# Baikal-GVD neutrino telescope in 2024

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on behalf of the Baikal-GVD collaboration

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# Location

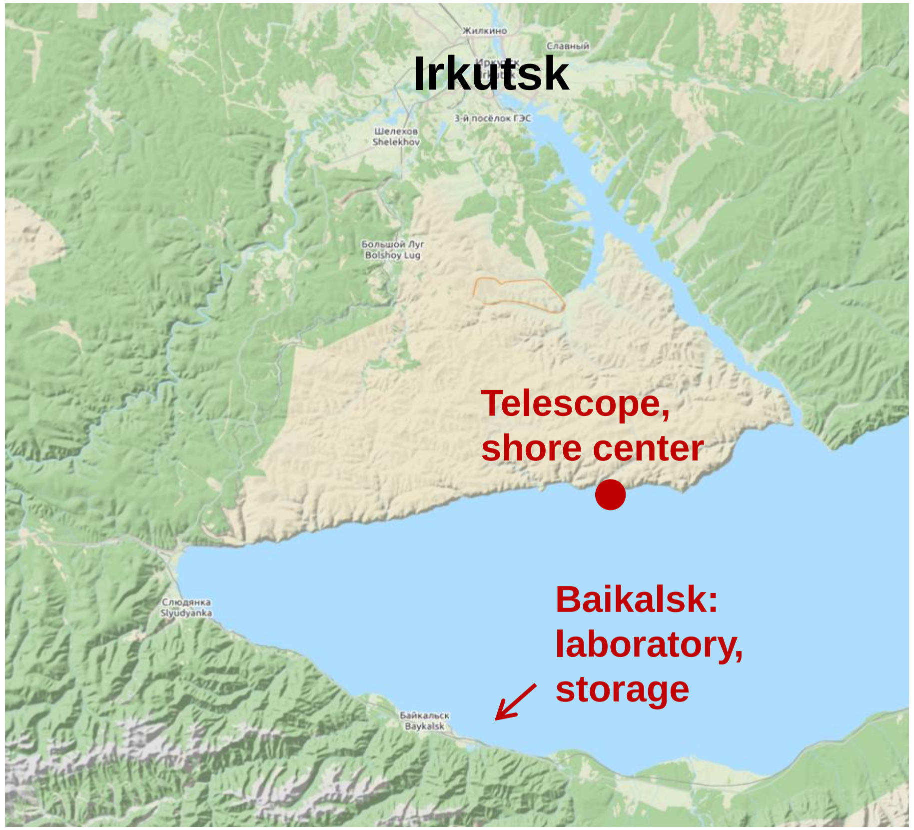
Platform “Ivanovskaya” of Circum-Baikal railway

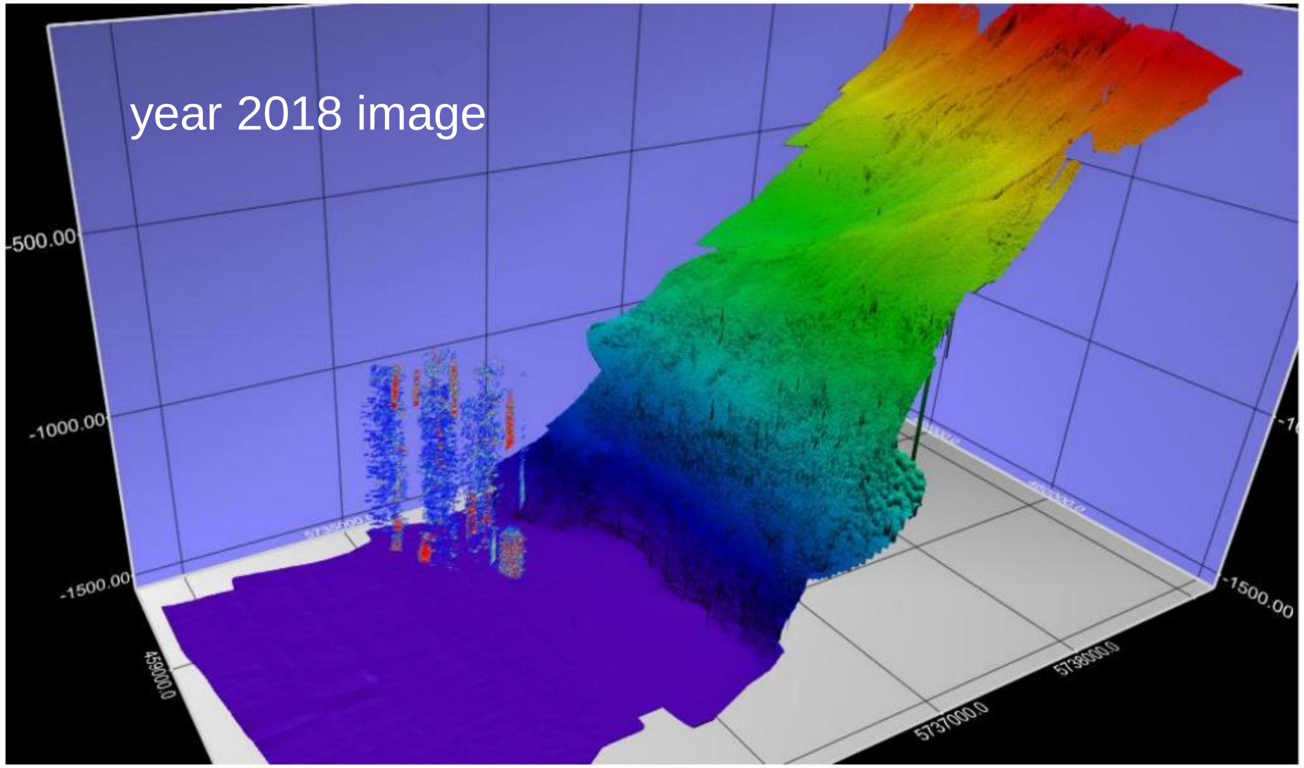
Telescope is located 3.6 km away from shore

Constant lake depth: 1366 - 1367 m

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

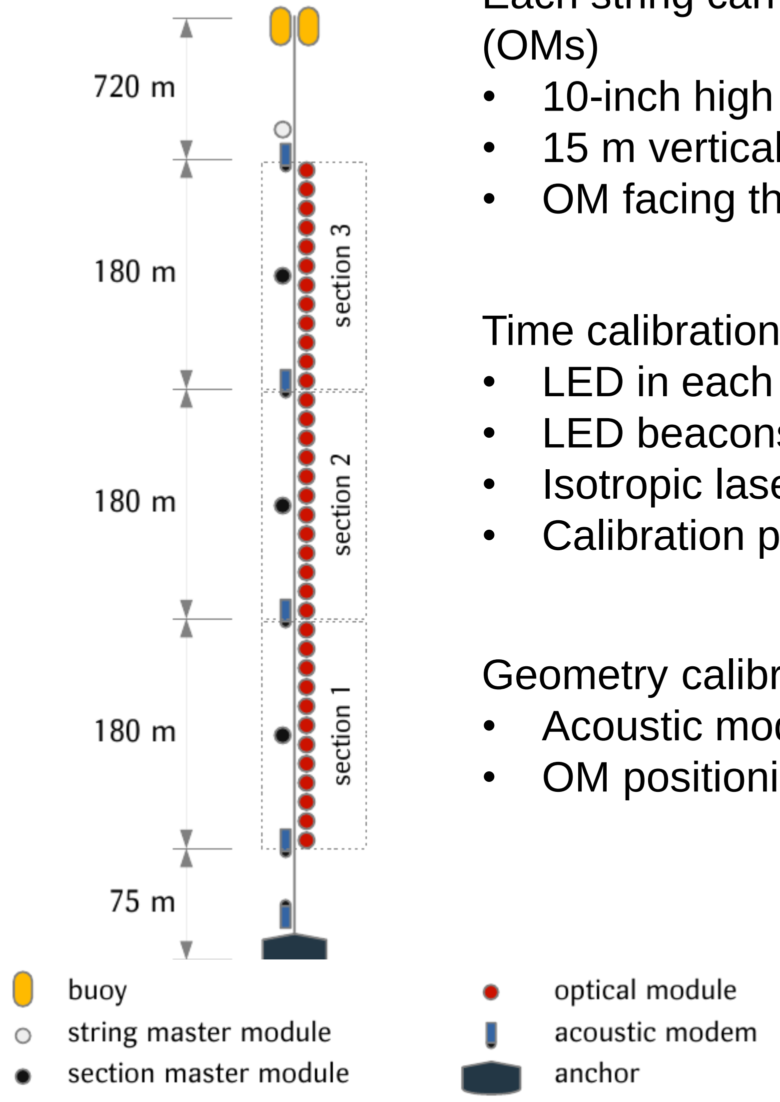
Stable ice cover over 7 - 8 weeks in February - April: detector deployment and maintenance



# 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

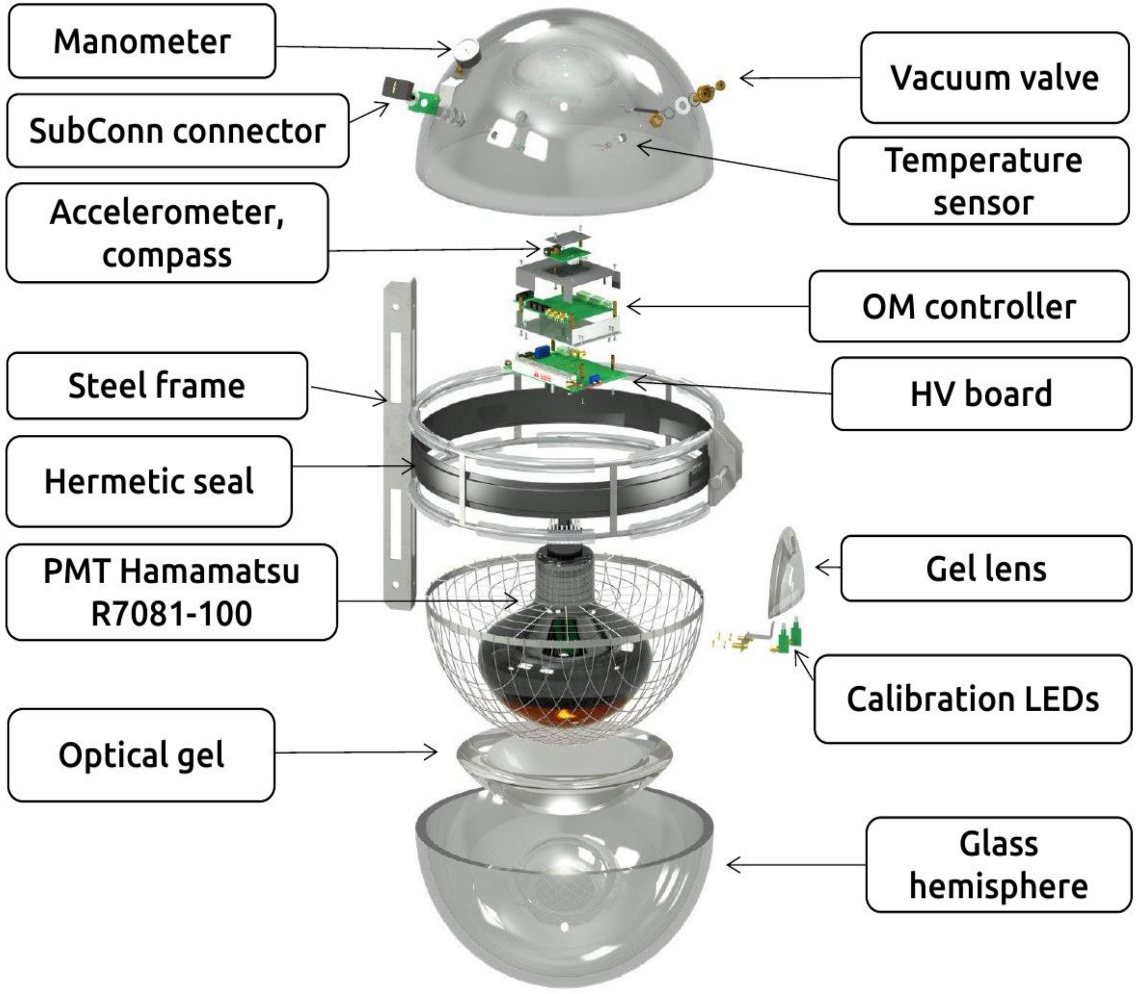
Time calibration systems

- 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**

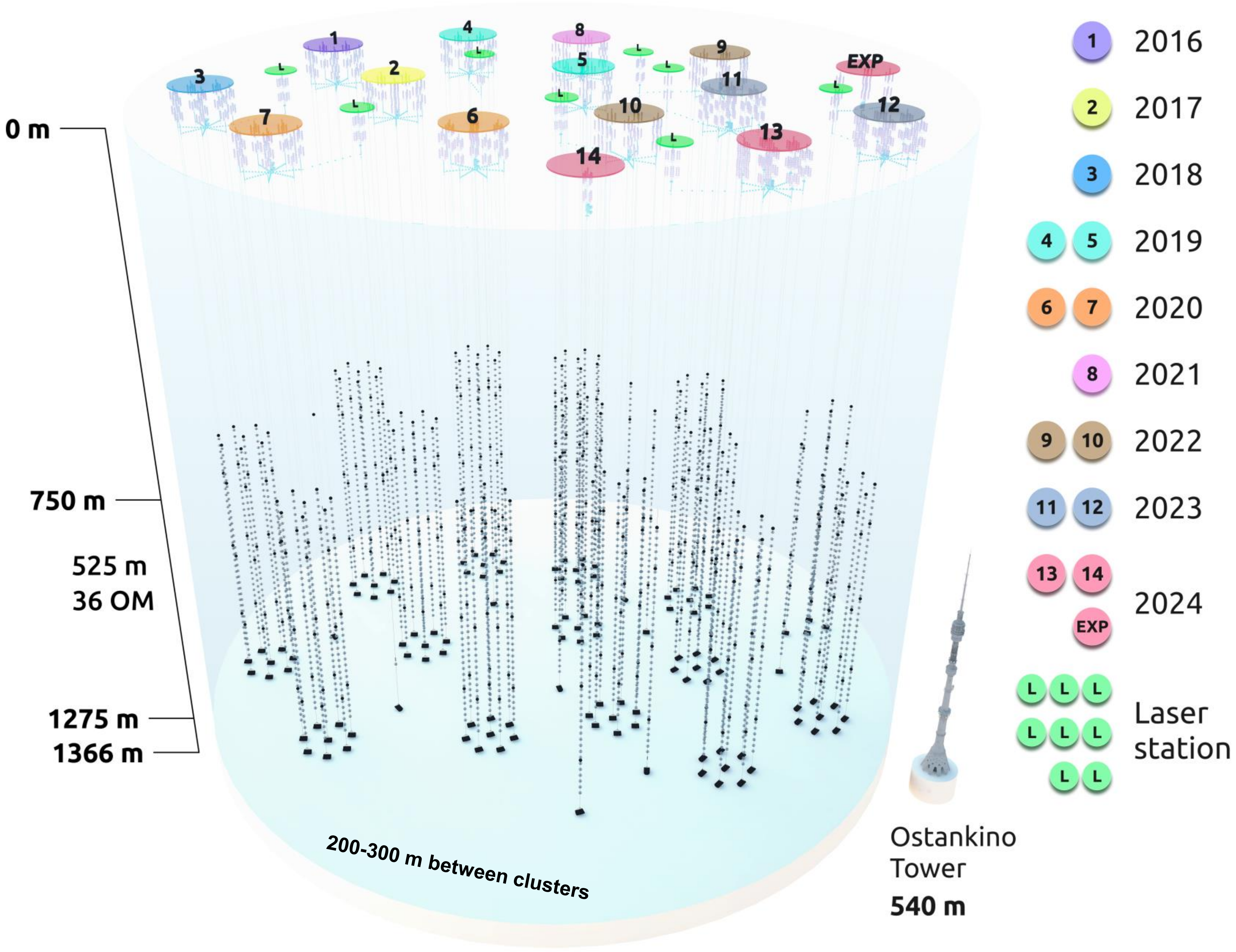
- 3960 OMs in total

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”:

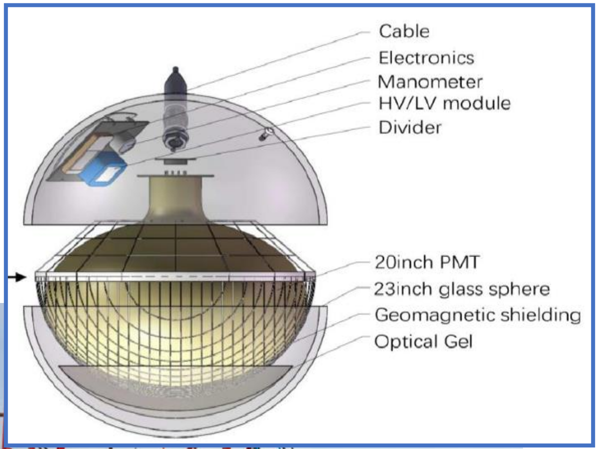
- 4 strings with experimental high-speed DAQ



# Expedition 2024

**Successfull 2024 deployment campaign 16/02 - 07/04**

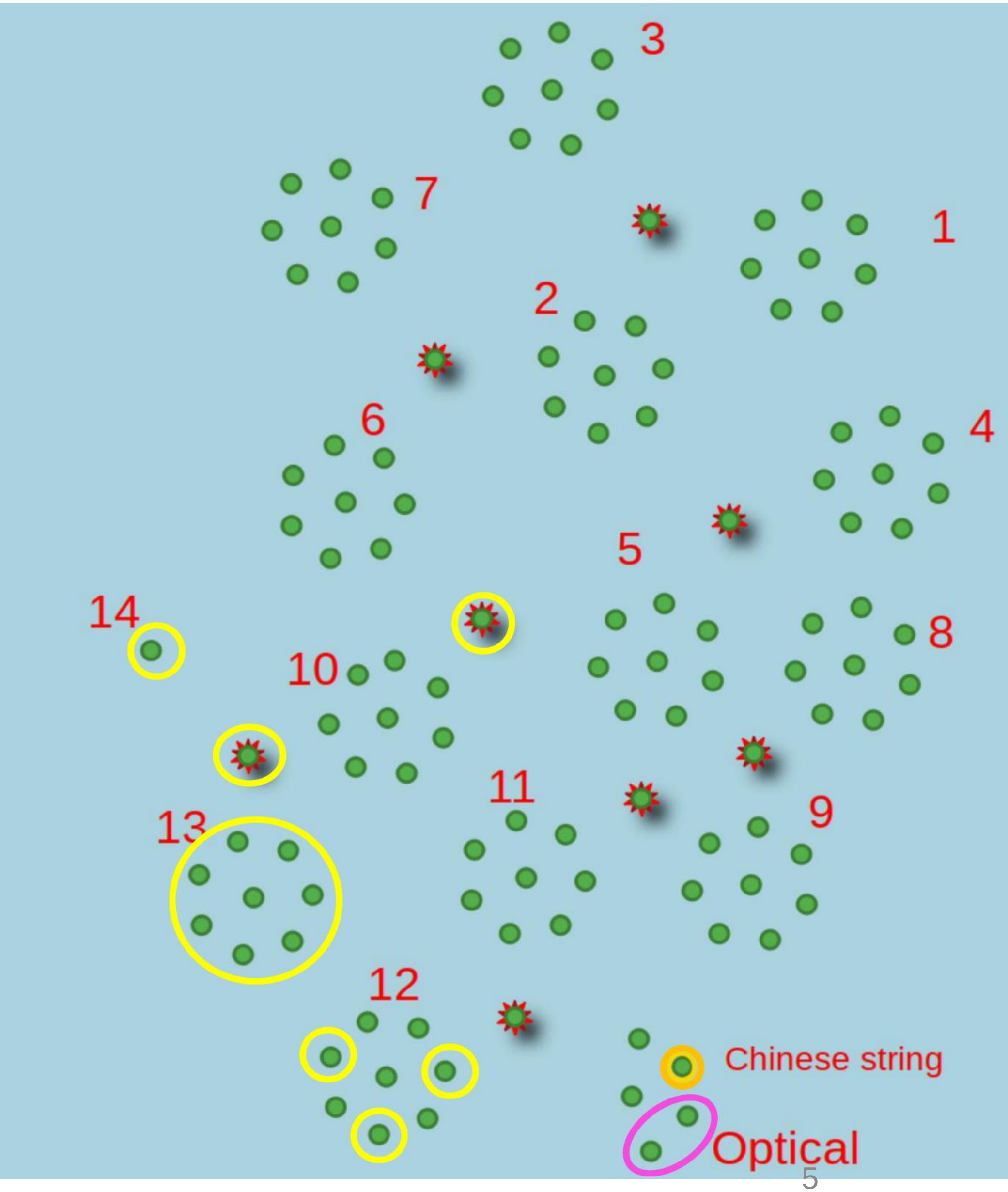
- 14 regular strings carrying 36 OMs installed
- 2 strings added to experimental (“optical”) cluster
- Pilot string for HUNT project




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

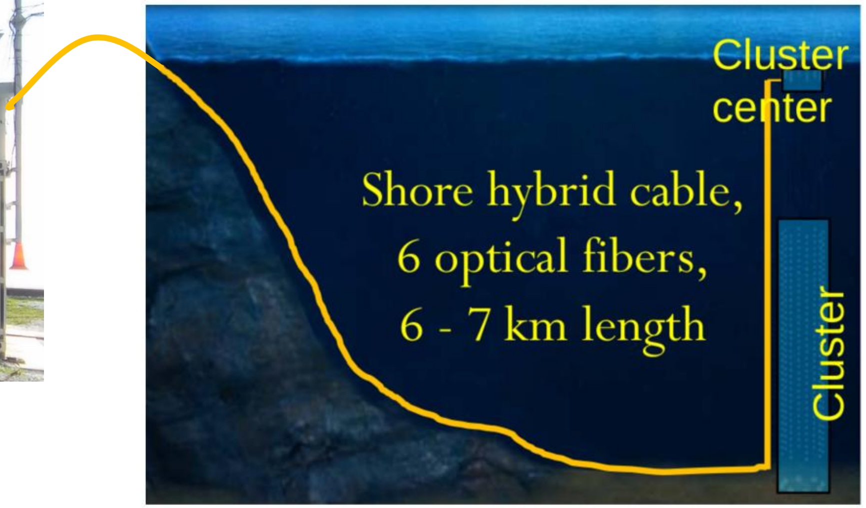
OMs based on 20-inch PMT

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

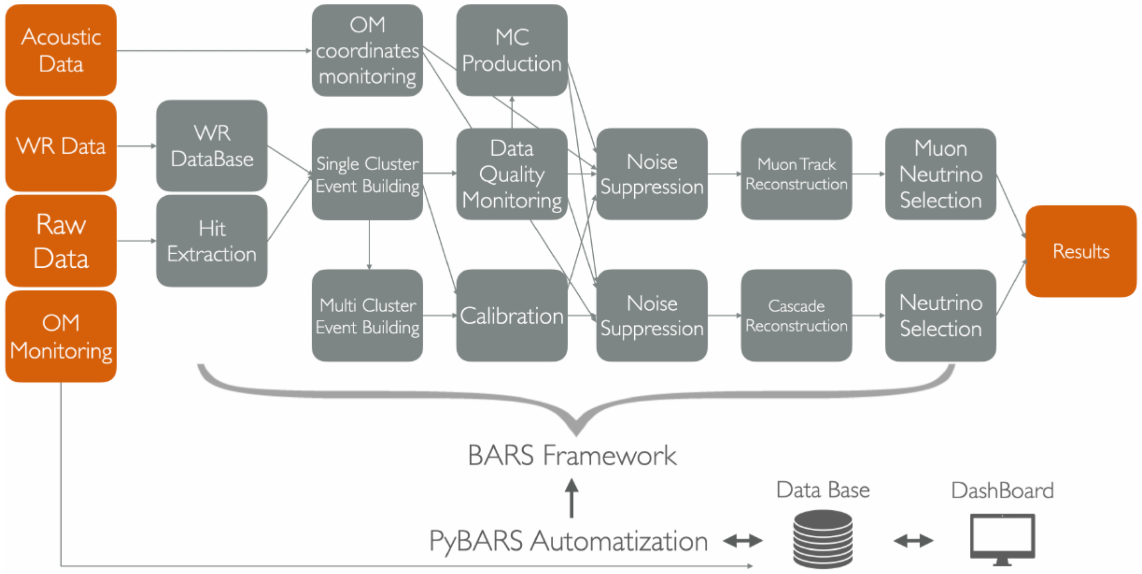




**Baikal shore center:**
- Power distrubution
- Data readout hardware/software
- Data-taking management (shifter)
- Data quality control
- Long-term storage of raw data
- Alert system (to be deployed)

# Data flow


**Raw data are transferred from the Shore center to JINR**

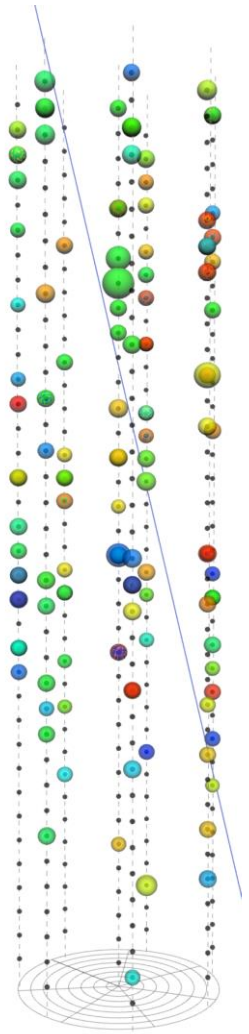
- Shore center → Baikalsk: 300 Mbit/s radiochannel
- Baikalsk → JINR: Ethernet
- Compressed data volume ~10-40 GB per day per cluster
- Full-scale reconstruction at JINR
- Delay due to shore → JINR data tranfer: < 1 min




**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 $\mu$s

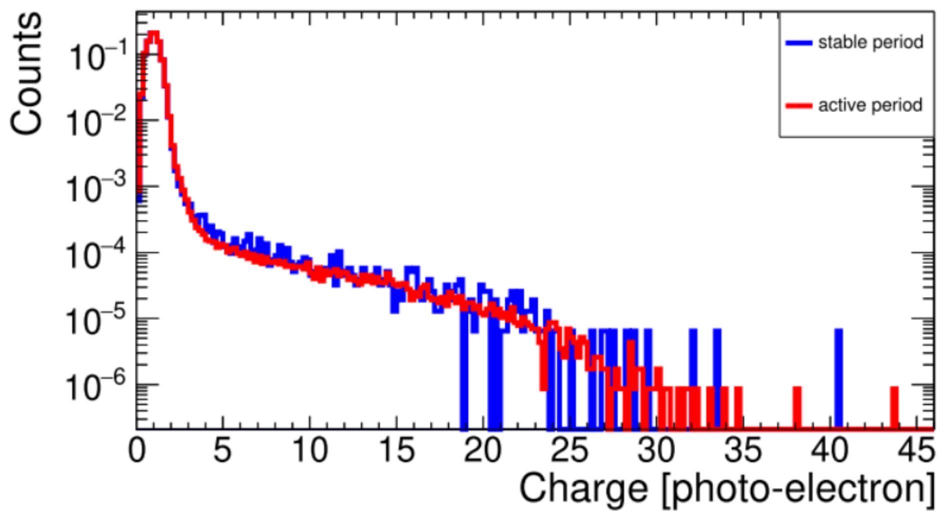
Most of pulses (or hits) in the event frame are noise from lake water luminiscence:

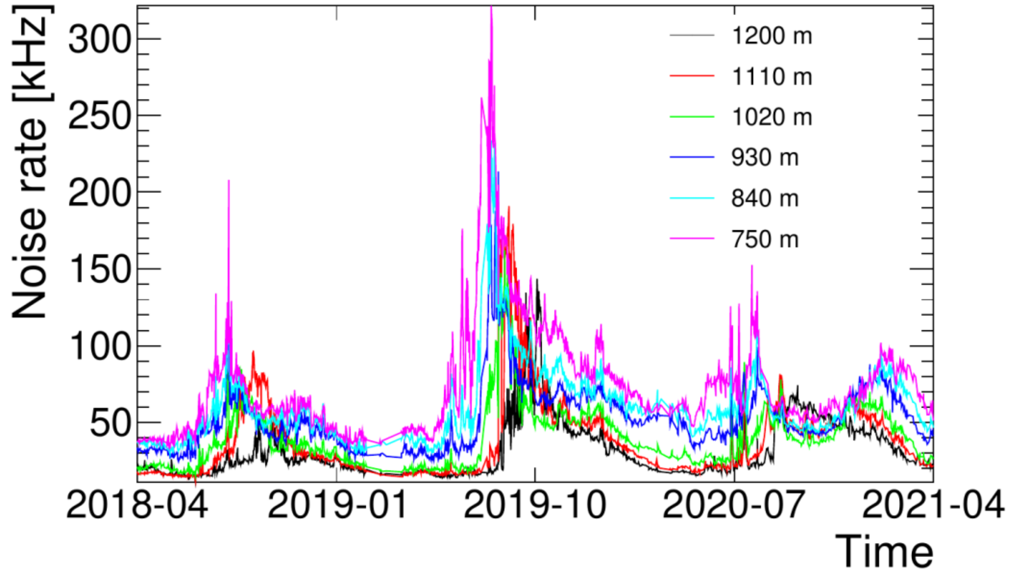
- Typical pulse rate 20-100 kHz
- ~1 photoelectron (p.e.) charge deposition
- Substantial seasonal variations
- Rate is larger on top layers

Challenge for our MC simulation

Variety of algorithms for noise suppression

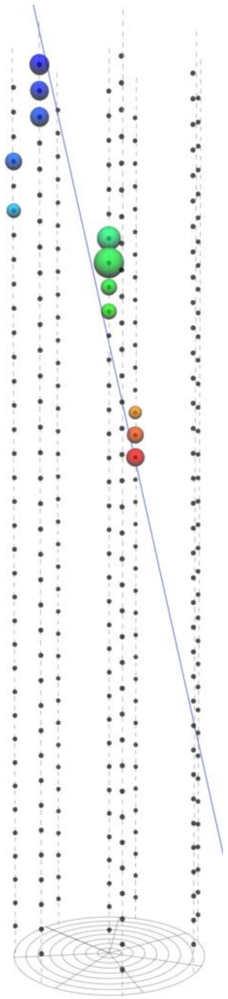
Machine learning-based algorithm in development:
**[arXiv:2210.04653]**



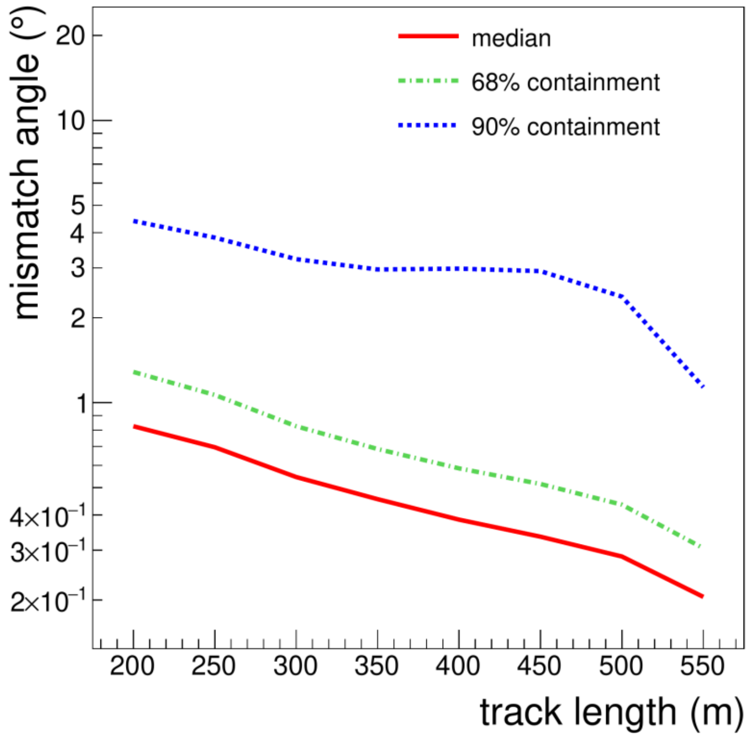
# Event reconstruction

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

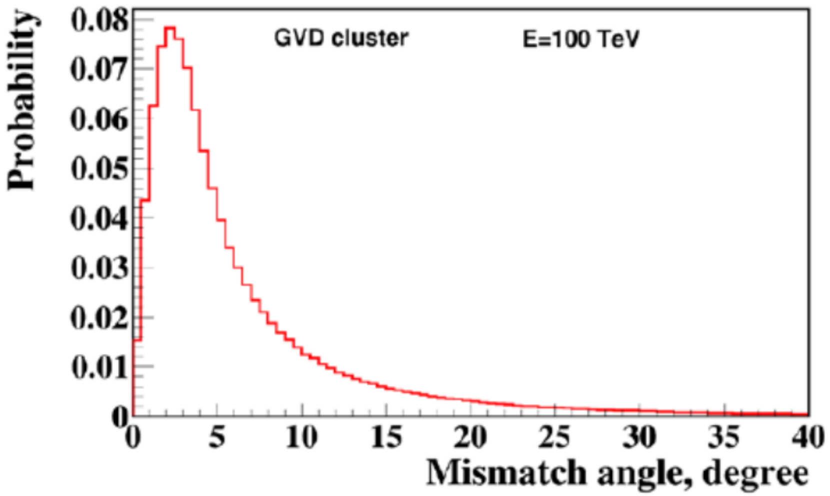


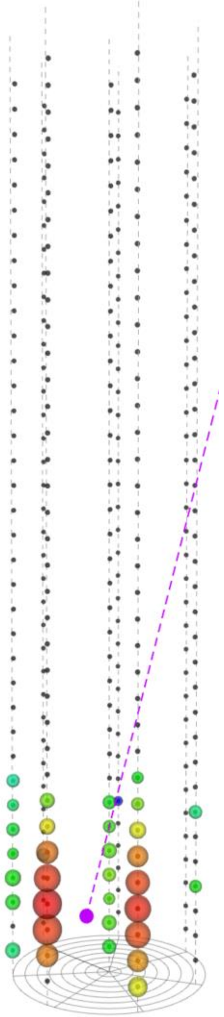
track-like,
data 2019

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




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

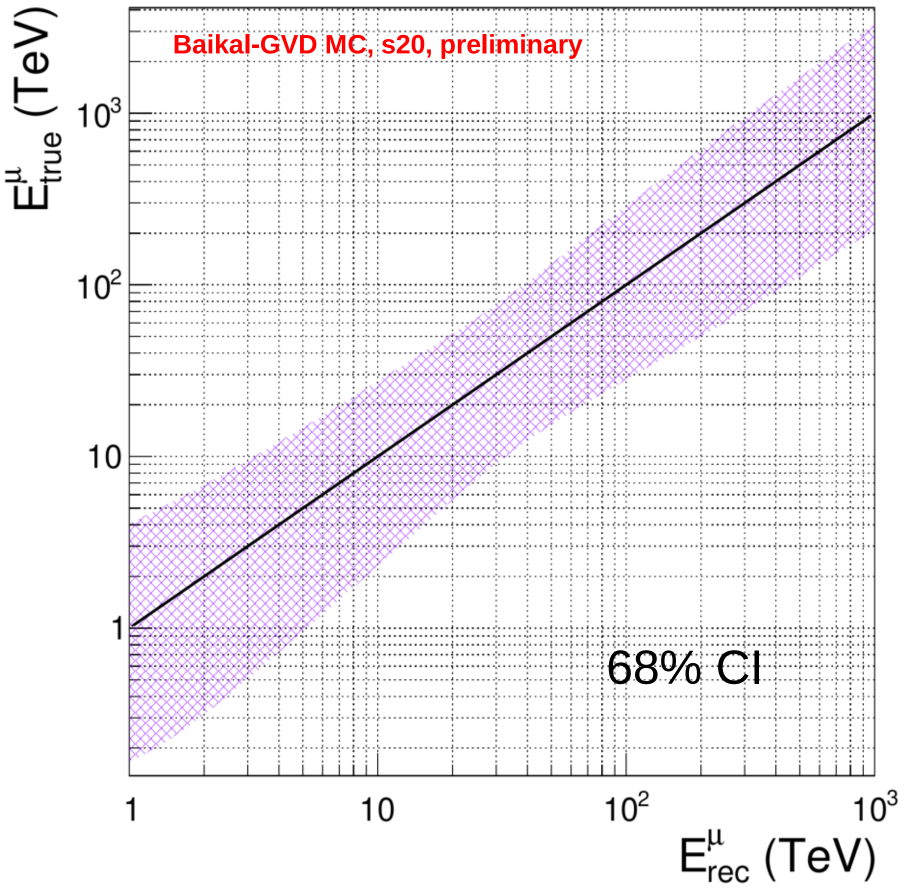


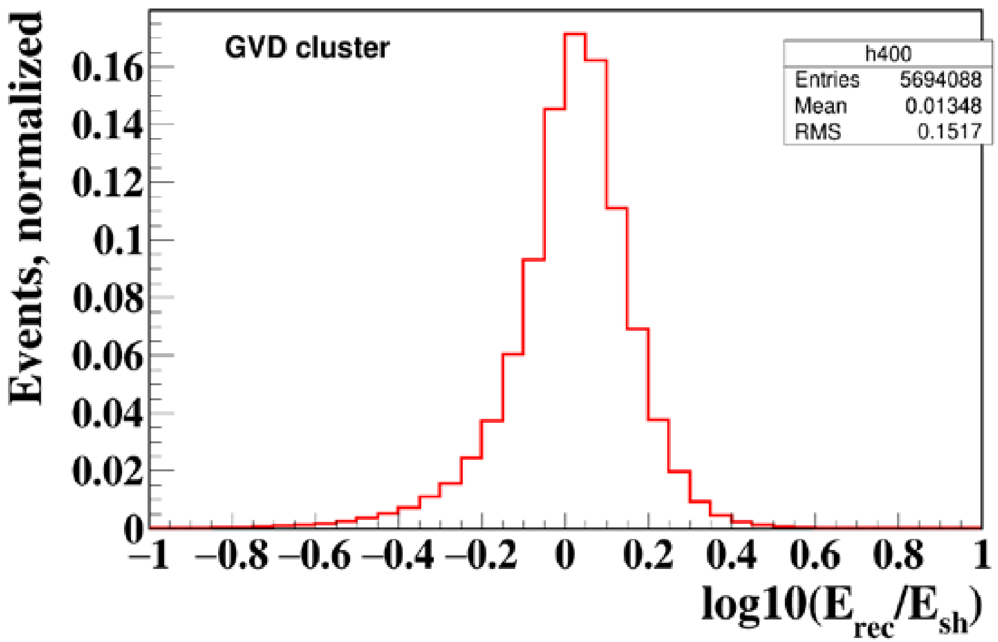
cascade-like,
data 2022

# 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 with Baikal-GVD

Data:

previously: 2018-2021, effective livetime: 4928 days/eq.cluster (13.5 yr./cl.)

recently: 2018-2024, effective livetime: 9778 days/eq.cluster ( 26.8 yr./cl.)

- All-sky search for HE cascades:

  threshold of E > 100 TeV allows to observe events from upper hemisphere

- Search for upward moving events:

  lower energy threshold (E>15 TeV) due to low atmospheric background for cascade detection channel

# All-sky search for HE cascades (2018-2023) preliminary

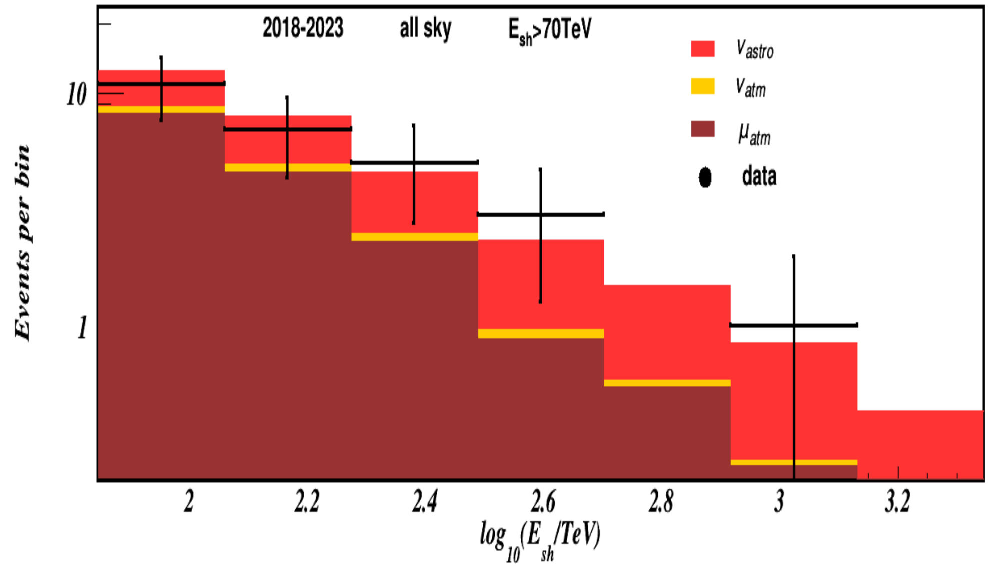
Additional selection requirements:
($N_{hit\_\mu}$ = 0, $E_{rec}$ ≥ 70 TeV) or
($N_{hit\_\mu}$ = 1, $E_{rec}$ ≥ 100 TeV)
$N_{hit\_\mu}$ is number of hits in time interval where hits from muons are expected

Expected:
14.7 events from atm. muons
1.0 events from atm. neutrinos
11.6 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

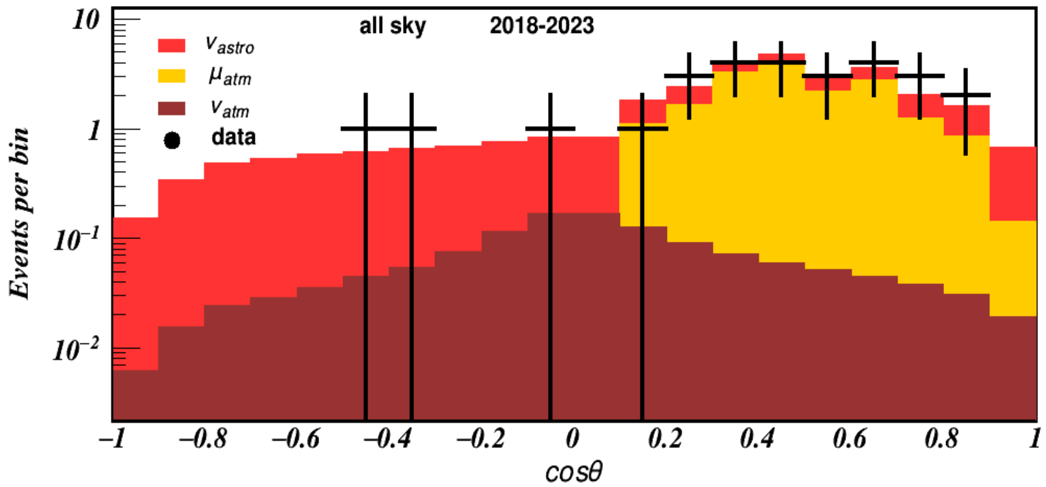
Found in real data: 28 events

| Date | $N_{data}$ | $N_{bg}$ | P-value | Significance (no syst.) |
|---|---|---|---|---|
| 18-21 | 16 | 8.2 | $2.09\times10^{-2}$ | 2.31σ |
| 18-23 | 27 | 15.7 | $3.19\times10^{-3}$ | 2.73σ |

Energy distribution (18-23)




Zenith distribution (18-23)



# Search for upward moving events (2018-2023) preliminary

Additional selection requirements:

E > 15 TeV & $N_{hit}$ >11 & cosθ < -0.25

Expected:

1.0 events from atm. muons

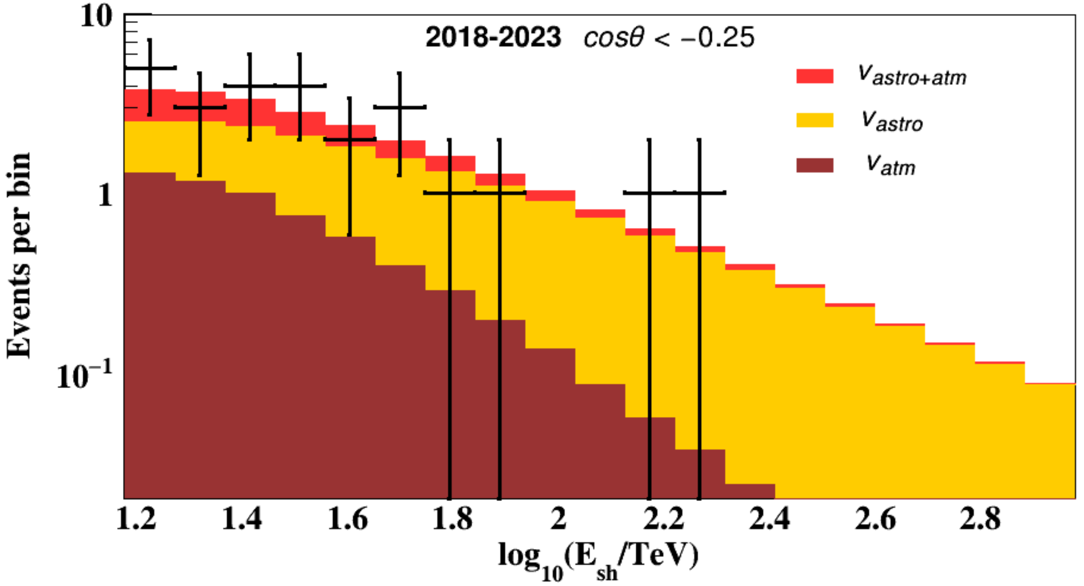
5.3 events from atm. neutrinos

18.9 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

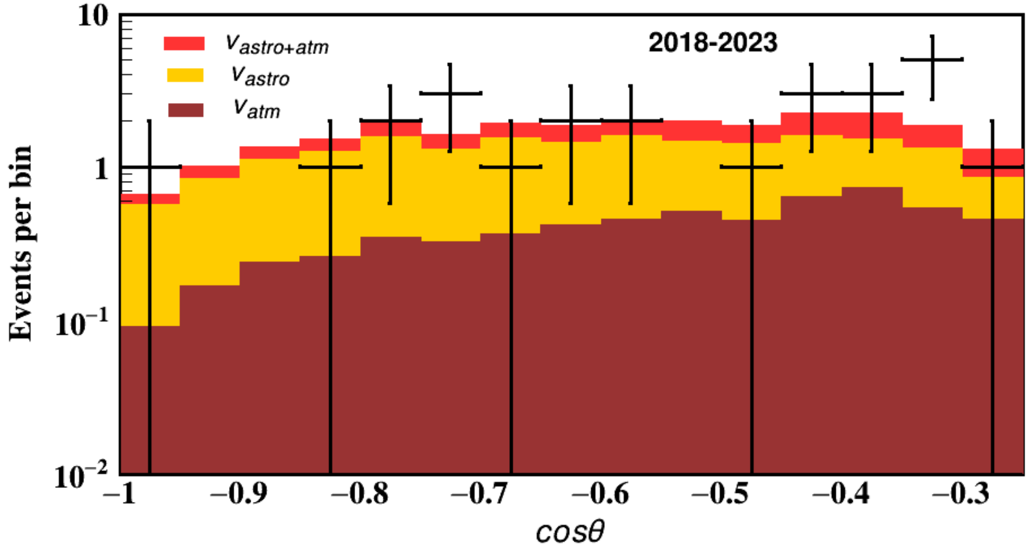
Found in data: 25 events

| Date | $N_{data}$ | $N_{bg}$ | P-value | Significance (no syst.) |
|---|---|---|---|---|
| 18-21 | 11 | 3.2 | $1.76\times10^{-3}$ | 3.13σ |
| 18-23 | 25 | 6.3 | $1.5\times10^{-8}$ | 5.54σ |

Energy distribution (18-23)

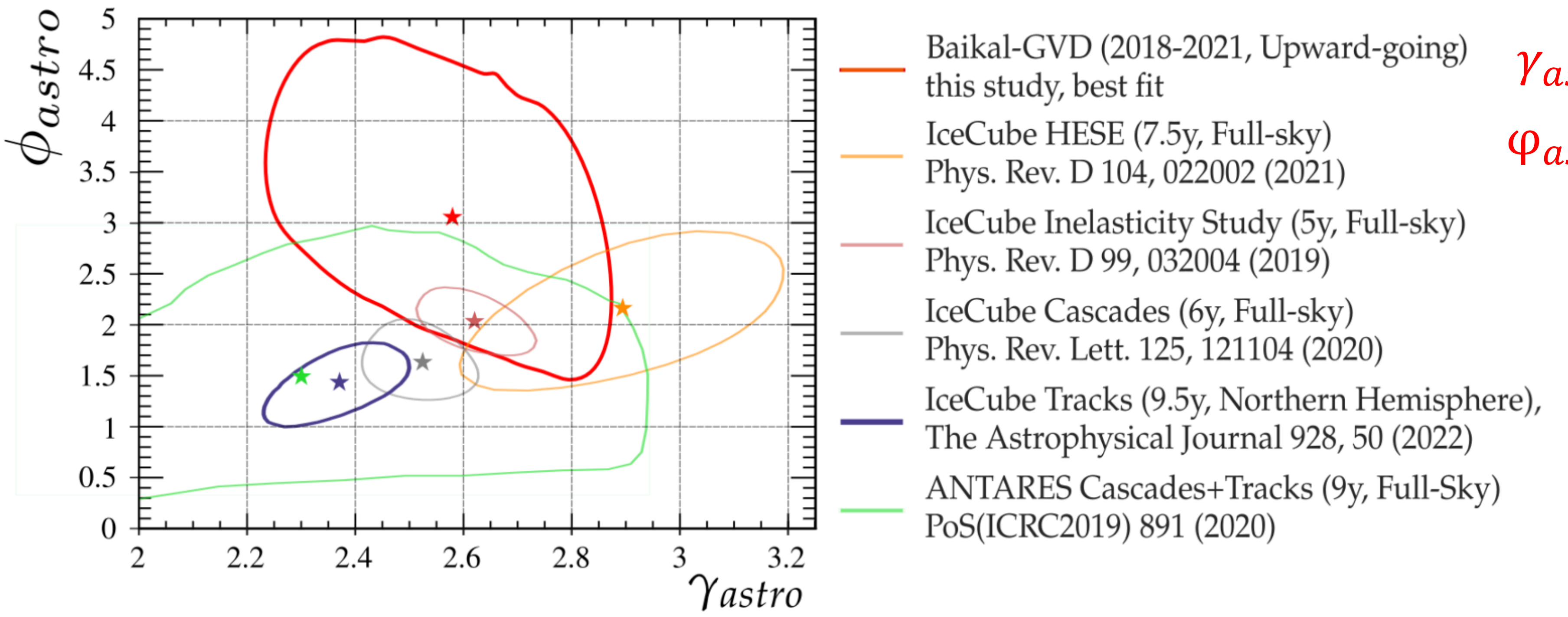



Zenith distribution (18-23)



# Diffuse spectrum
(2018-2021 dataset)

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




$\gamma_{astro} = 2.58$

$\varphi_{astro} = 3.04\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$

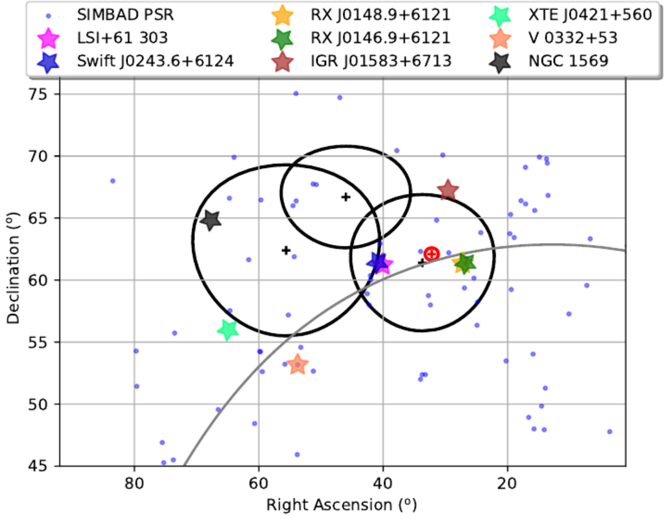
Results are in agreement with previous measurements by IceCube and ANTARES

**First "non-IceCube" evidence for diffuse $\nu_{astro}$ flux at above 3σ !**

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

# HE cascade sky map
(2018-2021 dataset)

[MNRAS 526 (2023) 942]



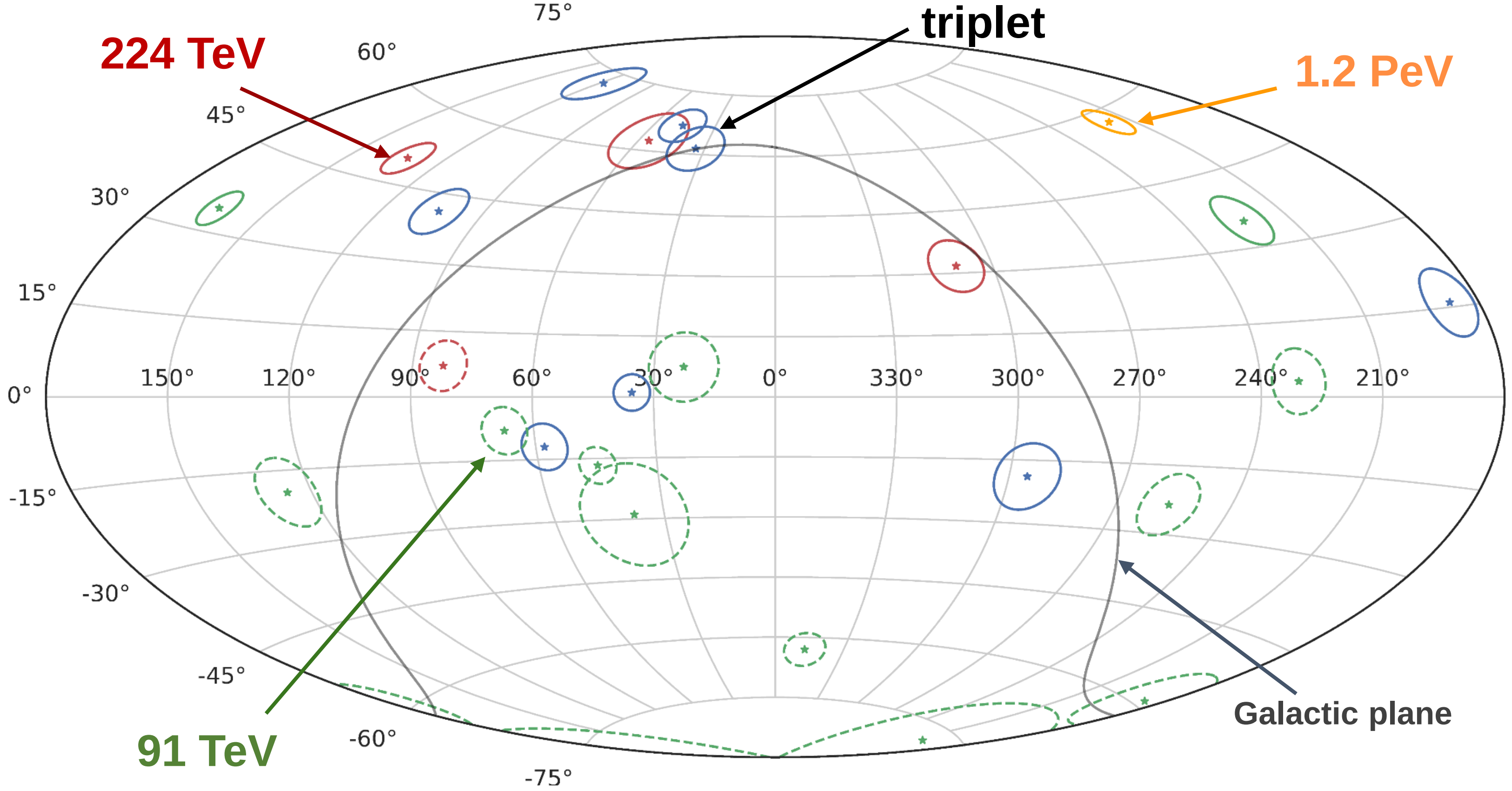

Three events close to the Galactic plane (grey line)

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



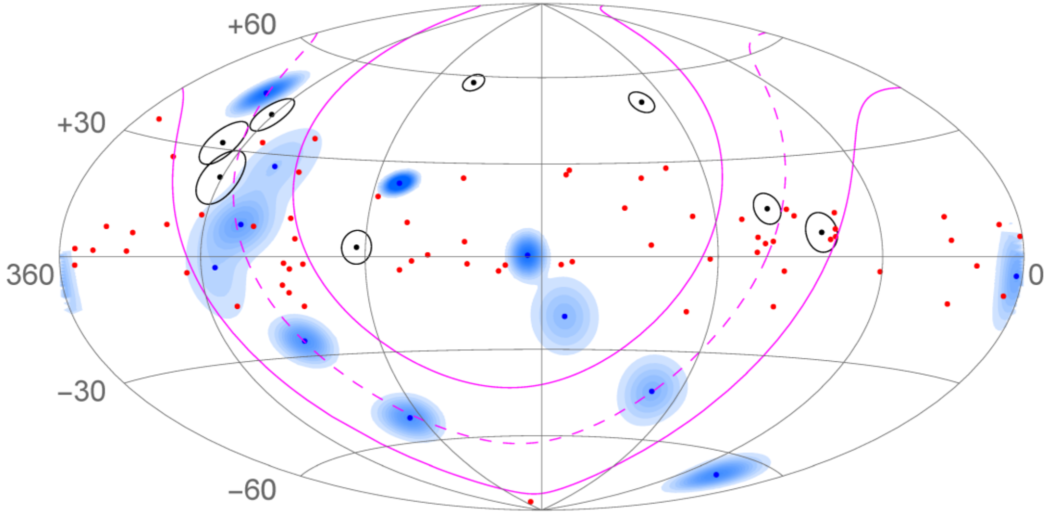

color represents energy:

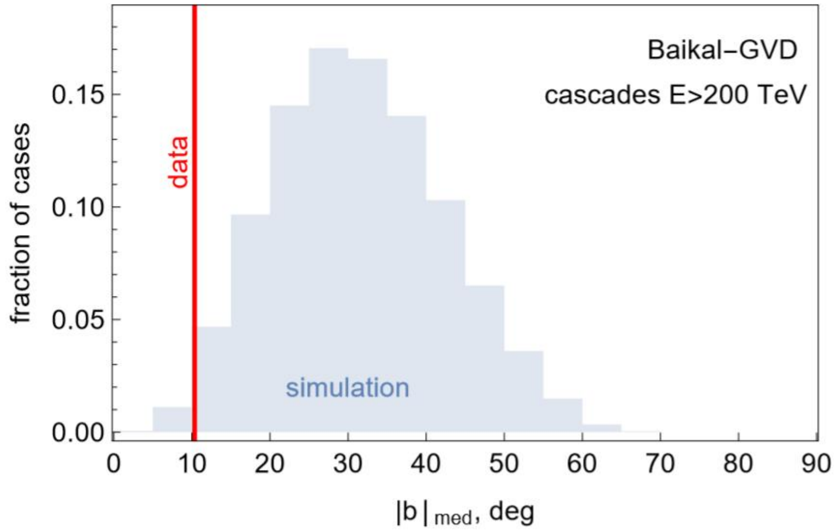
$E_{rec}$ < 100 TeV
100 TeV < $E_{rec}$ < 200 TeV
200 < $E_{reco}$ < 1000 TeV
$E_{rec}$ > 1 PeV

# Galactic neutrinos with Baikal-GVD

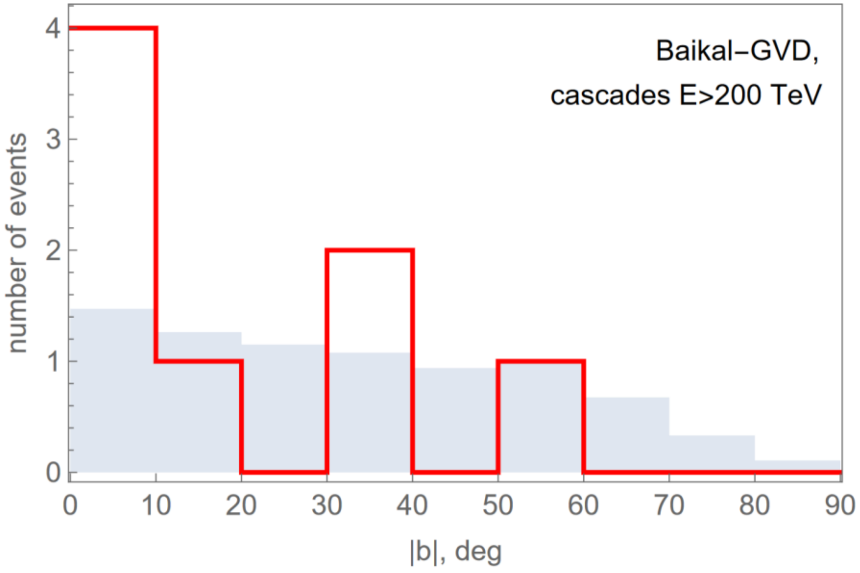
arXiv:2411.05608

- test the Galactic excess at E>200 TeV
- high-energy cascades 2018-2023
- simplest, model-independent median |b| test like in Kovalev et al. 2022



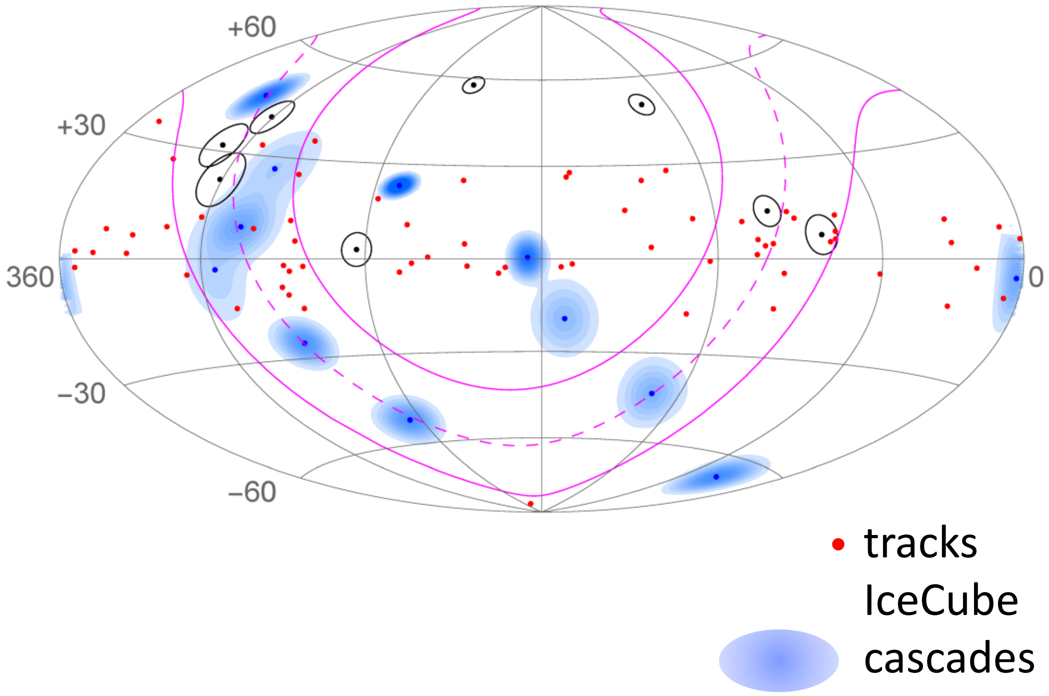

| Sample | $\lvert b\rvert_{\rm med}$ observed | $\langle \lvert b\rvert_{\rm med}\rangle$ expected | $p$ |
|---|---|---|---|
| Baikal-GVD cascades | 10.4° | 31.4° | $1.4 \cdot 10^{-2}$ (2.5$\sigma$) |



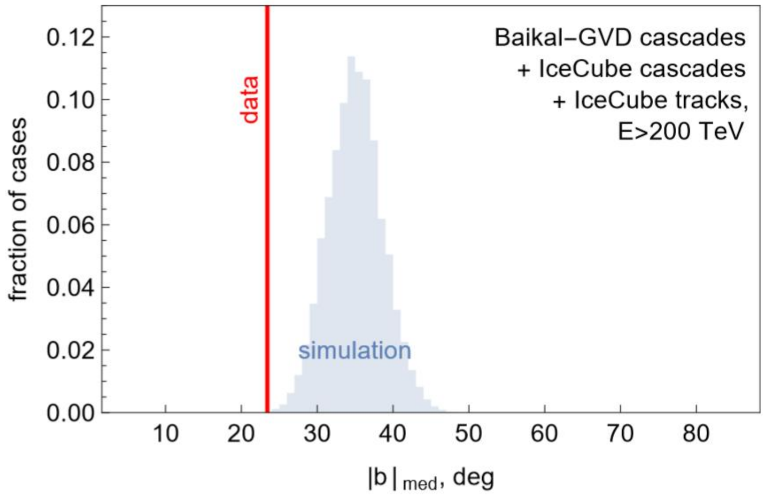

credits to Sergey V. Troitsky

# Galactic neutrinos above 200 TeV: Baikal-GVD cascades, IceCube cascades and tracks

- newest IceCube public data
  - ✓ HESE cascades *IceCube 2023*
  - ✓ ICECAT v2 tracks *IceCube 2024*
- same selection (E>200 TeV)
- same median |b| test
- **same results**

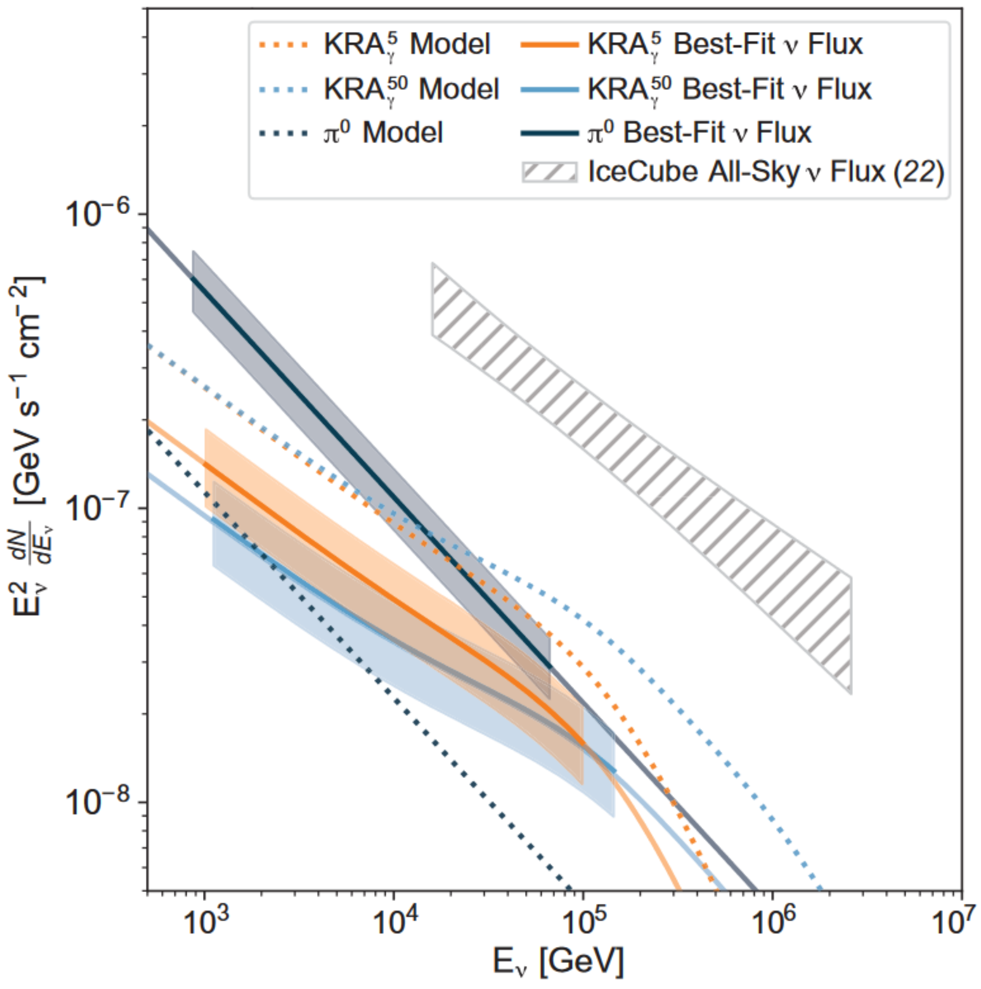



| Sample | $\lvert b\rvert_{\rm med}$ observed | $\langle \lvert b\rvert_{\rm med}\rangle$ expected | $p$ |
|---|---|---|---|
| Baikal-GVD cascades | 10.4° | 31.4° | $1.4\cdot10^{-2}$ (2.5$\sigma$) |
| IceCube cascades | 12.4° | 31.9° | $8.7\cdot10^{-3}$ (2.6$\sigma$) |
| IceCube tracks | 24.7° | 36.0° | $1.8\cdot10^{-3}$ (3.1$\sigma$) |
| combined | 23.4° | 35.0° | $3.4\cdot10^{-4}$ (3.6$\sigma$) |




credits to Sergey V. Troitsky

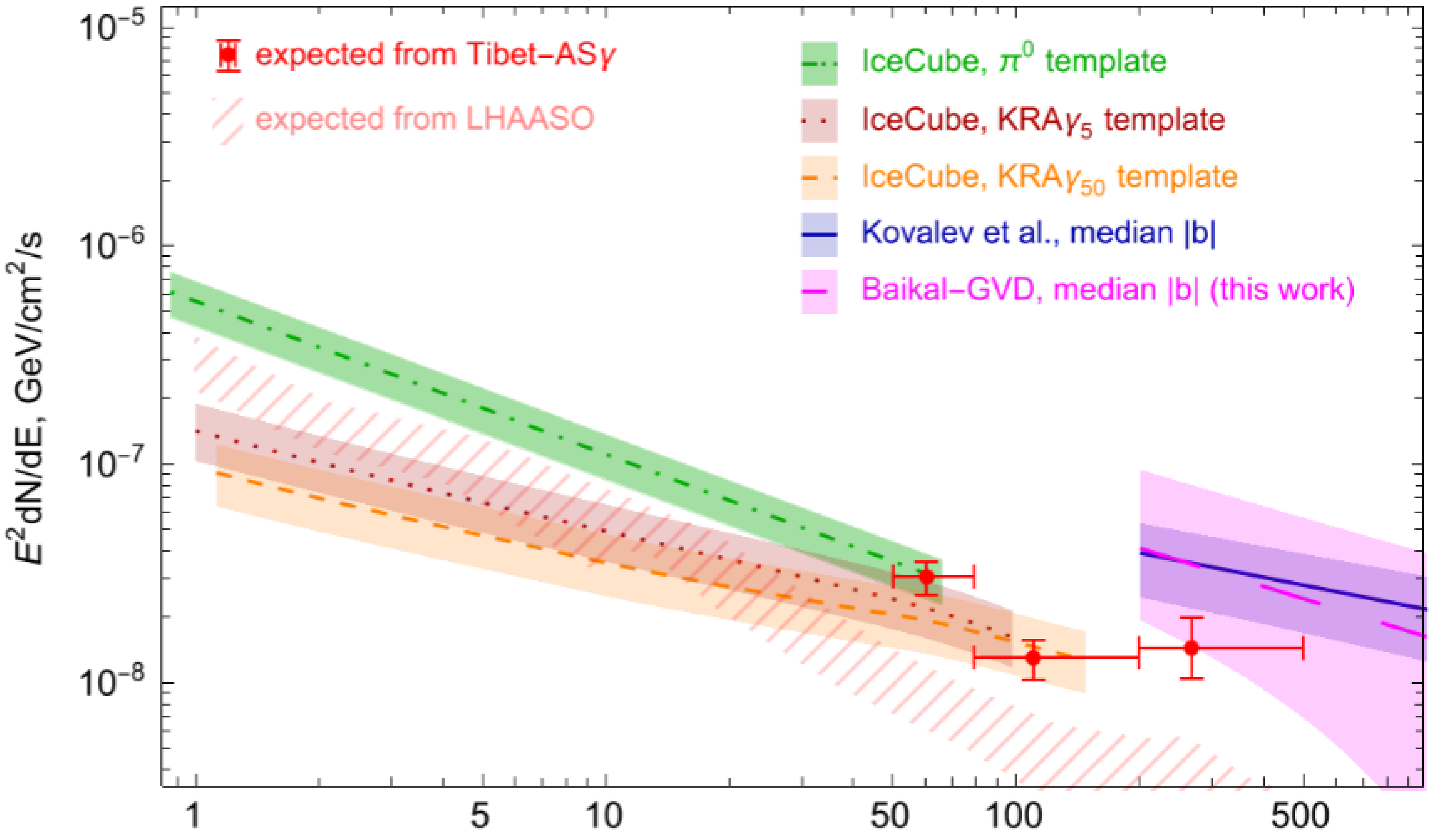
# Templates query




| 200 TeV < E < 1000 TeV, Milky Way: | Flux | Fraction |
|---|---|---|
| **Predicted by templates:** | | |
| KRA$\gamma_5$ | 0.34 | – |
| KRA$\gamma_{50}$ | 0.78 | – |
| $\pi^0$ | 0.077 | – |
| **Templates normalized to IceCube [8]:** | | |
| KRA$\gamma_5$ | $0.19^{+0.06}_{-0.05}$ | $0.044^{+0.016}_{-0.014}$ |
| KRA$\gamma_{50}$ | $0.29^{+0.10}_{-0.09}$ | $0.067^{+0.026}_{-0.024}$ |
| $\pi^0$ | $0.37^{+0.09}_{-0.08}$ | $0.086^{+0.026}_{-0.025}$ |
| **Estimated in Ref. [6]:** | | |
| IceCube tracks | $1.27 \pm 0.49$ | $0.28 \pm 0.09$ |
| **Estimated in the present work:** | | |
| Baikal-GVD cascades | $1.20^{+1.59}_{-0.75}$ | $0.49^{+0.51}_{-0.24}$ |
| IceCube cascades | $0.96^{+1.14}_{-0.56}$ | $0.26^{+0.30}_{-0.12}$ |
| IceCube tracks | $1.72^{+0.91}_{-0.71}$ | $0.34^{+0.17}_{-0.12}$ |

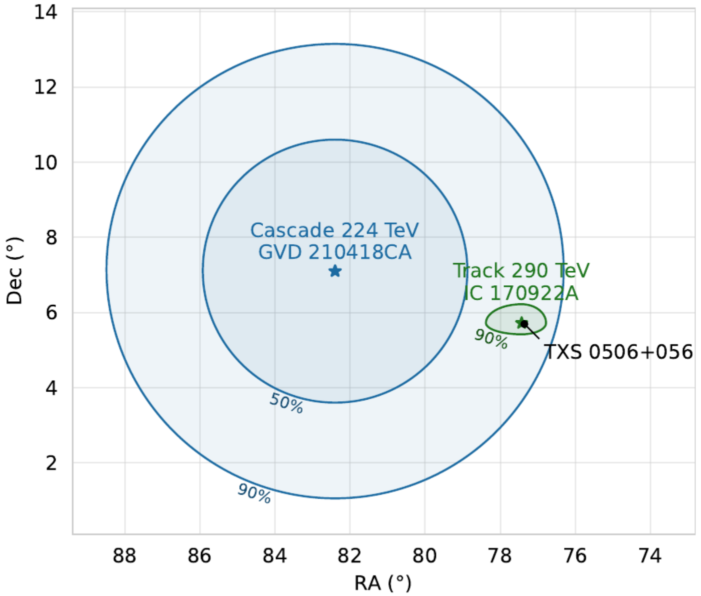
credits to Sergey V. Troitsky

# Galactic neutrinos




credits to Sergey V. Troitsky

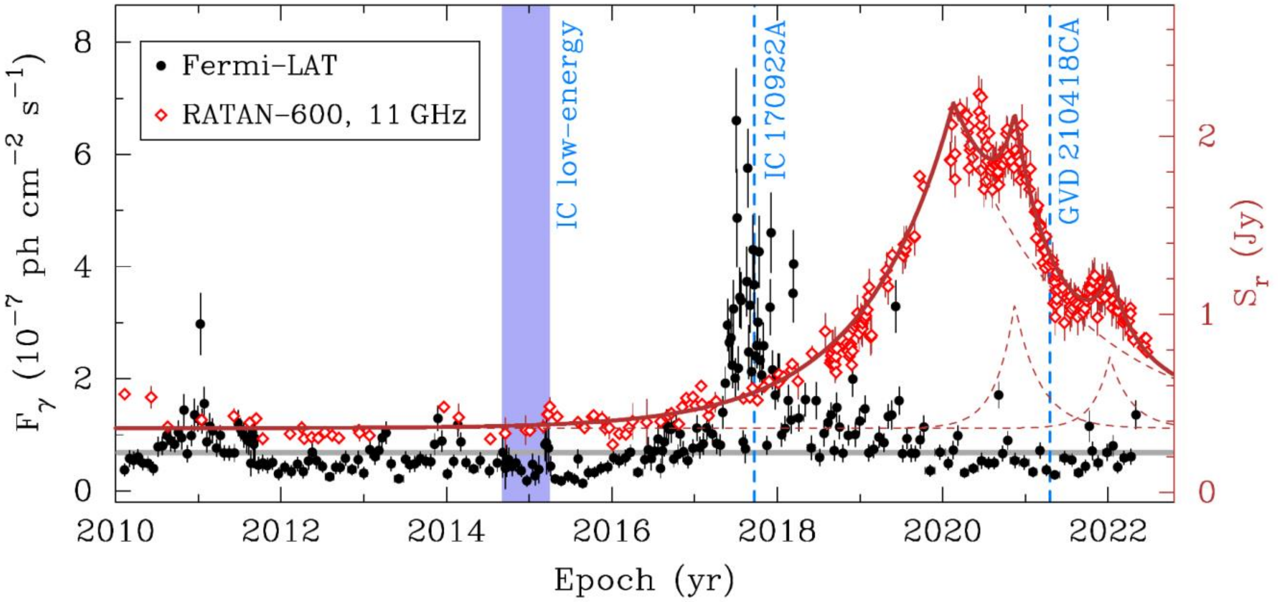
# Cascades: TXS0506 coincidence




[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

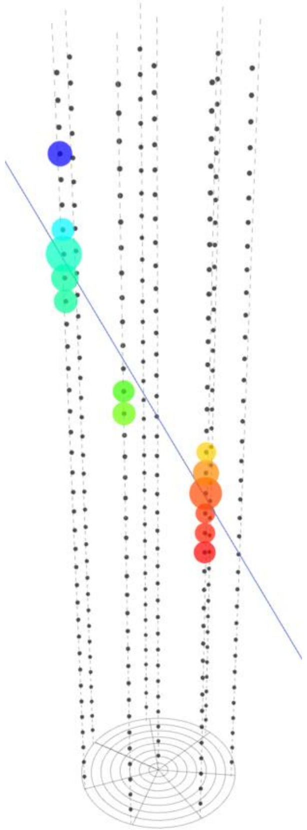
- IC event registered during γ flare
- Baikal event during radio flare
- Consistency with IC observations: 8% or 13% depending on ν spectrum assumption

# Track-like channel

# Track-like events

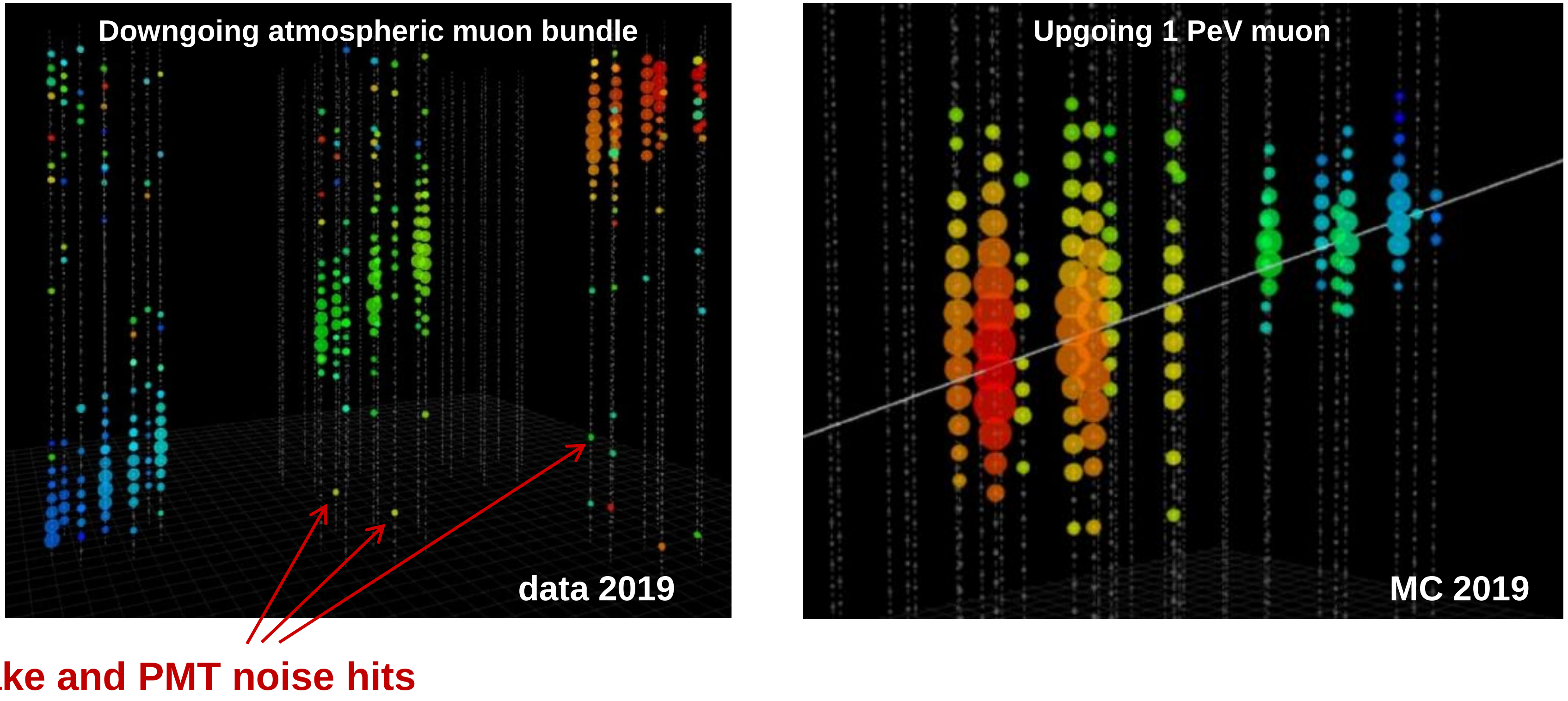
Two modes of analysis
- Single-cluster: each cluster is treated as an independent detector
- Multi-cluster: common reconstruction for simultateously triggered single-cluster events

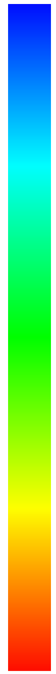
**Single-cluster upgoing event:**



**data 2019**

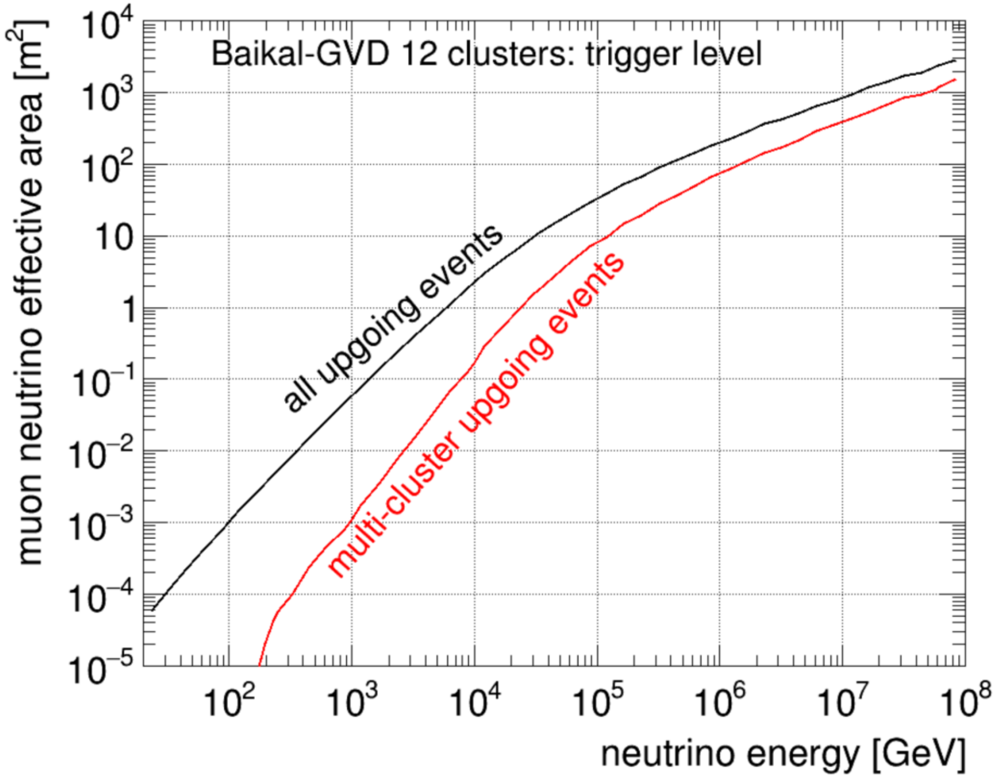
**Multi-cluster events:**



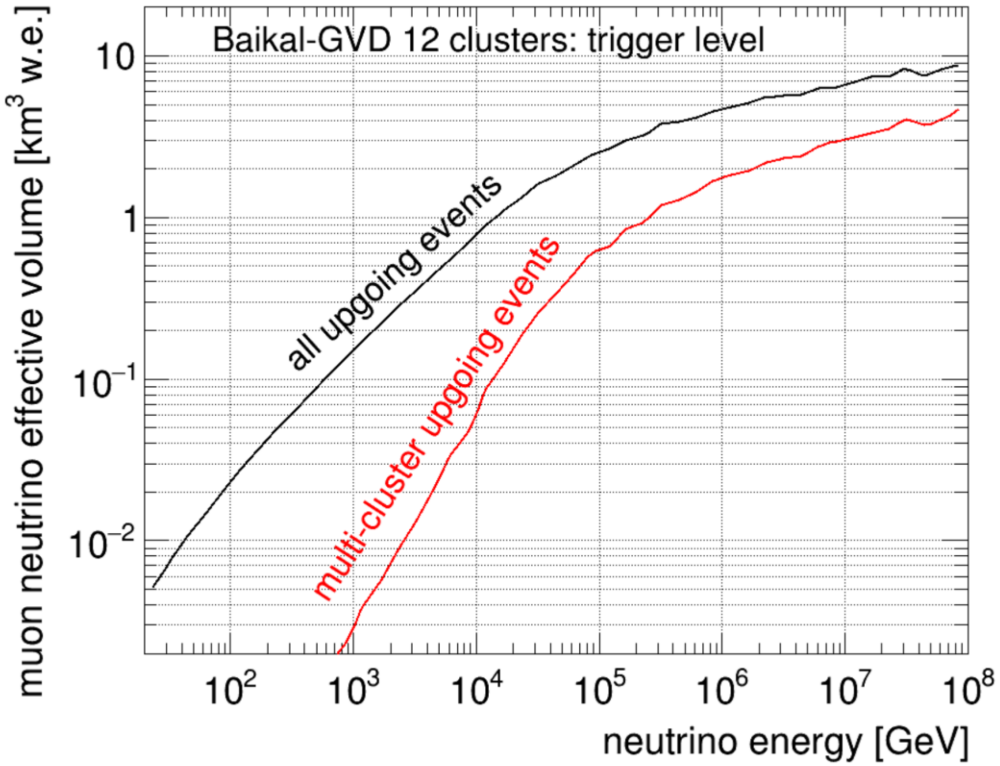



# Track trigger-level sensitivity, 12 clusters

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)

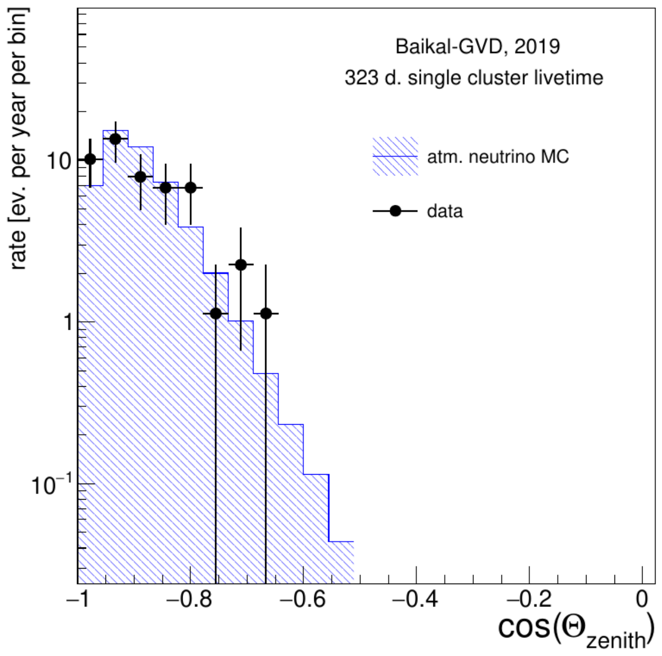
# First track-like neutrino candidate event sample

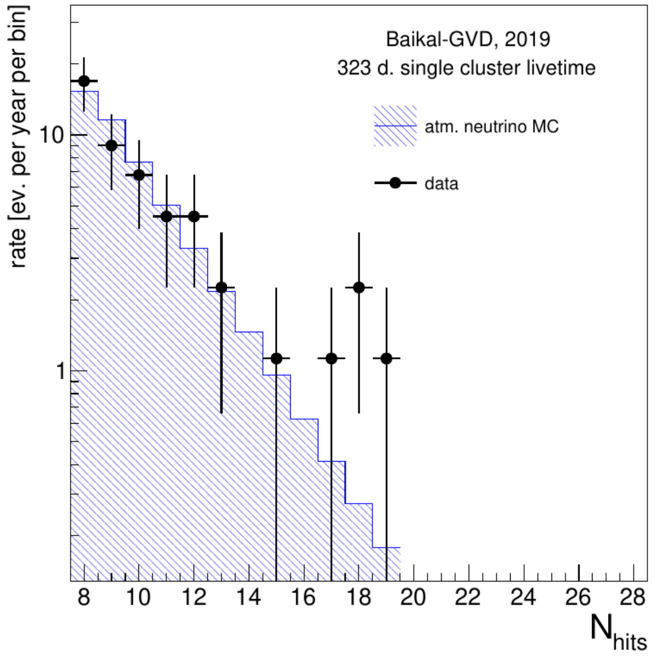
First set of single-cluster muon neutrino candidates based on 2019 data

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

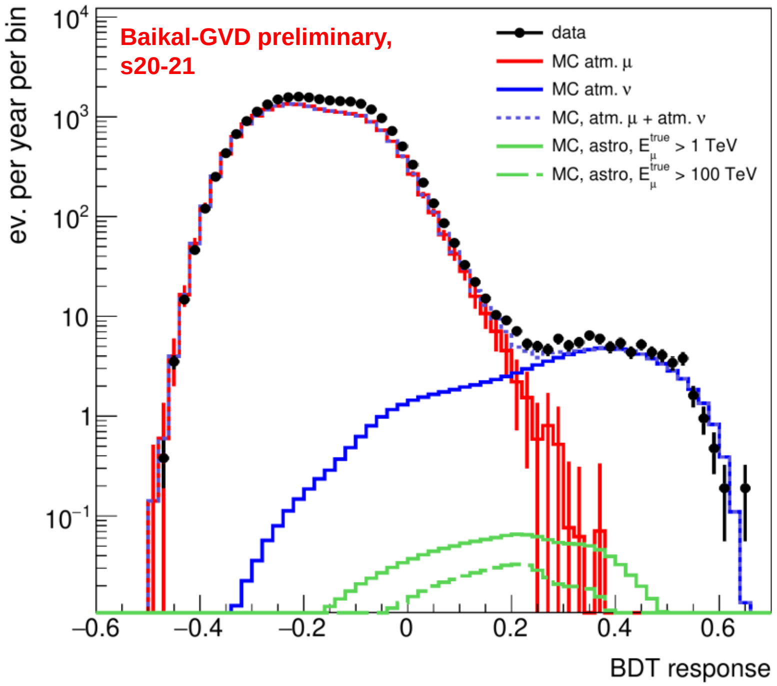
Improved muon reconstruction
- New noise suppression algorithm
- More precise track fit algorithm
- Improved neutrino selection capabilities

Improvement in tools for muon background suppression

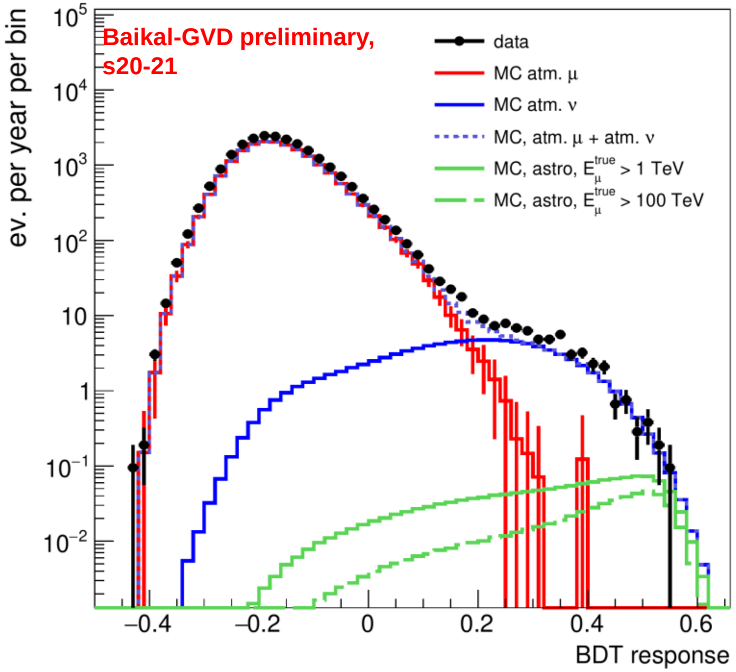
BDT discriminant as a main variable for neutrino selection

Good data-MC agreement
→ background is under control

Low-E BDT




High-E BDT



# Increasing $\nu_\mu$ candidate dataset

Seasons 2020-2021 were reprocessed in single-cluster regime

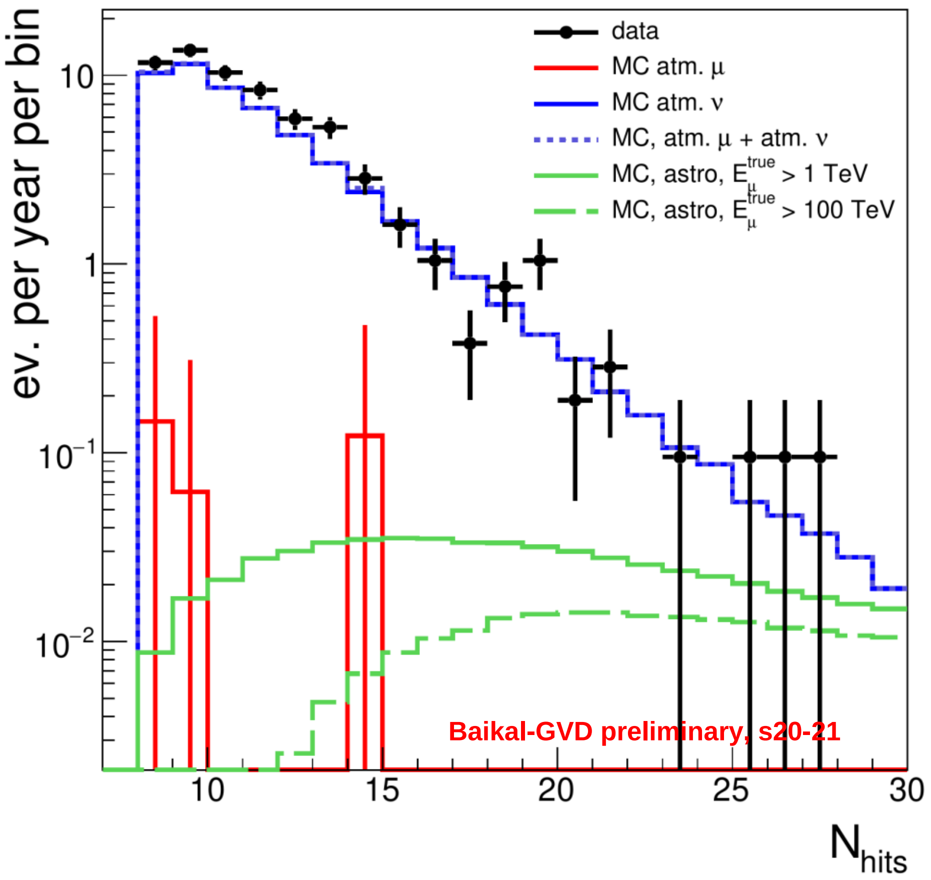
- 3845 days single-cluster livetime equivalent
- Validation of reconstruction results is ongoing
- Optimisation of high-energy ν selection is ongoing

Demonstration sample of $\nu_\mu$ 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

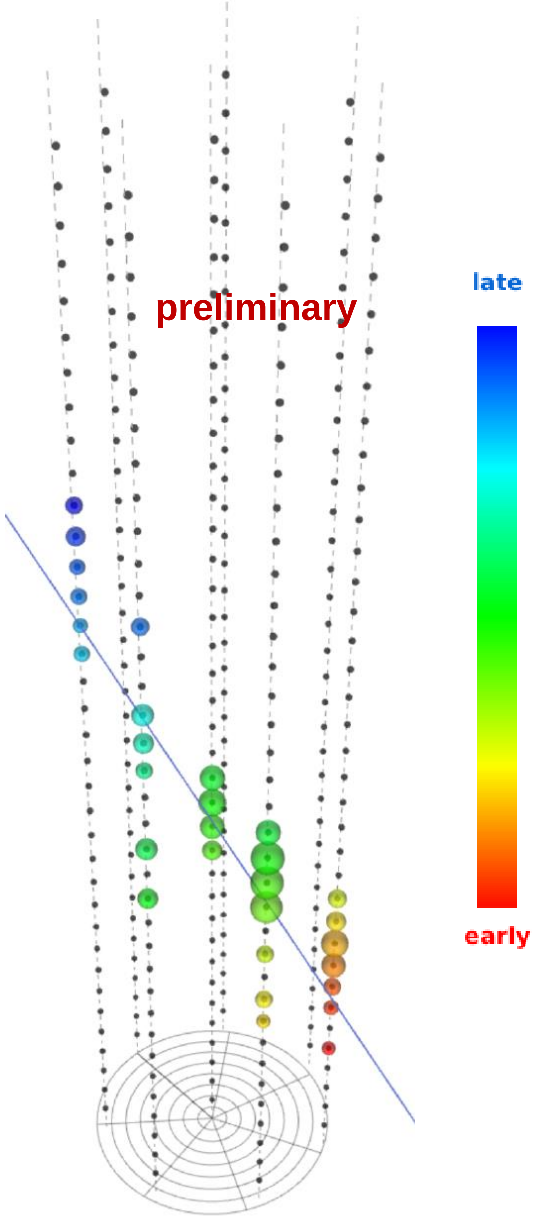


# High-energy track event candidate

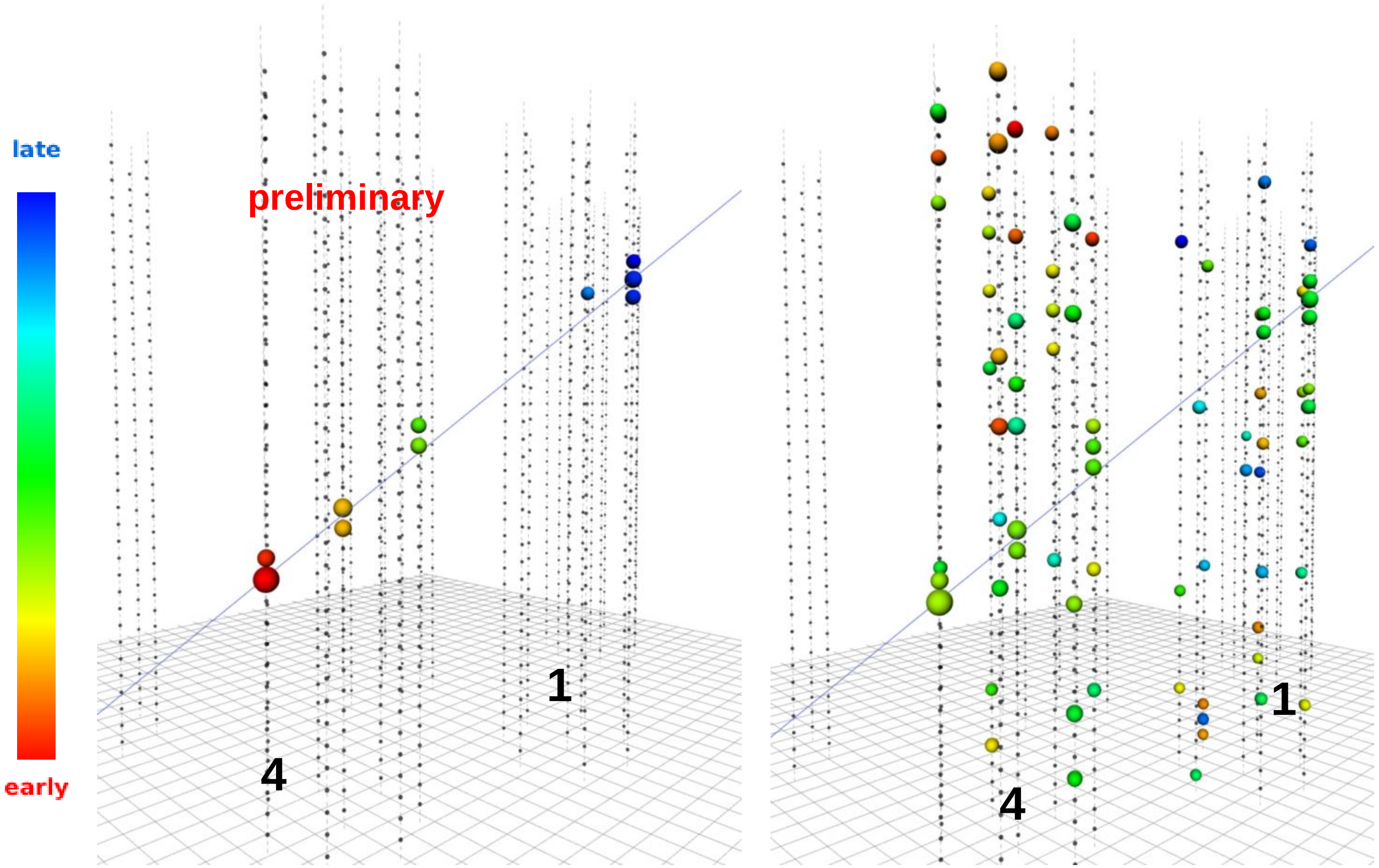
**Preliminary:** spectacular single-cluster event with high probability of astrophysical origin

Season 2019, Cluster 3, run 590
$\theta_z$ = 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

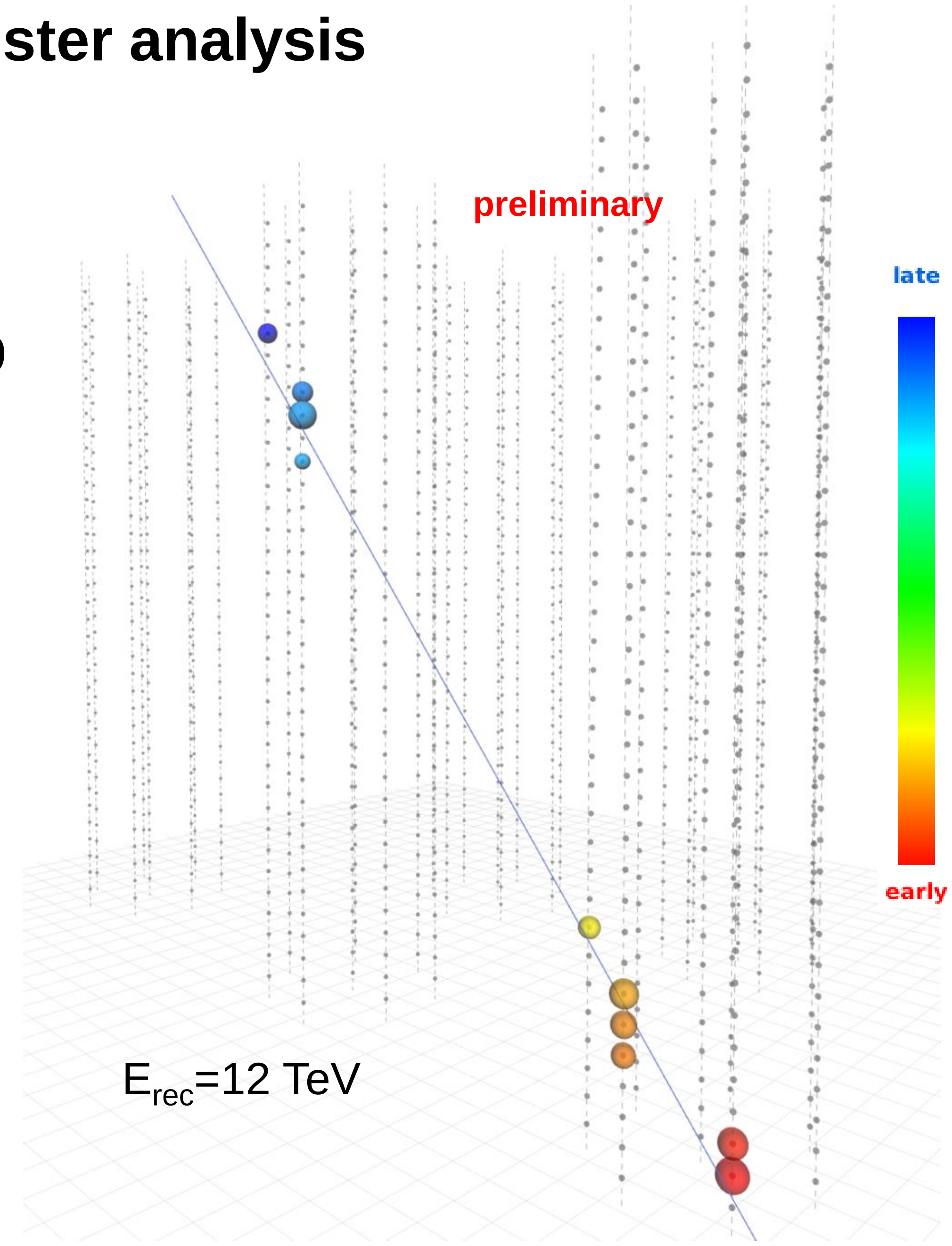
**Example of ν candidate event:**

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

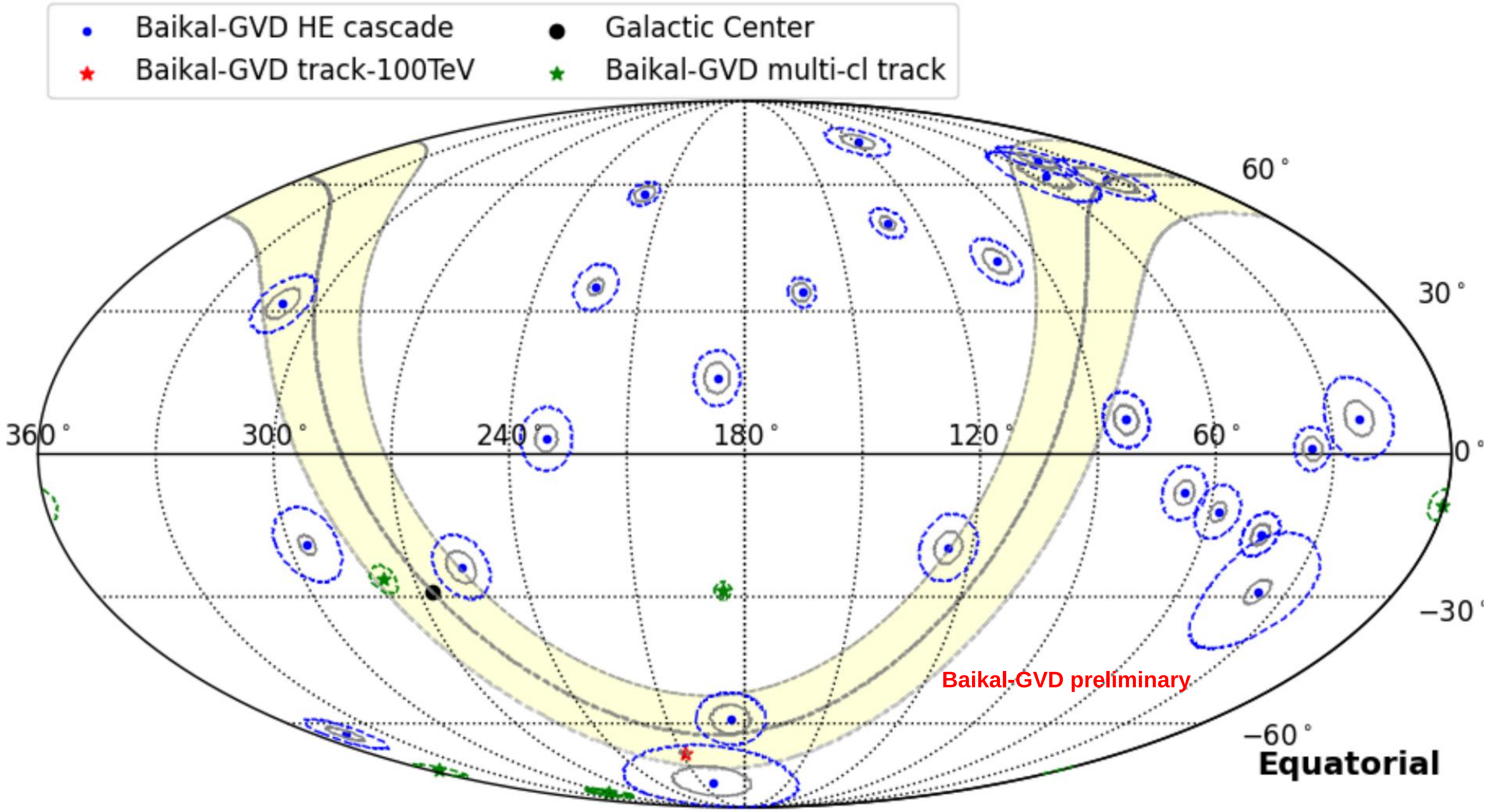
# Track-like event multi-cluster analysis

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

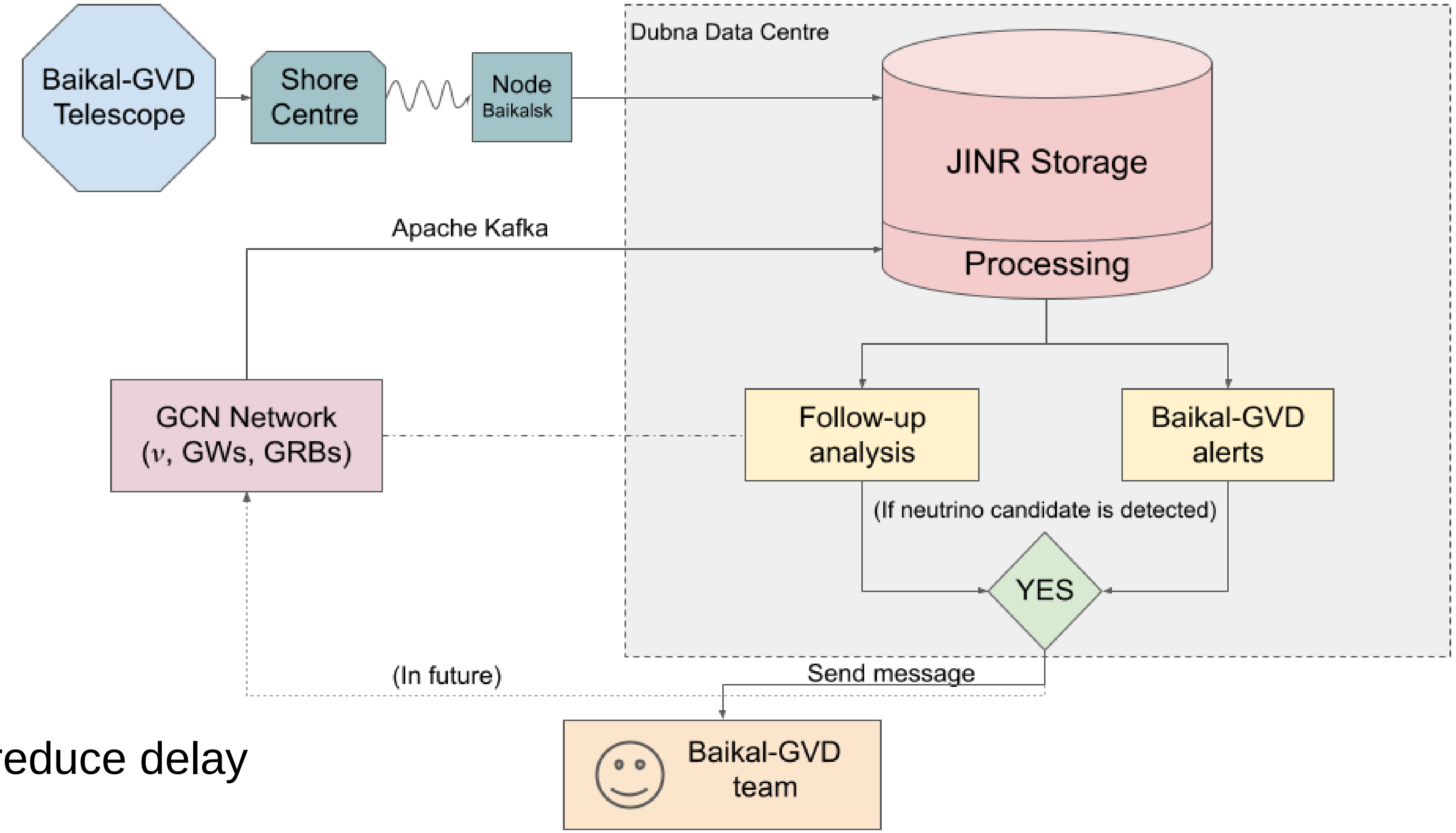
Getting ready to full-scale participation in real-time multi-messenger alert exchange

**Automated alert generation and follow-up system**

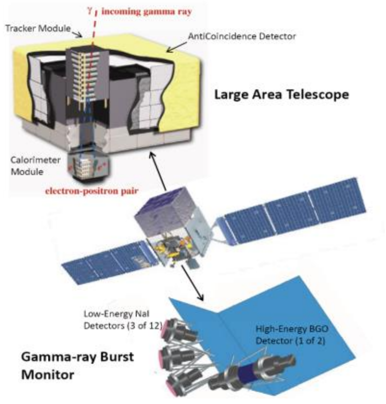
- Baikal-GVD alerts: distribution of our own alerts for events with high probability of astro origin
- Follow-up: follow-up analysis of external alert events

**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]

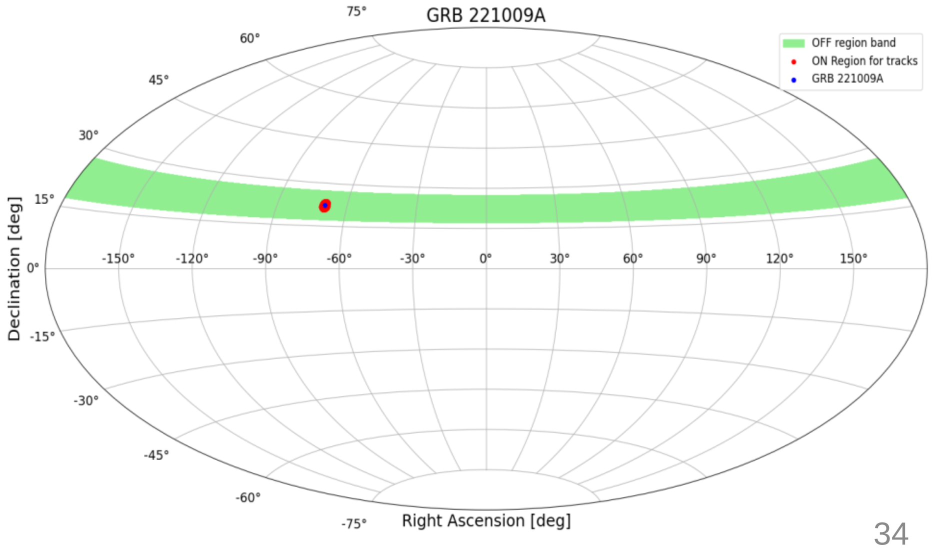
## LIGO-Virgo-KAGRA:

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

## IceCube:

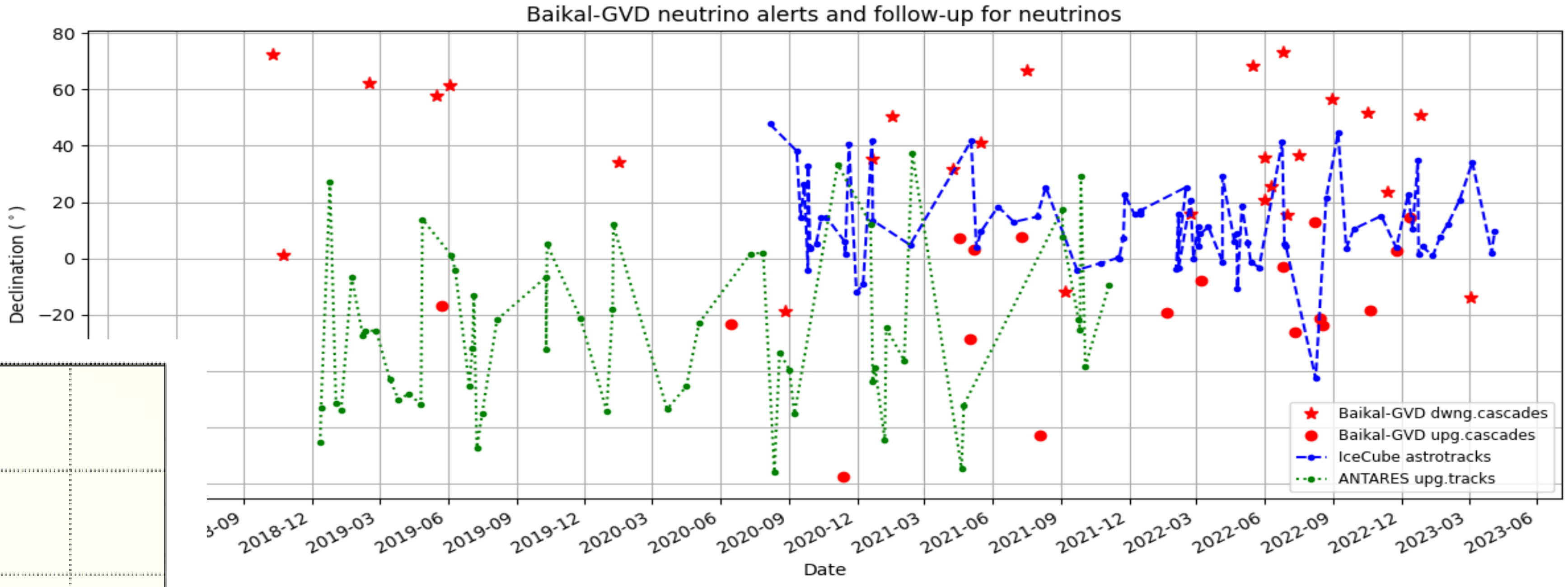
[T0 - 1 h, T0 +1 h]
[T0 - 1 day, T0 +1 day]

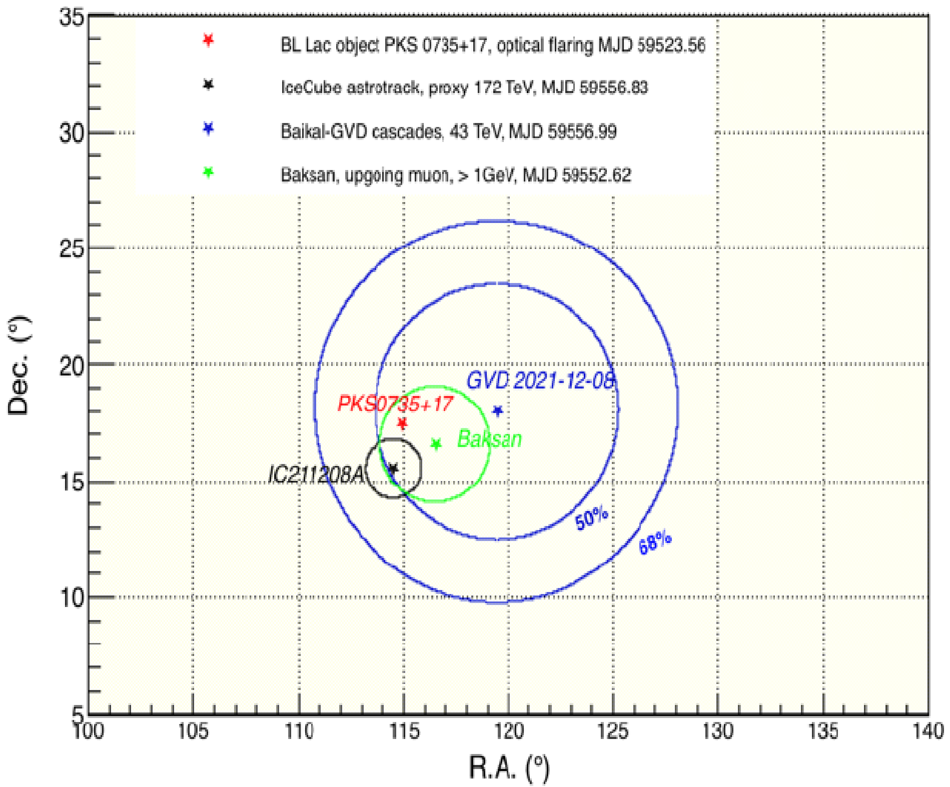
**Search for online coincidences:**
- ON/OFF method
- ON includes 90% localization error and Baikal-GVD median angular resolution
- OFF is extended within a ± 5 declination band
- OFF is evaluated using real data from previous seasons



# 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

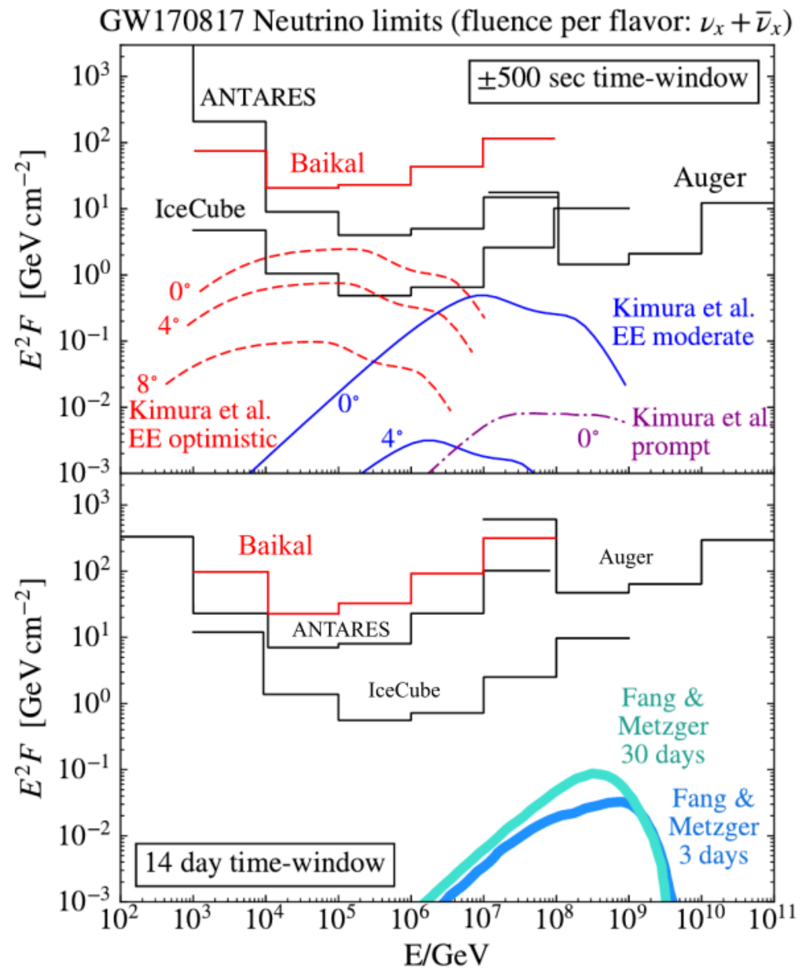
Baikal-GVD follows reported multimessenger high-energy events, e.g.:

**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 5σ (preliminary)
- Experiment participates in high-energy alert follow-up and alert exchange


Thank you for your attention!