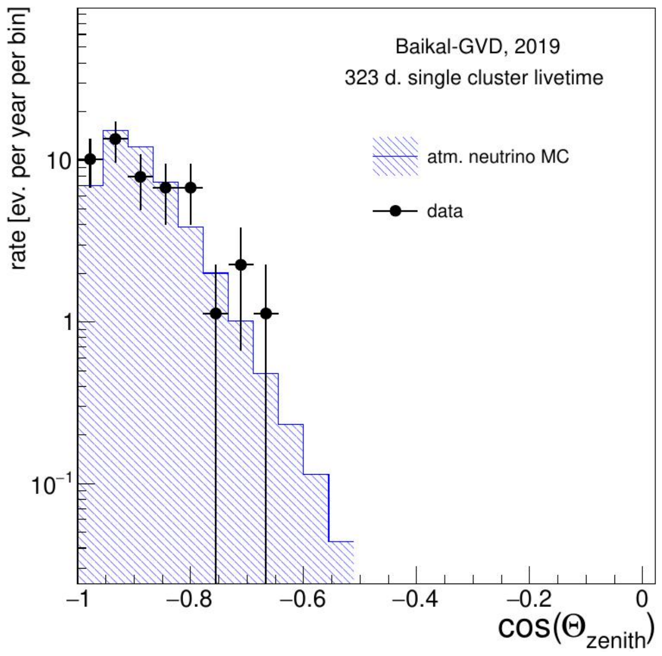
First track-like neutrino candidate event sample

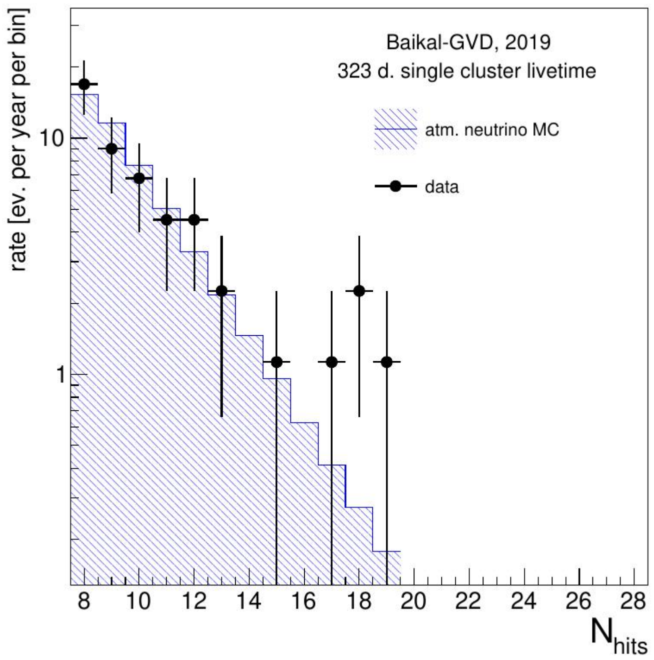
First set of single-cluster muon neutrino candidates based on 2019 data

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, $<E_\nu> \sim 500$ 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

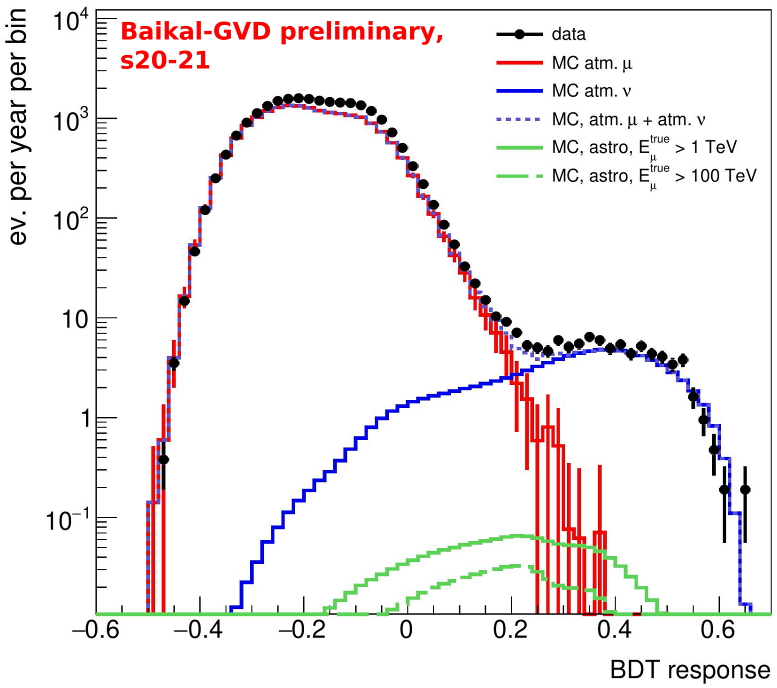
Improved muon reconstruction
- New noise suppression algorithm
- More precise track fit algorithm
- Improved neutrino selection capabilities

Improvement in tools for muon background suppression

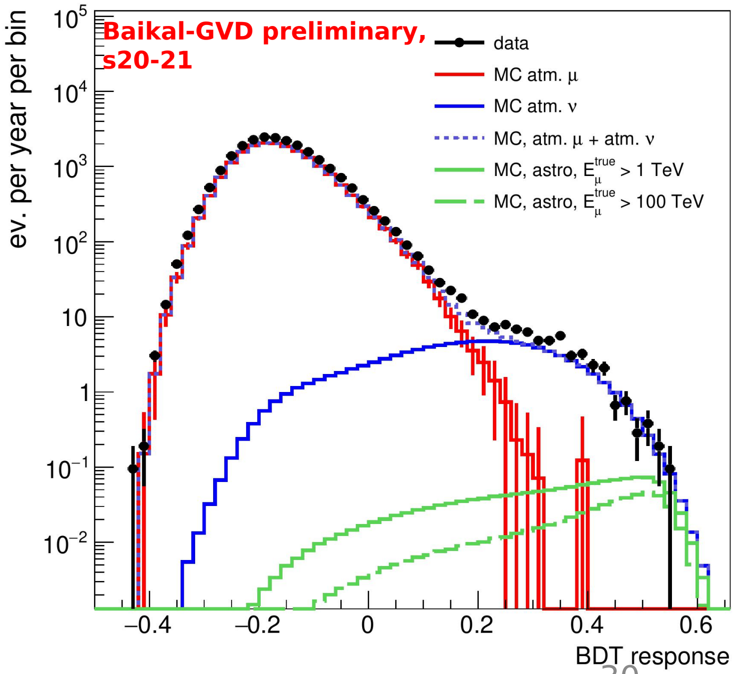
BDT discriminant as a main variable for neutrino selection

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

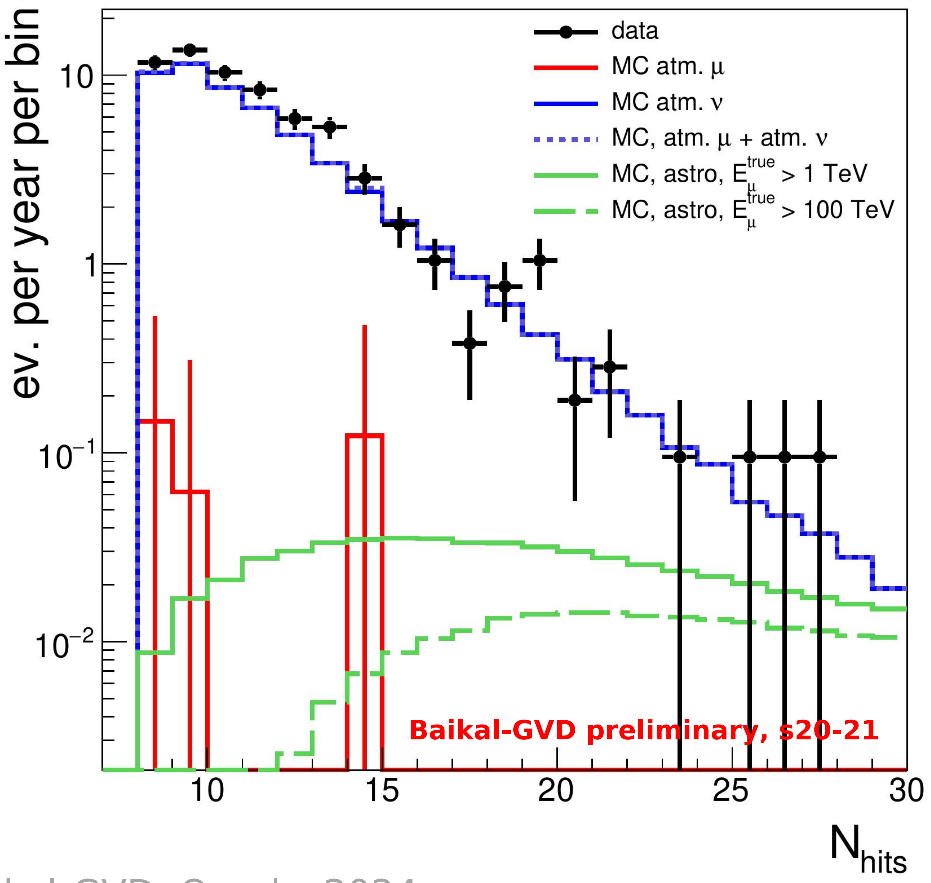
- 3845 days single-cluster livetime equivalent
- Validation of reconstruction results is ongoing
- Optimisation of high-energy ν selection is ongoing

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

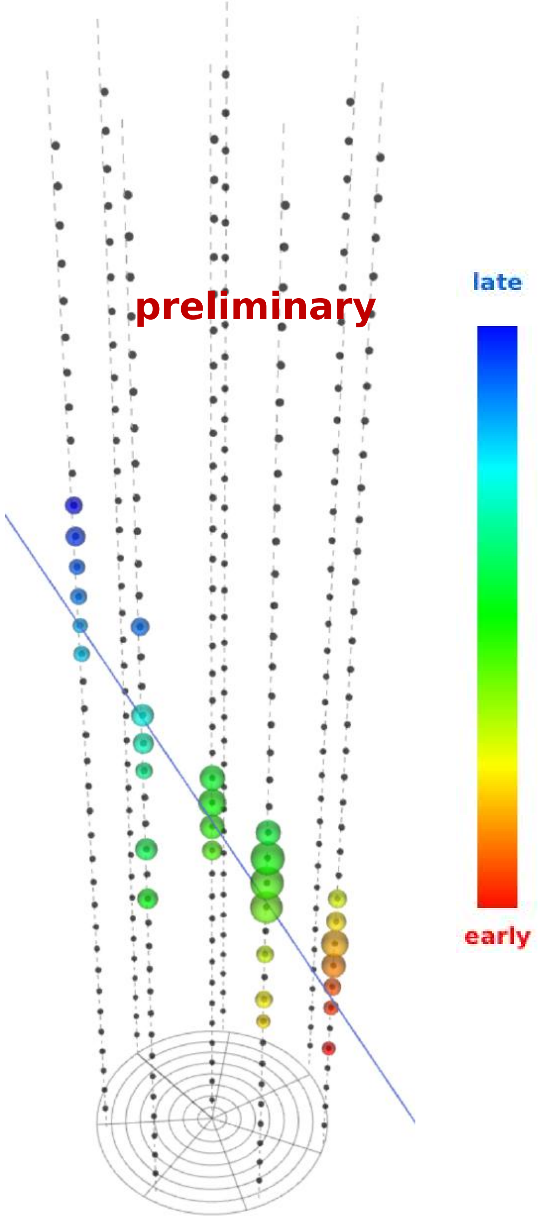


High-energy track event candidate

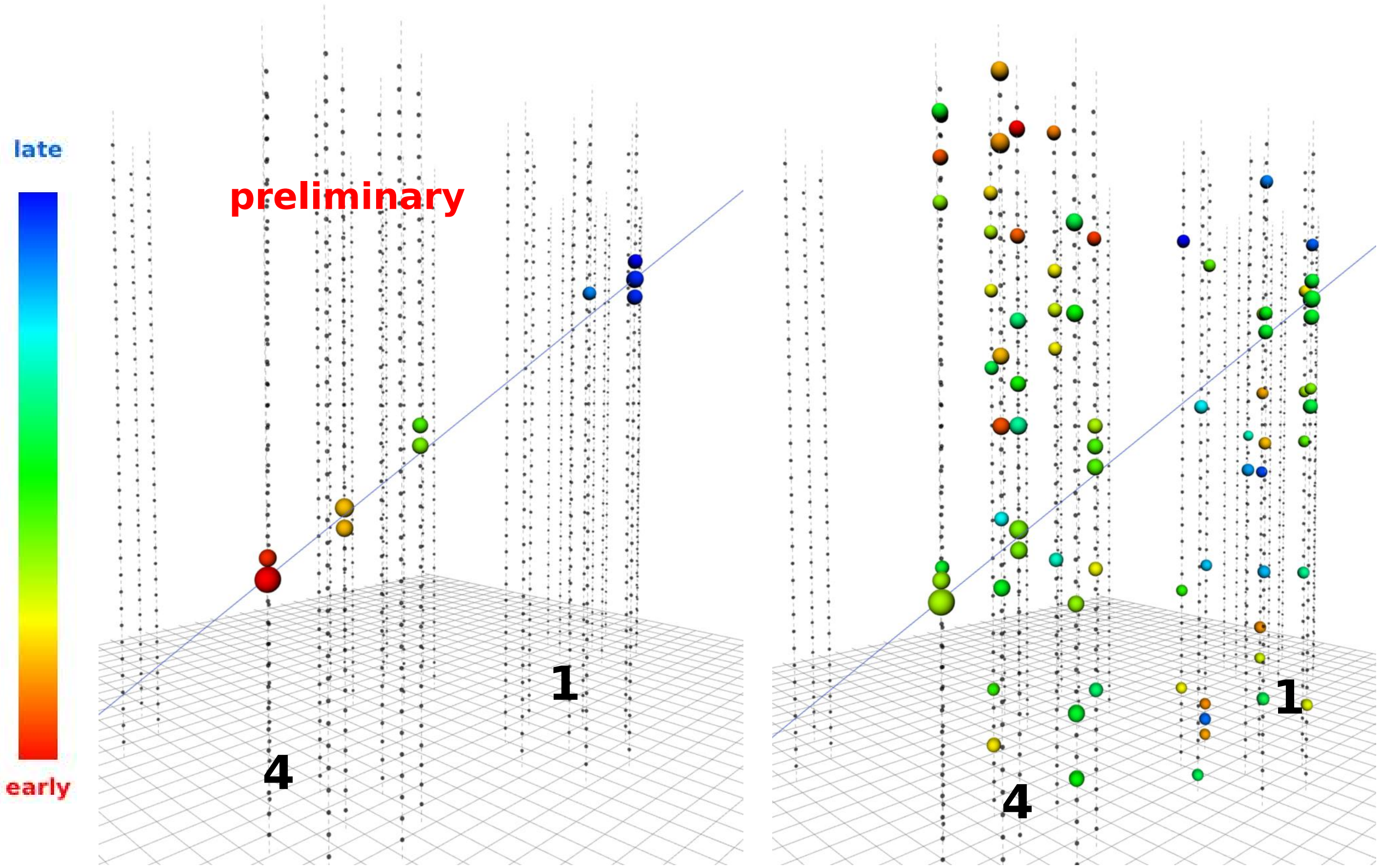
Preliminary: spectacular single-cluster event with high probability of astrophysical origin

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

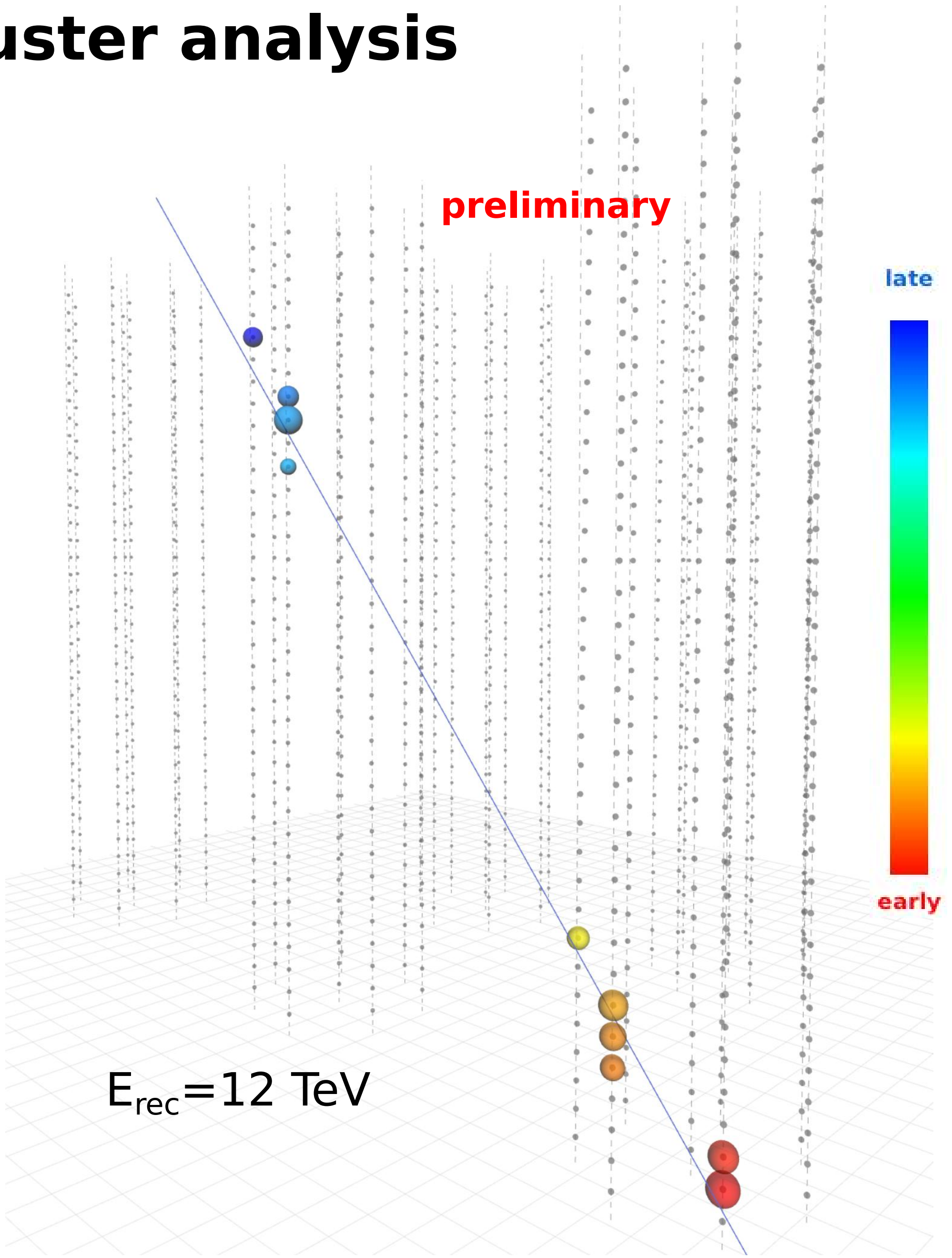
Example of ν candidate event:

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

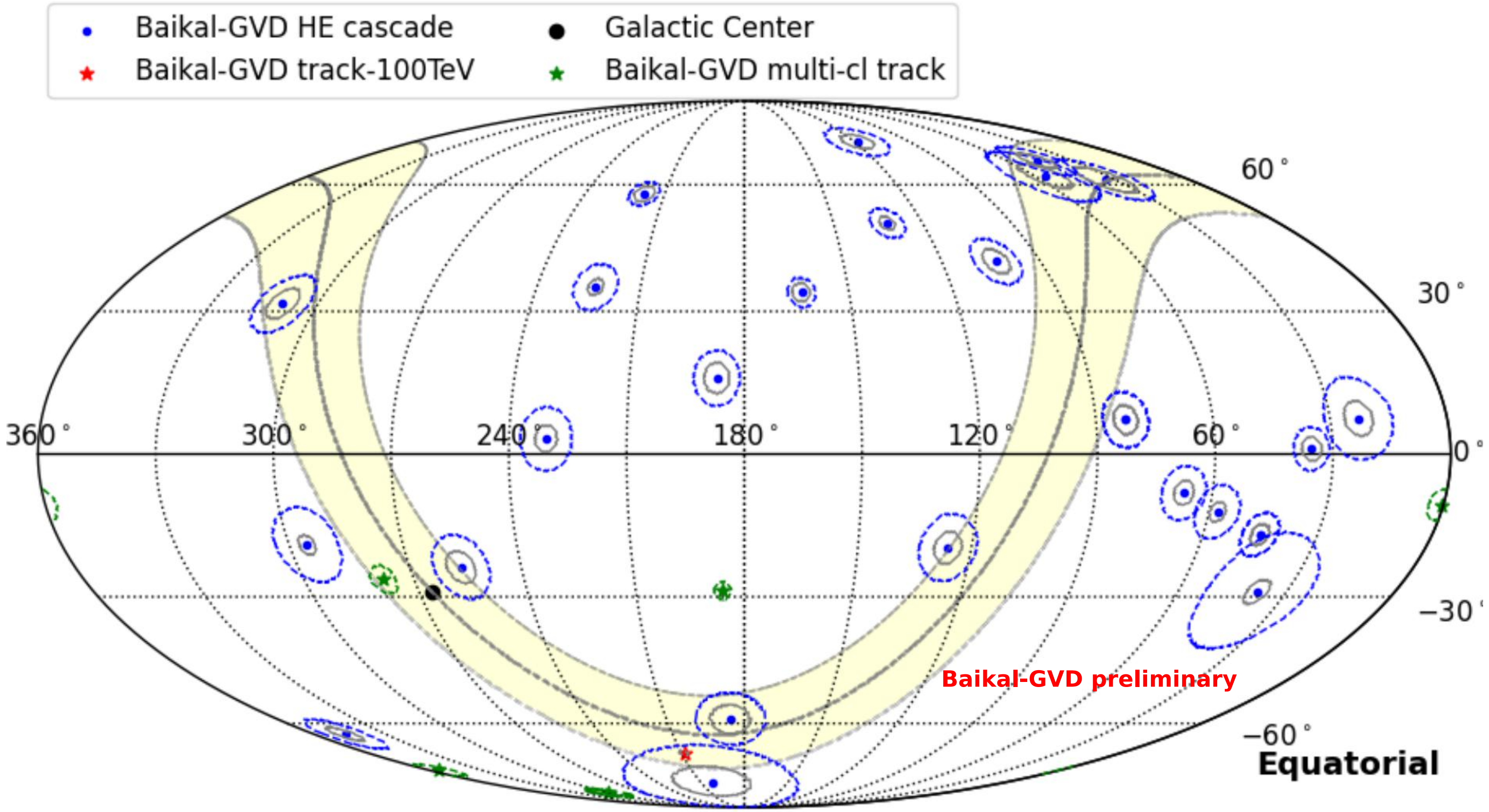
Track-like event multi-cluster analysis

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

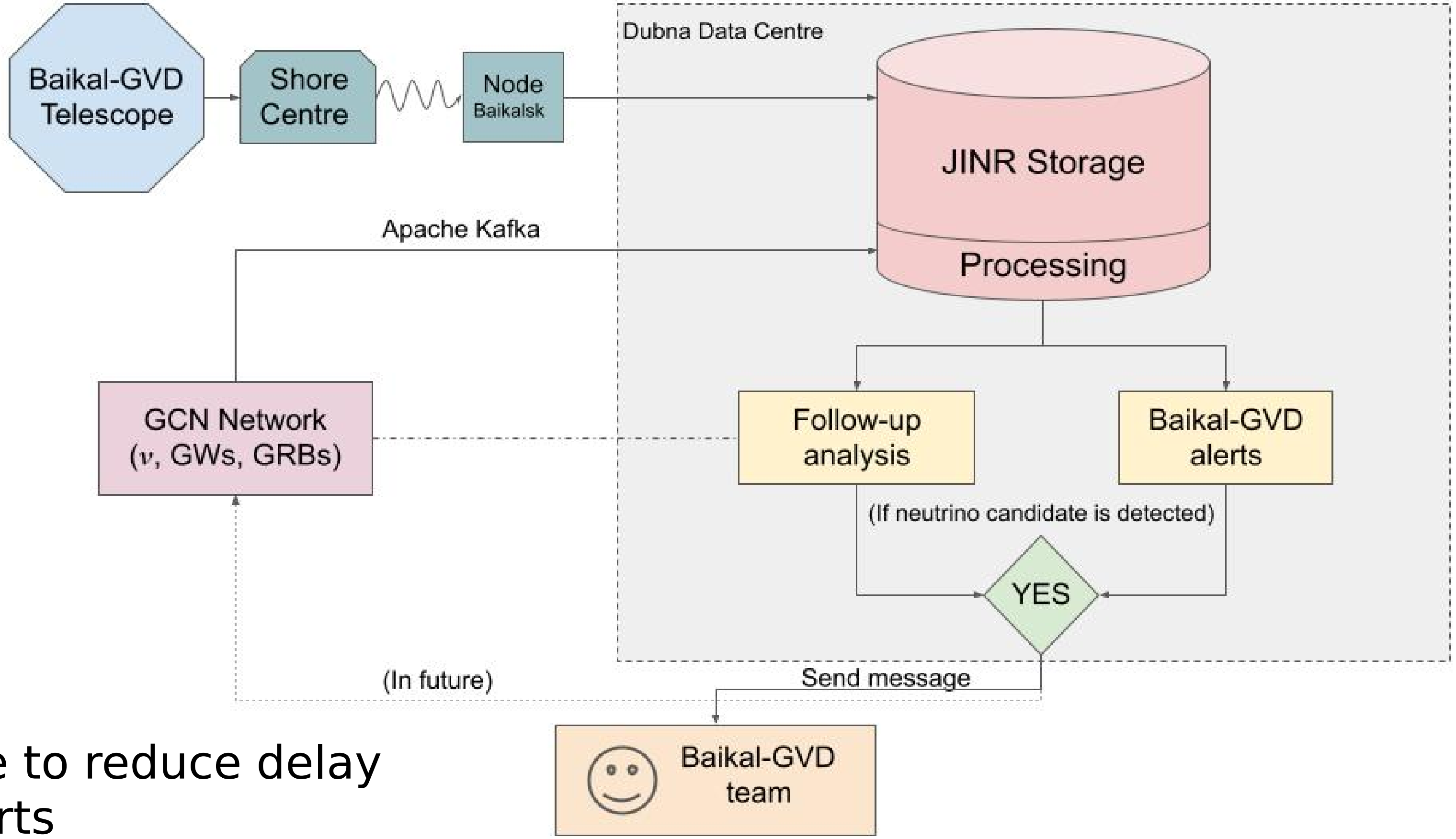
Alert program

Alert workflow

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

Automated alert generation and follow-up system

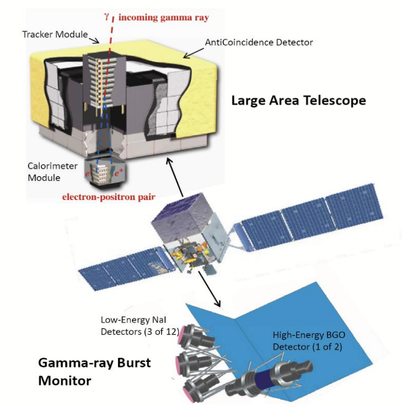
- Baikal-GVD alerts: distribution of our own alerts for events with high probability of astro origin
- Follow-up: follow-up analysis of external alert events



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:

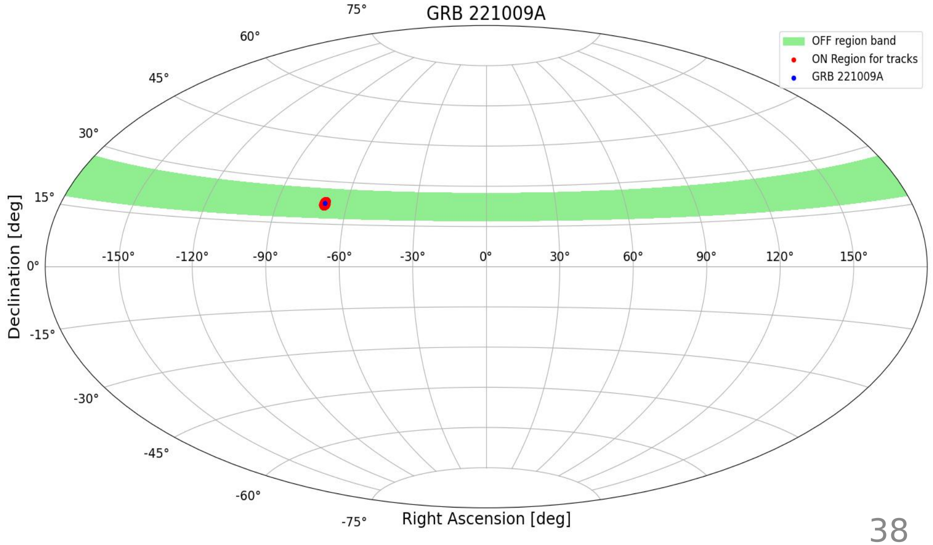
IGWN reception: “significant” = 1
[T0 - 1000 s, T0 + 1000 s],
[T0 - 1000s, T0 + 14 days]

IceCube:

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

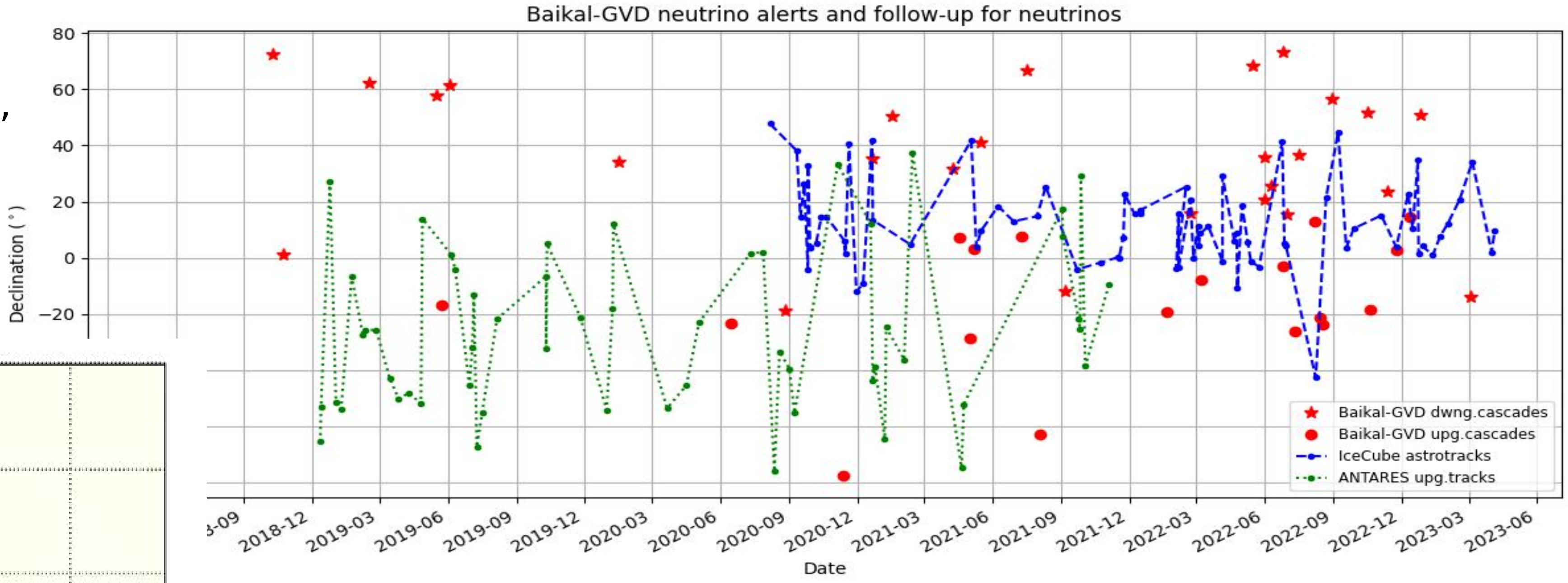
Search for online coincidences:

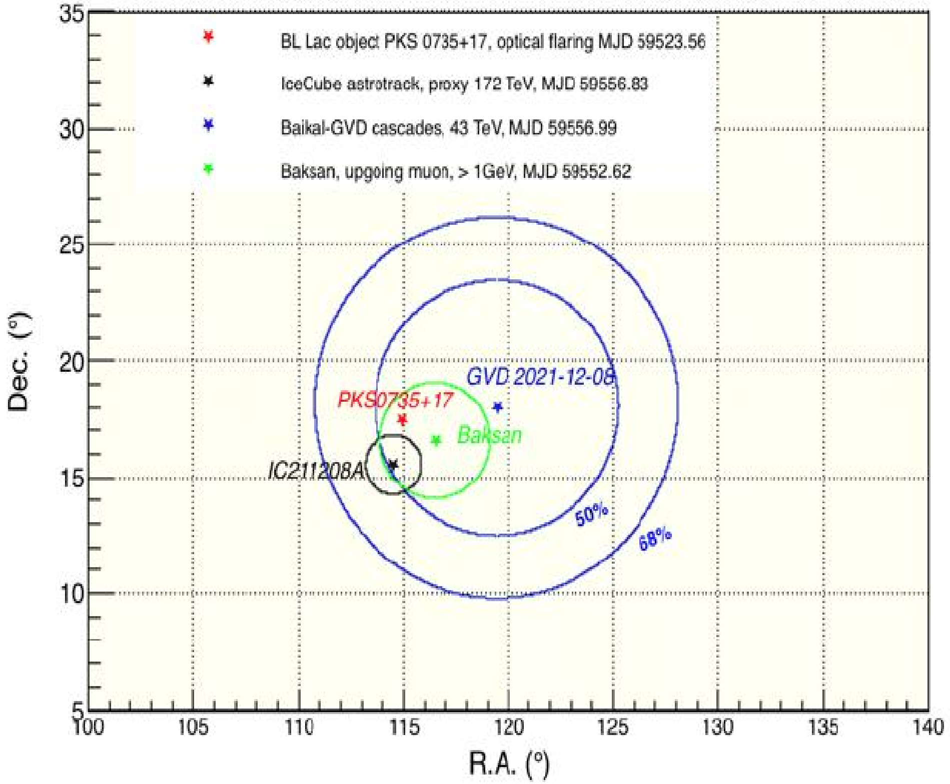
- ON/OFF method
- ON includes 90% localization error and Baikal-GVD median angular resolution
- OFF is extended within a ± 5 declination band
- OFF is evaluated using real data from previous seasons



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

Multi-messenger follow-ups

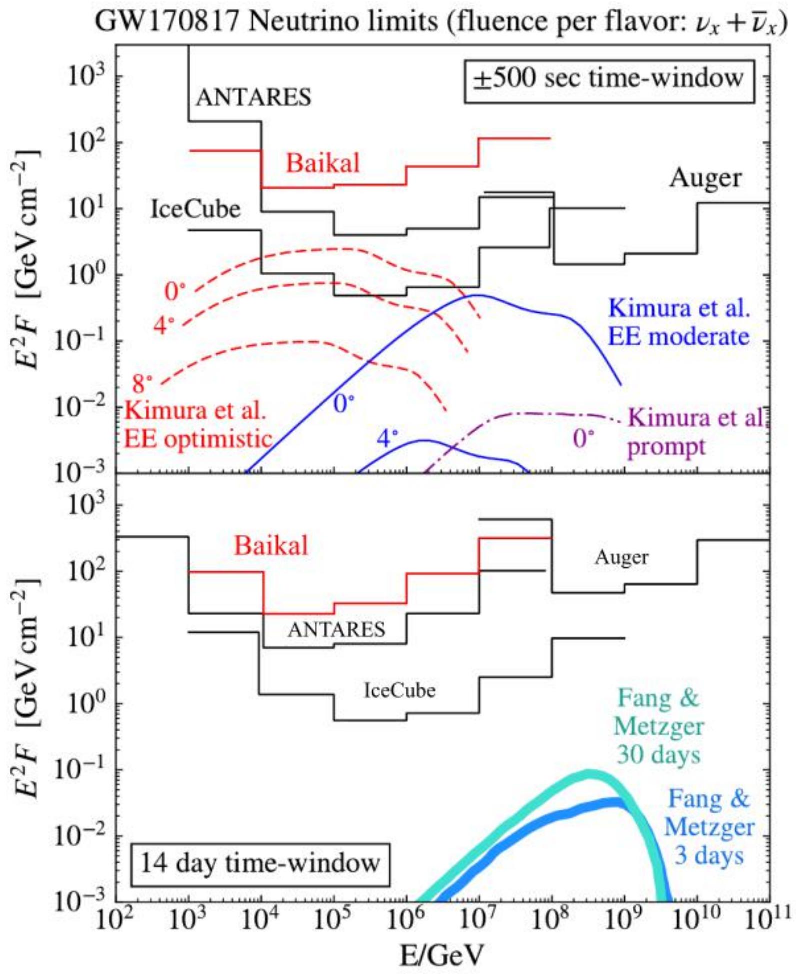
Baikal-GVD follows reported multimessenger high-energy events, e.g.:

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



Summary

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

- Also: 4 strings with experimental high-bandwidth DAQ

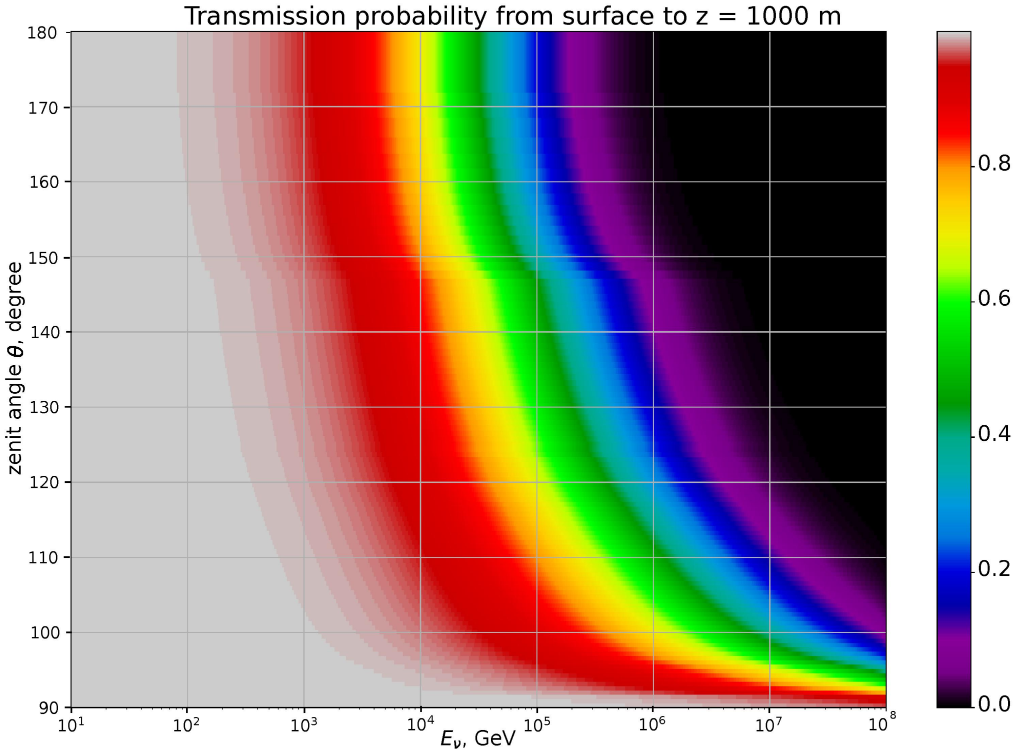
Baikal-GVD is joining the astrophysical neutrino origin quest

- 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

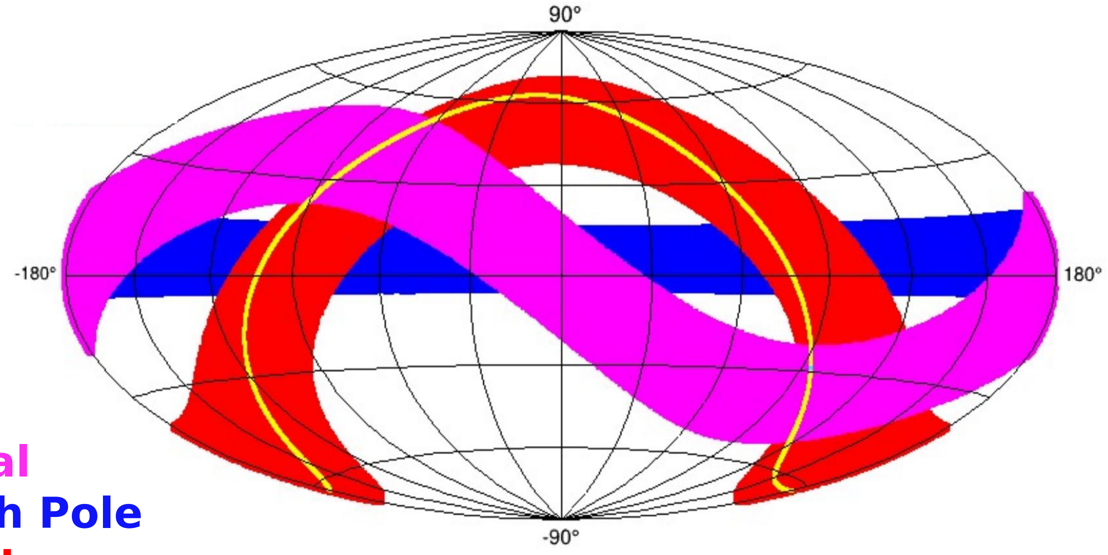
BACKUP

Neutrino detection principle

Earth opaqueness increases with increasing energy



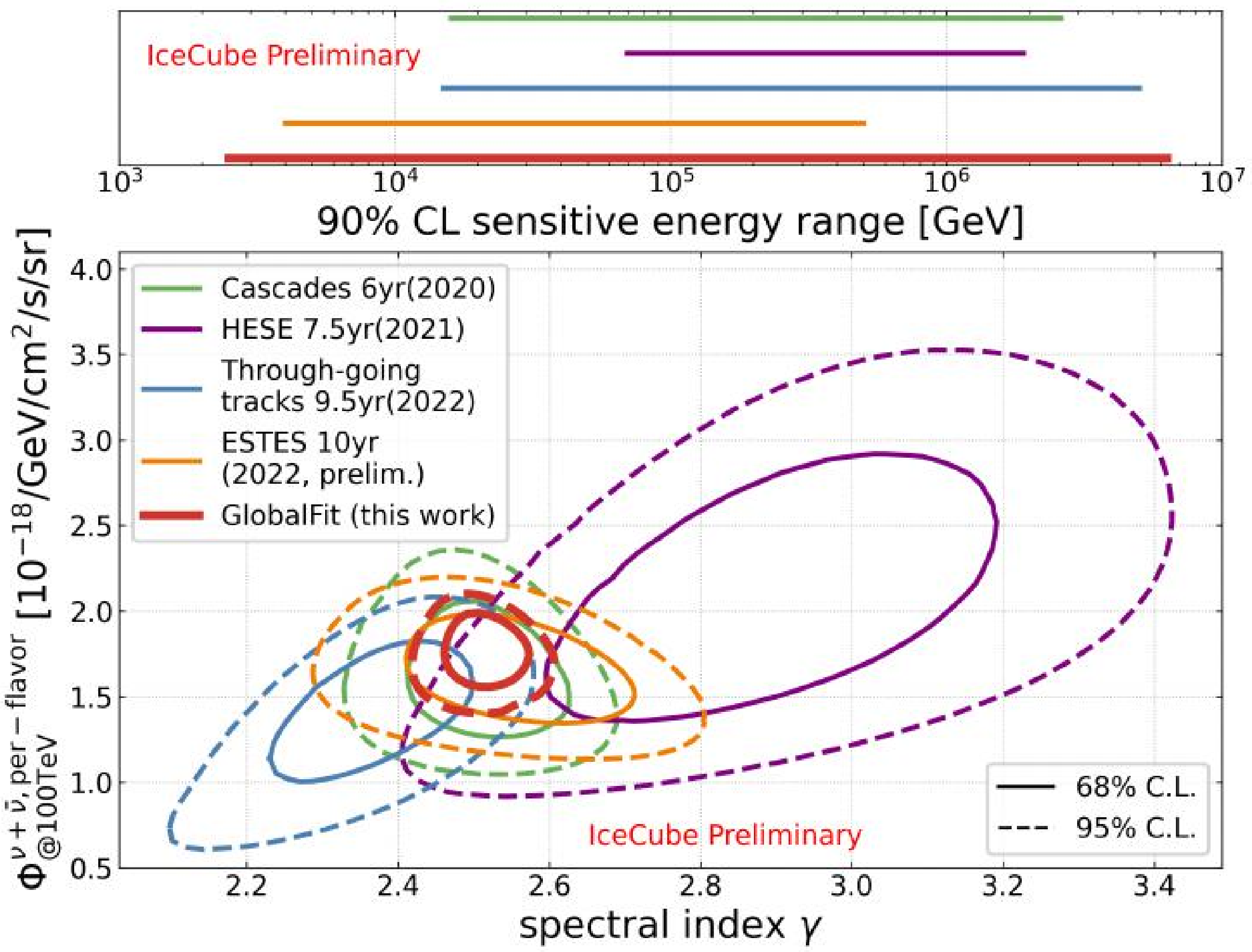
Complimentary maximum sensitivity areas for different telescopes



Baikal
South Pole
Mediterranean

P. Coyle, ICRC2021

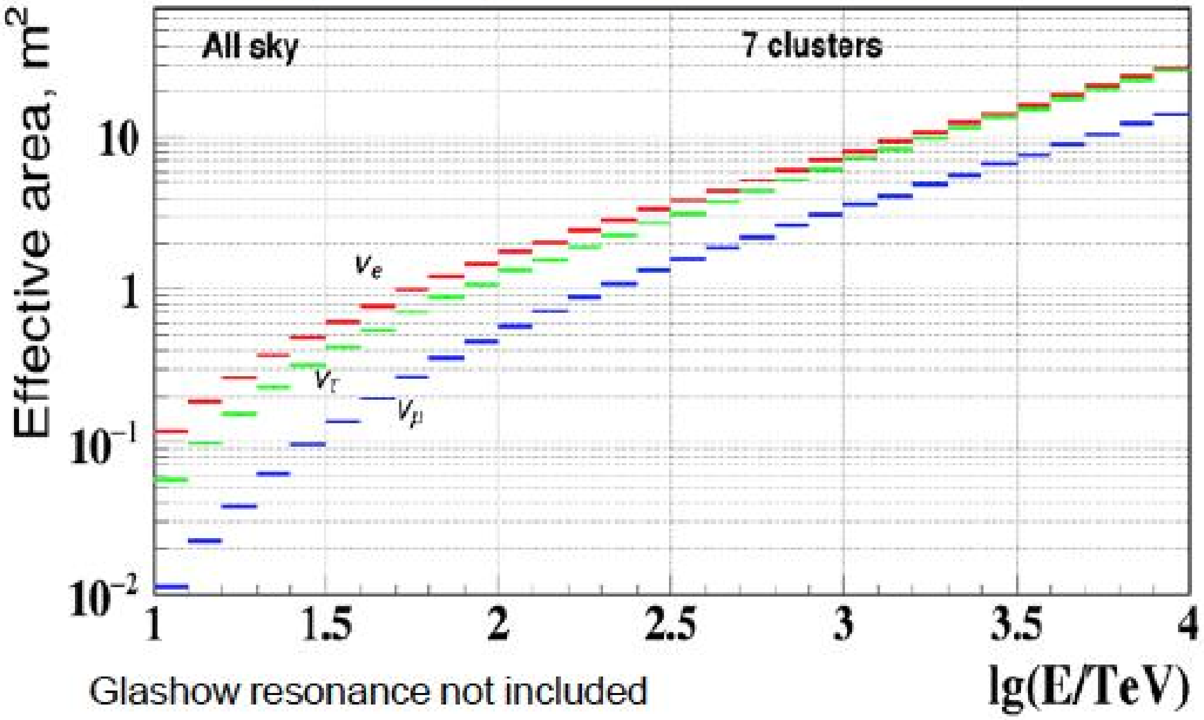
IC global fit
PoS-ICRC2023-1064



Cascade analysis : effective area and rates

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

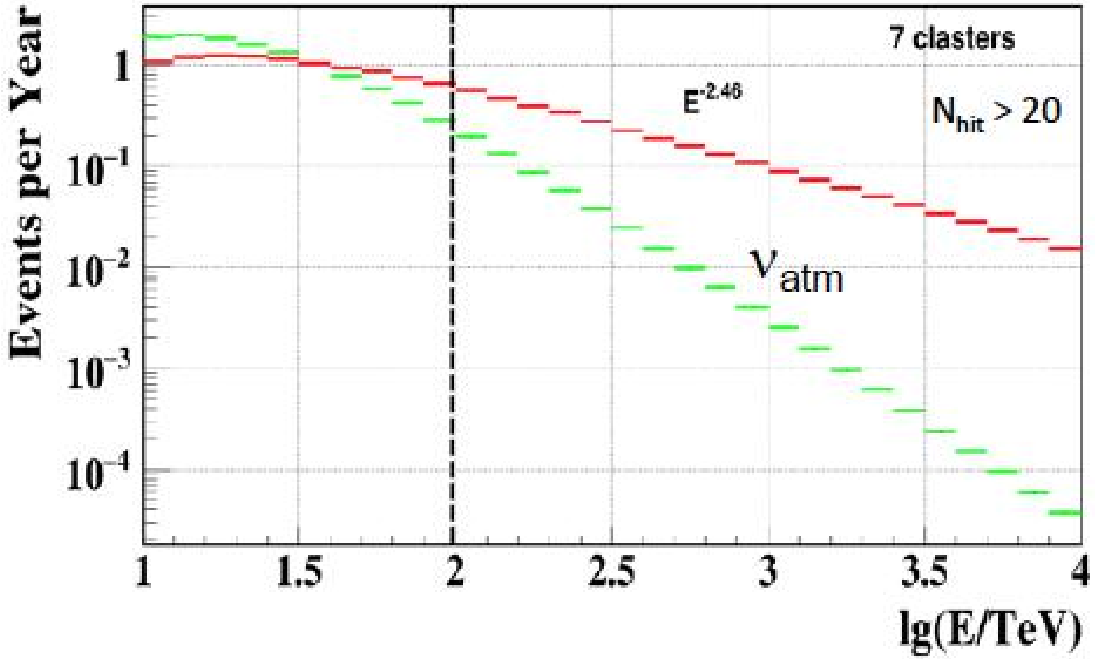
neutrino effective area for cascade detection



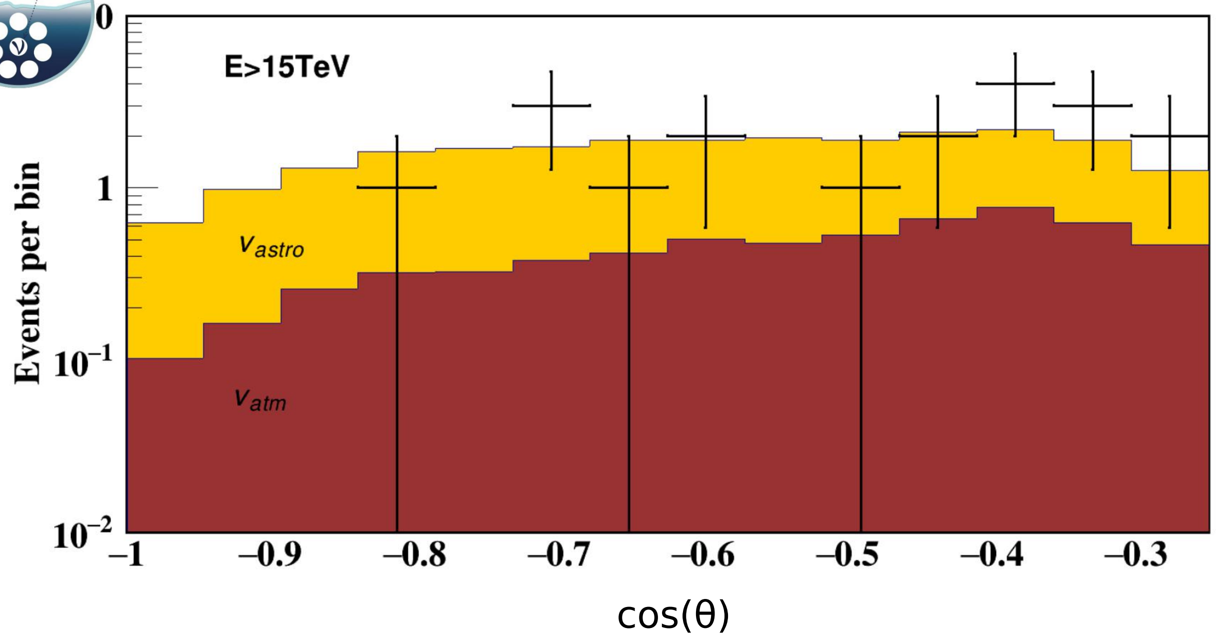
Glashow resonance not included

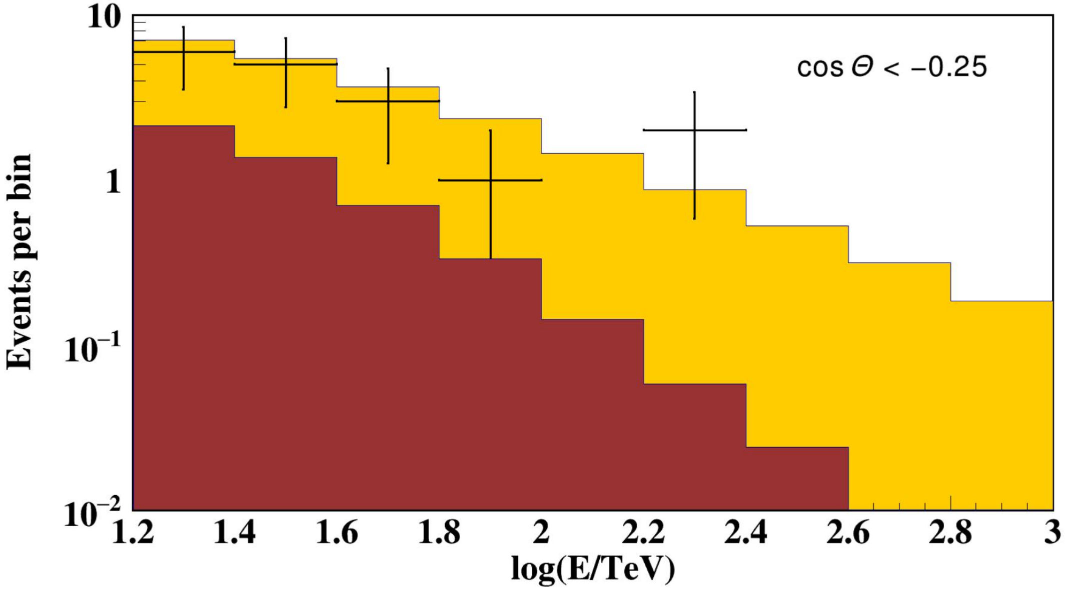
Assumption for astrophysical neutrino energy spectrum (IceCube fit):
$4.1 \cdot 10^{-6}\ E^{-2.46}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$

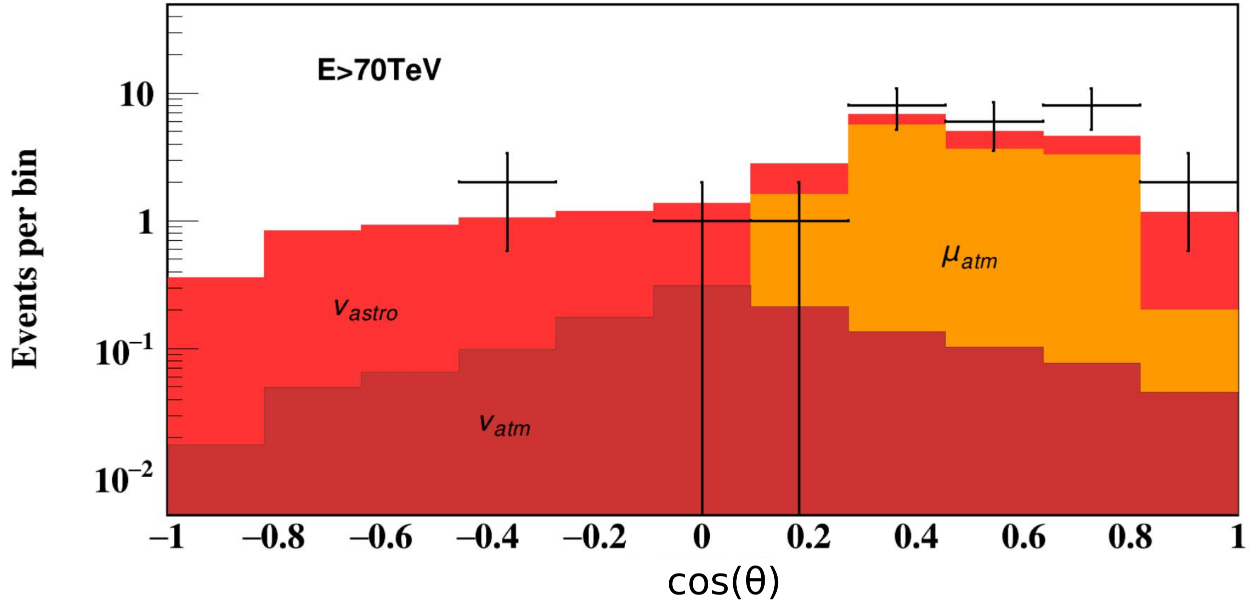
Expected number of cascade events per year

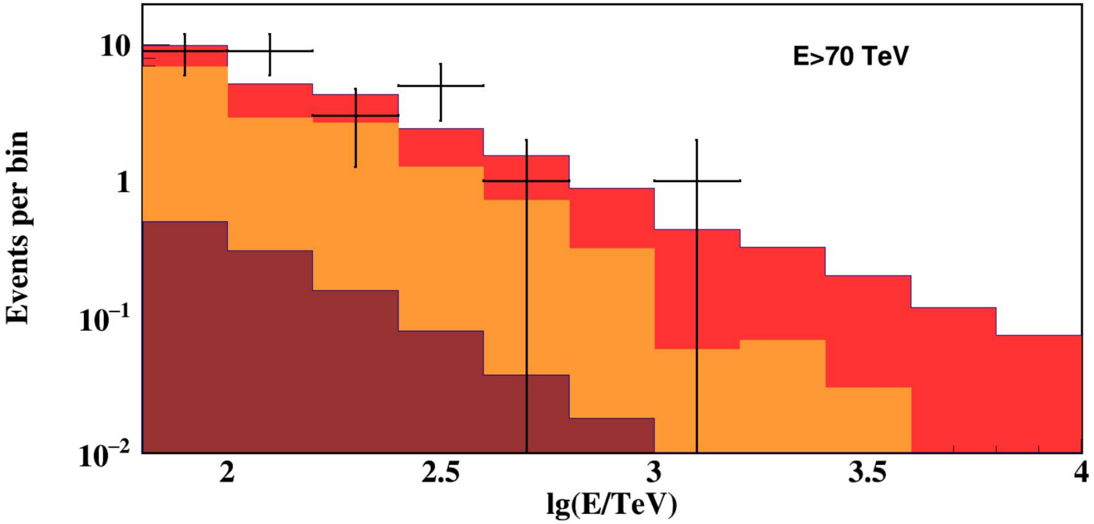


- 3–4 ev/yr with E_{sh} >100 TeV for 7 clusters


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}
μ_{atm}
ν_{atm}
Events per bin
cos(θ)


E>70 TeV
Events per bin
lg(E/TeV)