Status of the Baikal-GVD neutrino telescope and selected results

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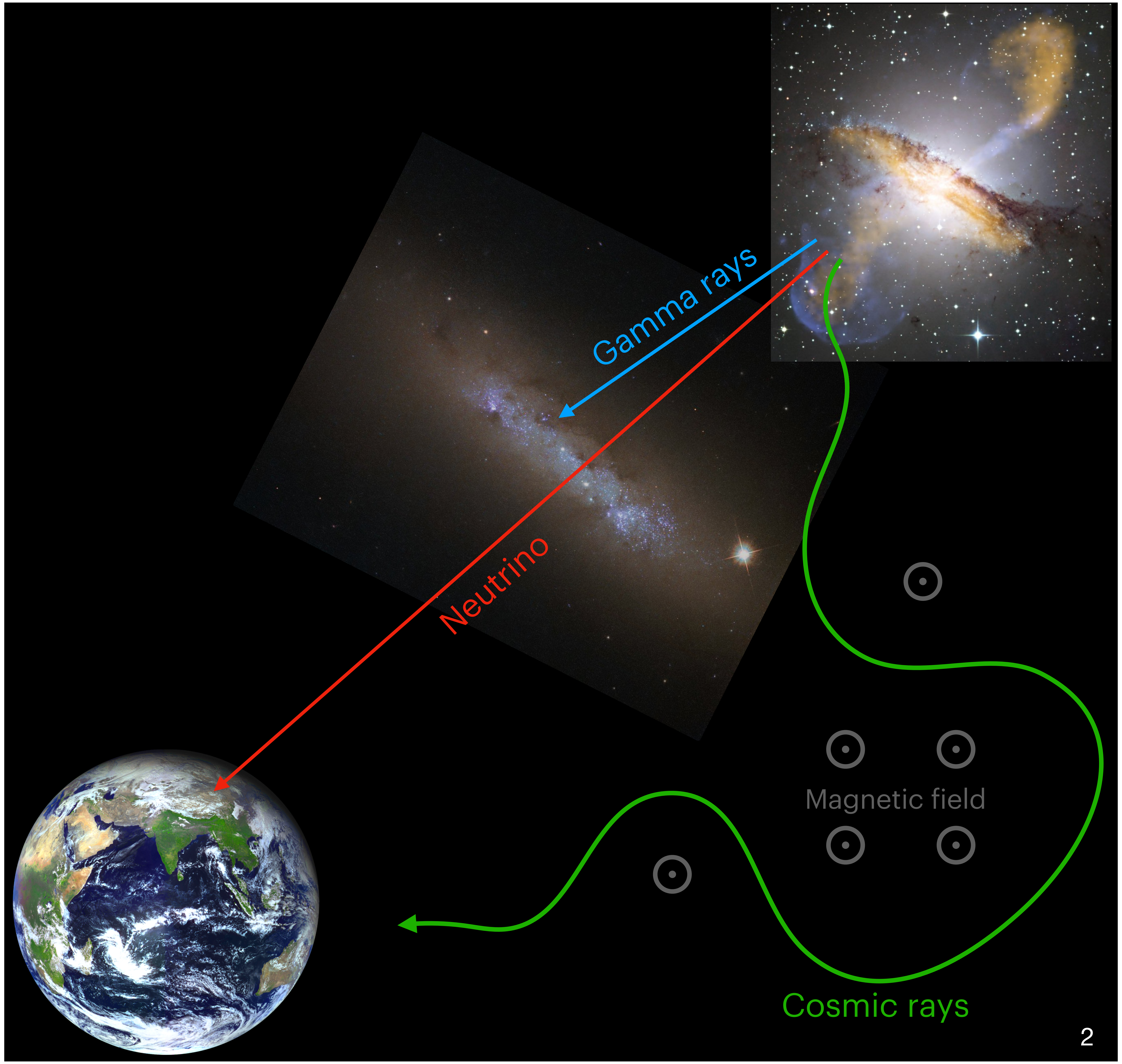
18.10.2023, India-JINR workshop

High-energy neutrino (>10 GeV) as astrophysical messenger

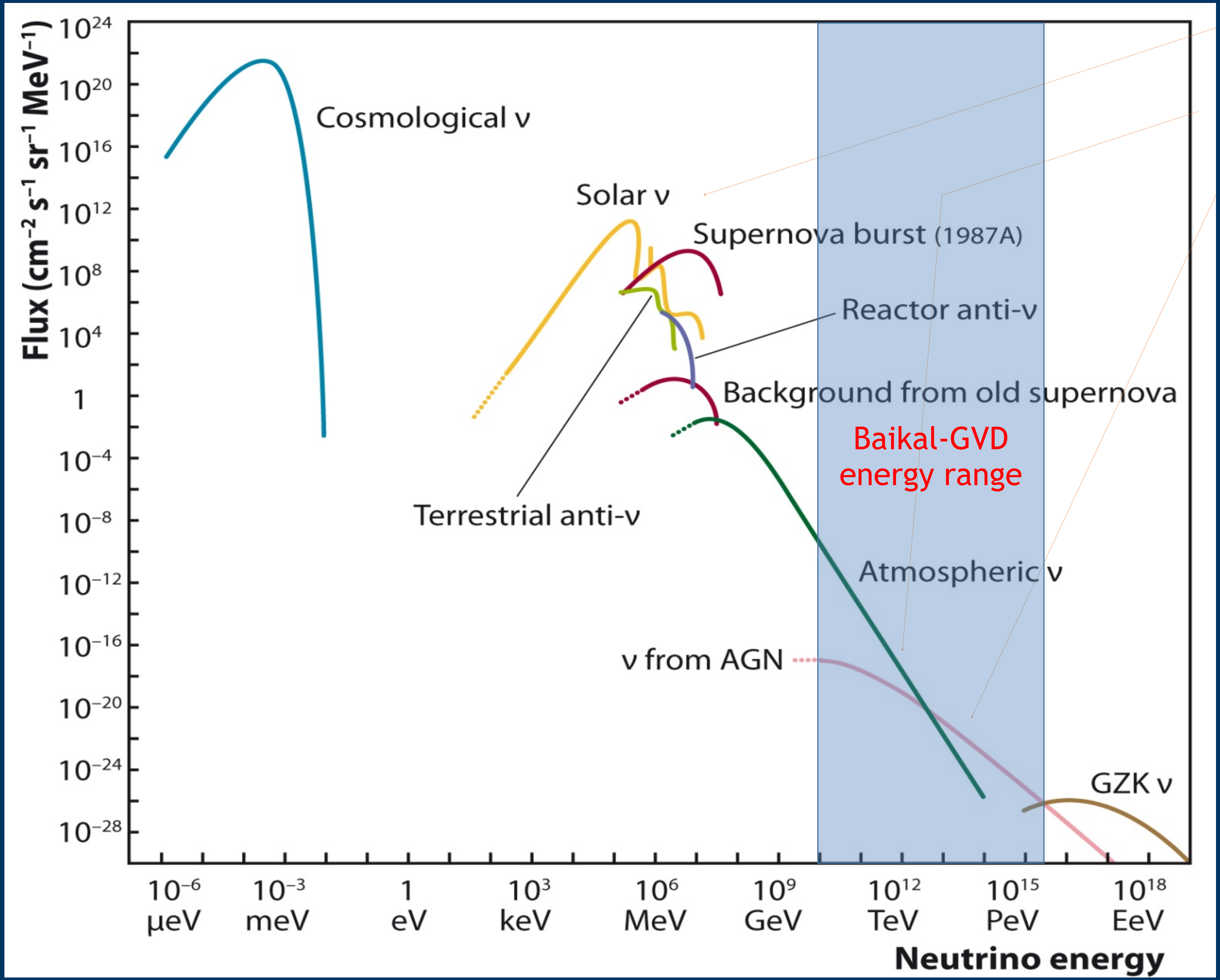
- Neutrino is a neutral stable light elementary particle weakly interacting with matter
- Cross section grows rapidly with increasing energy (~1 nb @1PeV)
- Abundantly born in hadronic processes in space accelerators (active galactic nuclei, supernova remnants, microquasars, gamma-ray bursts, tidal disruption events etc.)
- Unlike high-energy gamma rays:
    - freely escape from the source
    - freely distributed in the Universe
- Unlike cosmic rays (high-energy p, He, etc.):
    - not deflected by magnetic fields
    - trace production and acceleration sites of neutrino and thus cosmic rays



M.Markov, **1960**: (JINR)

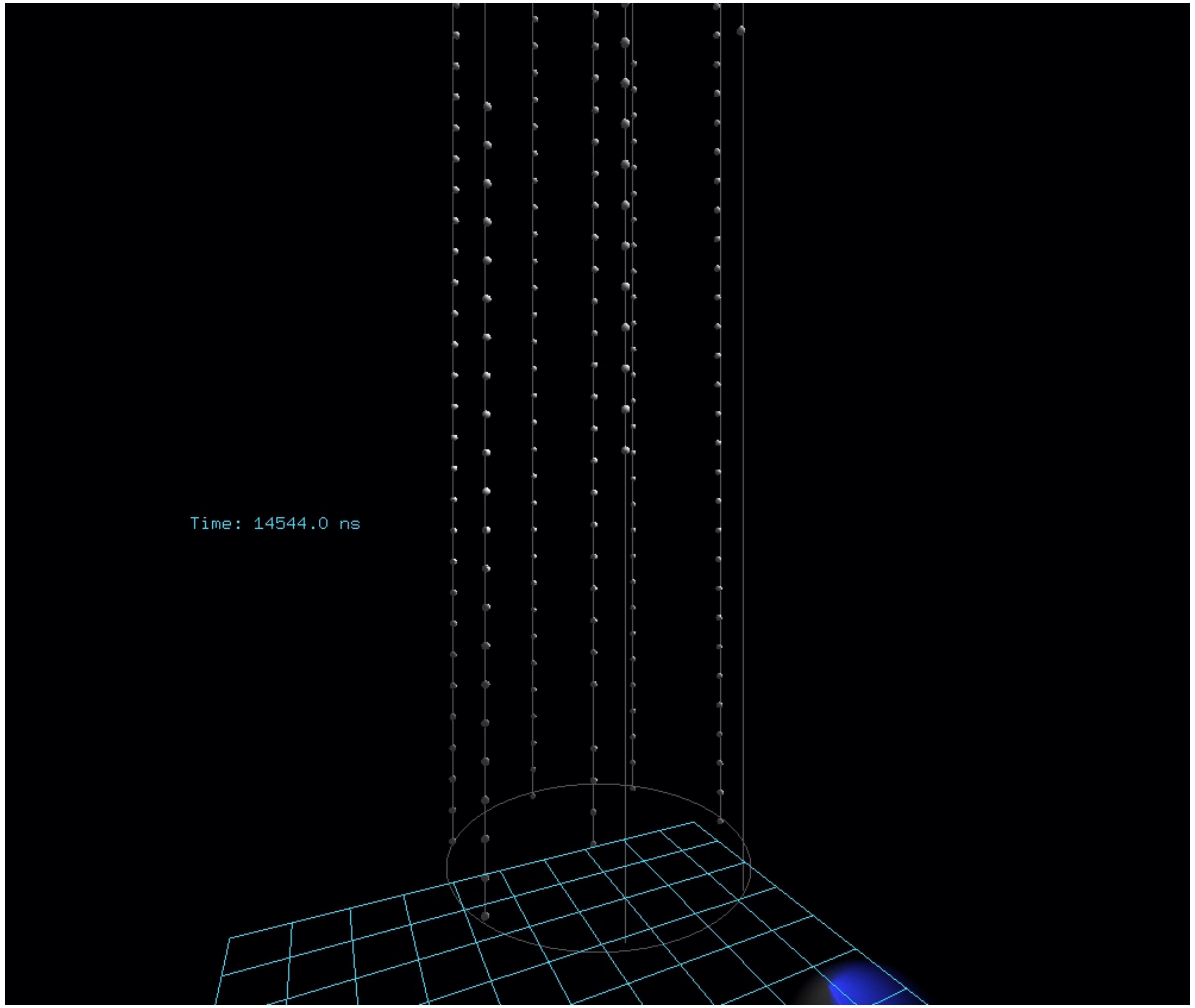
„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation" Proc. 1960 ICHEP, Rochester, p. 578.

Neutrino sources and energy scale



Neutrino telescope: operation principle

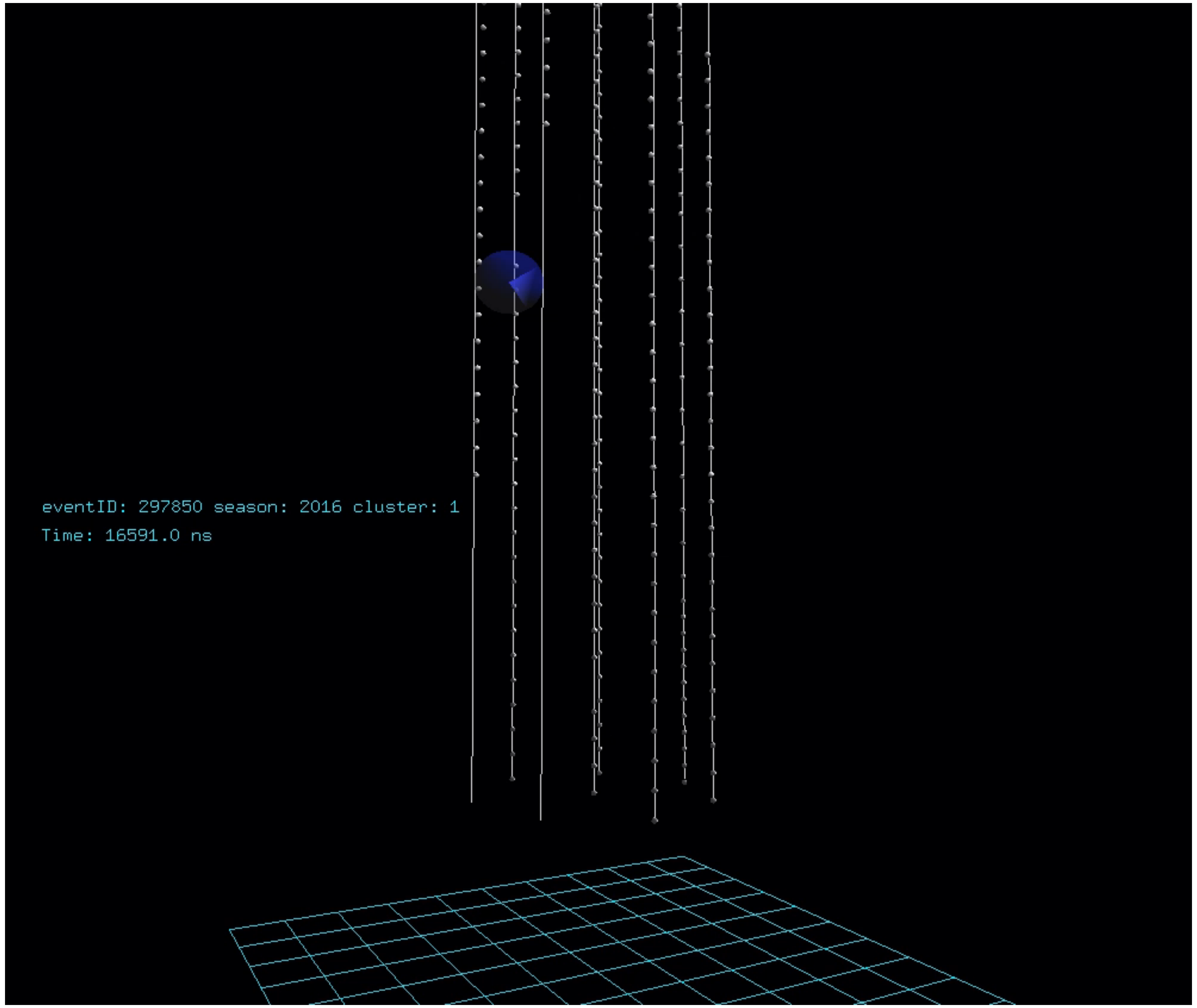
Track-like event



- Large arrays of PMTs in deep water or ice
- Cherenkov light detected by PMTs
- Track-like events from ν_μ CC
- Cascade-like events from ν_e & ν_τ CC + NC
- Direction reconstructed from hit positions and times
- Energy reconstructed from hit charges
- Look downward through the Earth to suppress atmospheric muon background

Neutrino telescope: operation principle

Cascade like event



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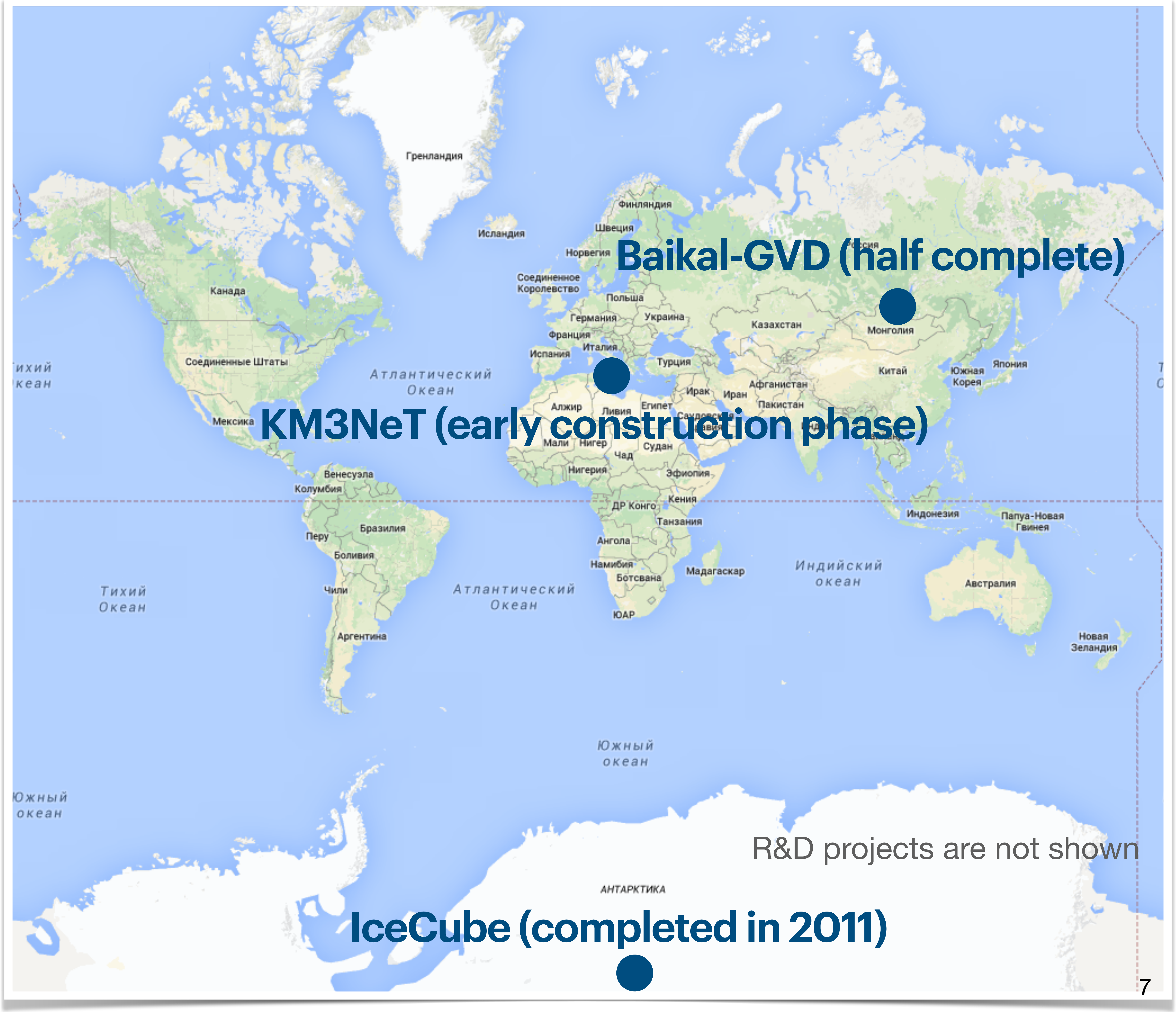
Current neutrino telescopes

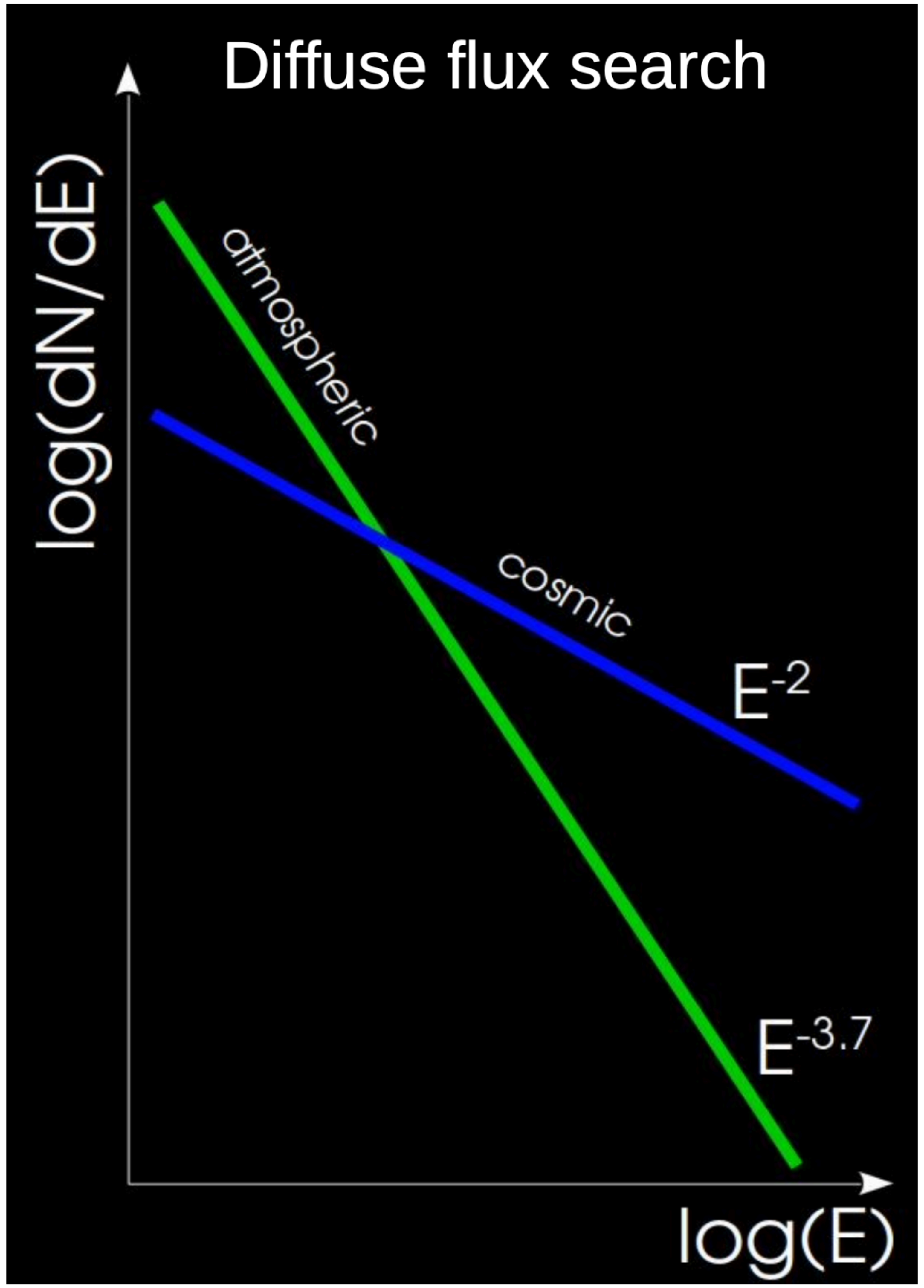
A difficult task both technically and scientifically:

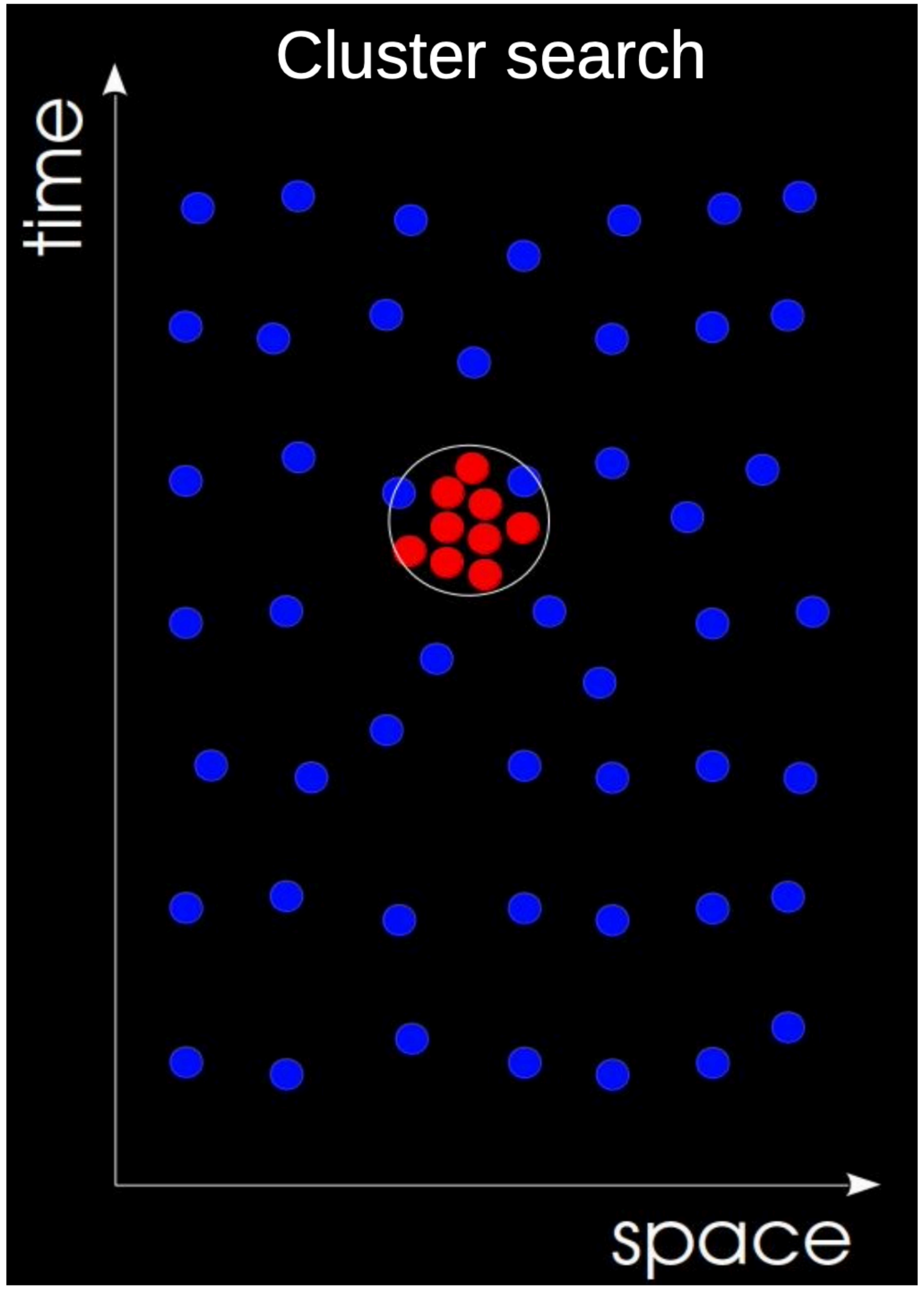
- Detector volume should be 1 km^3 or more of natural environment
- Clear water or ice
- Deep underwater, under ice to suppress the background of other particles
- Located in both the Northern and Southern hemispheres to cover the entire celestial sphere

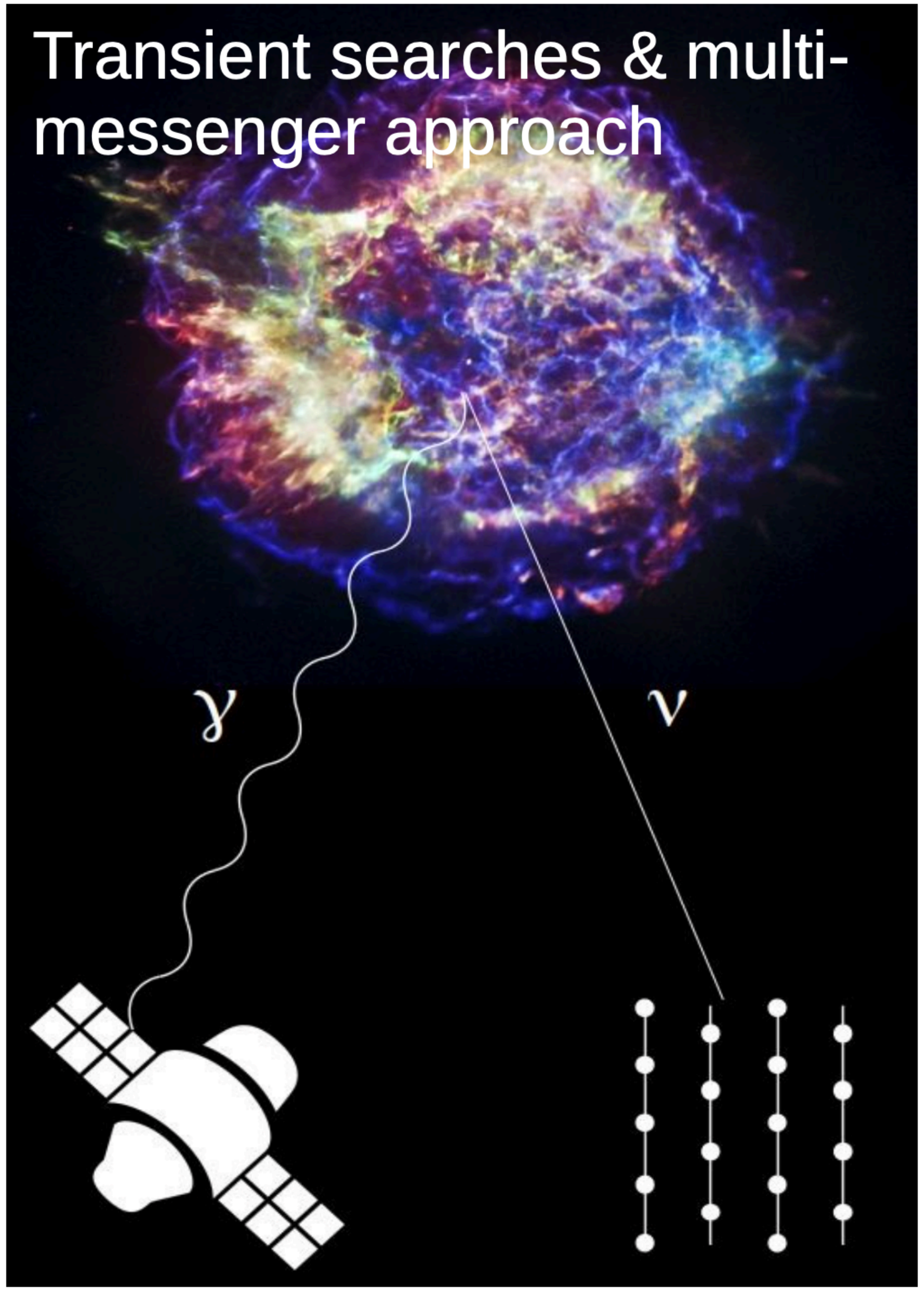
Combined into the global neutrino network (GNN)



Methods of background suppression

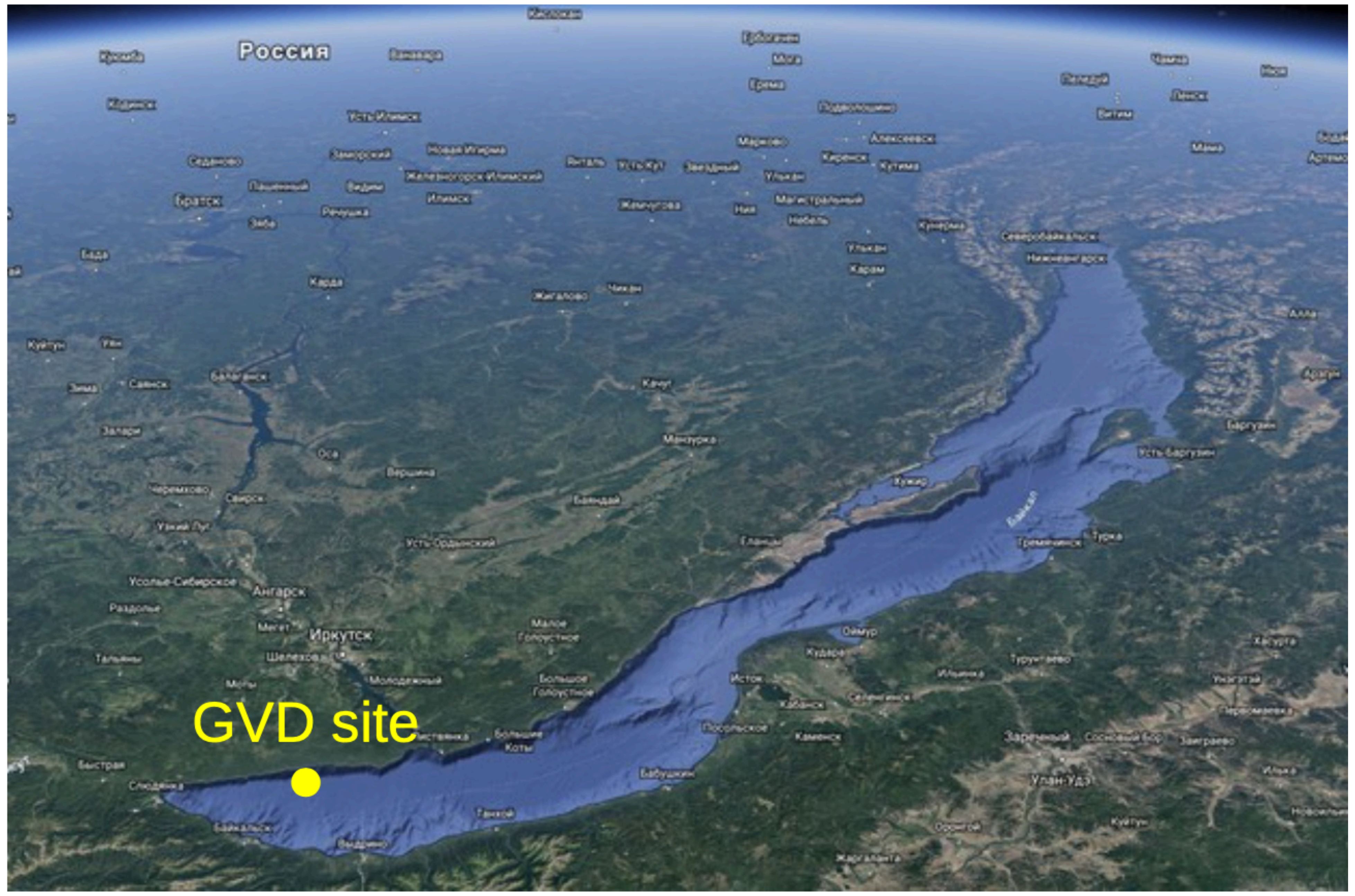


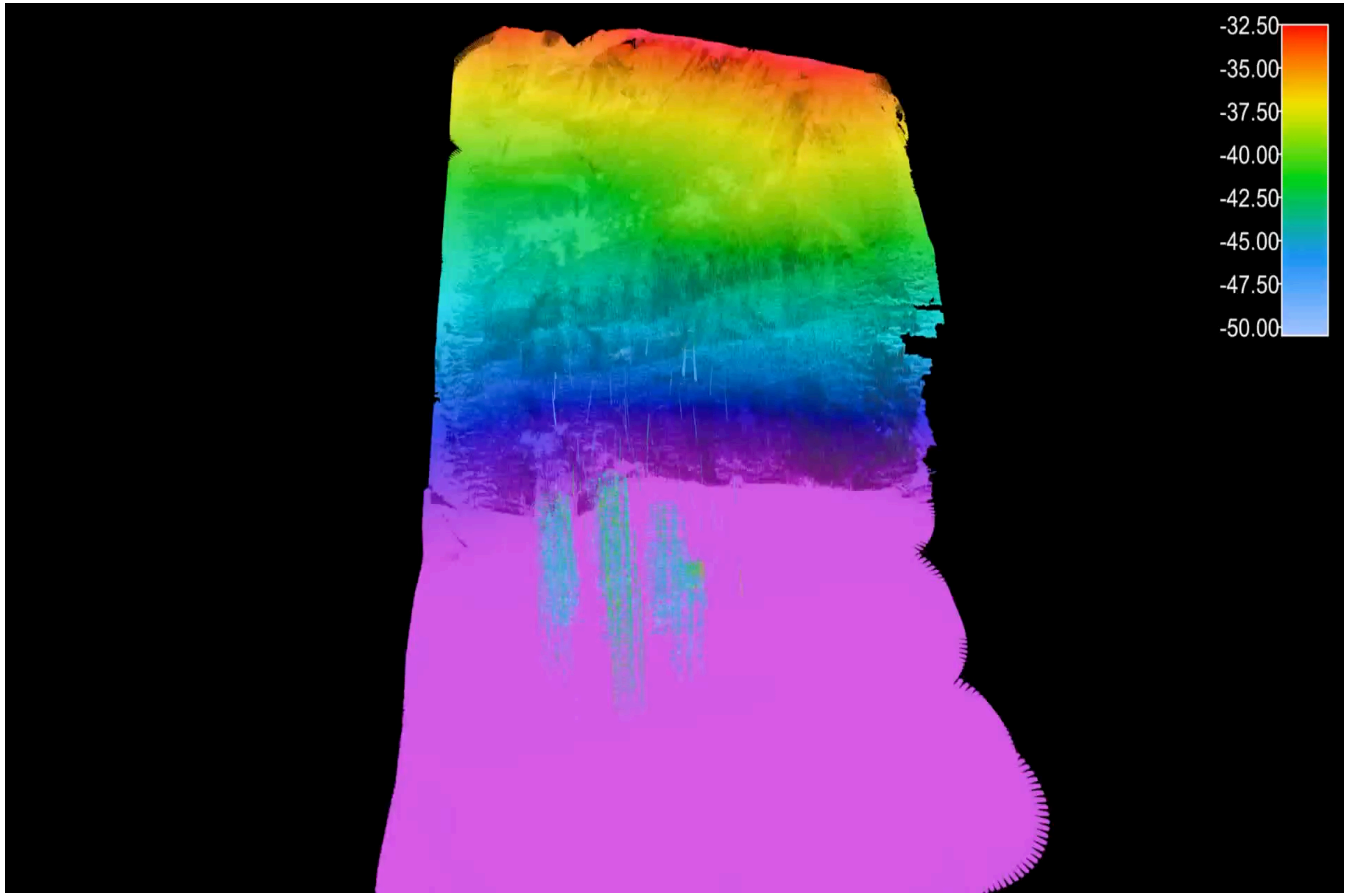




Pictures borrowed from talk by R. Ruiz

Baikal-GVD site

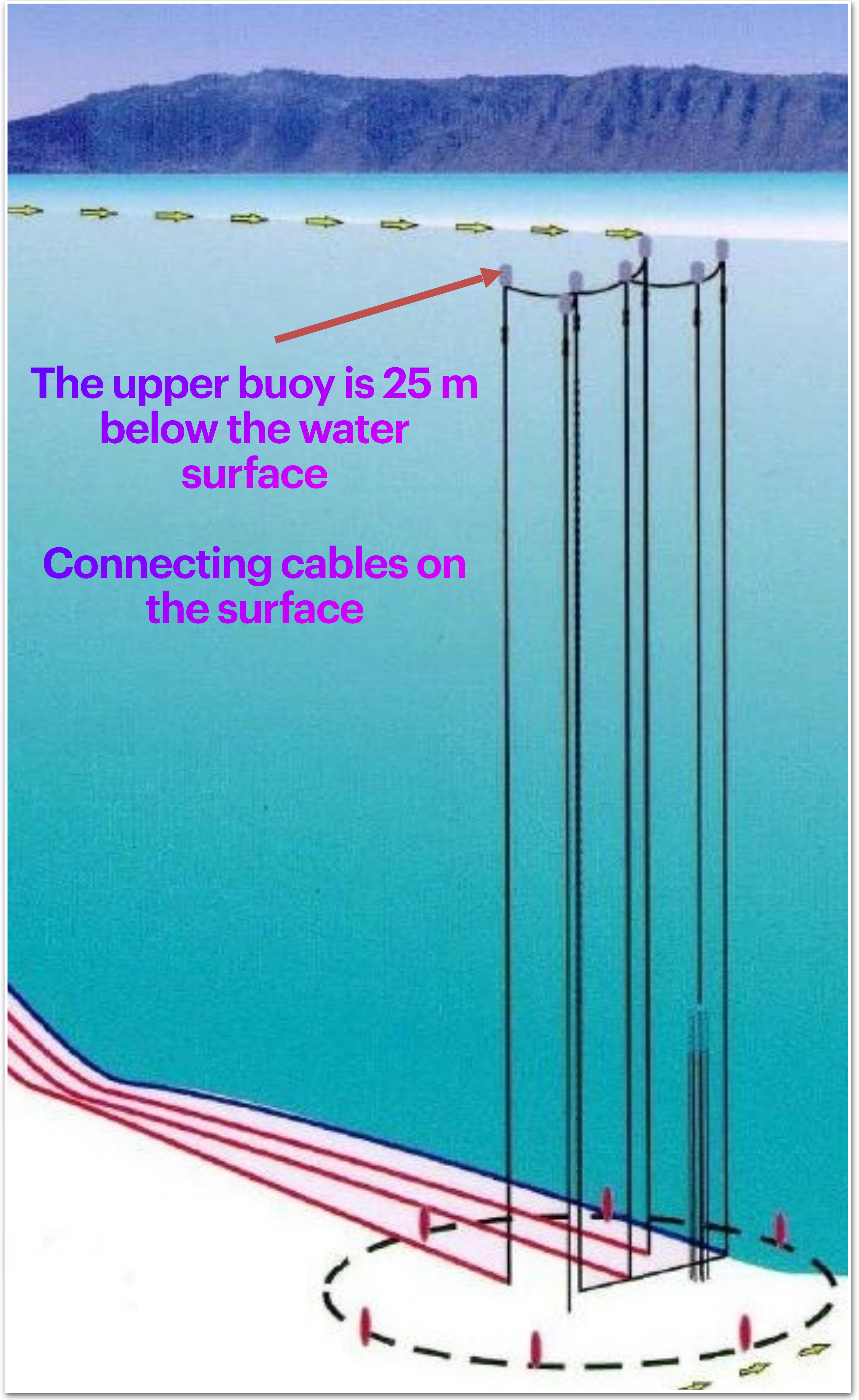


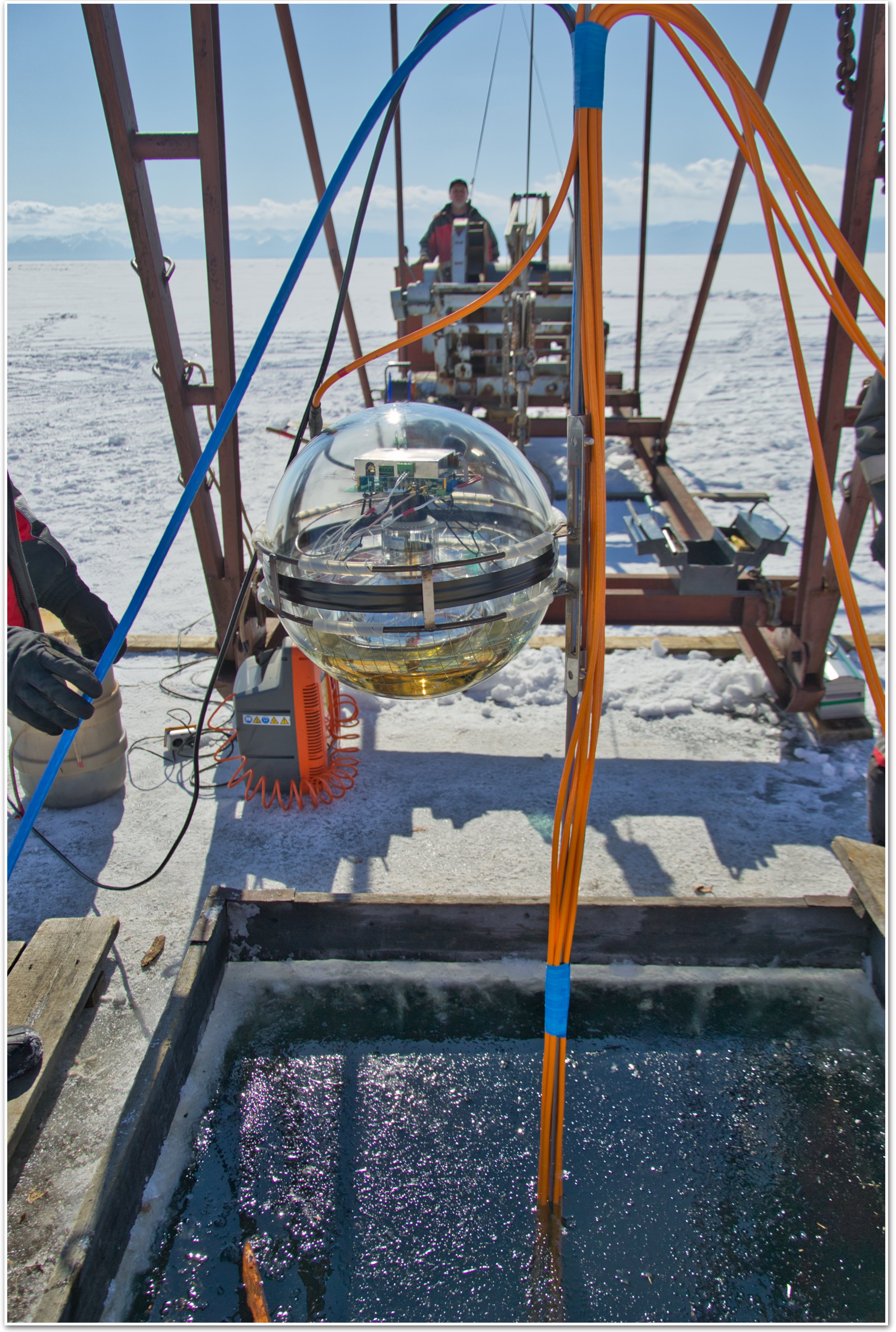


- Southern basin of the lake
- ~3.6 km offshore
- Flat area at depths 1366–1367 m
- High water transparency:
    - Absorption length: 22 m
    - Effective scattering length: 480 m
- Moderately low optical background: 15–50 kHz

Telescope deployment

From the ice cover of the lake (mid-February - early April)





Bed cable laying

The optical module - basic element of the telescope

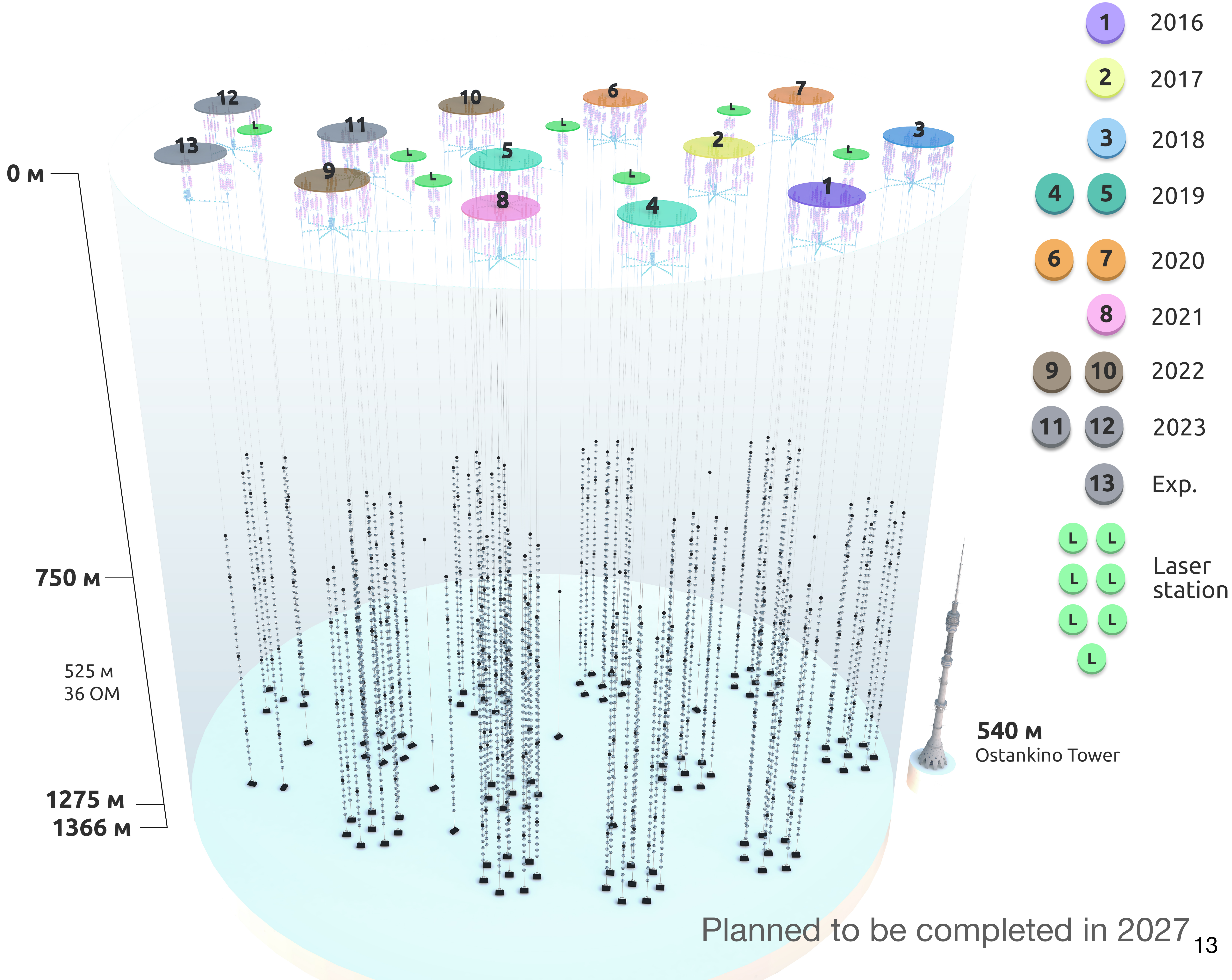
17 inches sphere
(42 cm)

10 inch Hamamatsu PMT
R7081-100

Baikal-GVD status

April 2023

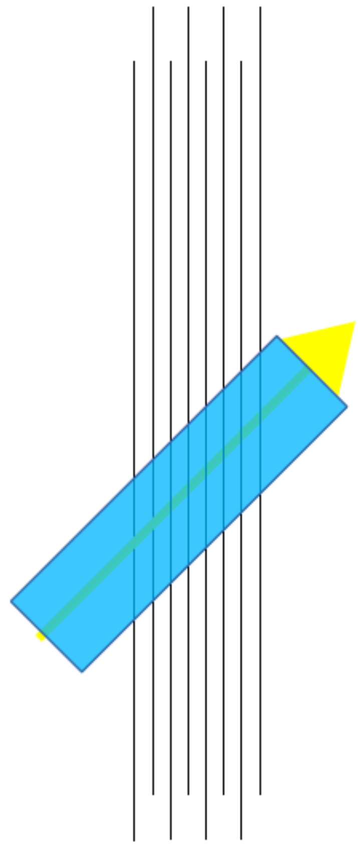
- 3456 Optical modules on 96 strings (12 clusters)
- 8 strings form a cluster - independent array of optical modules
- 36 optical modules per string
- 60 m between strings in a cluster, 250-300 m between clusters
- More than half of 1 km³ of water volume
- 384 Acoustic modules for positioning
- 72 LED beacons and 11 powerful laser sources for calibration



Planned to be completed in 2027

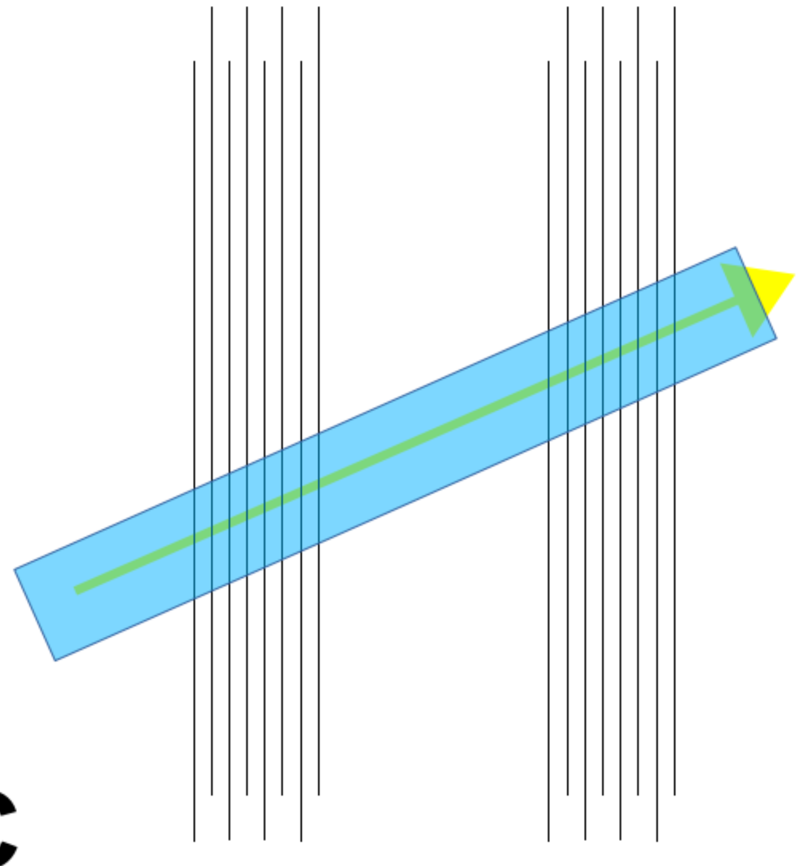
Event types

Single-cluster tracks



- Low energy threshold
- Optimal sensitivity to nearly vertical tracks
- 90% of recorded track events

Multi-cluster tracks

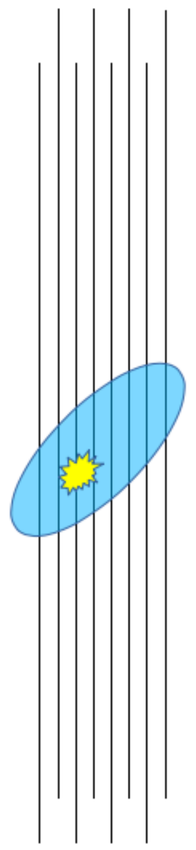


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

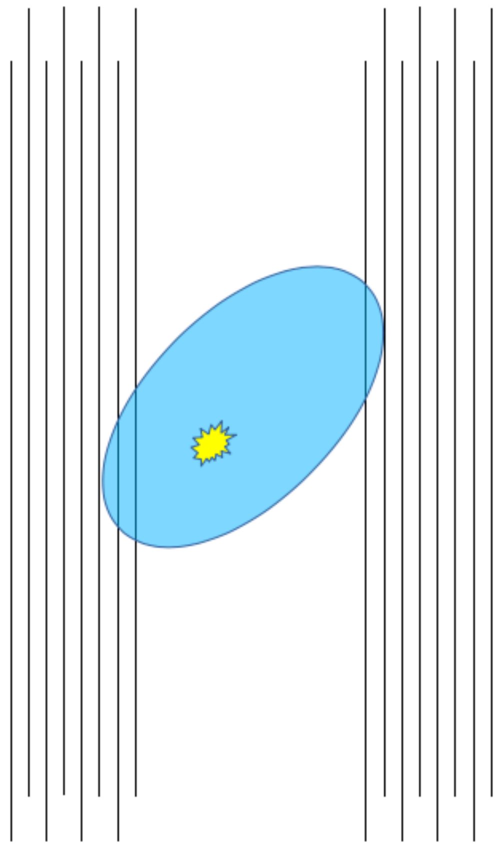
NC, ν_e ν_τ CC

Single-cluster cascades



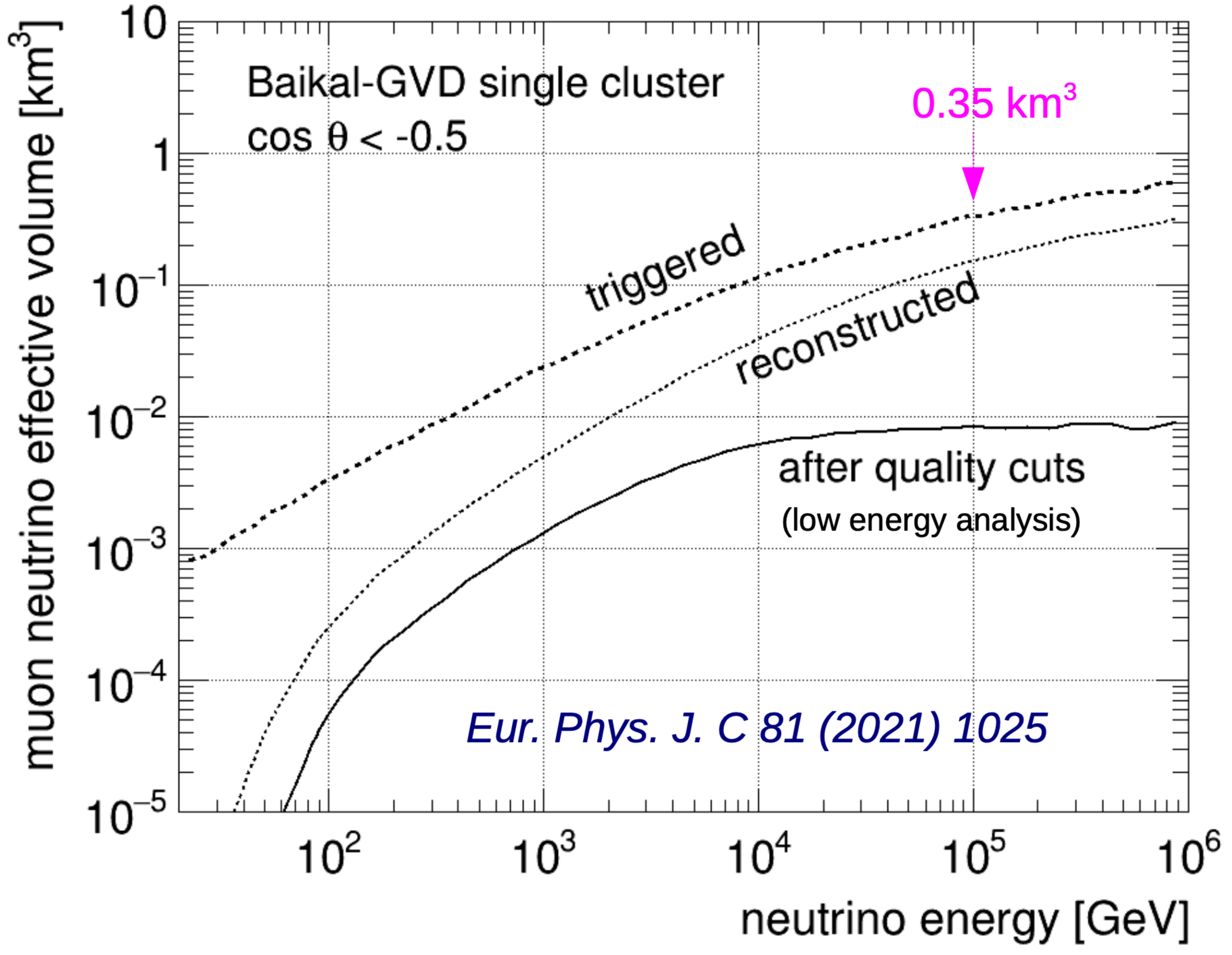
- High energy threshold
- Good energy resolution
- Relatively rare events

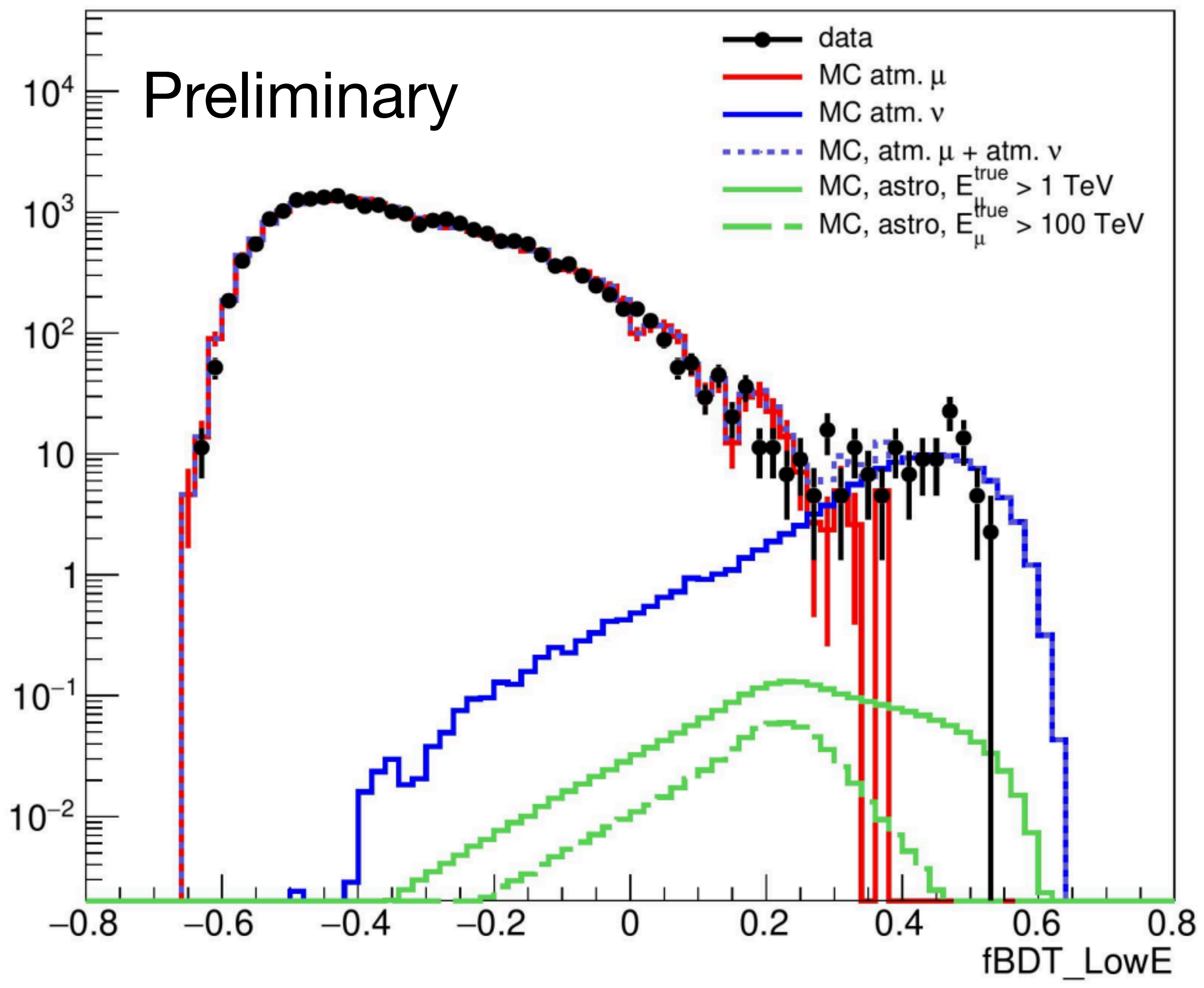
Multi-cluster cascades



- Very high energy threshold
- Excellent energy resolution
- Very rare events

Single cluster muon track analysis





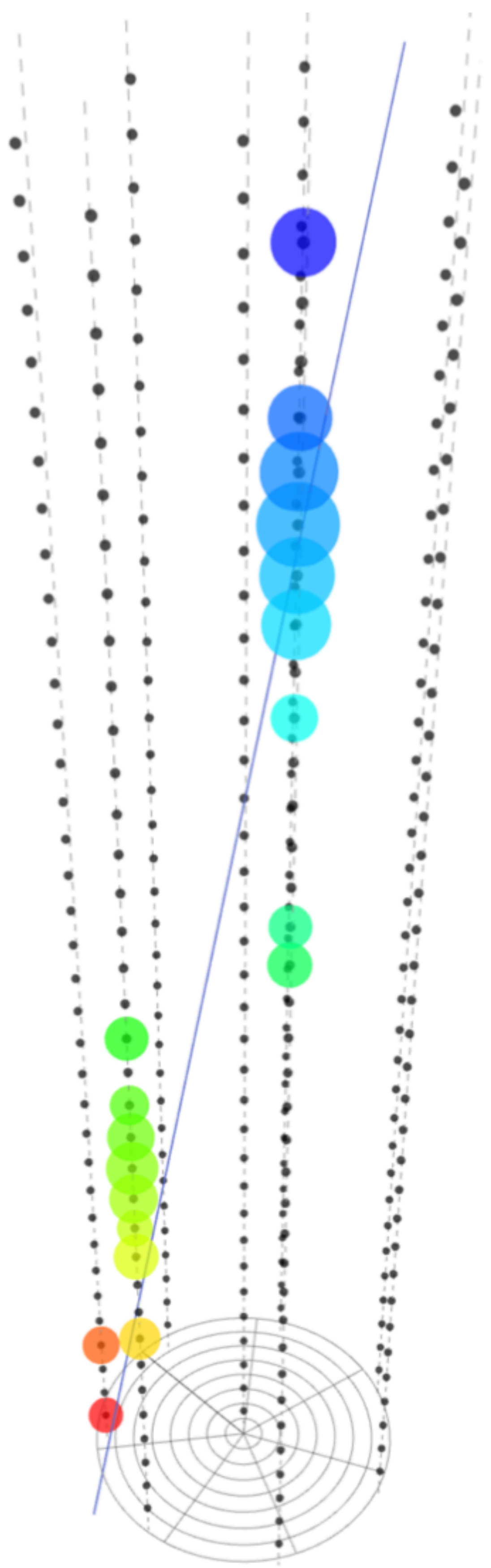
- Direction resolution: 0.3-1.0 degrees
- Energy resolution: factor of 3
- Work in progress towards higher sensitivity and resolution

Events per year per cluster

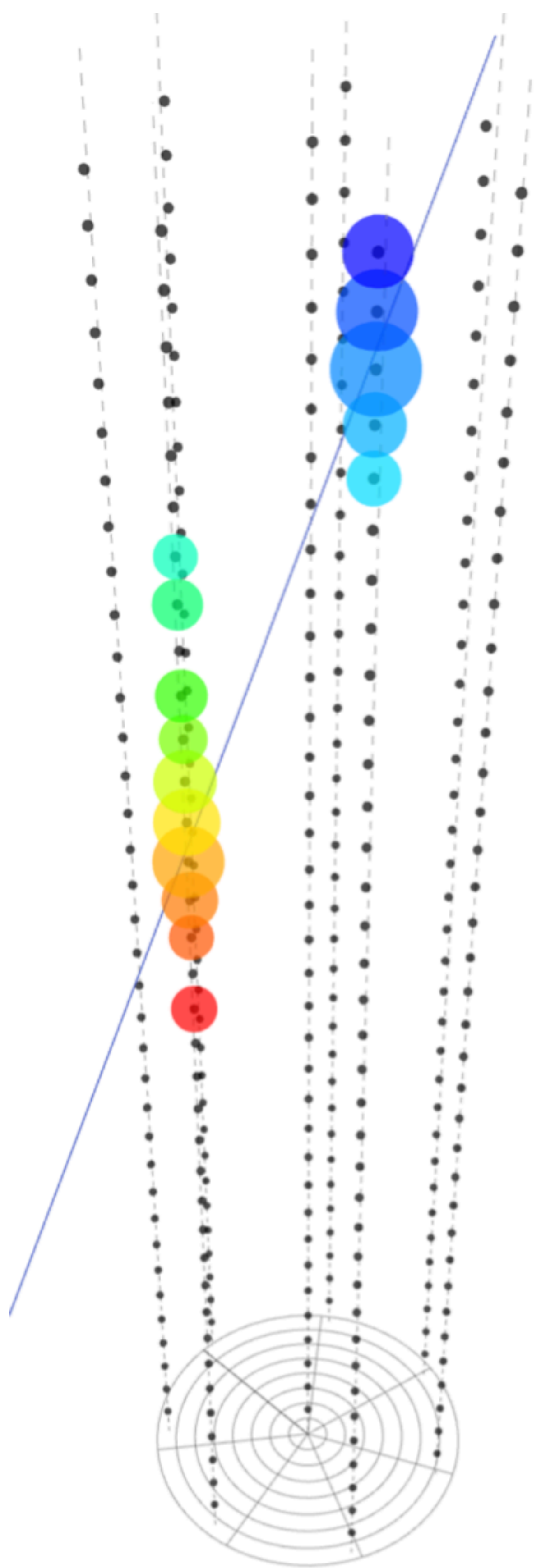
atm. nu	102.2
atm. mu	12.5
SUM:	**114.7**
data	**106.0**

Preliminary

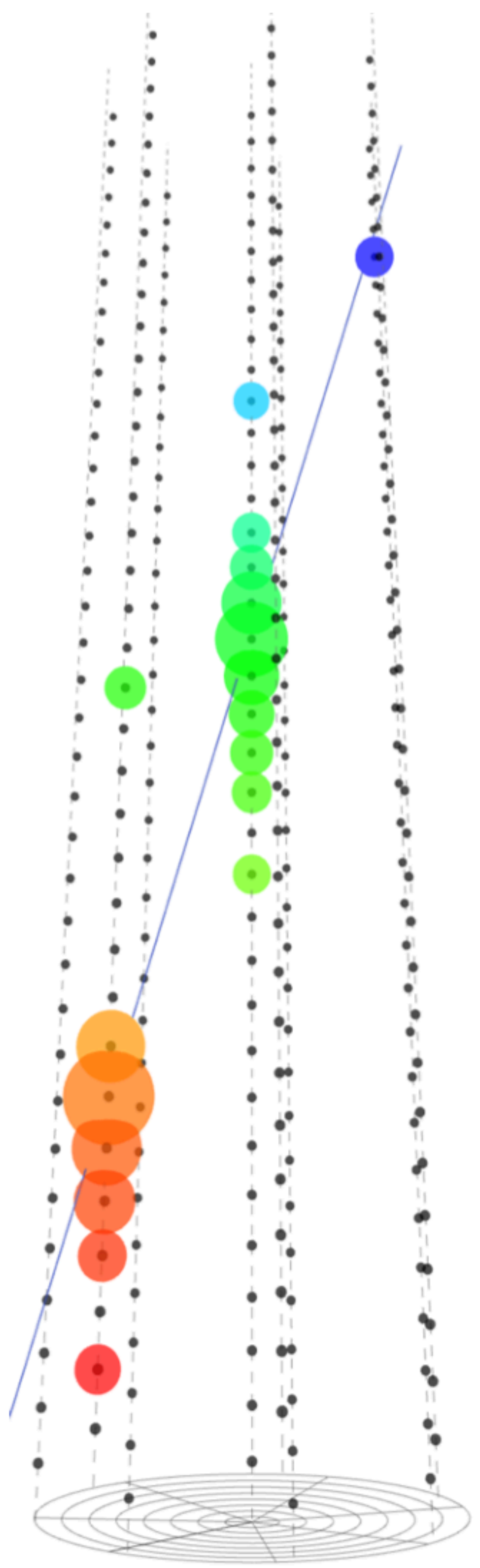
Muon track events



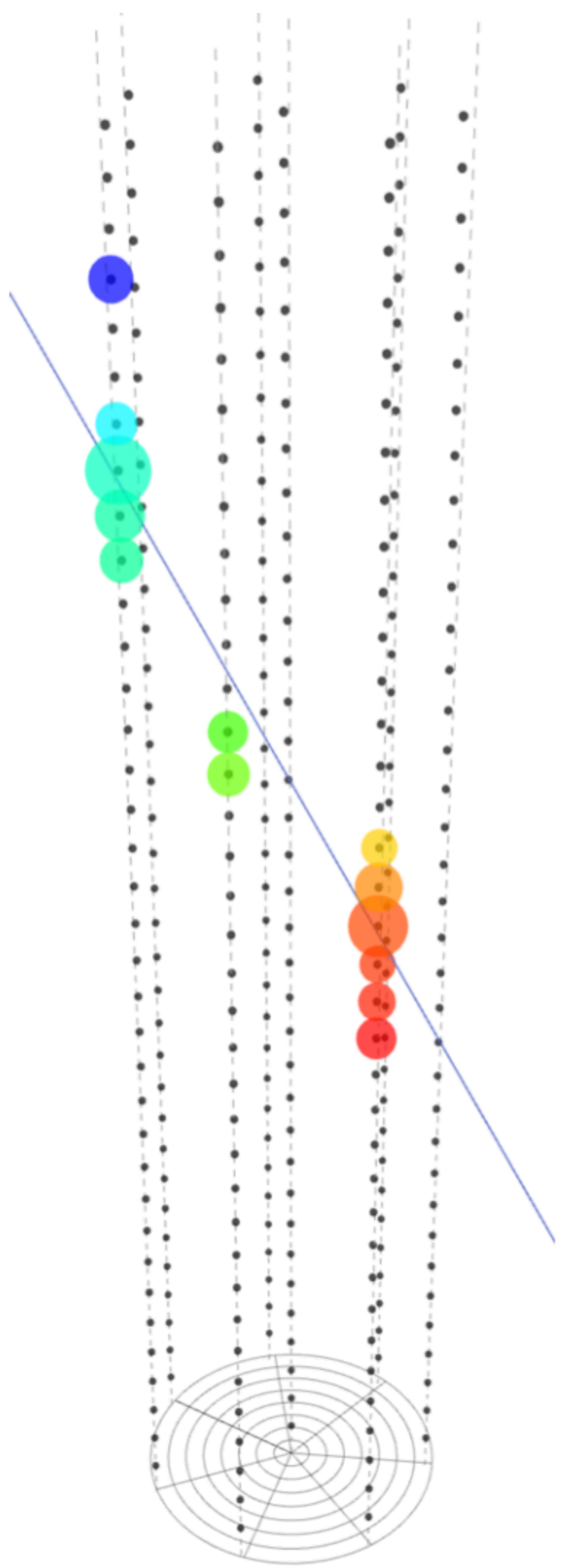
cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
N_{hits} = 19



cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
N_{hits} = 15

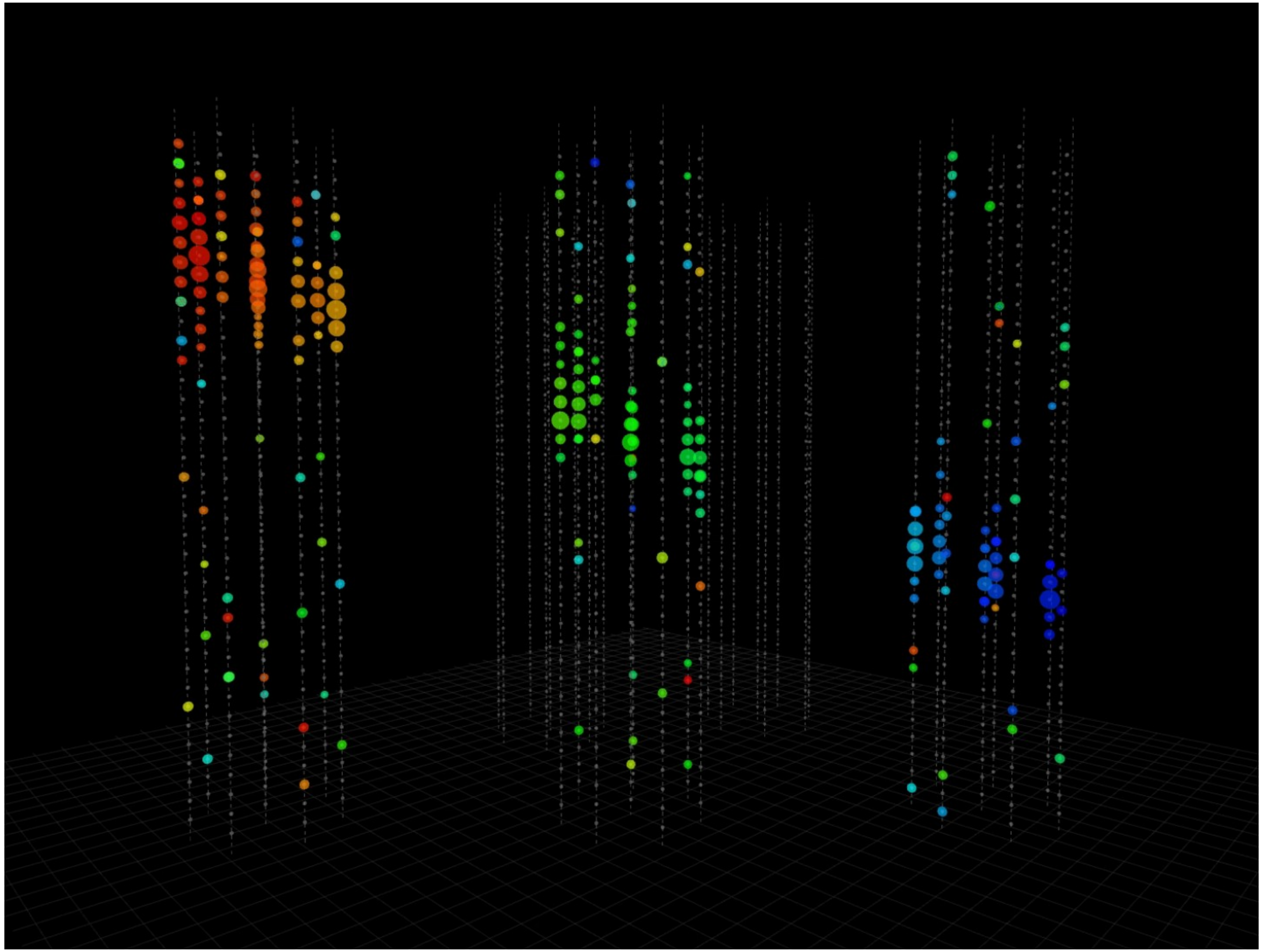


cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18

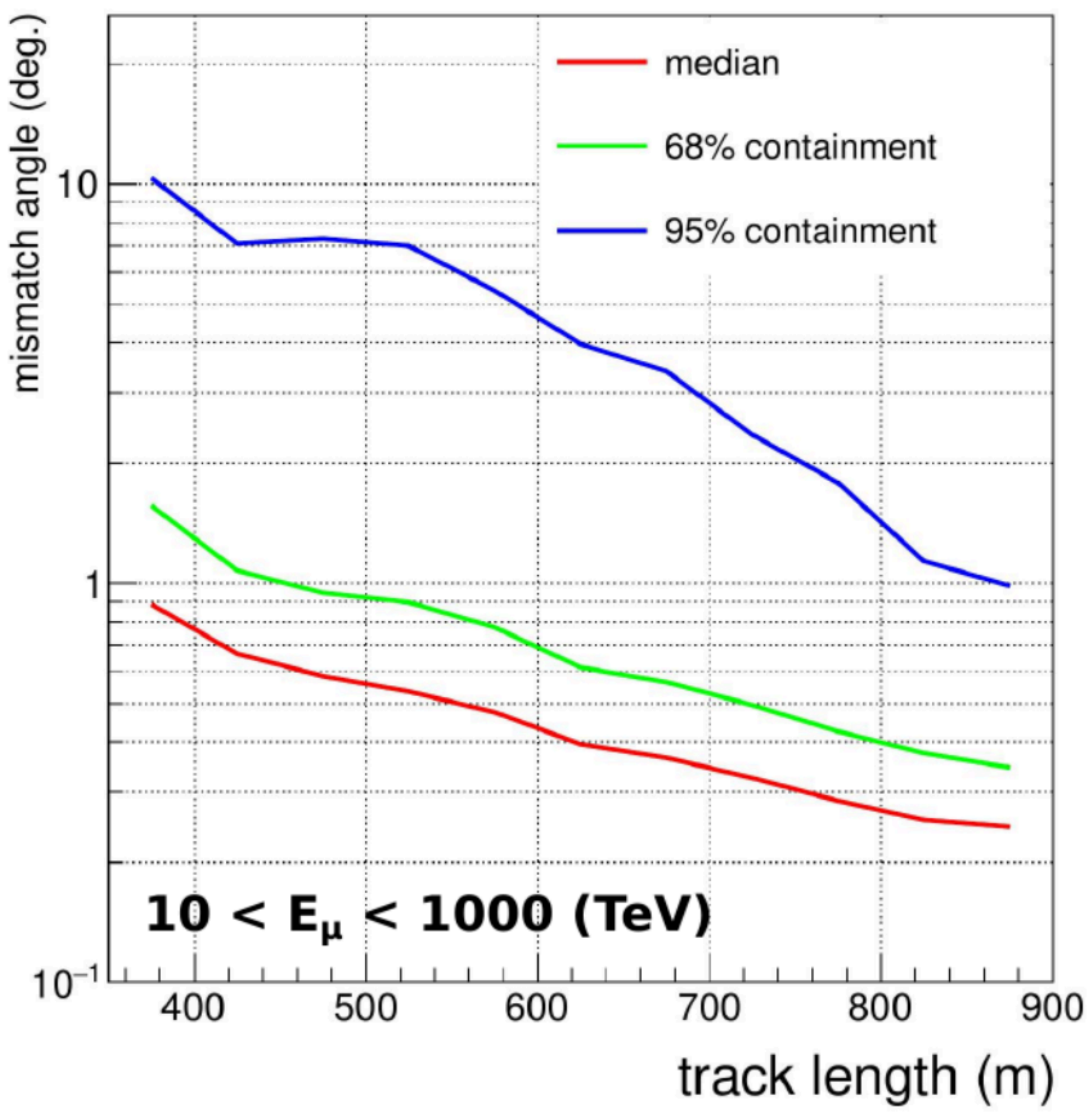


cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
$N_{strings}$ = 3
N_{hits} = 13

Multi-cluster track event



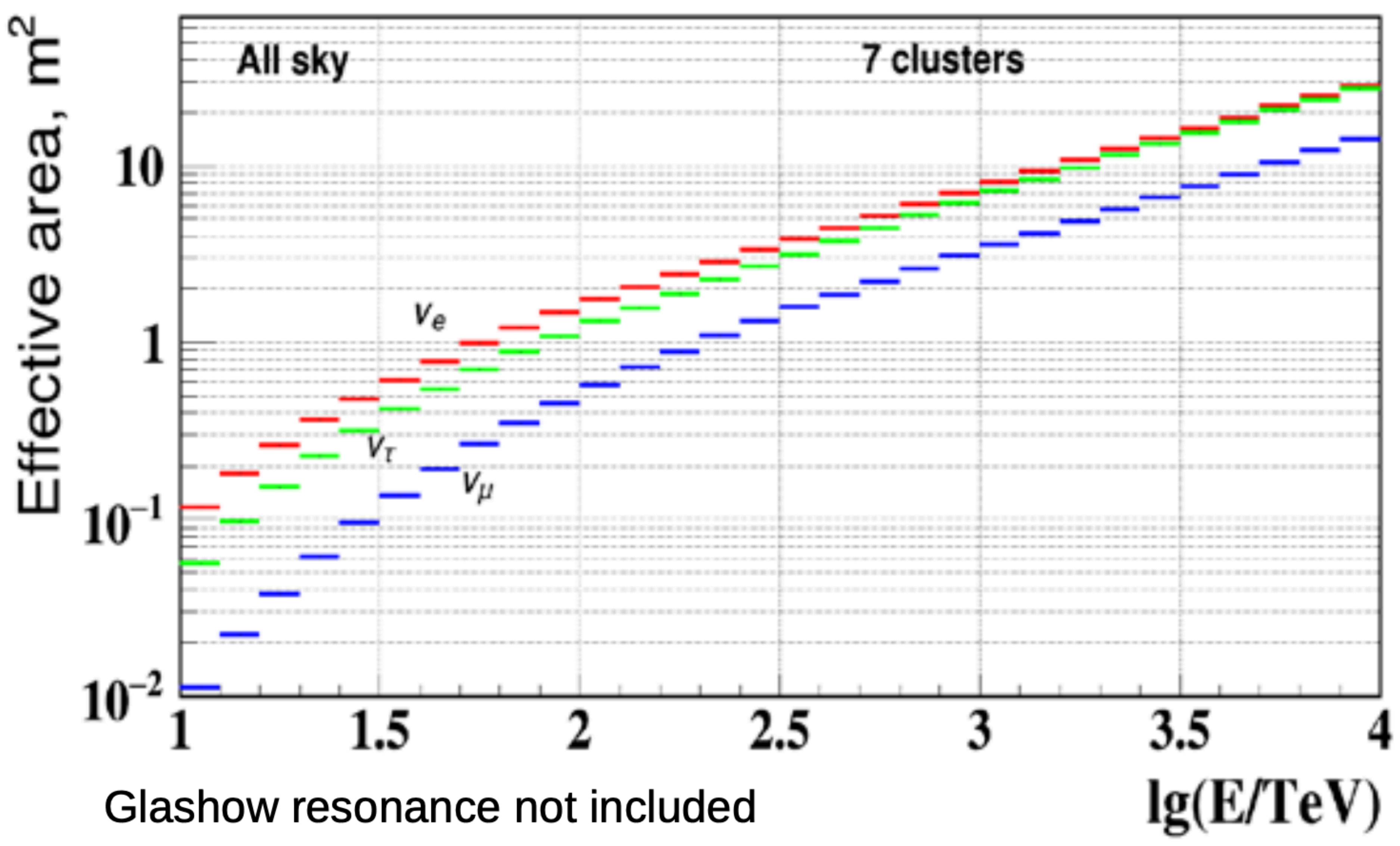
Real Multi-cluster event example



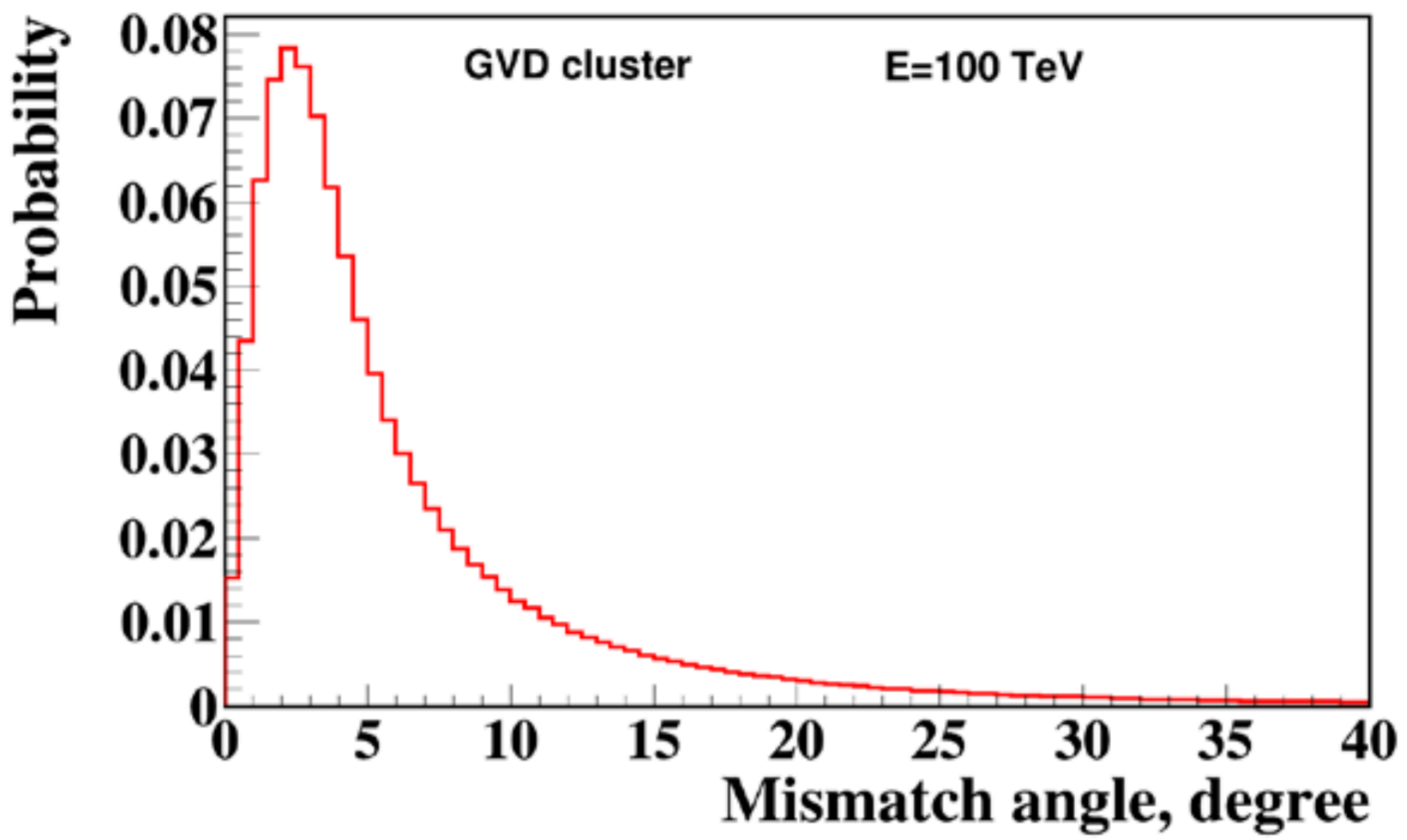
Median energy ~ 4 TeV
Work in progress

Cascade event analysis

neutrino effective area for cascade detection

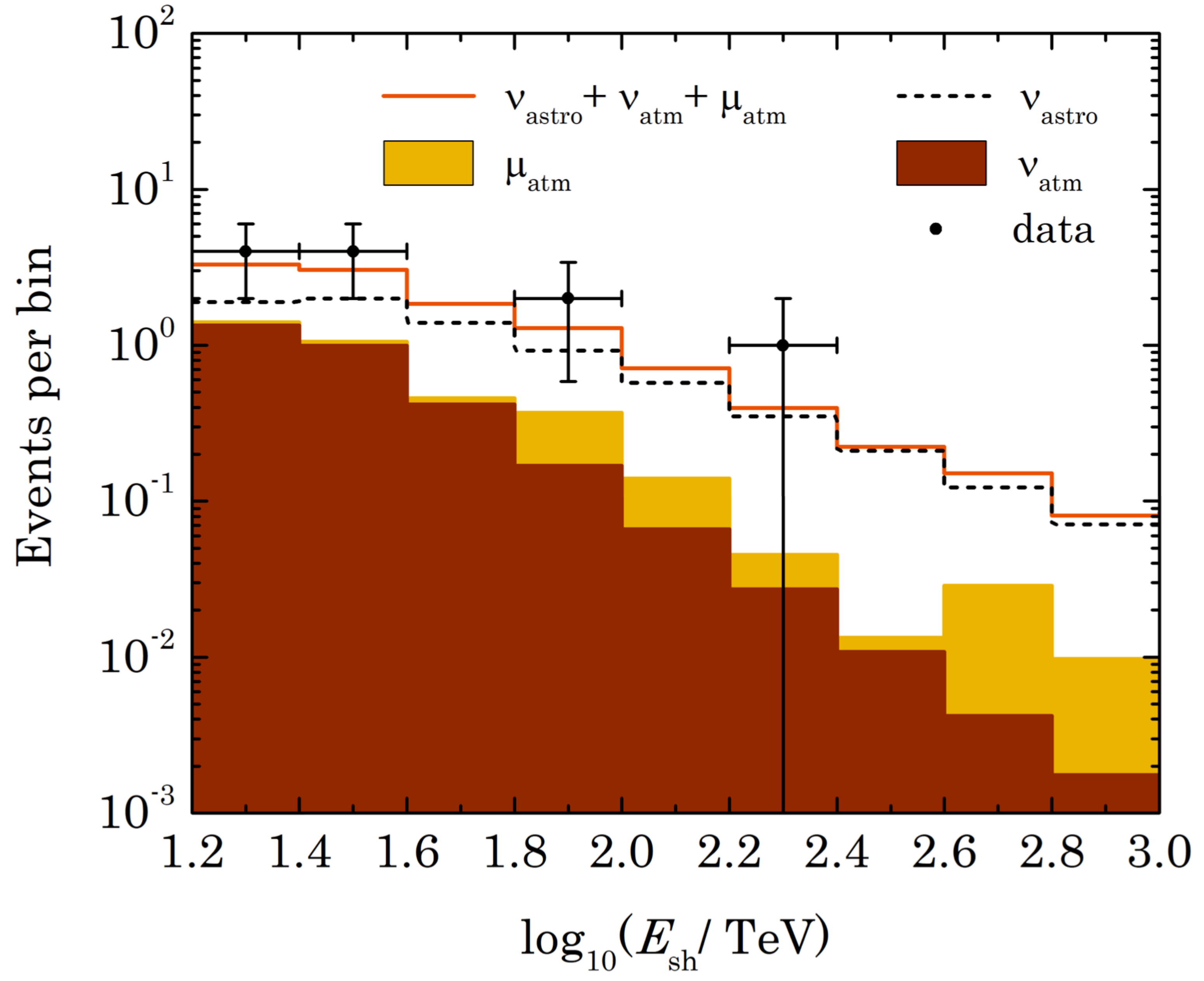


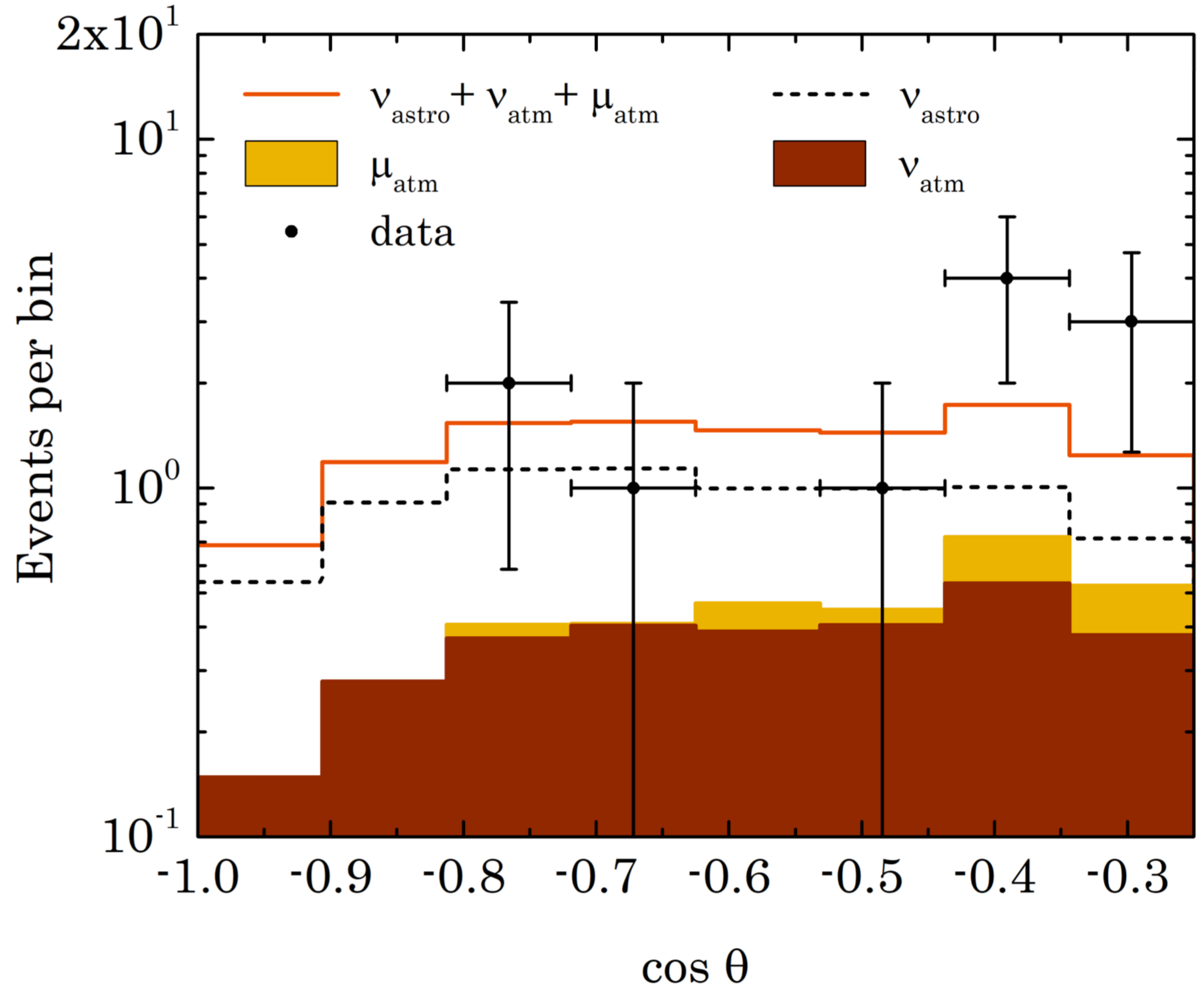
Glashow resonance not included



- Sensitive to all-flavour CC and NC interactions over the whole sky
- Effective volume for E > 100 TeV >0.5 km^3
- Directional resolution for cascades: ~ 4.5°
- Energy resolution: ~ 30%

Astrophysical Diffuse neutrino flux with Baikal-GVD





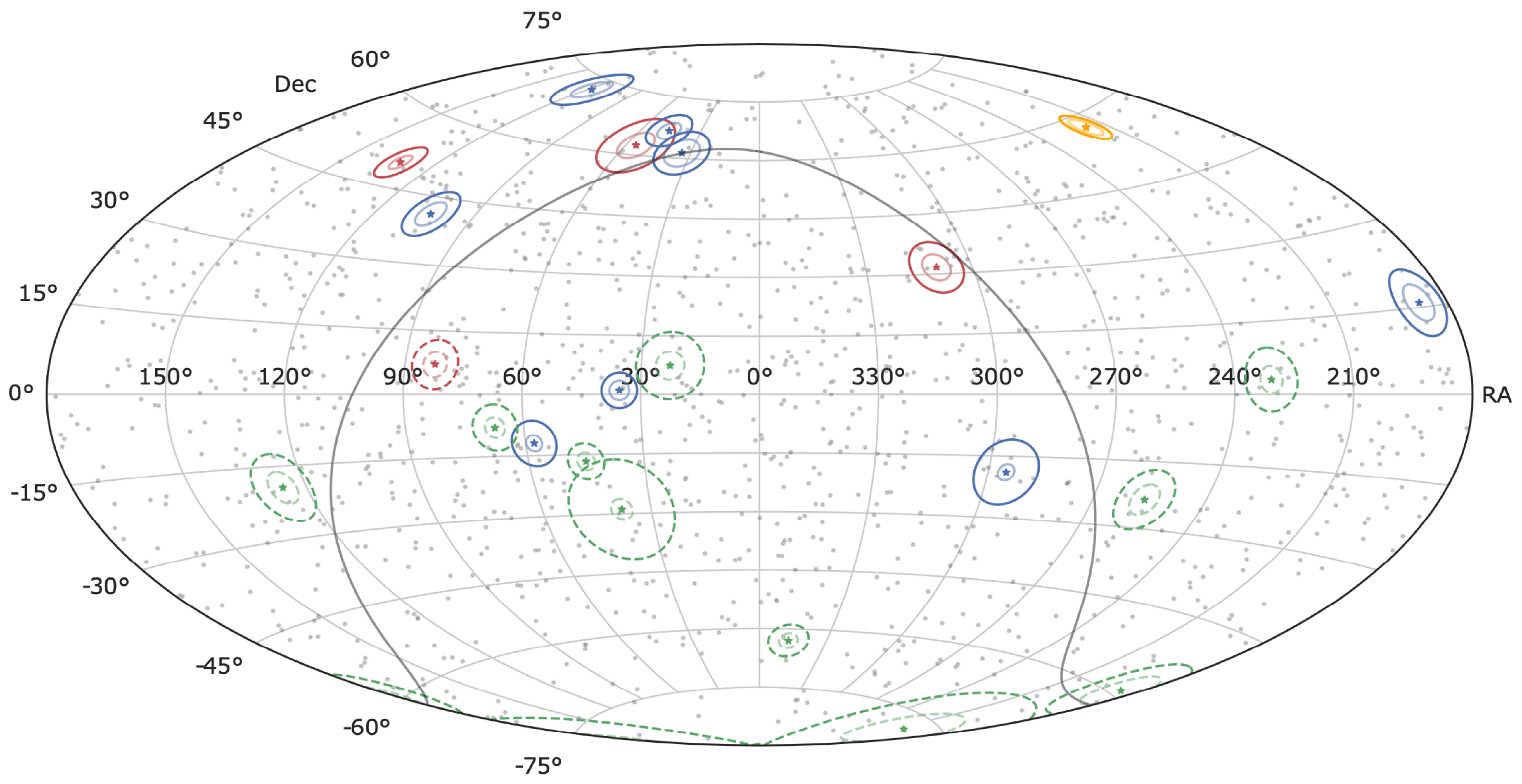
- Data analysed April 2018 - March 2022
- Cascade energy >15 TeV
- Upward going cascades

	Events
Atm. muons MC	0.5
Atm. neutrino MC	2.7
Astro neutrino MC best fit	6.3
Data	11

https://doi.org/10.1103/PhysRevD.107.042005

Excess over the atmospheric background: 3.05σ

High-energy cascade sky map and flux

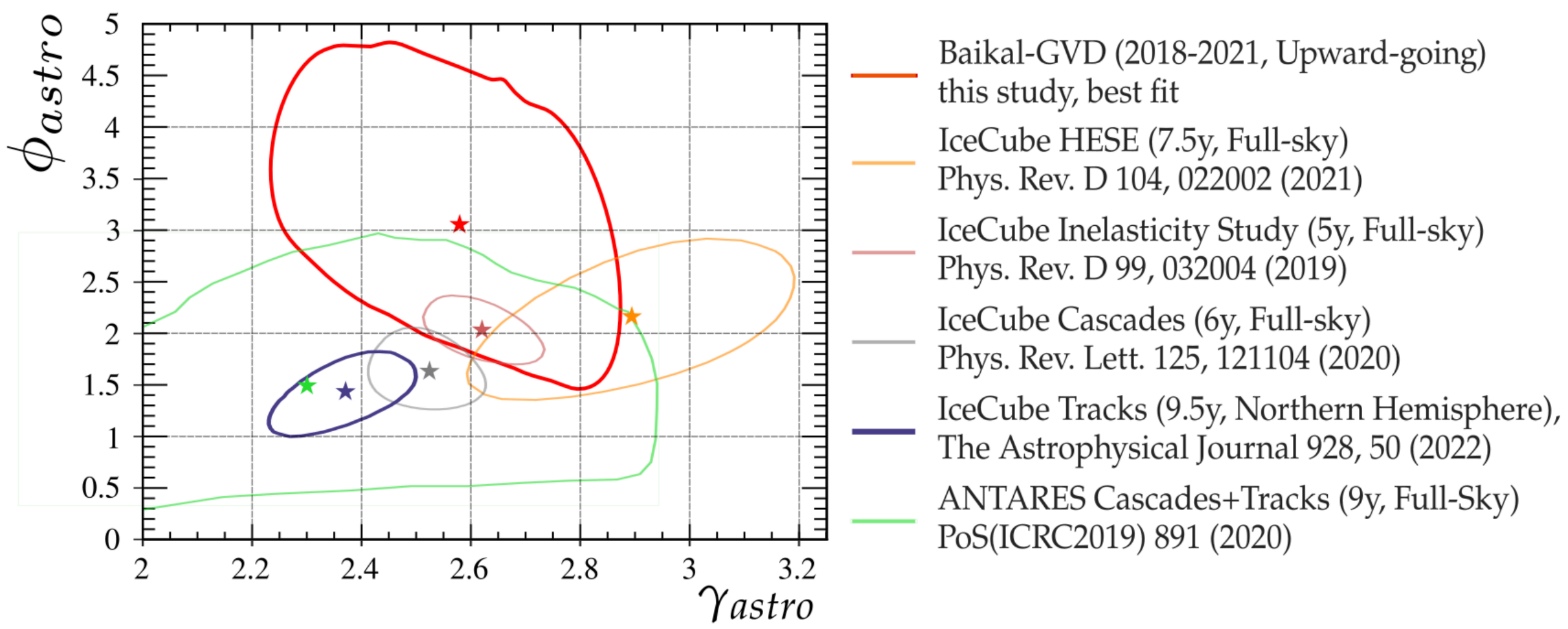


Most prominent downgoing and upgoing cascade events

https://doi.org/10.1093/mnras/stad2641

- The best fit parameters for the single power law hypothesis:

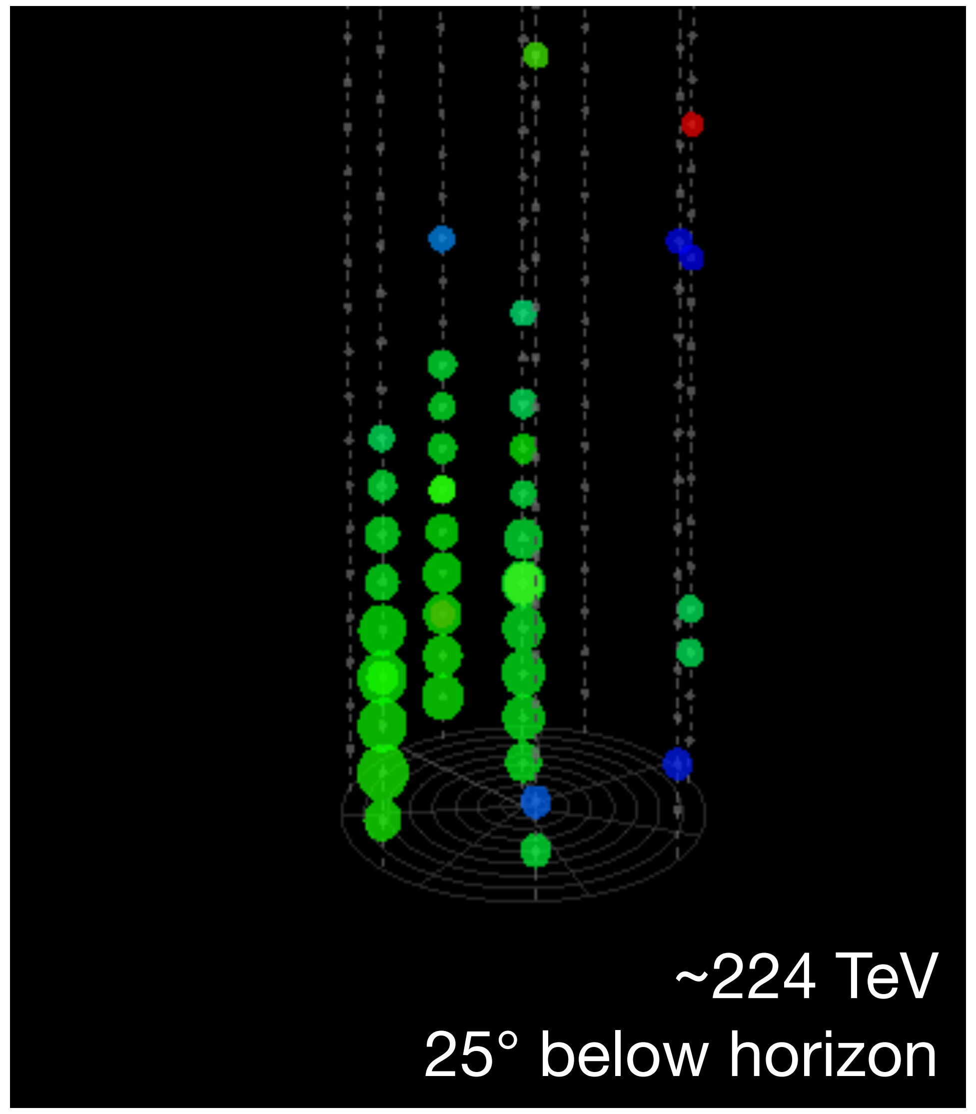
$$\Phi^{\nu+\bar{\nu}}_{astro} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0} \right)^{-\gamma_{astro}}$$

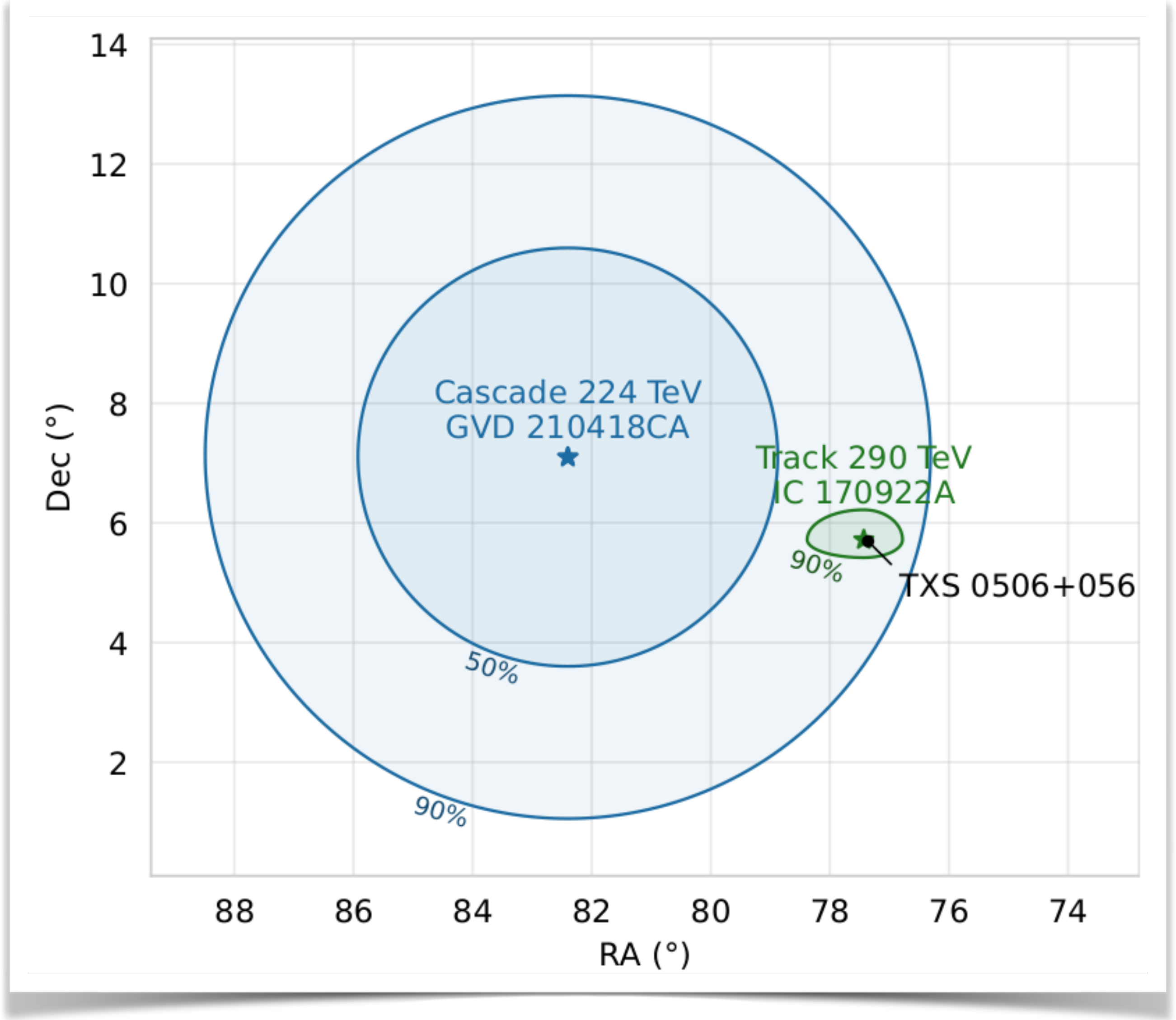


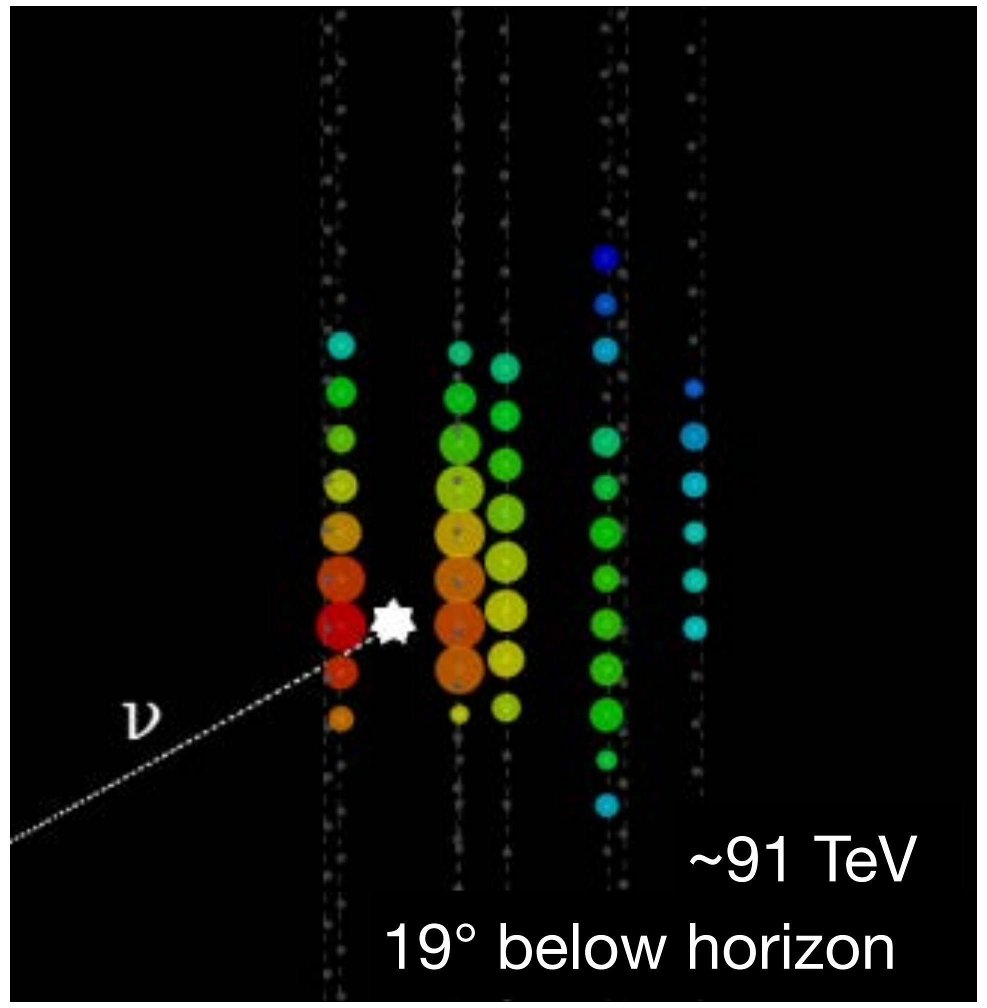
https://doi.org/10.1103/PhysRevD.107.042005

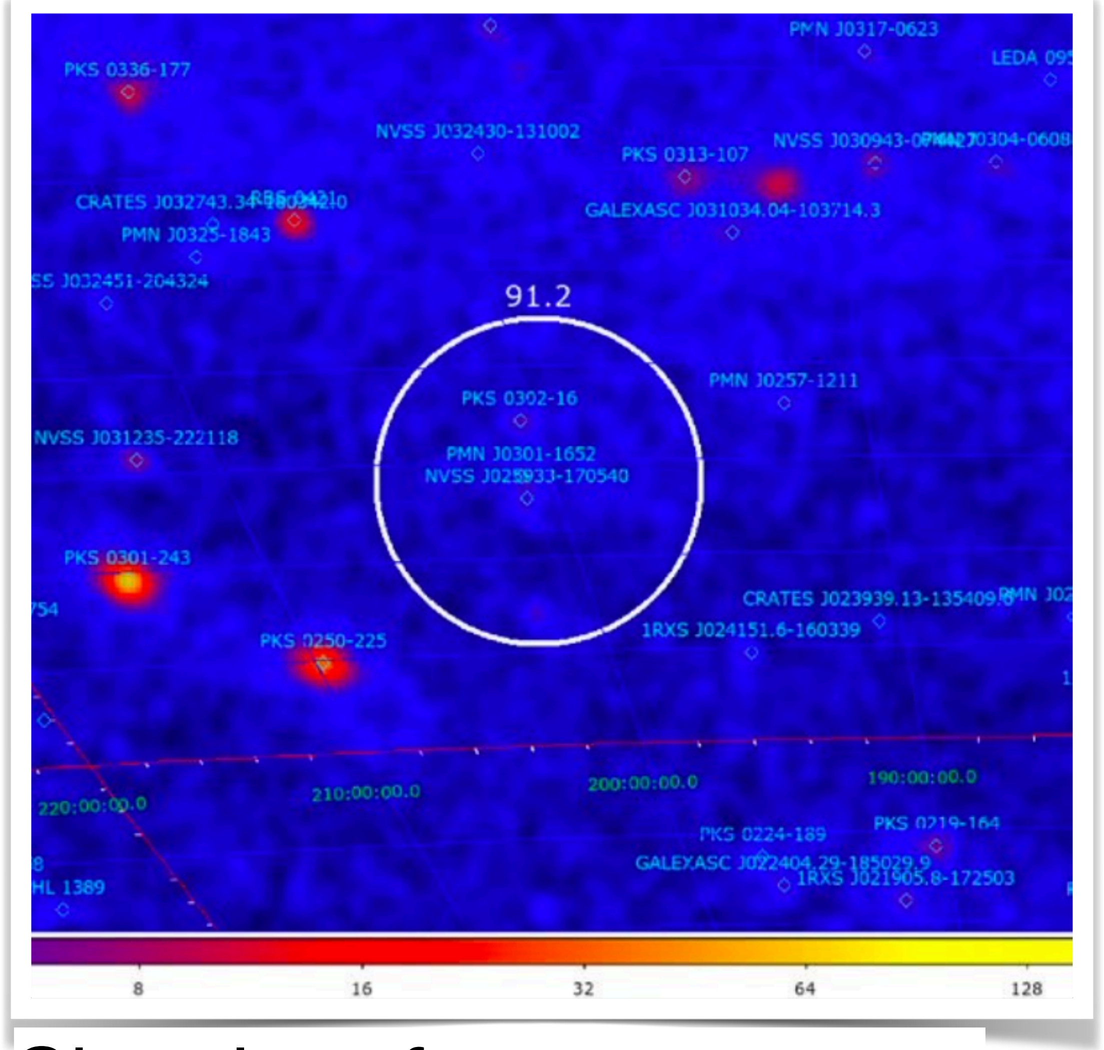
Most energetic upgoing cascade events

Best candidates for neutrino events of astrophysical origin









Sky plot of γ-ray sources and event uncertainty circle

Closest sources (in 6 degrees):

- TXS 0506+056 Blazar (BL Lac) at z= 0.34 (5.7 Gly) is IceCube neutrino source observed at 3.7σ
- This event is probably of astrophysical origin (signalness = 97%).

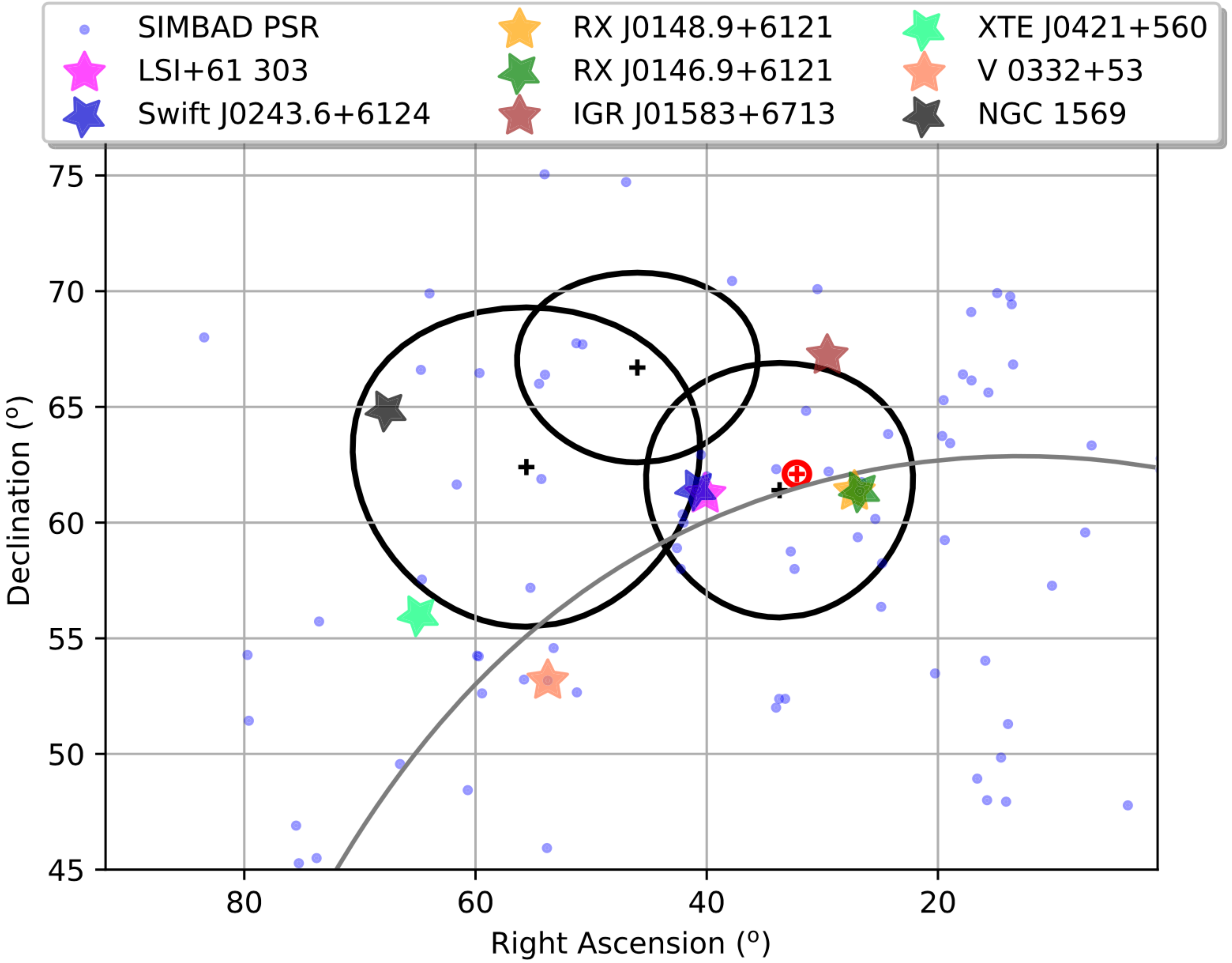
Closest sources (in 3 degrees):

- PKS 0302-16 : unknown type of source
- PMN J0301-1652 : unknown type of source

arXiv:2210.01650

Event triplet near Galactic plane

Intriguing events



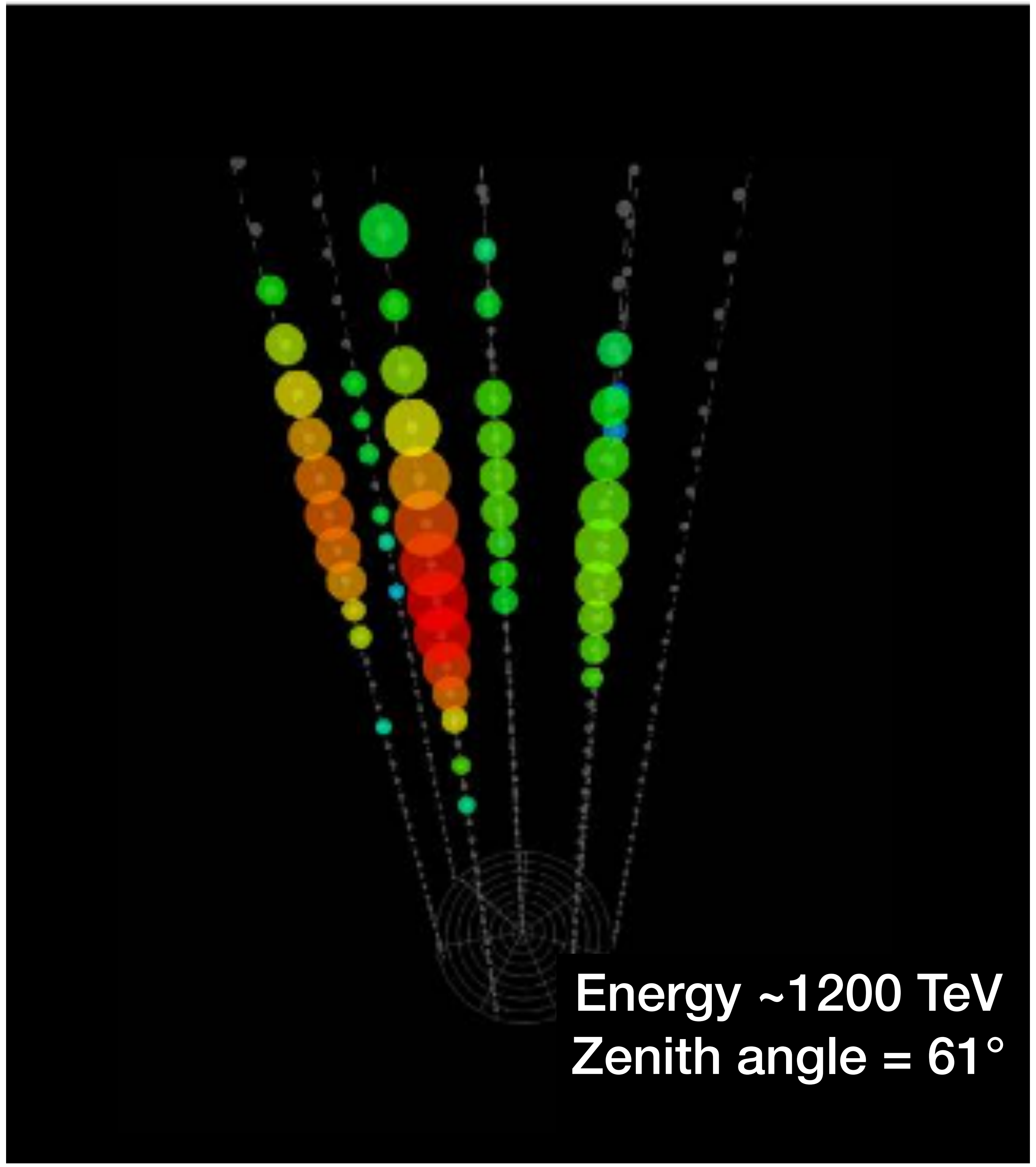
https://doi.org/10.1093/mnras/stad2641

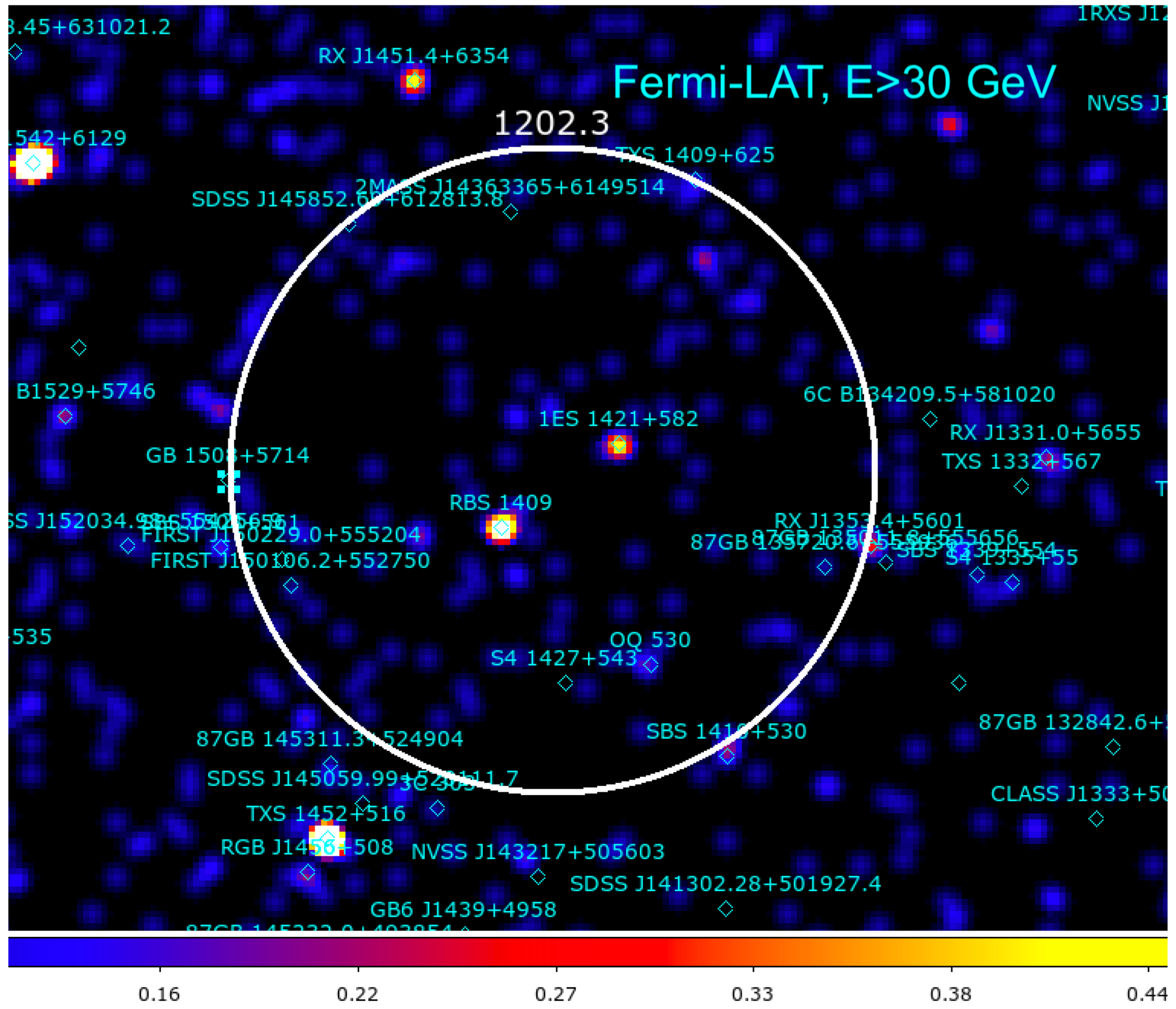
Chance probability to observe such a triplet was estimated as 0.024 (2.3 σ)

- γ-ray microquasar LS I +61 303 (very well known high energy Galactic source) and the two Baikal-GVD events with 3.1° and 7.4° from the source (both are downgoing events)
- Highest significance IceCube persistent Northern hot spot (red plus and circle)

PeV downgoing cascade

Most energetic cascade so far





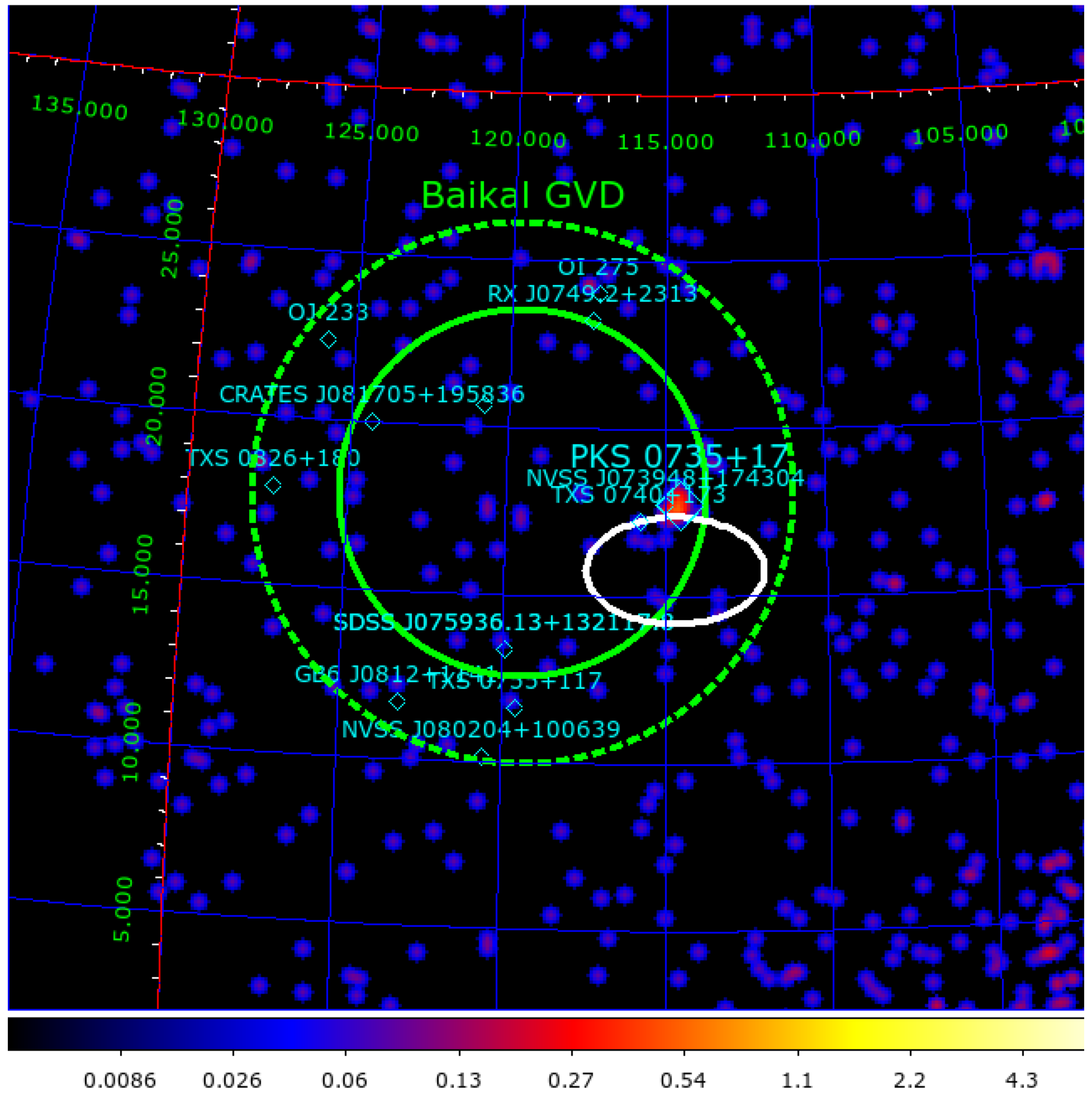
Sky plot of γ-ray sources and event uncertainty circle

Closest sources (in 5 degrees):

- RBS 1409 BL Lac z=unknown
- 1ES 1421+582 z=unknown

Baikal-GVD follow up of IceCube-211208A / PKS 0735+17

- Dec 8, 2021 20:02: IceCube "Astrotrack Bronze" neutrino event in vicinity of bright blazar PKS 0735+17
- Active state of PKS 0735+17 reported in optical (MASTER), HE gamma-rays (Fermi LAT), X-rays (Swift XRT) and radio
- Baikal-GVD found a downward-going (30° above horizon) cascade-like event 4 hours after the IceCube alert and in 5.3° from it and 4.7° from PKS 0735+17
  - E ≈ 43 TeV
  - PSF 50% (68%) containment radius = 5.5 deg (8.1 deg)
  - Pre-trial p-value = 0.0044 (2.85 σ) [24 hr, 5.5 deg cone]
  - Trial factor ~ 40 (total number of IceCube alerts analyzed)



Astronomy telegram ATeL 15112

Conclusion

- Baikal-GVD is the second largest neutrino telescope and the first in the Northern hemisphere
- Baikal-GVD has already >0.5 km^3 water volume and grows every year
- Cascade analysis shows astrophysical neutrino flux (3.05 σ) and some intriguing events
- Muon track analysis is under way. Stay tuned


Thank you for your attention!

Baikal-GVD collaboration

- Joint Institute for Nuclear Research, Russia
- Institute for Nuclear Research of the Russian Academy of Sciences, Russia
- Comenius University, Slovakia
- Czech Technical University in Prague, Czech Republic
- Irkutsk State University, Russia
- Skobeltsyn Research Institute of Nuclear Physics, Russia
- Institute of Nuclear Physics ME RK, Kazakhstan
- AO ‘LATENA’ (Joint Stock Company), Russia
- St. Petersburg State Marine Technical University, Russia