Recent results from the Baikal-GVD neutrino telescope

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for the Baikal-GVD collaboration

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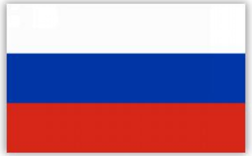
Baikal-GVD neutrino telescope

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

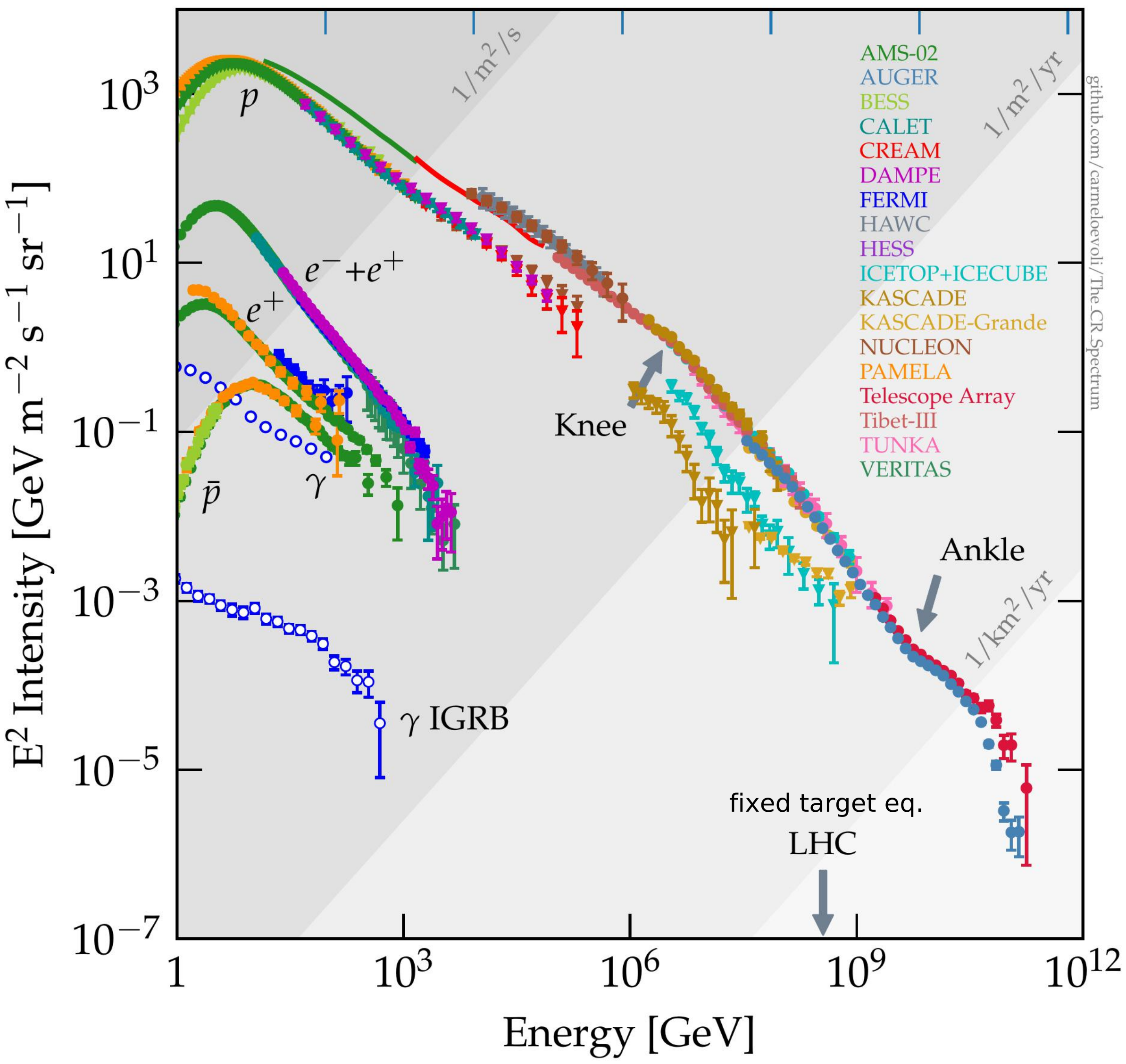
11 organisations from 4 countries, ~60 collaboration members



- 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 I

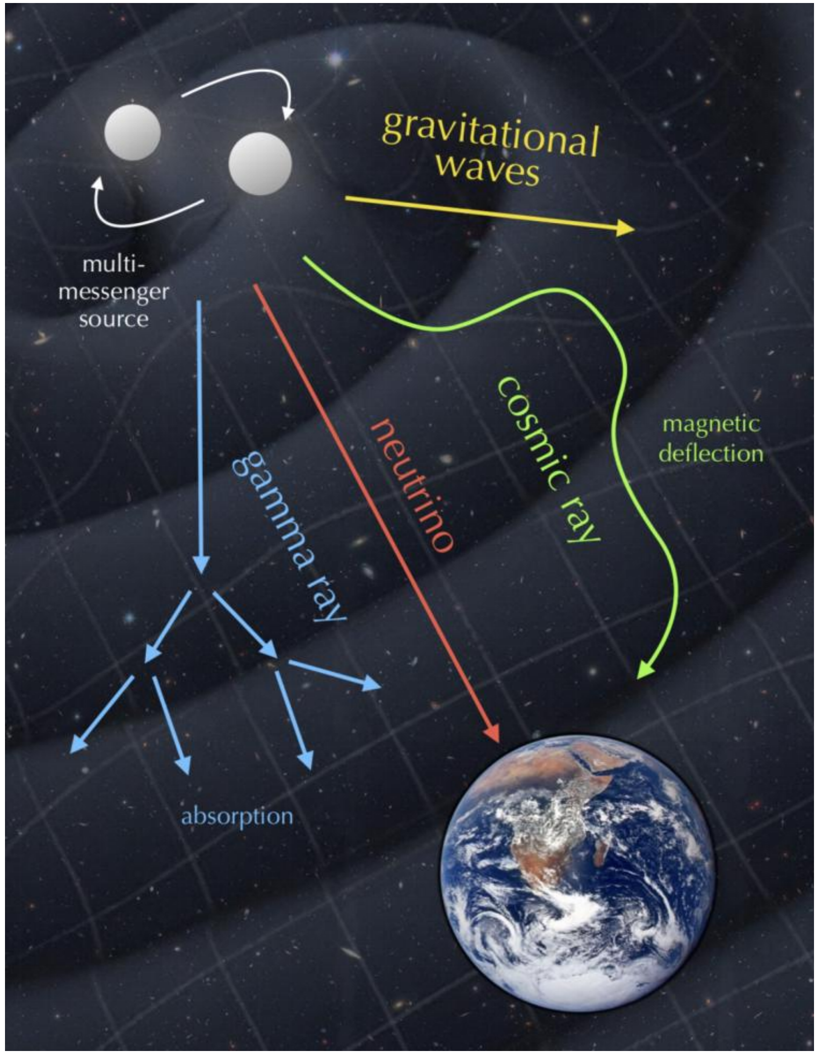
Diffuse cosmic ray flux



The range of measured charged cosmic ray (CR) particle energies extends up to 10^{11} GeV [10^{20} eV]

That's an evidence for the existence of cosmic systems accelerating particles far beyond the LHC energy

Physics motivation II



Probing high-energy (HE) processes in remote systems directly is complicated

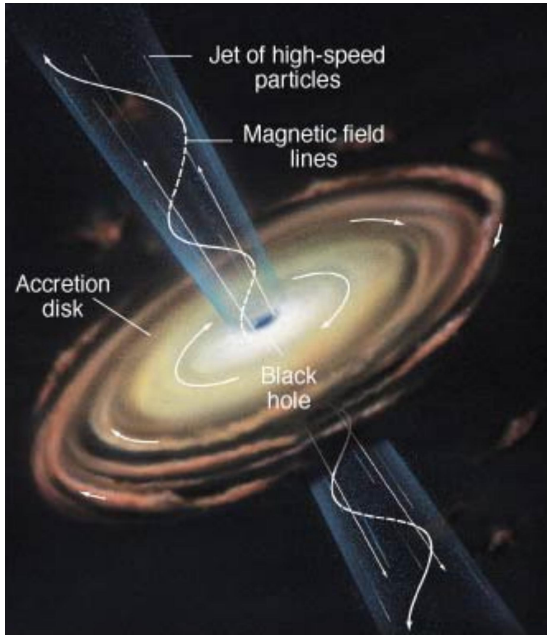
Multi-messenger observations:

- Charged CR particles are deflected by galactic magnetic fields
- VHE photons are absorbed in interactions with cosmic microwave background (CMB) and extragalactic background light (EBL)
- Neutrino can provide a direct probe of energy and source location

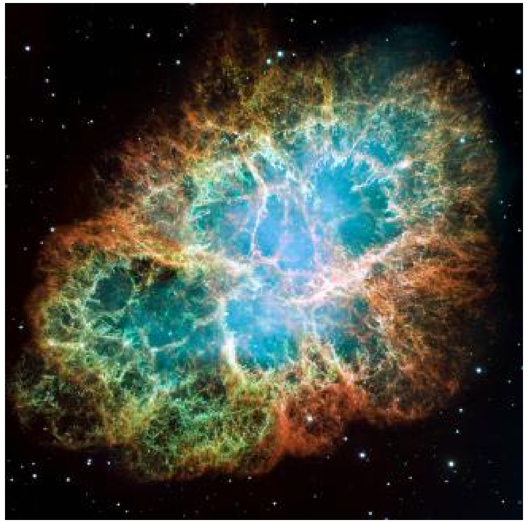
Physics motivation III

Some of CR acceleration site candidate types

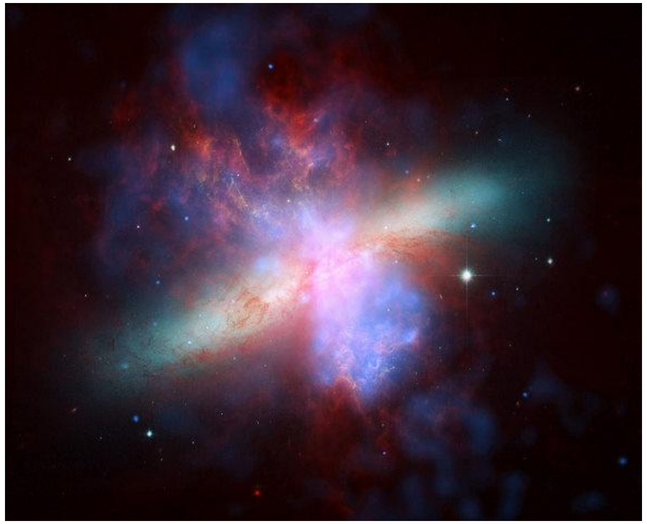
active galactic nuclei



supernovae remnants

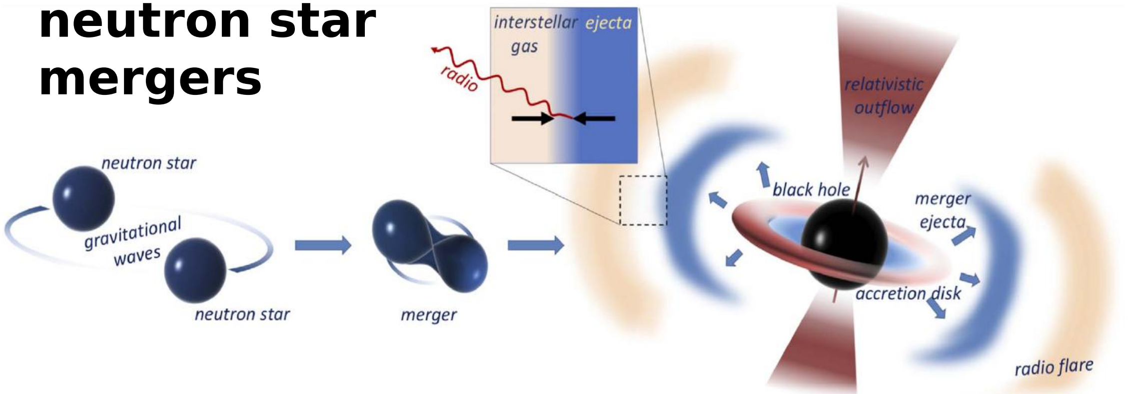


starburst galaxies

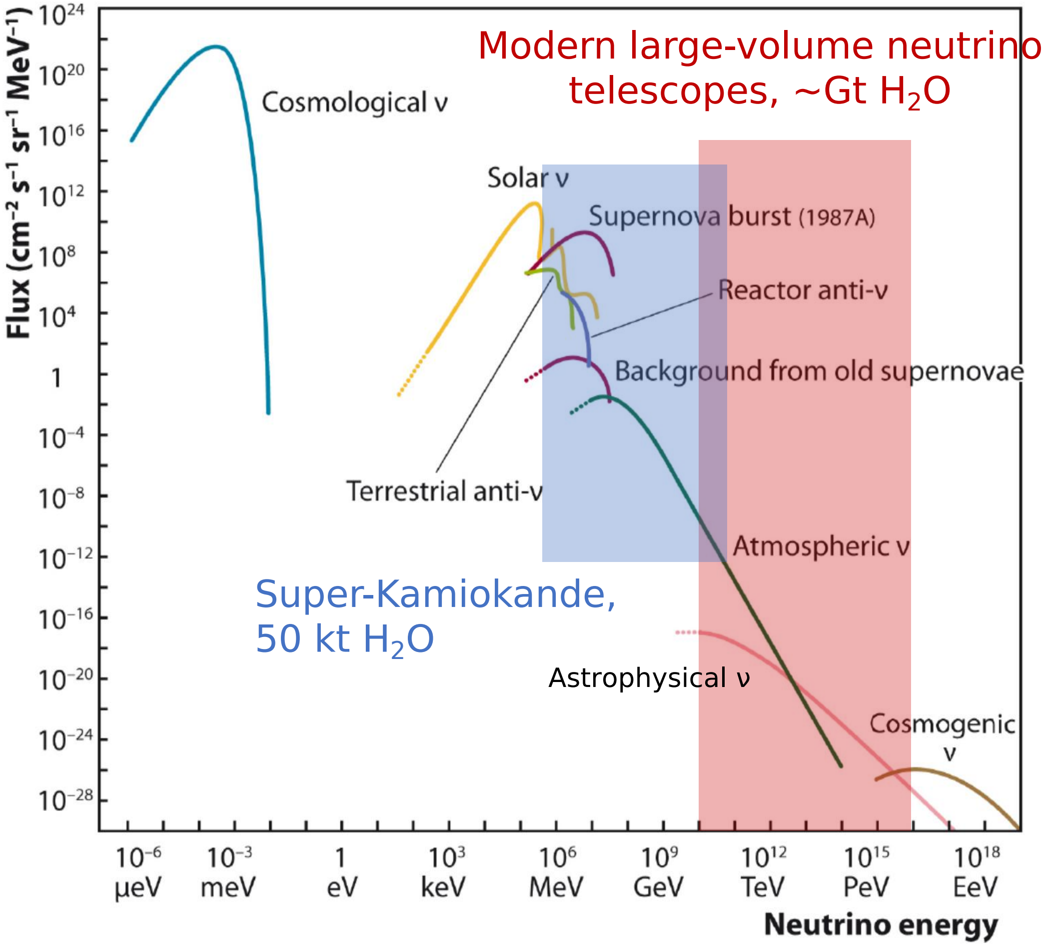


tidal disruption events (TDE)

neutron star mergers



Physics motivation IV

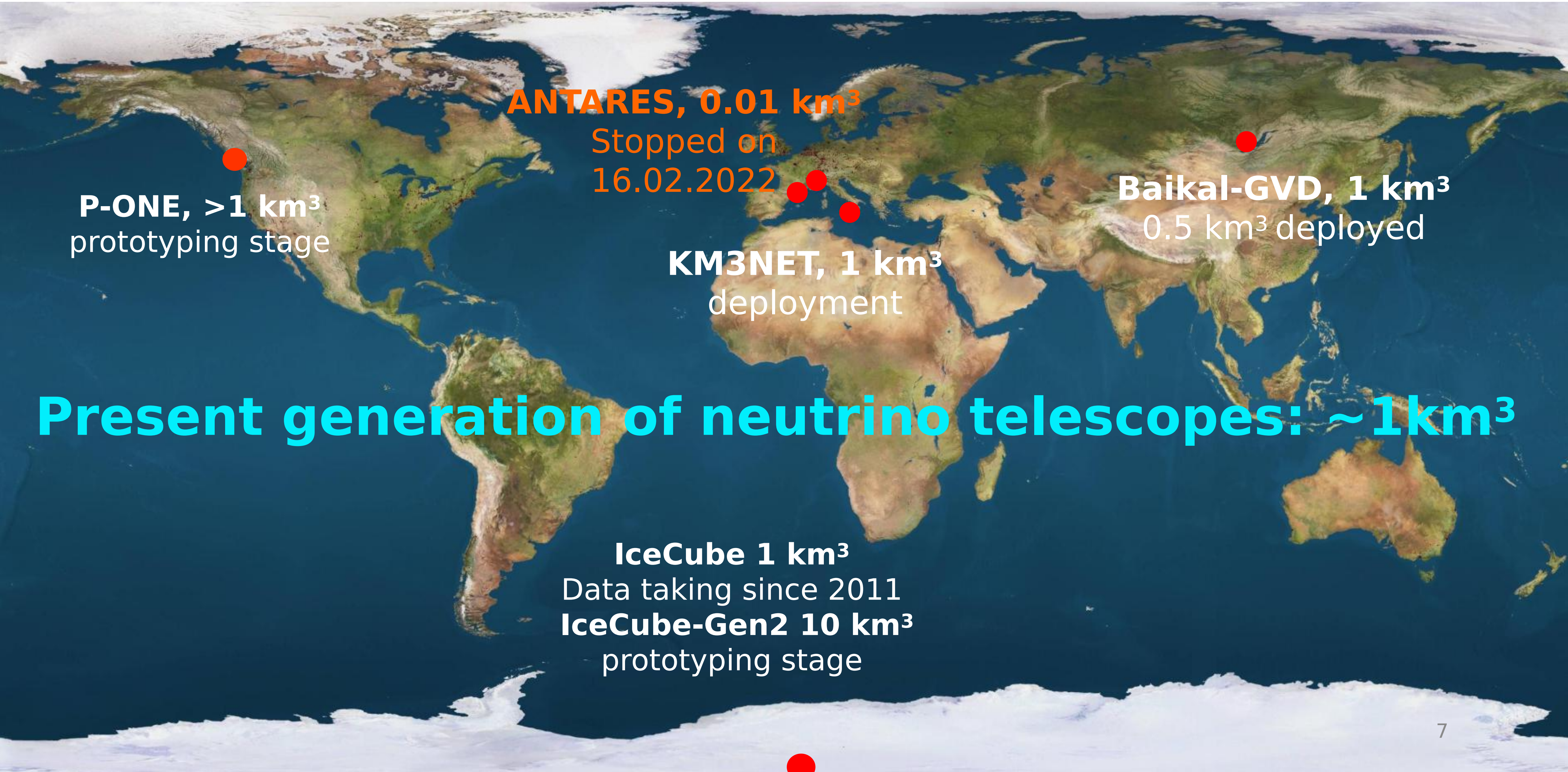


HE neutrinos are produced in CR pp or pγ interactions

- In the vicinity of the remote acceleration sites
- With CMB along CR path (GZK effect)
- In Earth atmosphere

HE neutrino flux study is the primary goal of large-volume neutrino telescopes like **Baikal-GVD**

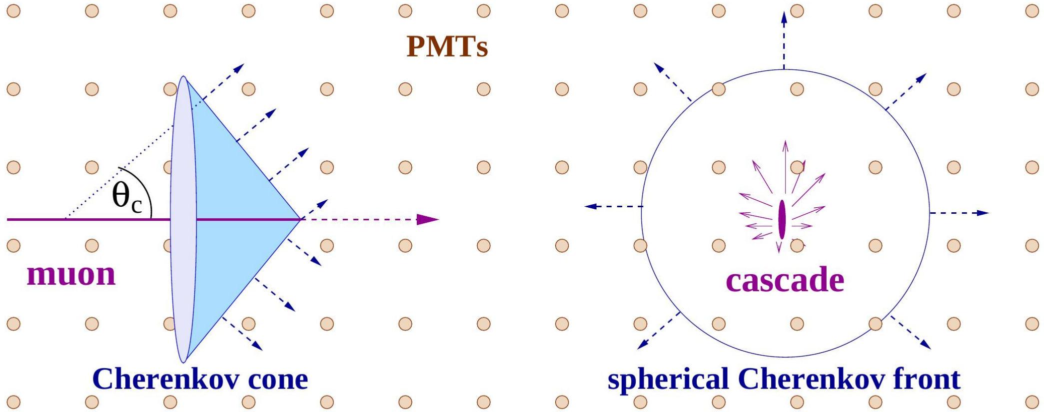
Neutrino telescope network



Neutrino detection principle

Sparse array of photodetectors in natural water(ice) reservoir

Cerenkov light from charged particle produced in neutrino interaction is detected



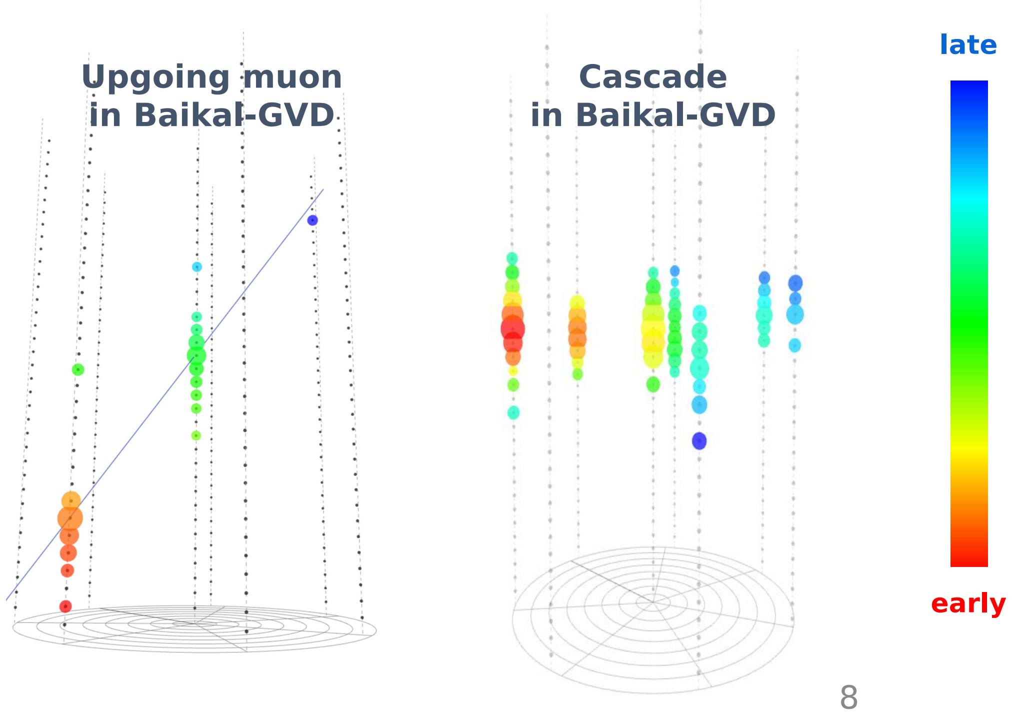
Neutrino event types:

Tracks (CC, ν_μ ν_τ):

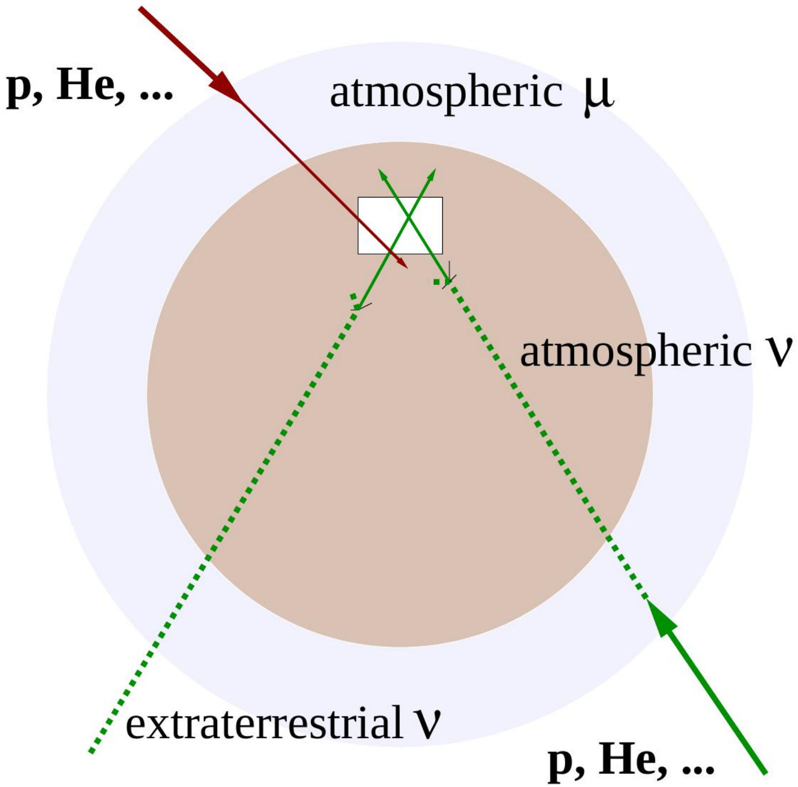
- Good angular resolution: ~0.3° - 0.5°
- Poor energy resolution: 200-300%
- Increased sensitive volume due to muon propagation range

Cascades (CC ν_e ν_τ, NC):

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

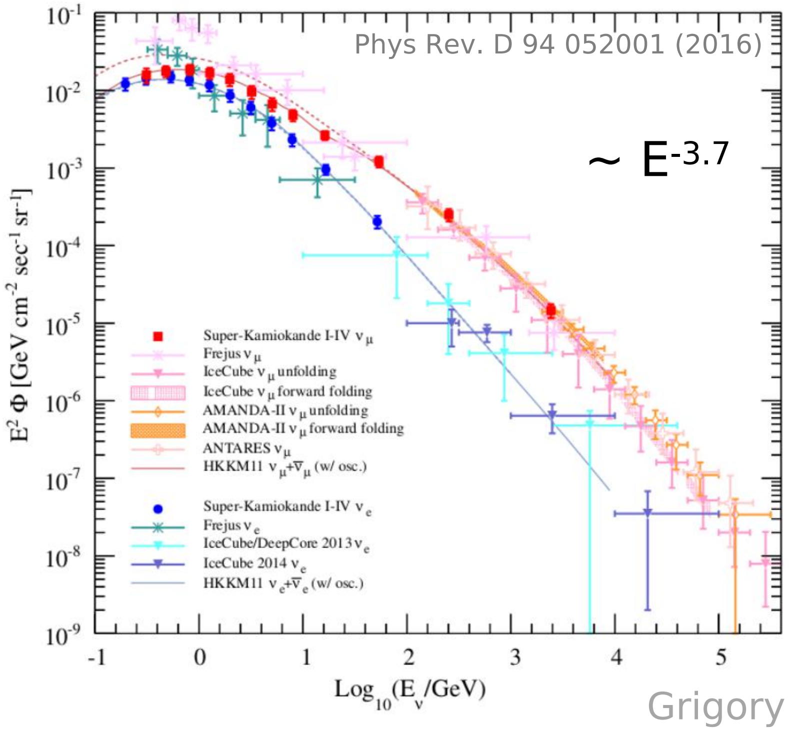


Backgrounds



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



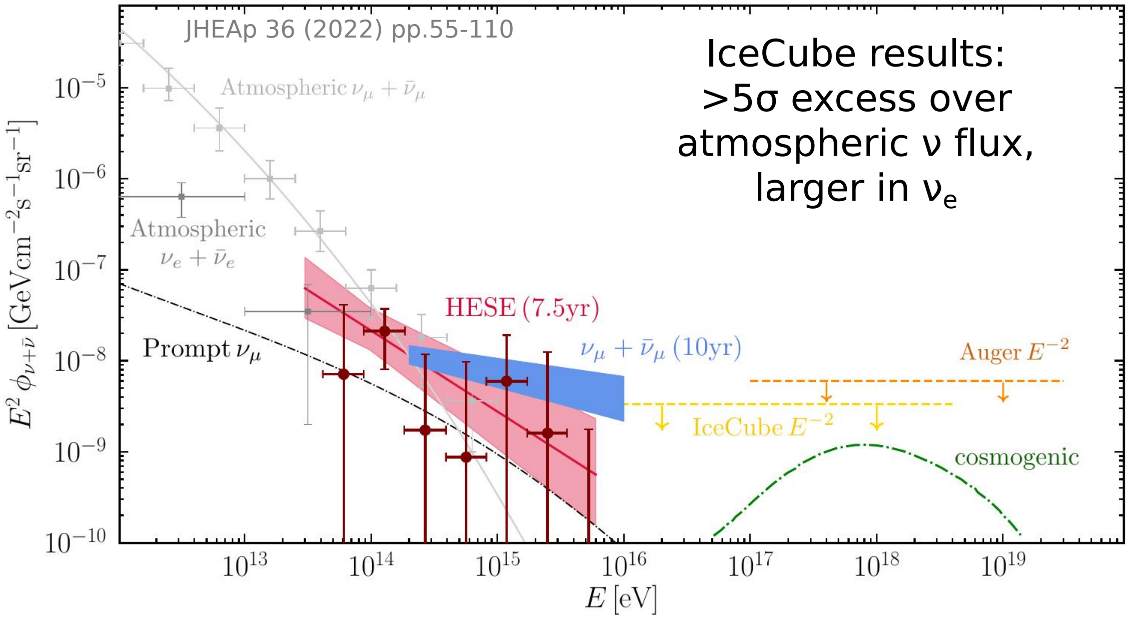
Atmospheric neutrino are dominated by ν_μ for E_ν > ~10 GeV

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

HE neutrino astrophysics key 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)]**

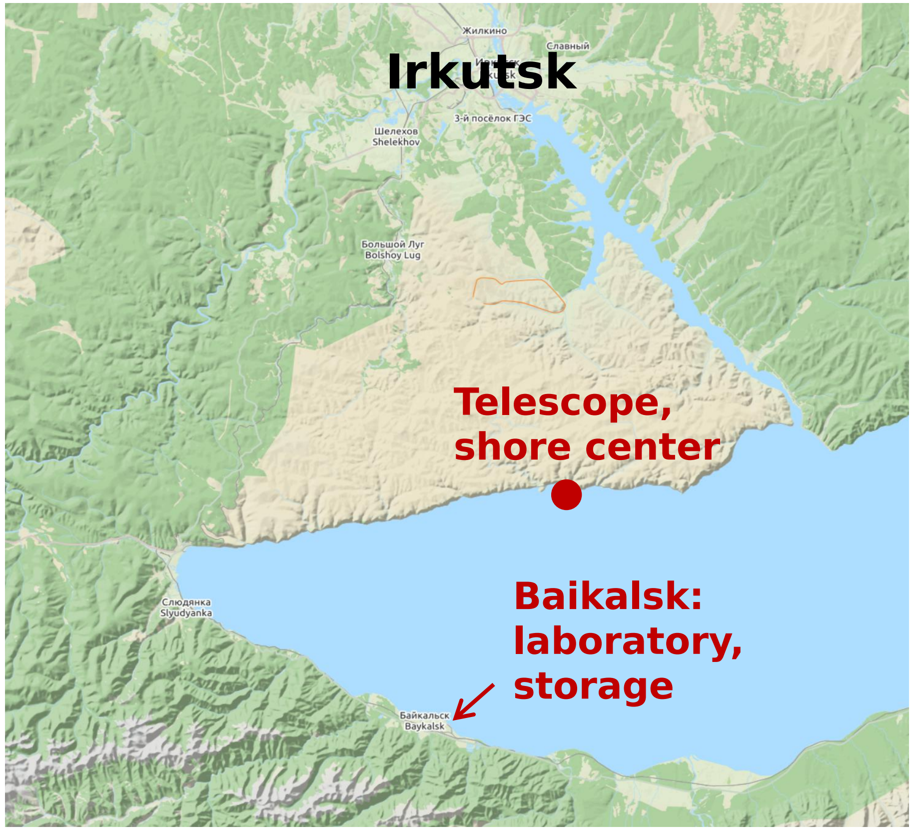
>99% of astrophysical neutrino flux remains unexplained

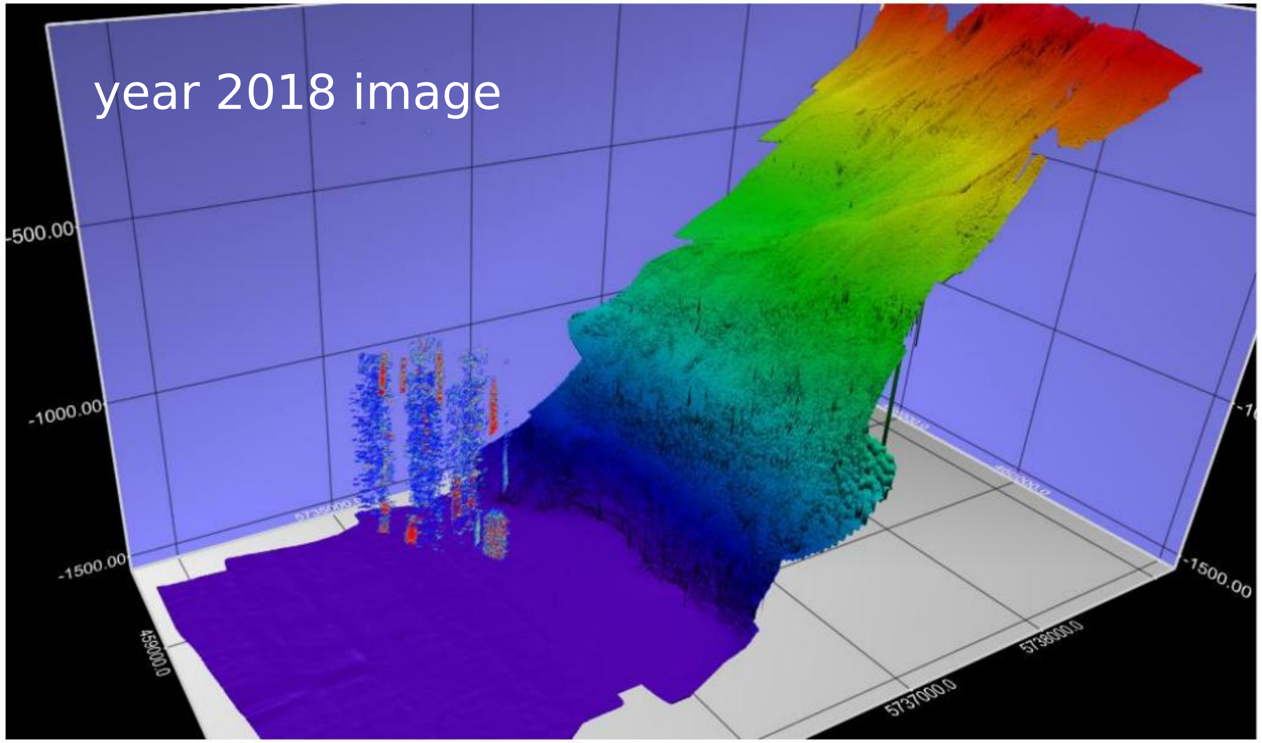
Deployment of new telescopes is crucial to resolve the diffuse flux origin problem
Complimentary field of view for projects located at different lattitude and longitude

Baikal-GVD experiment 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





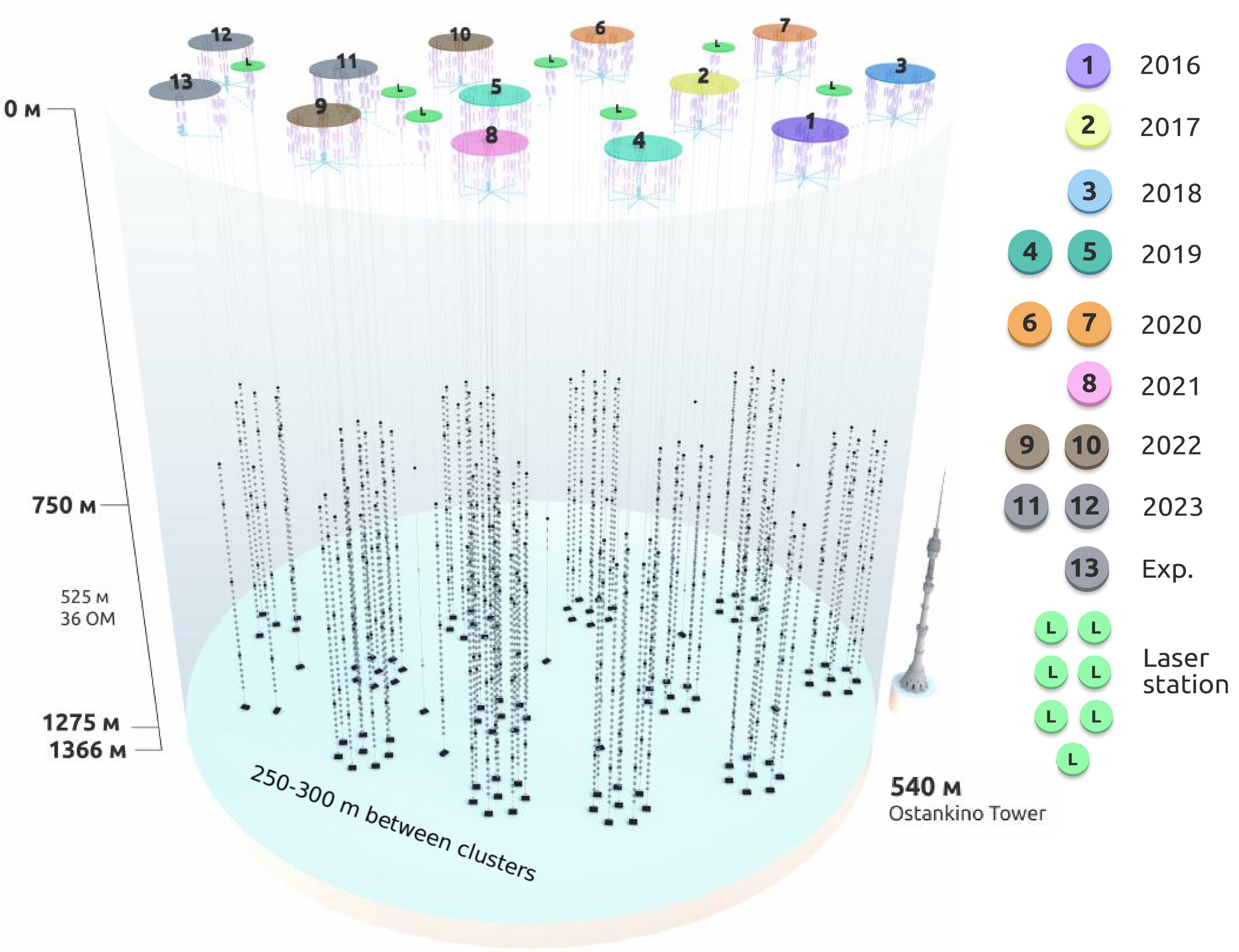
Detector status

Detector consists of 13 independent detectors - clusters

Baikal-GVD cluster:

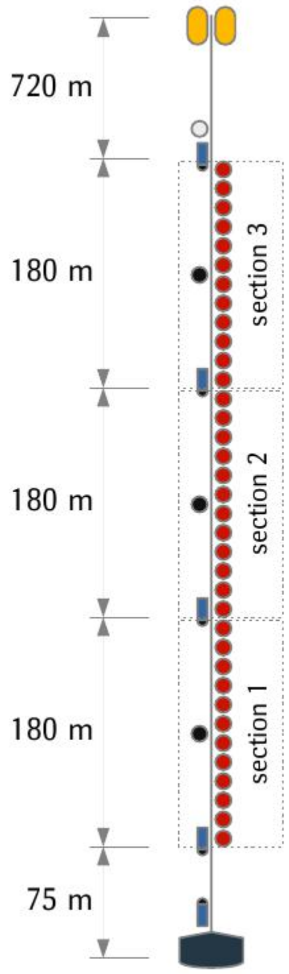
- 8 regular strings, 525 m is instrumented with optical modules (OM)
- 60m radius
- Inter-cluster strings carrying lasers, some instrumented with OMs
- Has its own trigger system
- Cluster 13: 2 strings with experimental high-speed DAQ

Single-cluster and multi-cluster event sets are available



Detector components

String:



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

Each string carries 36 OMs

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

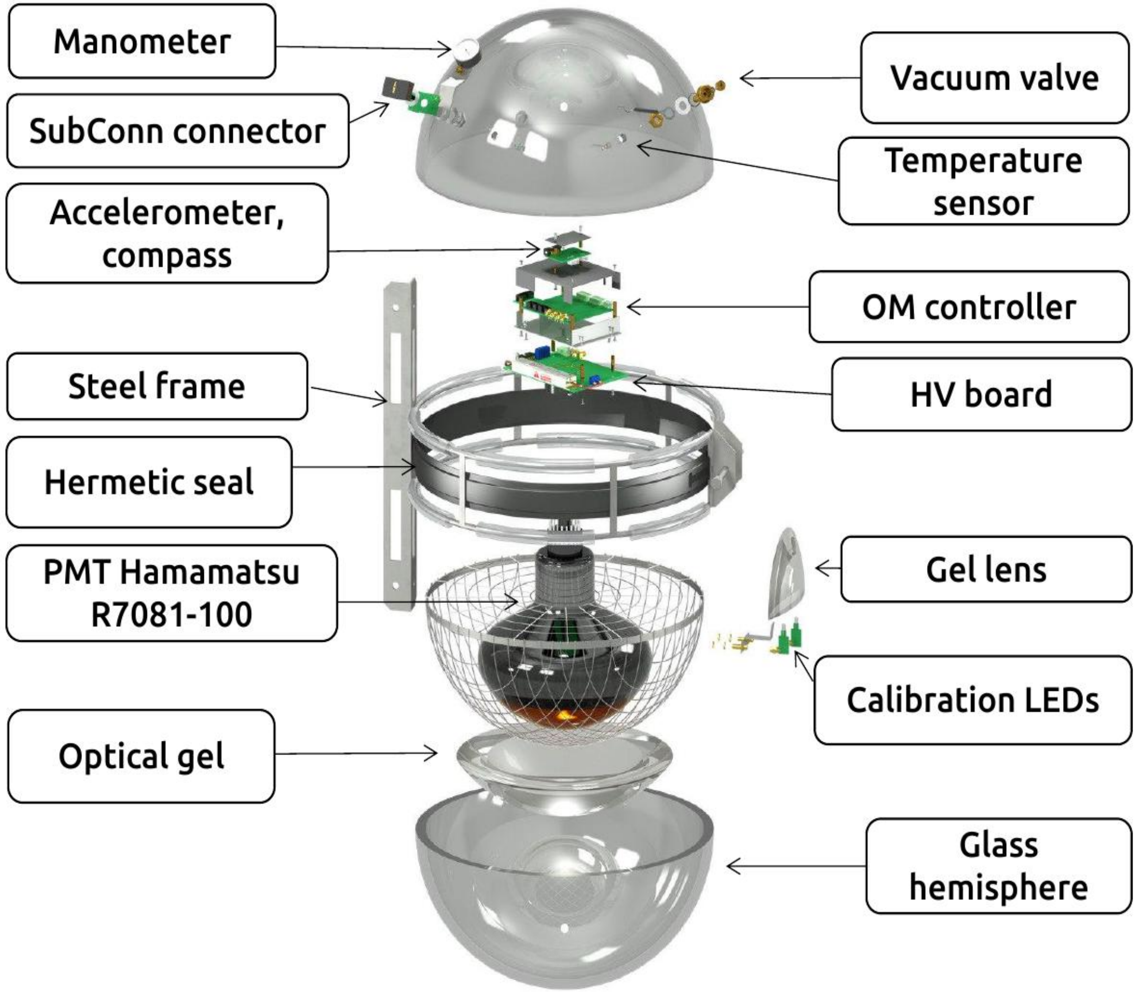
Time calibration systems

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

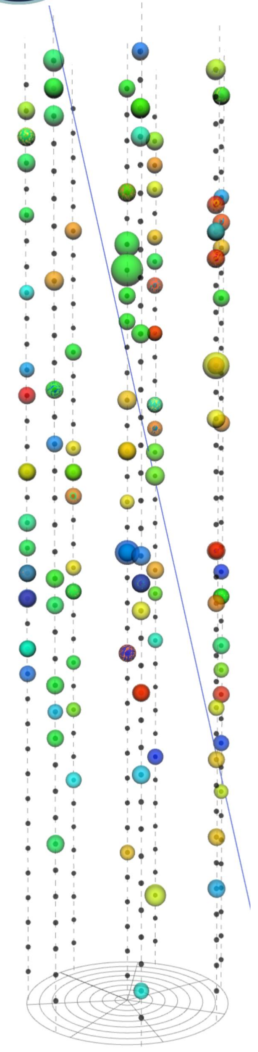
Geometry calibration system

- Acoustic modems on each string
- Acoustic polling each 1-6 minutes
- OM positioning precision ~ 20cm

Optical module (OM):



Event reconstruction I



track-like event before the noise cleaning, data 2019

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

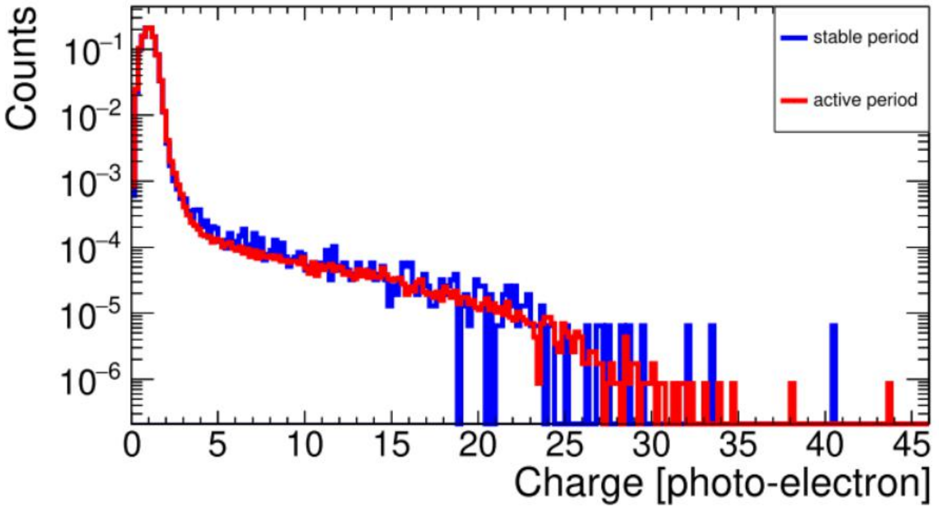
Most of pulses (or hits) in the event frame are noise from lake water luminiscense:

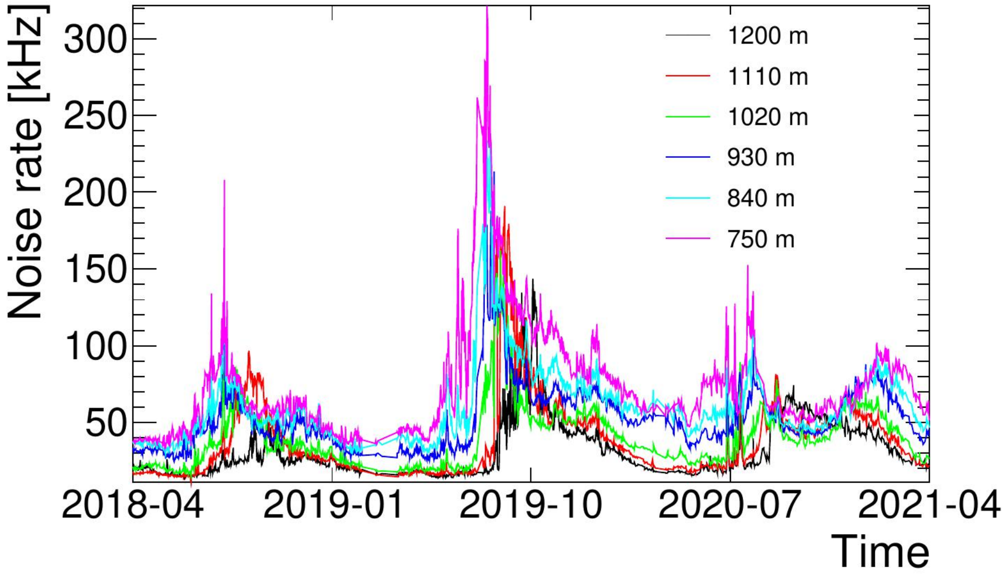
- Typical pulse rate 20-100 kHz
- ~1 photoelectron (p.e.) charge deposition
- Substantial seasonal variations
- Rate is larger on top layers

Challenge for our MC simulation

Variety of algorithms for noise suppression

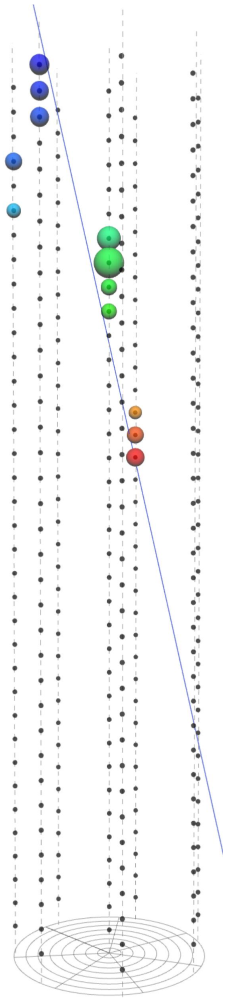
Machine learning -based algorithm in development: **[arXiv:2210.04653]**





Event reconstruction II

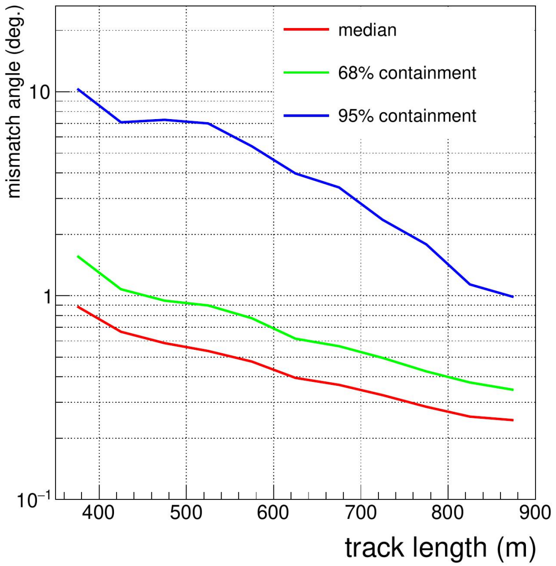
Time, location and deposited charge of each pulse
are used for the reconstruction

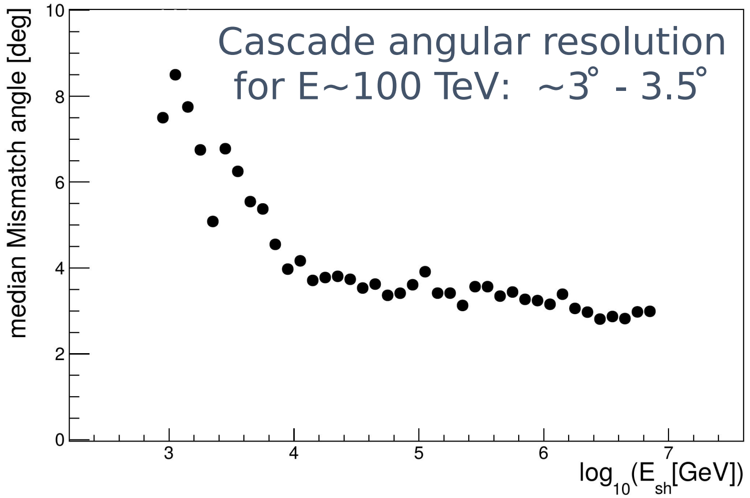


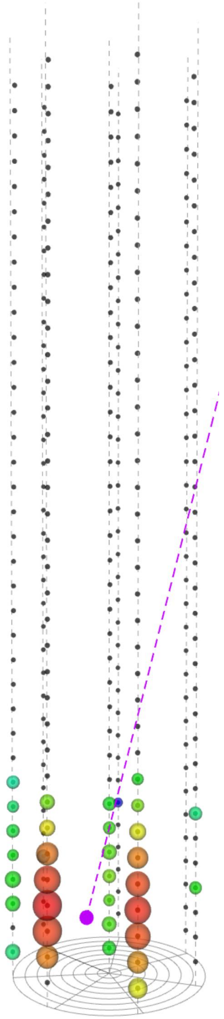
track-like,
data 2019

Track reconstruction
- Single-cluster and multi-cluster datasets
- Angular resolution: ~1° - ~0.25° for tracks longer than 300 m
- Energy resolution: factor 3 for 100 TeV

Cascade reconstruction
- Single-cluster dataset so far
- Angular resolution: 3-3.5° for E_{sh} > 10 TeV
- Energy resolution: δE/E ~ 10% - 30% depending on energy and location







cascade-like,
data 2022

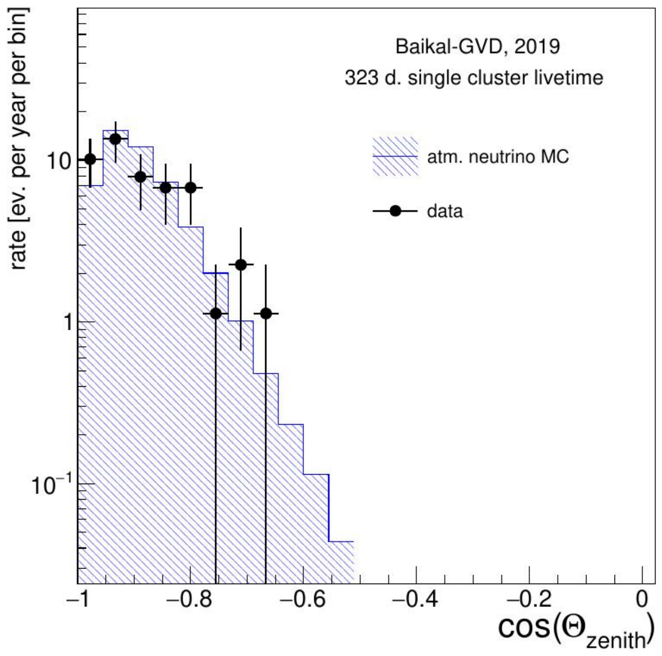
First track-like neutrino candidate event sample

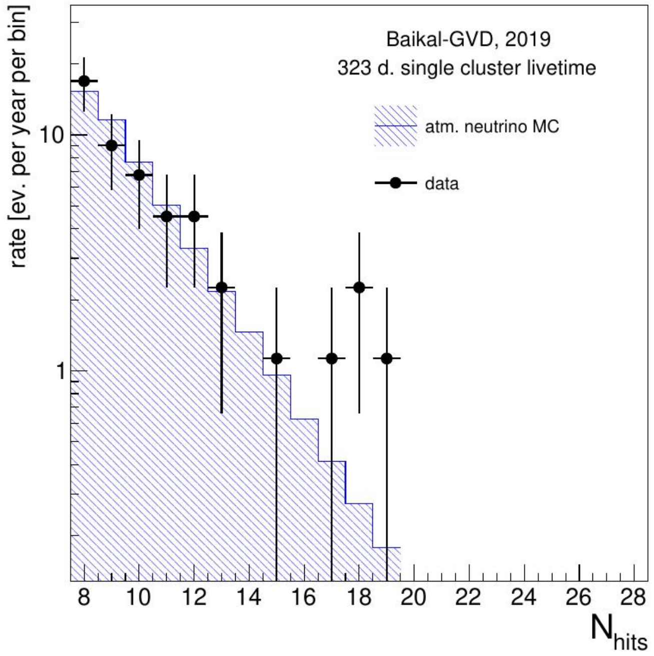
First set of single-cluster muon neutrino candidates is based on 2019 data

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, <E_ν> ~ 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

Track-like event analysis progress

An improvement in sensitivity by more than a factor of 2 with recent developments

- Improvement in noise suppression techniques
- Improvements in reconstruction accuracy
- More efficient neutrino selection using boosted decision trees (BDT)
- Multi-cluster reconstruction

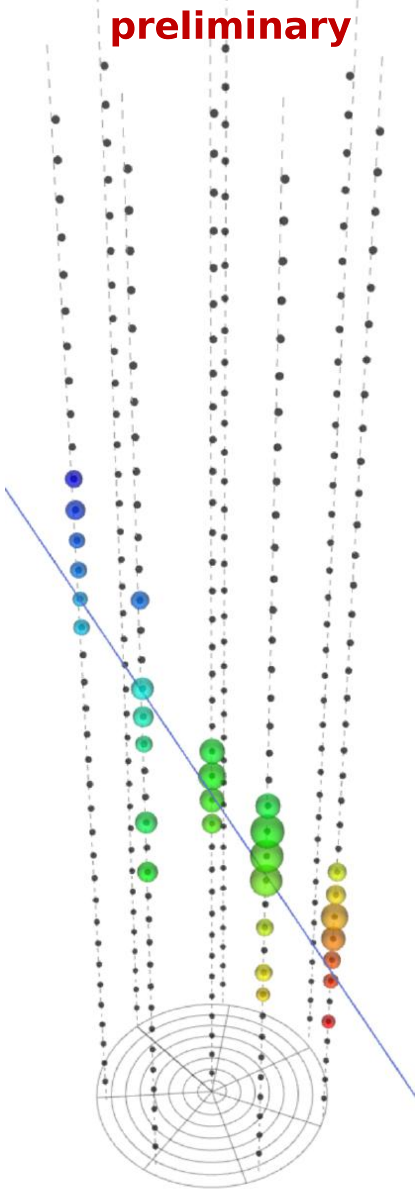
Massive single-cluster and multi-cluster data/MC reprocessing is ongoing

Preliminary: spectacular event with high probability of astrophysical origin

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

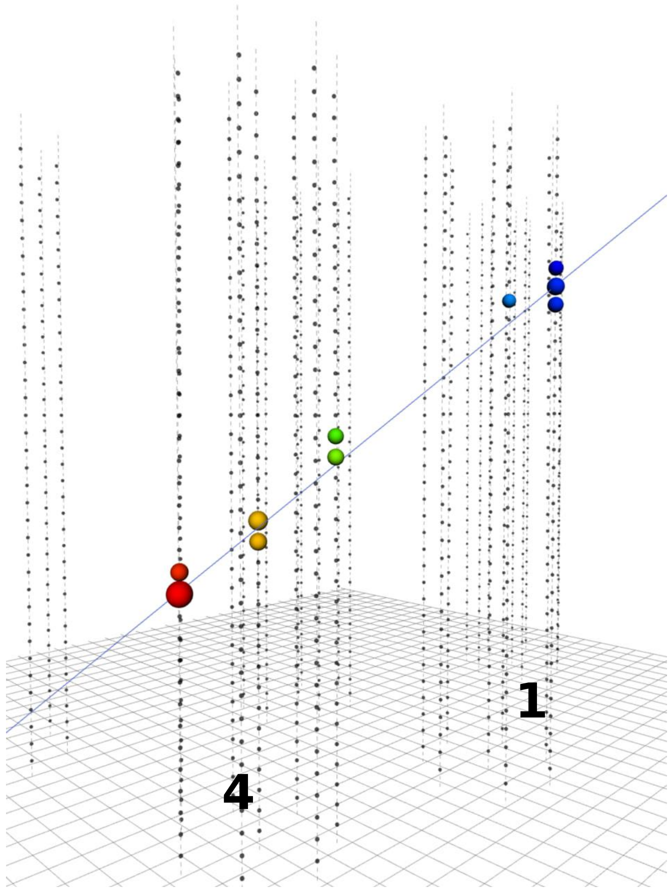
Signalness $[N_{astro}/(N_{astro}+N_{atm})]$: >88%

Angular resolution: 0.45 (50%)

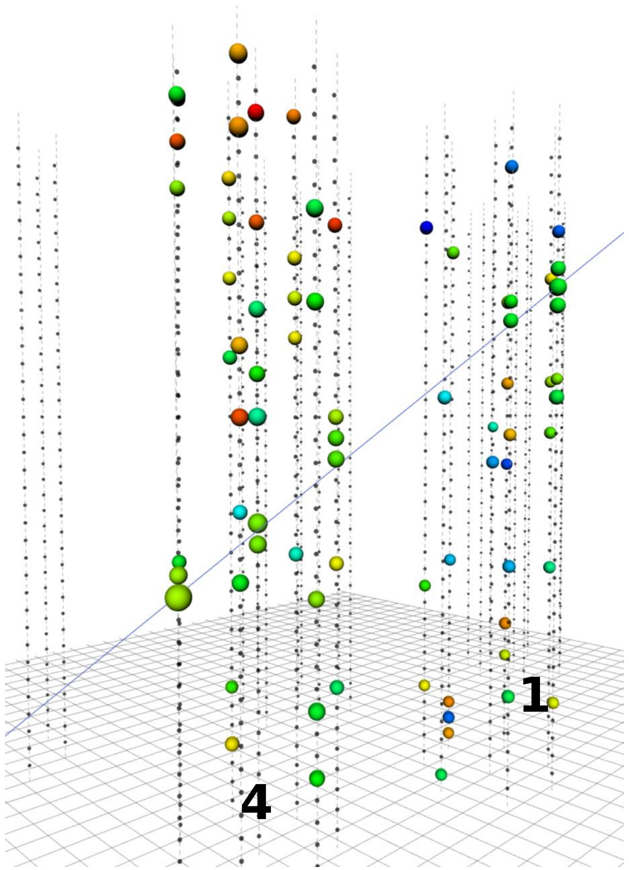


Stay tuned for new results!

Track-like event 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:

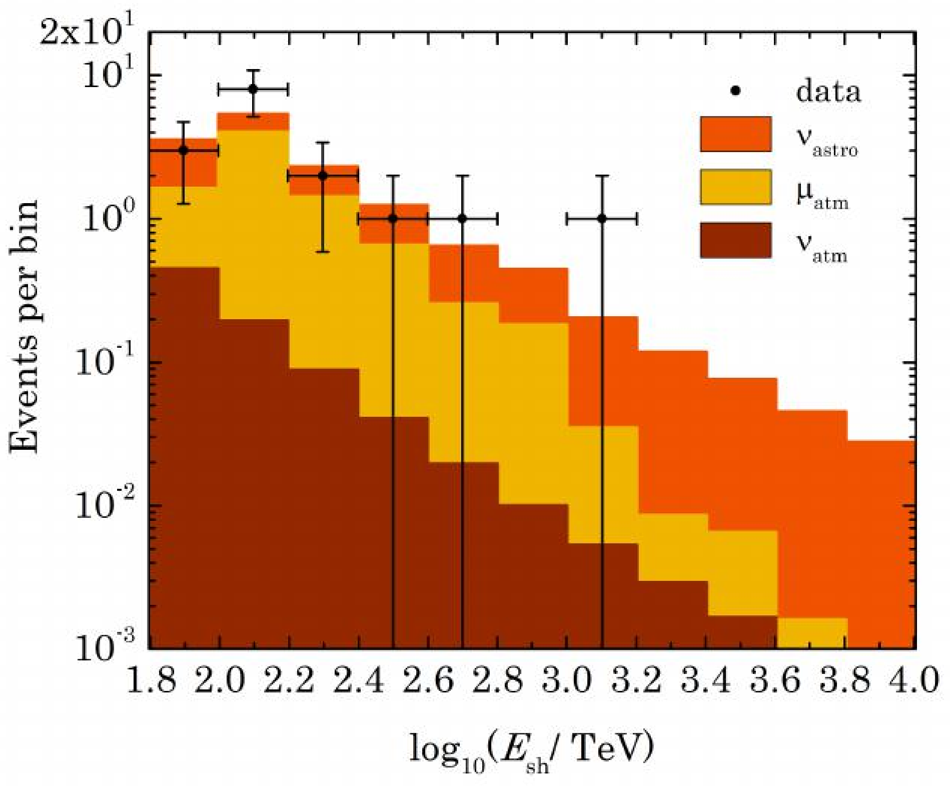
Summer 2019
Clusters 1 & 4
θ_z = 125.6°
N_{hits} = 10
track length = 399 m
E_{rec} < 1TeV

Diffuse flux in cascades I

Majority 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)]

Diffuse flux in cascades II

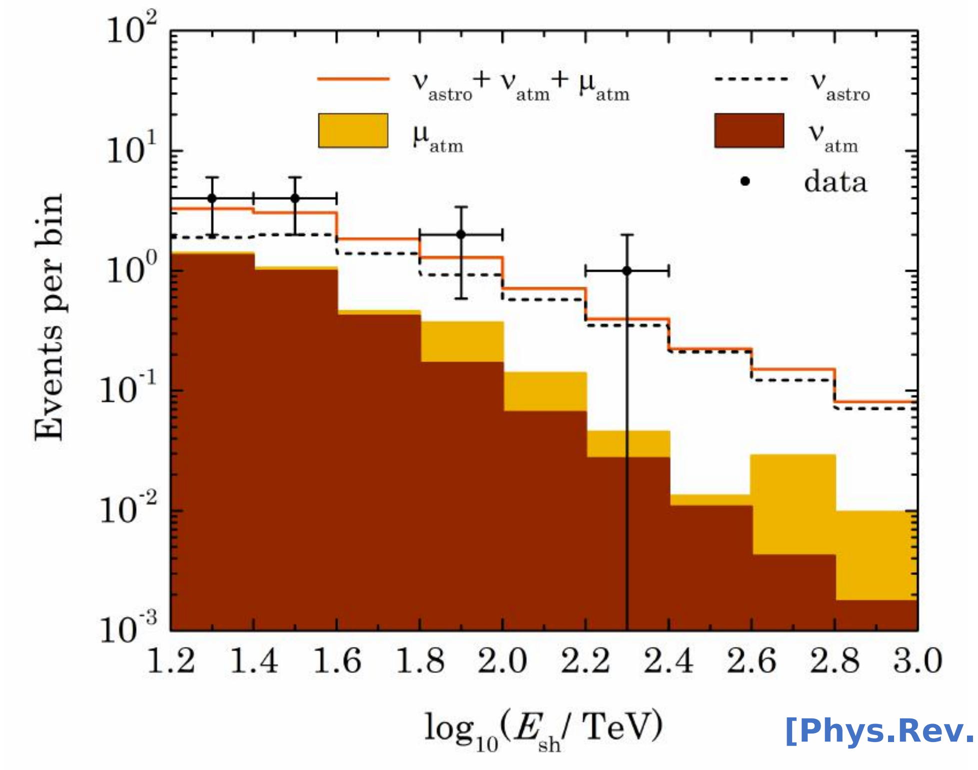
Analysis of upward-going events

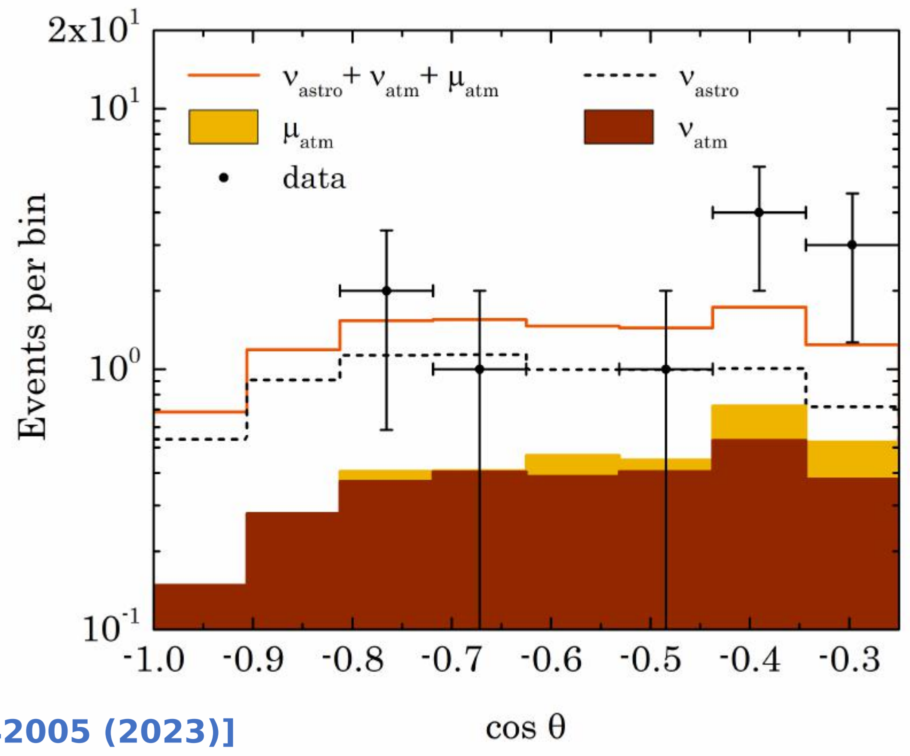
- Zenith angle cut: $\cos(\theta) < -0.25$
- Loosened cuts: $E_{sh} > 15$ TeV, $N_{hit} > 11$
- 11 events selected
- 3.2±1.0 atm. background ev. are expected
  - 0.5 μ_{atm}, 2.7 ν_{atm}
- Highest energy: 224 TeV

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

Main uncertainties

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



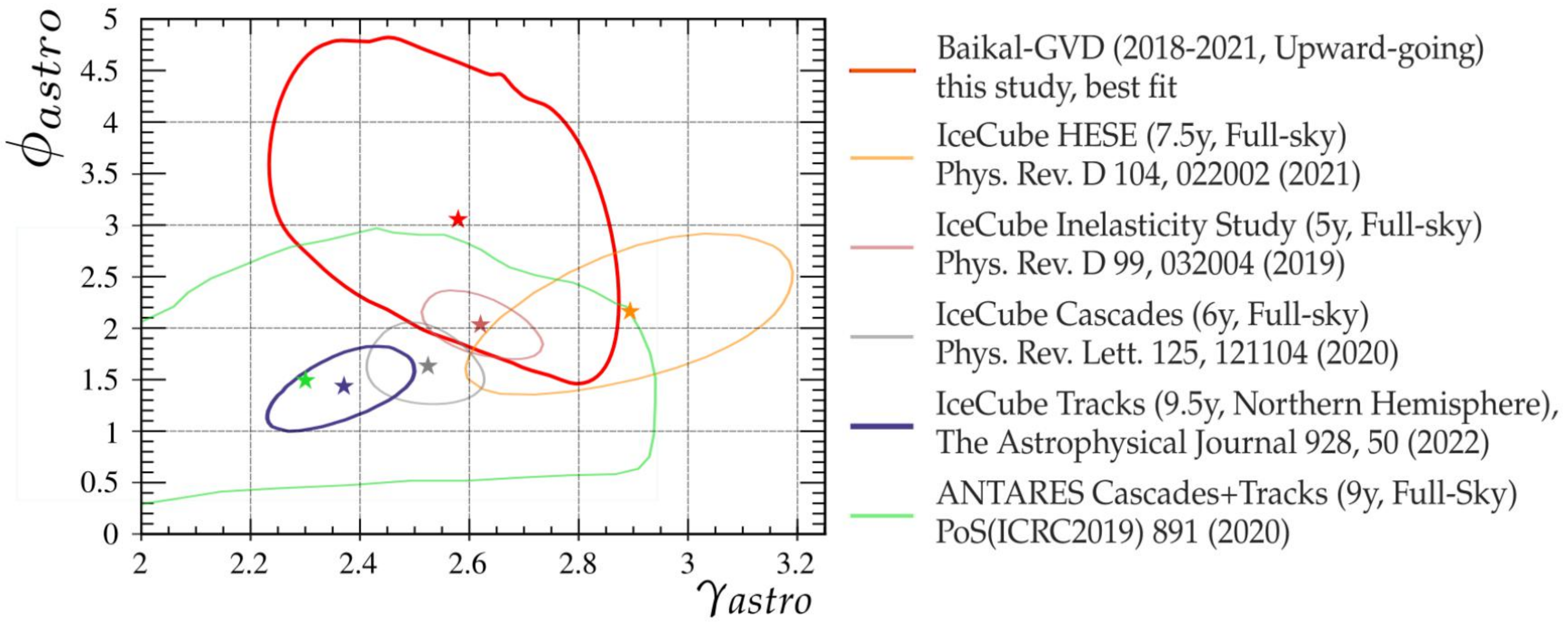


[Phys.Rev. D 107, 042005 (2023)]

Diffuse flux in cascades III

Extraction of spectrum power and flux normalisation:

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



Results are in agreement with previous measurements by IceCube and ANTARES

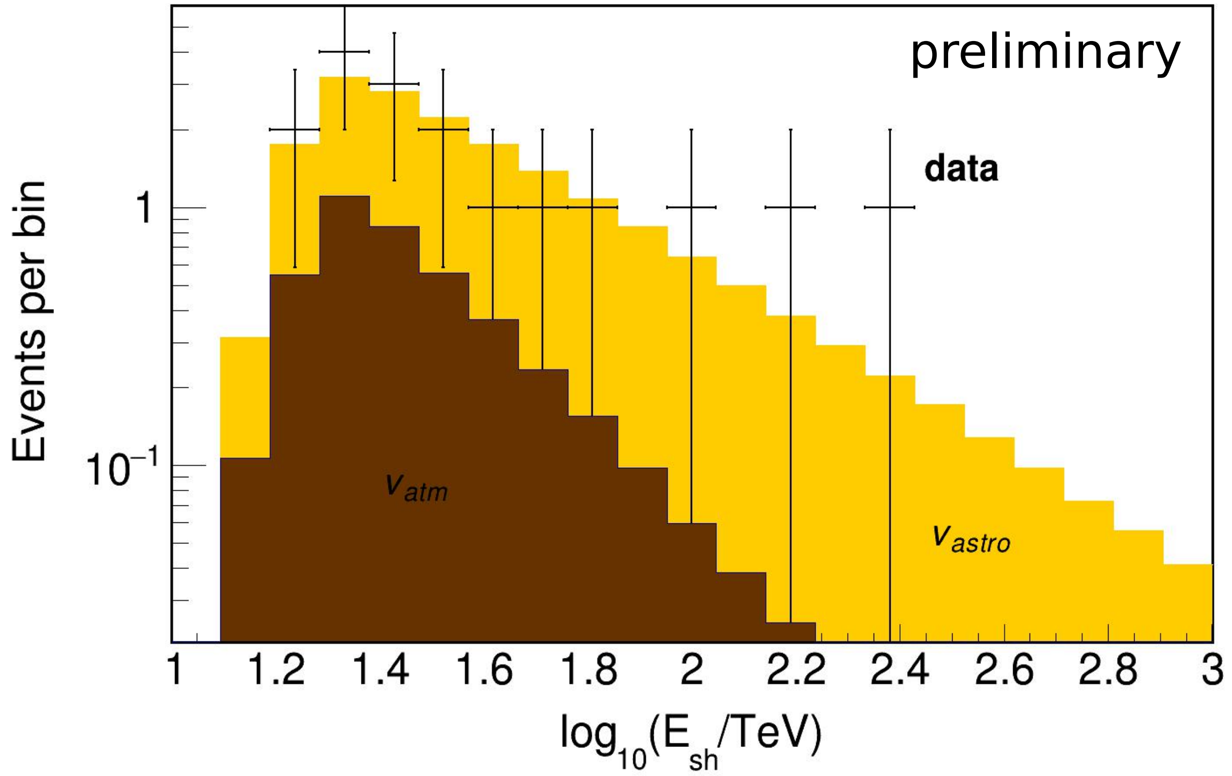
First “non-IceCube” evidence for diffuse ν_{astro} flux at above 3σ !

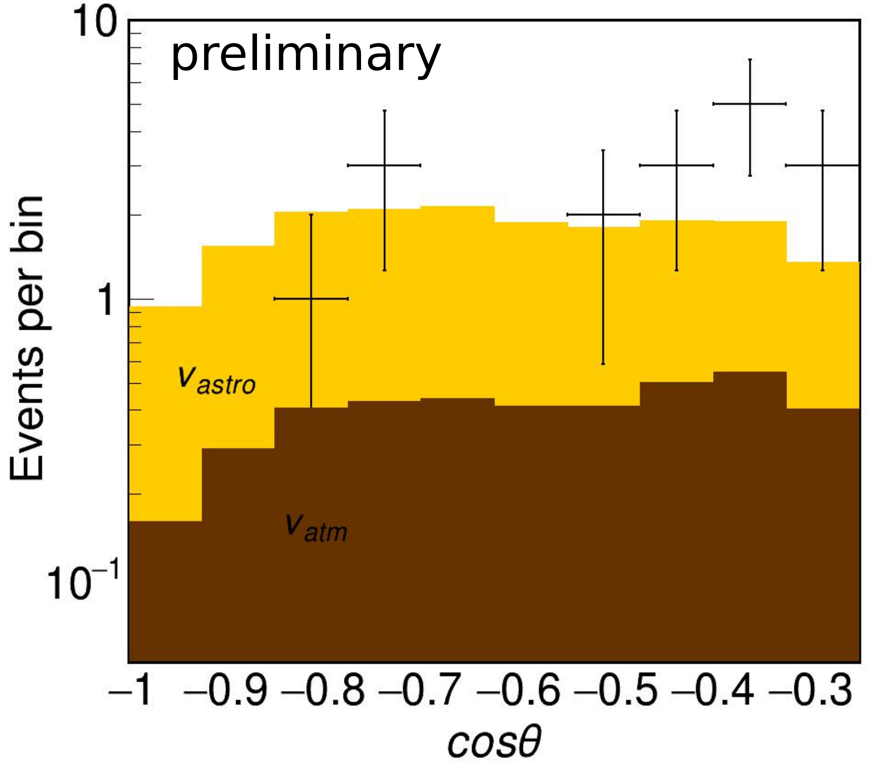
[Phys.Rev. D 107, 042005 (2023)]

Cascade diffuse flux update

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

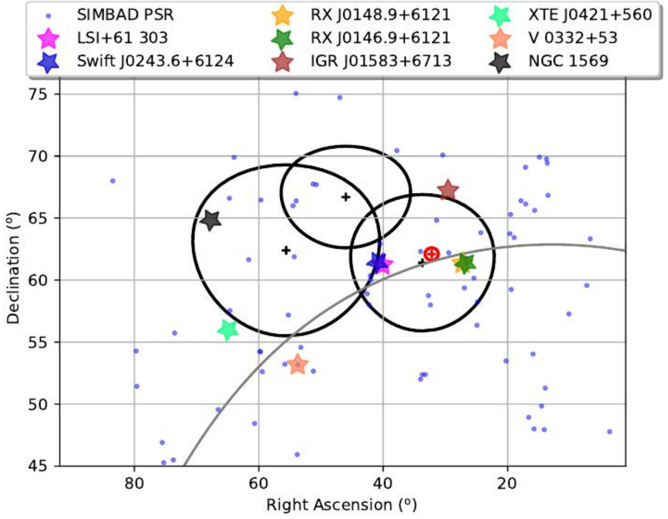
- Significance of the diffuse flux 4.31σ (statistical only)





HE cascade sky map

[arXiv:2307.07327]

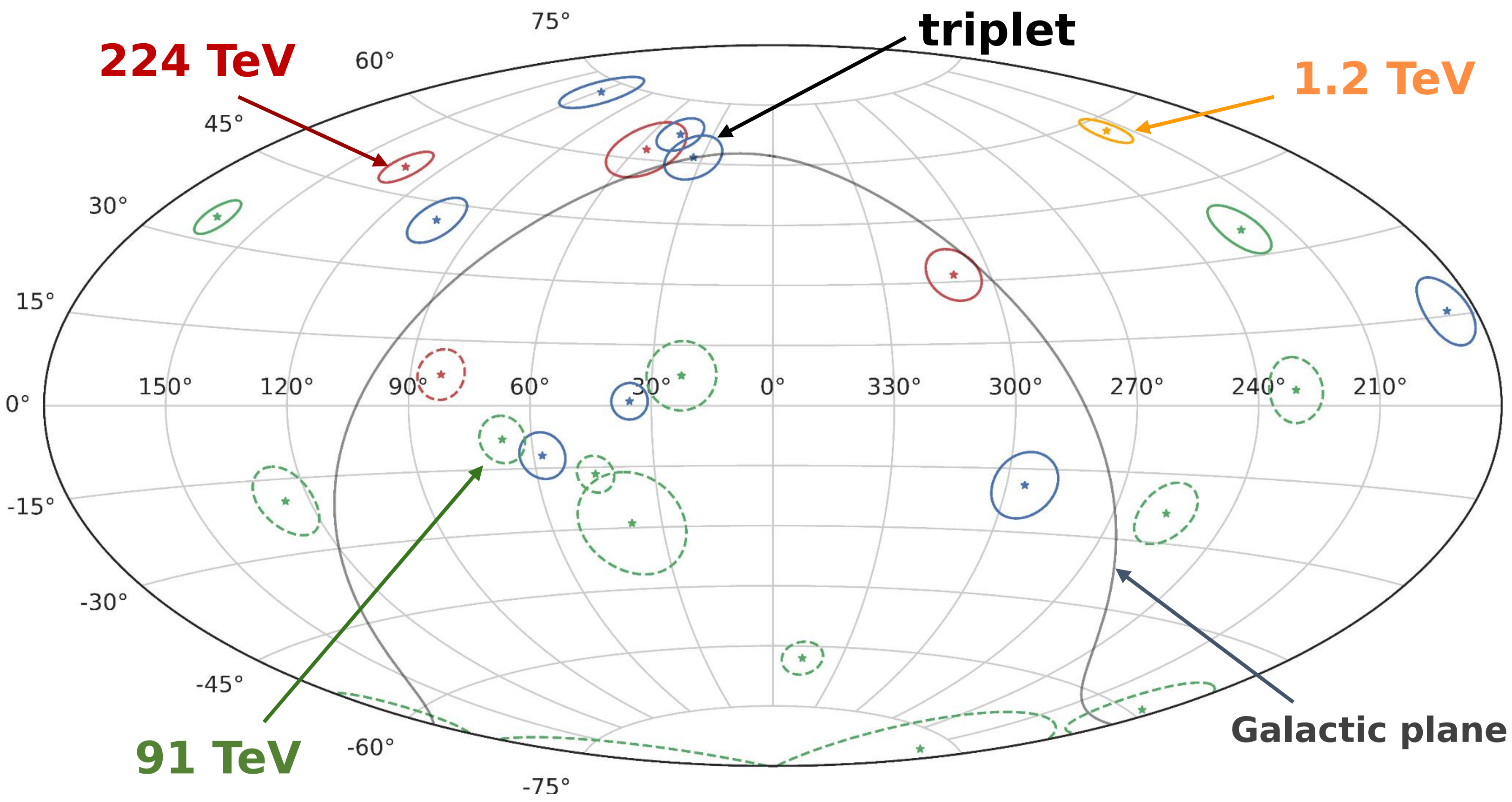


Three events close to
the Galactic plane (grey line)

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)]**

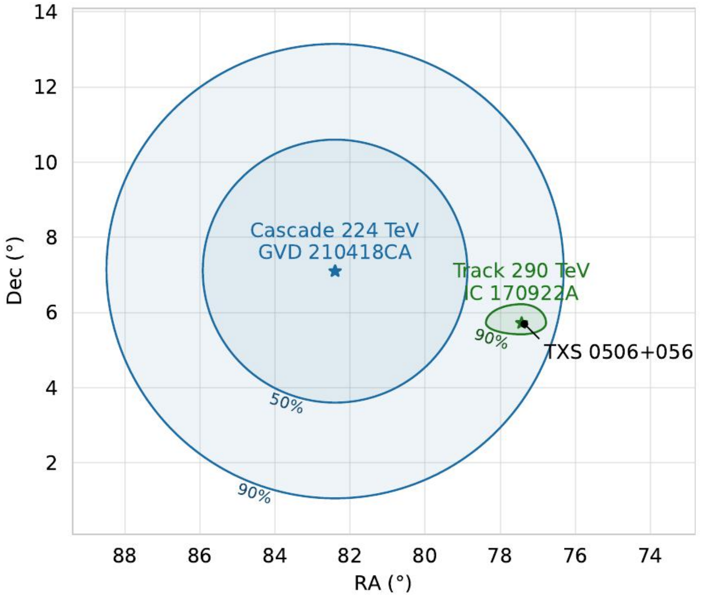
Best fit positions and 90% angular uncertainty regions



color represents energy:

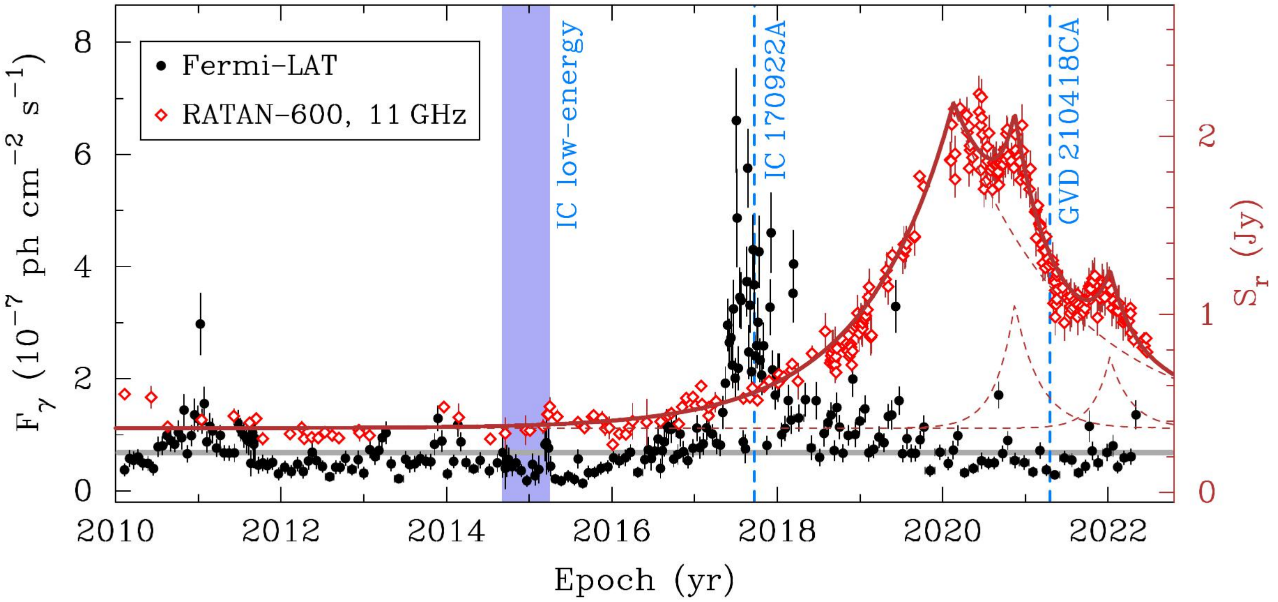
E_{rec} < 100 TeV
100 TeV < E_{rec} < 200 TeV
200 < E_{reco} < 1000 TeV
E_{rec} > 1 PeV

Cascades: TXS0506 coincidence



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 activity
- Probability of IC non-observation: 11%

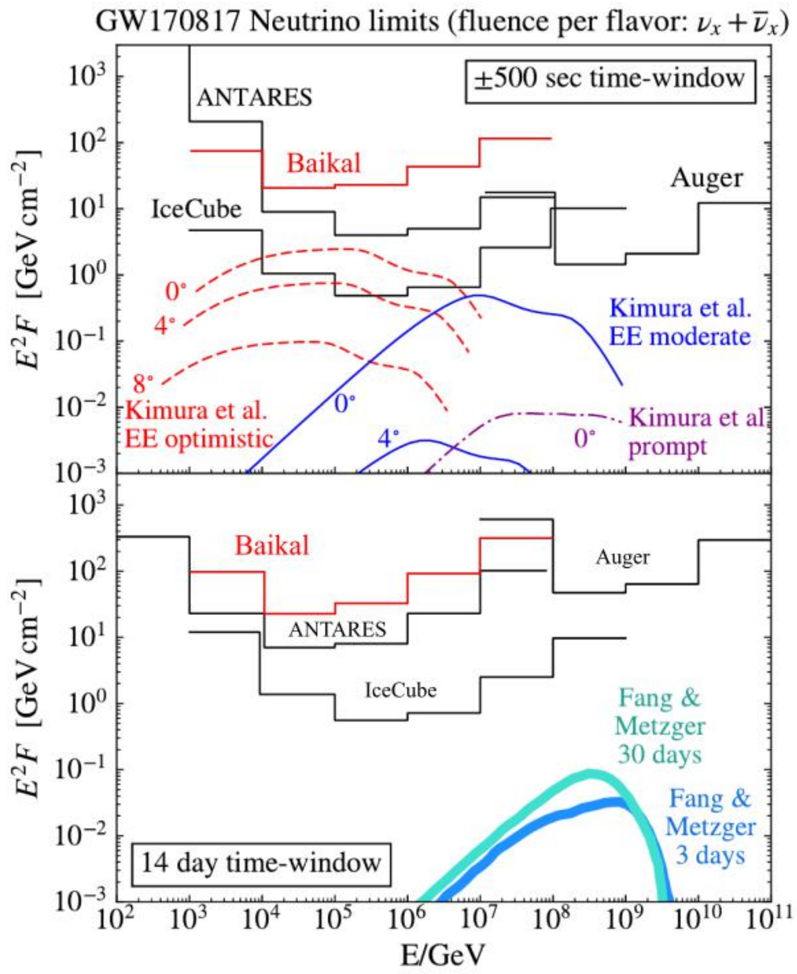
[arXiv:2210.01650]

Follow-up program

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

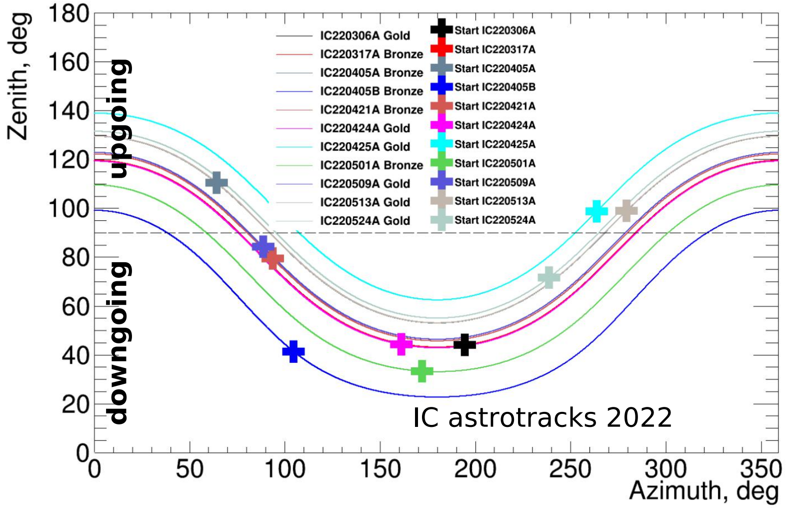
[Phys. ReV. Lett. 119, 161101]
[JETP Letters, v.108, issue 12]



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]

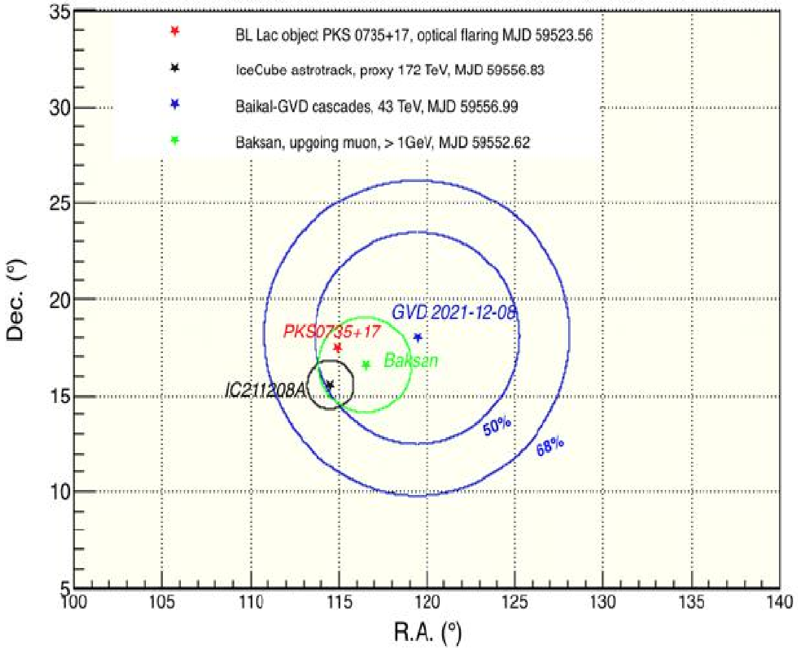
Neutrino alert exchange



Alerts: events with a high probability of astrophysical origin distributed between telescopes

Baikal-GVD alert system

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



[PoS(ECRS2022)096]

Follow-up of IceCube and ANTARES alerts

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

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

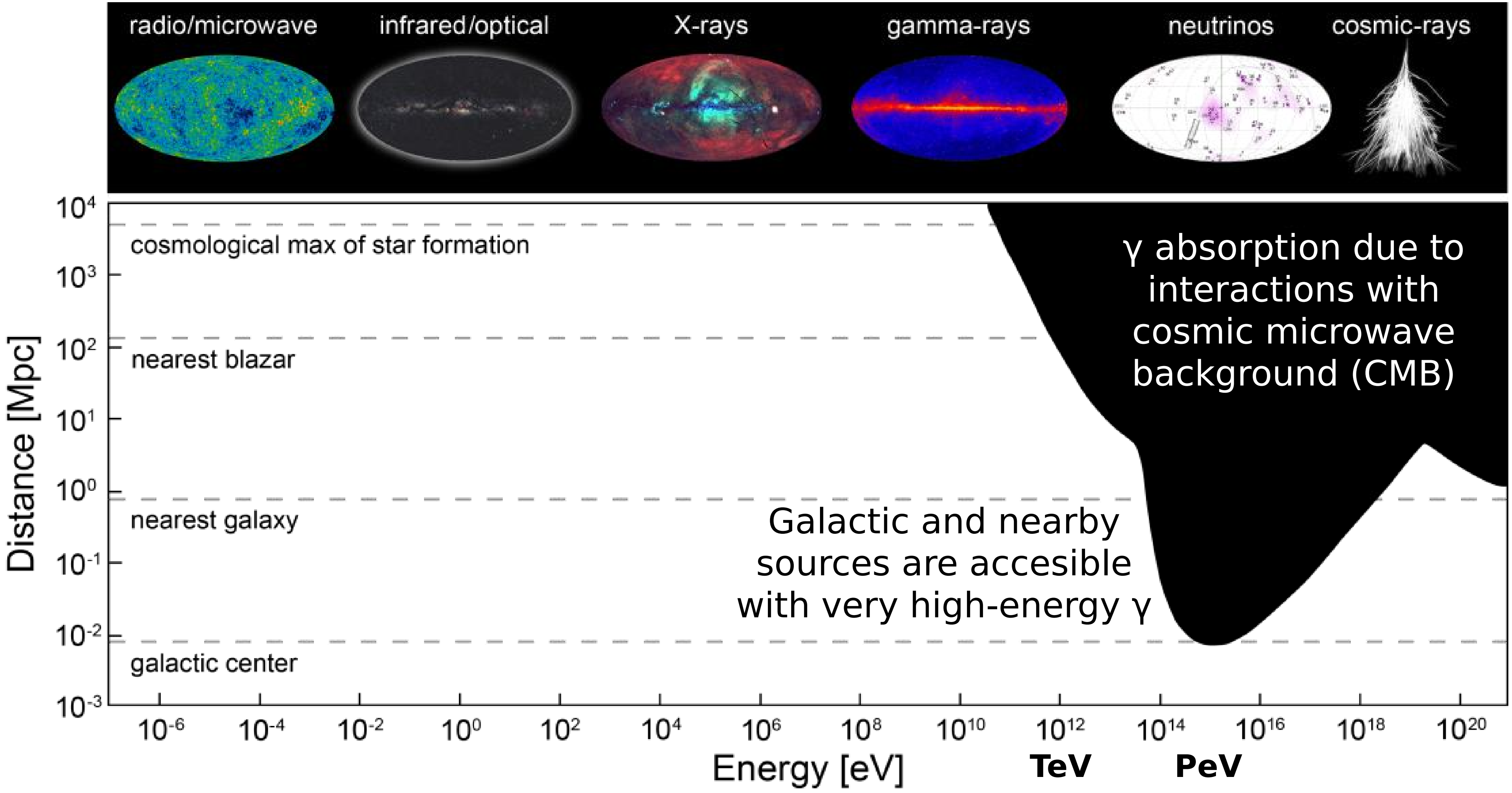
Summary

Baikal-GVD has reached ~0.5 km^3 instrumented volume:
96 strings carrying 3456 OMs

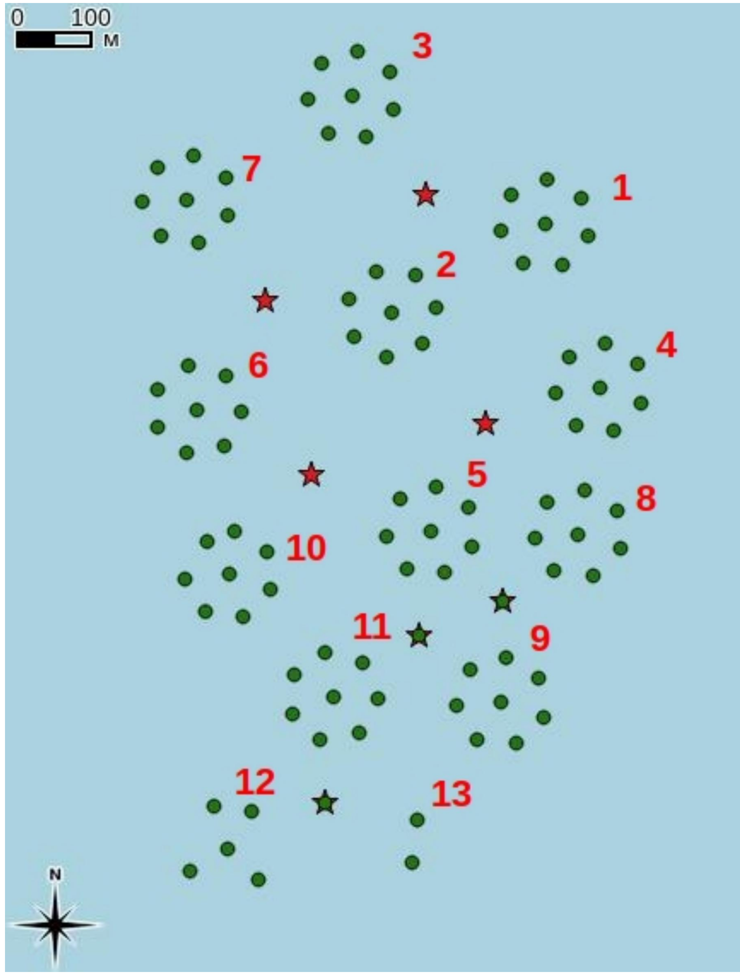
Baikal-GVD is joining the astrophysical neutrino origin quest
- Telescope performance was validated with the atmospheric neutrino flux observation
- First high-energy events are selected in track-like event analysis
- HE cascade event analysis confirms the diffuse flux observation at the level of 3.05σ
- Experiment participates in high-energy alert follow-up and alert exchange

BACKUP

Neutrino as cosmic messenger



Neutrino propagates to cosmological distances and points to its origin



Baikal-GVD 2023
top view

Data stream

Baikal shore center
- Power distrubution
- Data readout hardware/software
- Data-taking management (shifter)
- Data quality control
- Long-term storge of raw data
- Fast reconstruction (to be deployed)

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