Baikal-GVD: Deep-Underwater Neutrino Telescope: Status and Results

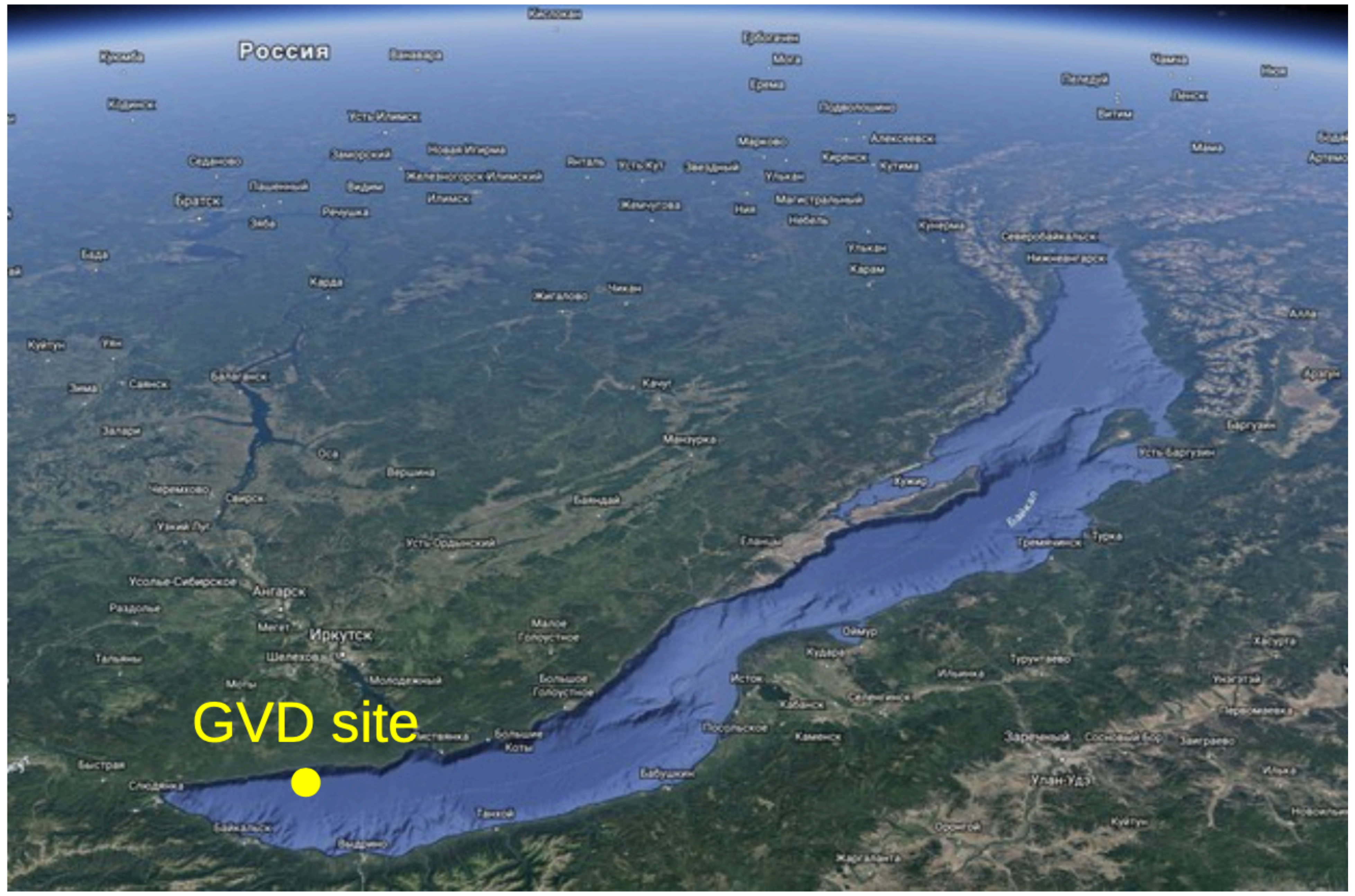
60th meeting of the PAC for Nuclear Physics

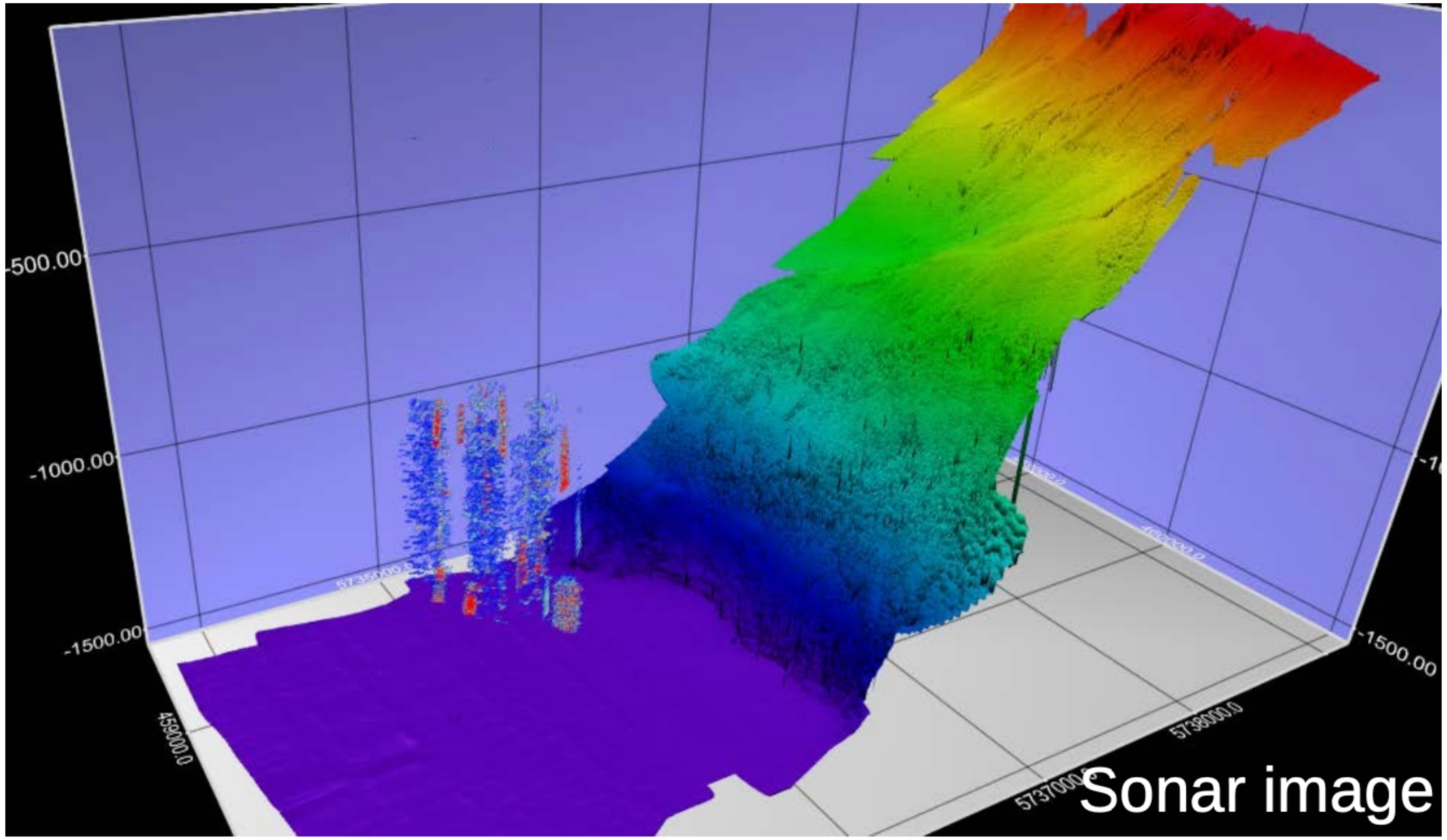
Bair Shaibonov on behalf of the Baikal-GVD collaboration, Dubna, 23.01.2025

Outline

- Baikal-GVD Telescope Description and Status
- Nearest Plans
- Recent Results:
  - Characterisation of diffuse astrophysical flux of high-energy neutrino
  - Search for astrophysical neutrino point sources
  - Search for extended neutrino source: Galactic plane
  - Follow-up activities

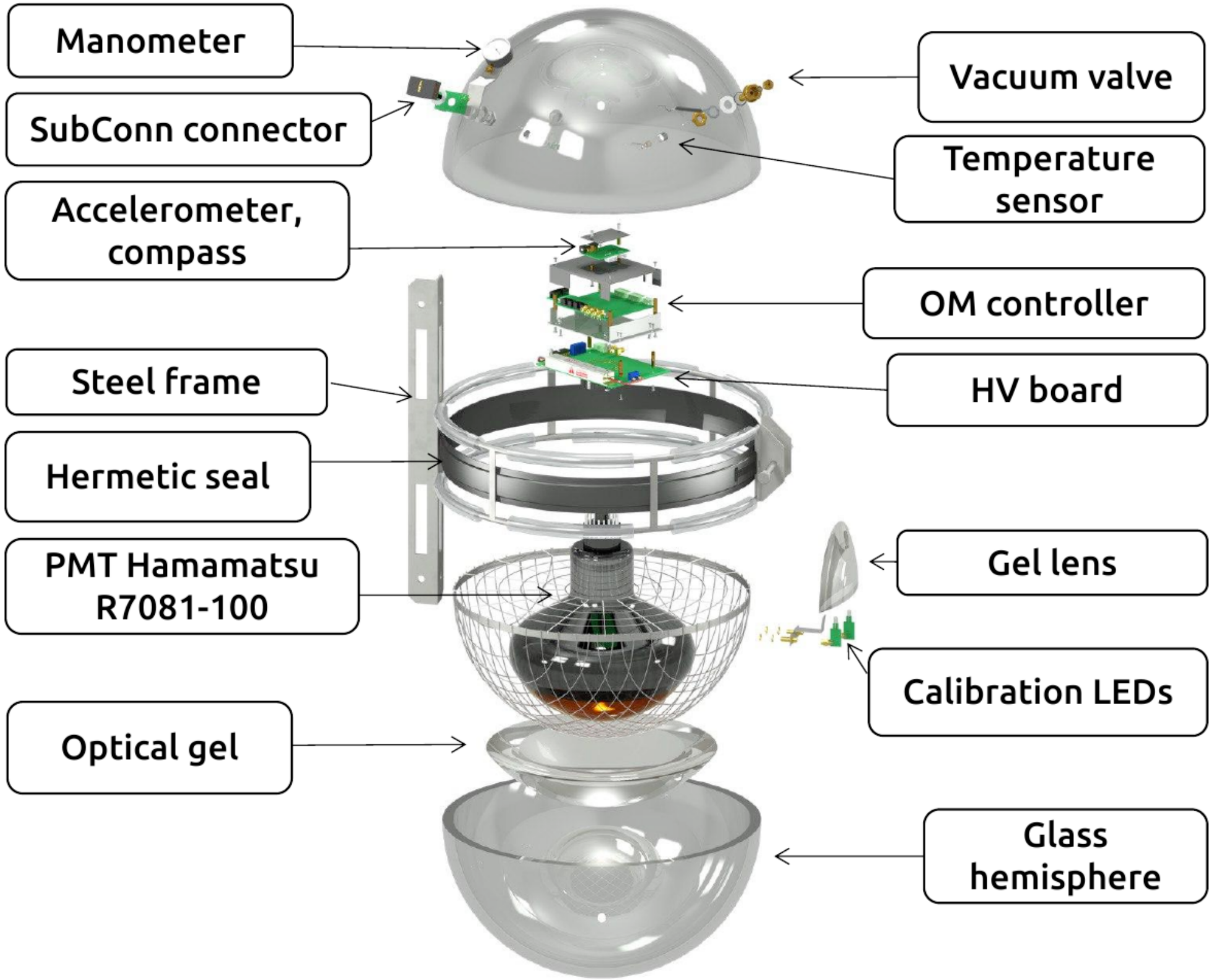
Baikal-GVD Site





- 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

Optical Module - Basic Element of the Telescope



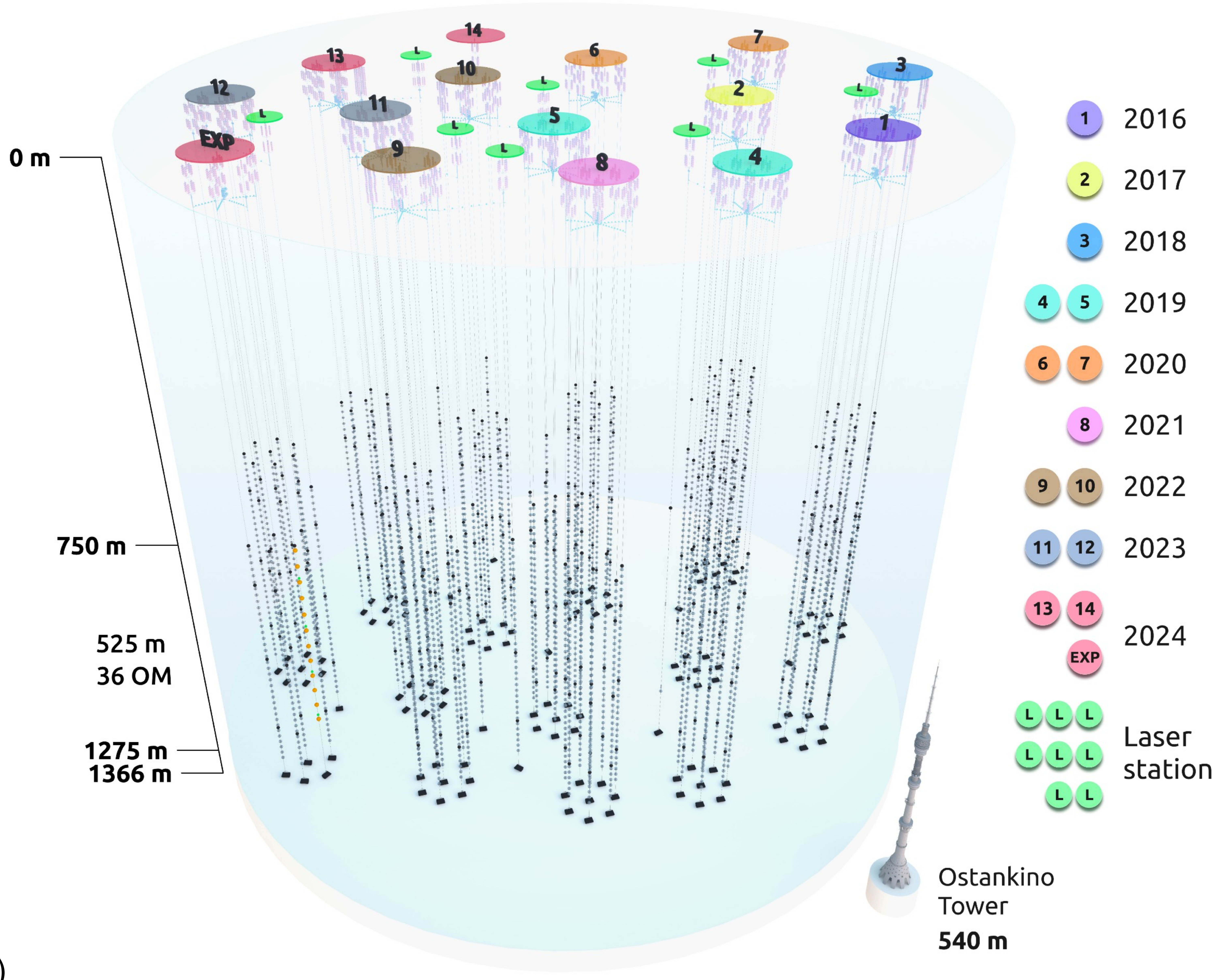
17 inches sphere (42 cm)

10 inch Hamamatsu PMT R7081-100

Baikal-GVD Status

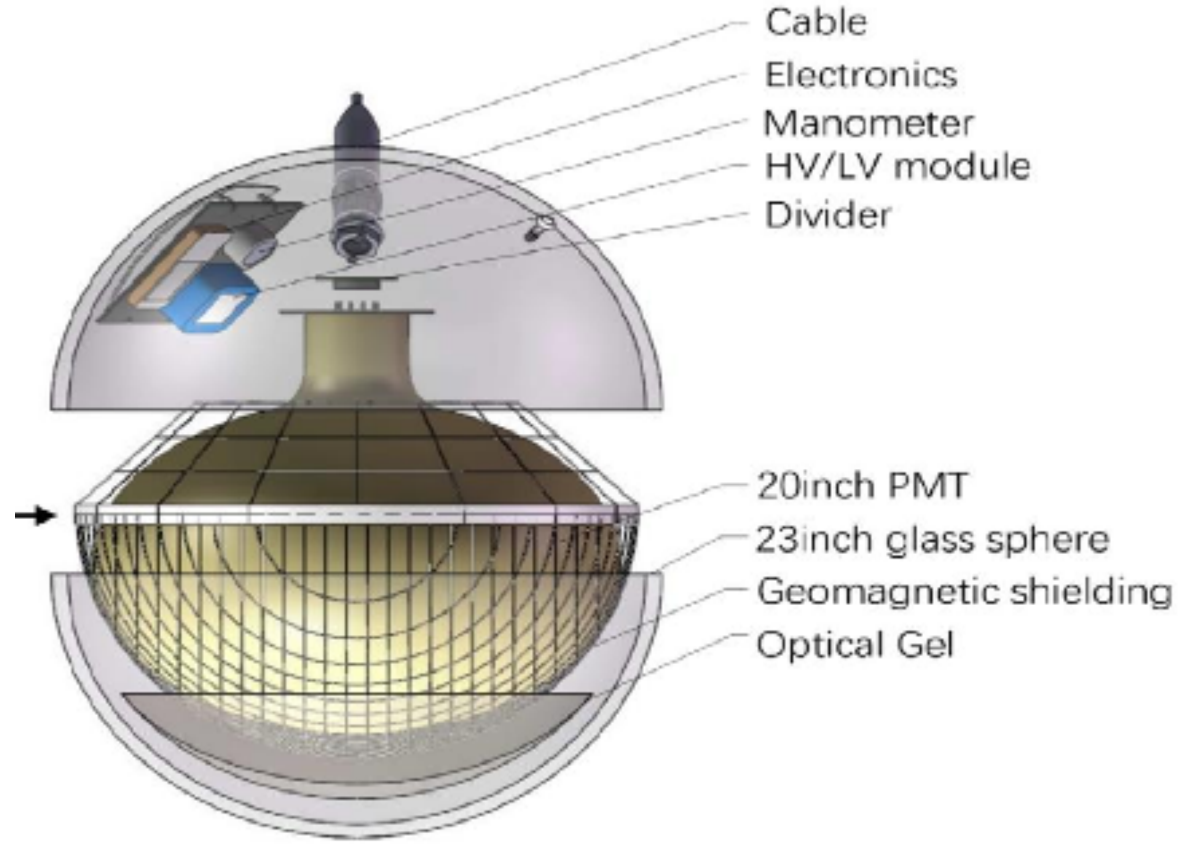
April 2024

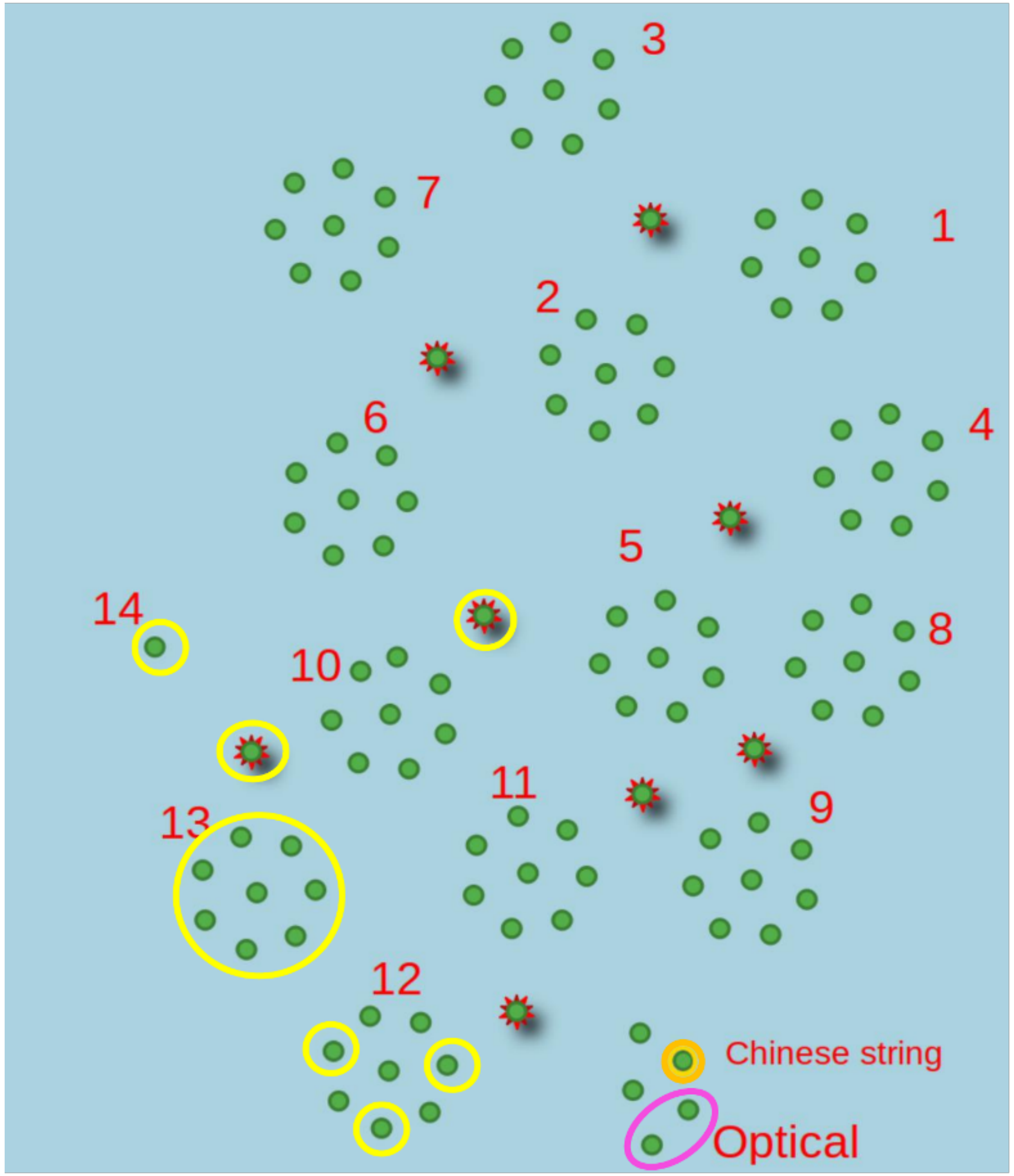
- 4104 Optical modules on 114 strings (13 clusters)
- 8 strings form a cluster - independent array of optical modules
- 36 optical modules per string
- 60 m between strings in a cluster, 250-300 m between clusters
- More than 0.6 km^3 of water volume
- 8 laser stations/inter-cluster strings
- More than 400 acoustic modules for positioning
- LED beacons and powerful laser sources for calibration
- 4 experimental strings for testing of new equipment
- Prototype string for HUNT project (12 new OMs)



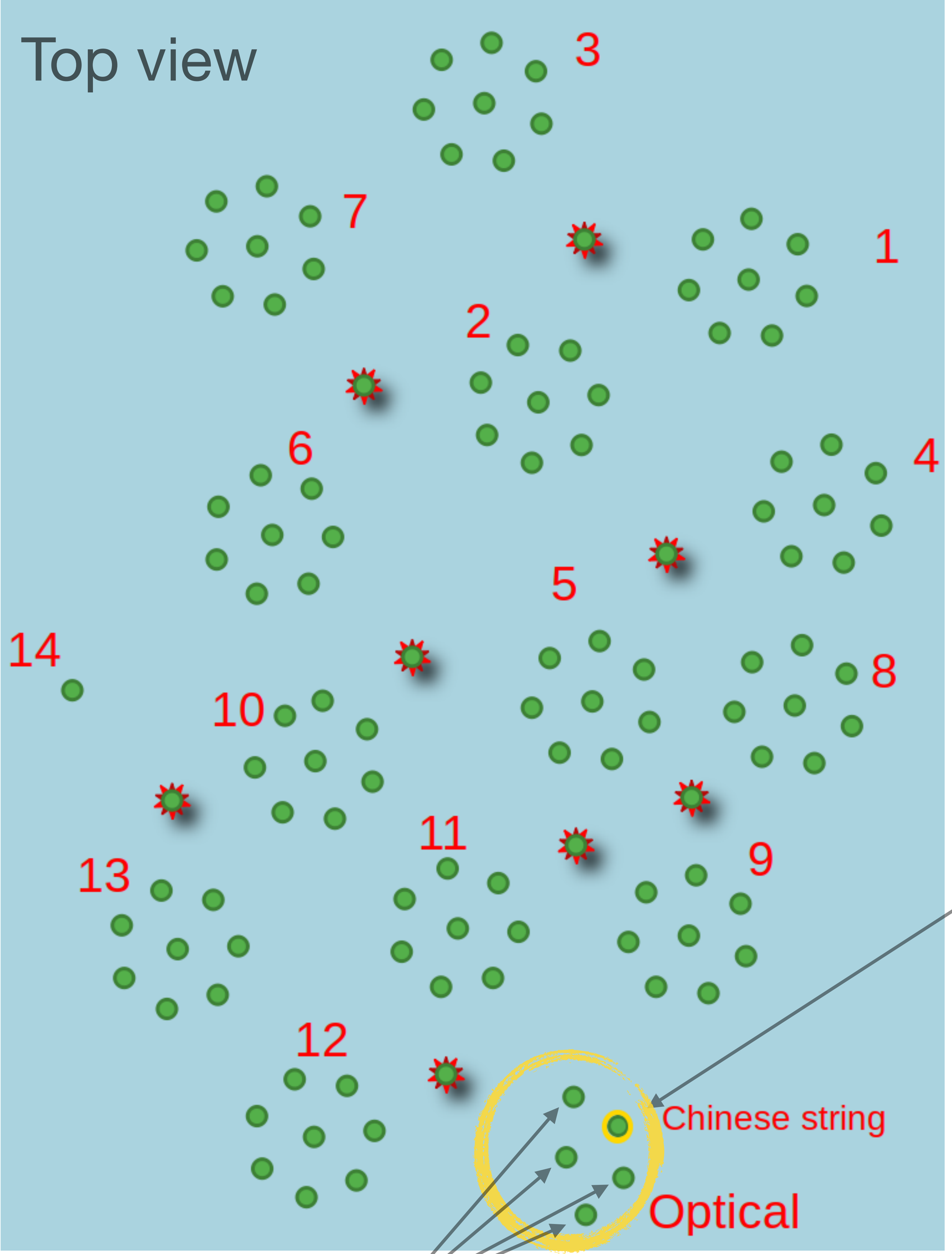
Expedition 2024

- Successful deployment campaign from 16.02 to 07.04
- 14 regular strings carrying 36 OMs each installed
- 2 strings added to experimental fiber-optical cluster
- Prototype string for HUNT project with 12 new OMs





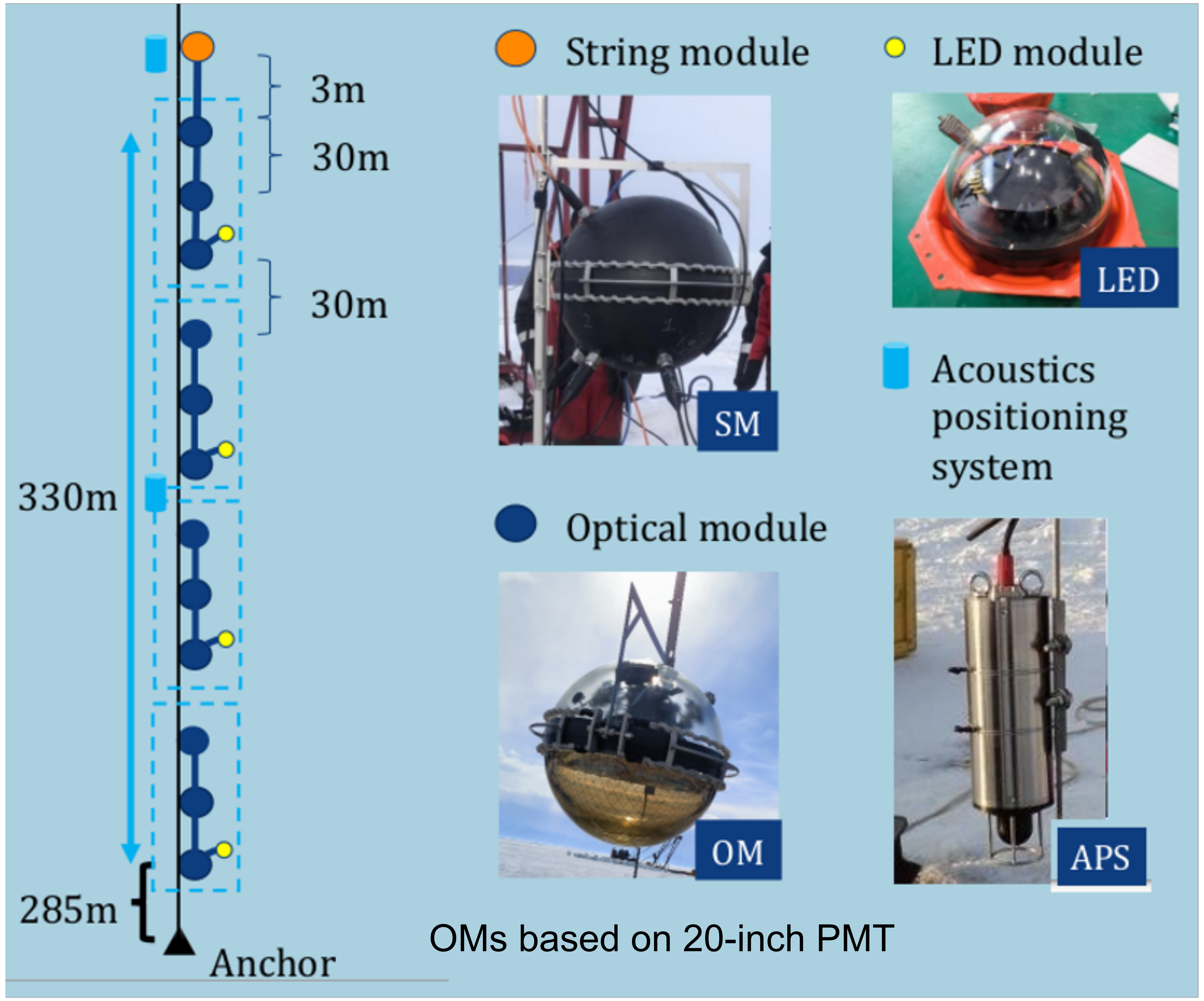
Technological prototype strings (2024)



Four “experimental” strings with new fiber-optic technology for data transmission

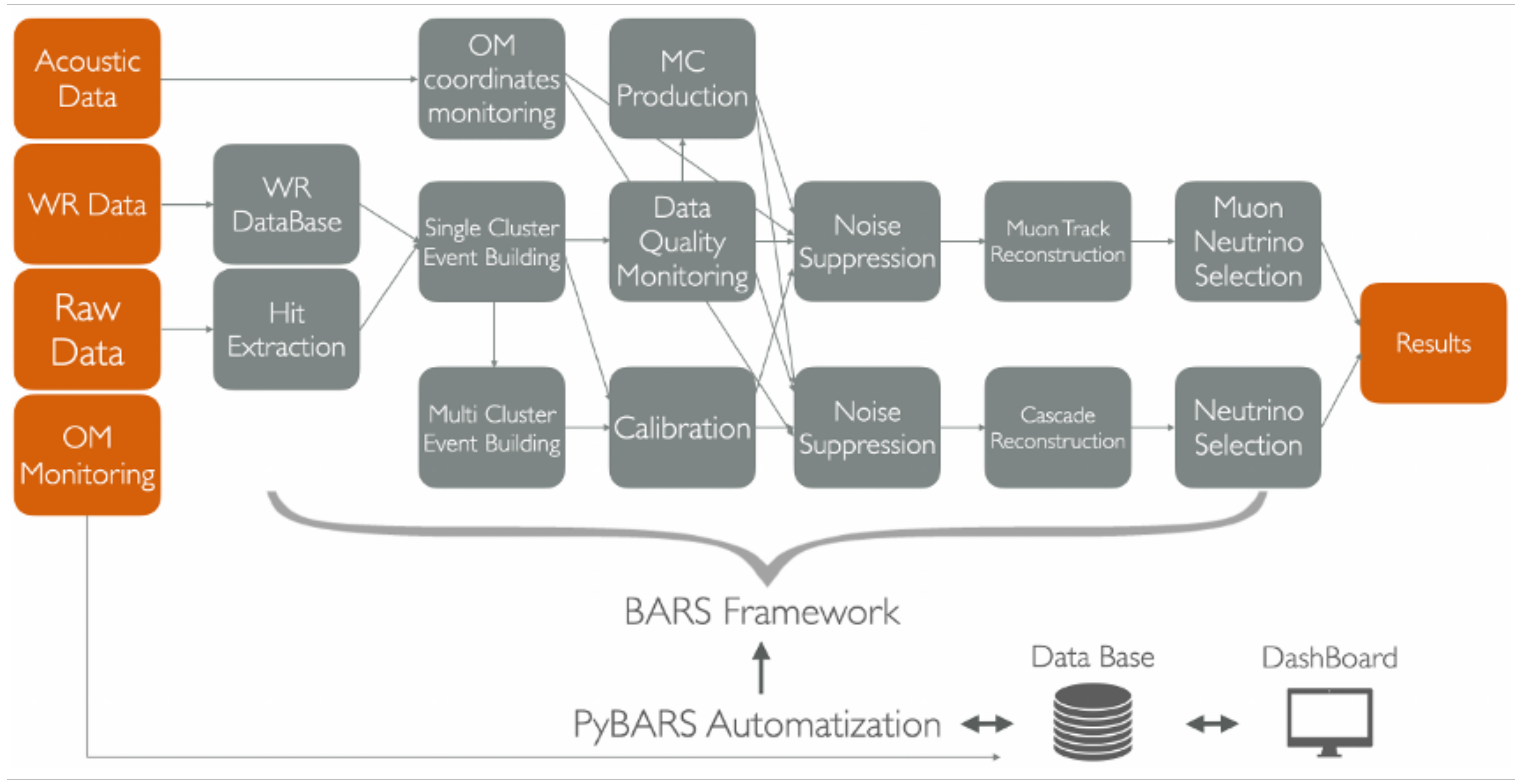
HUNT prototype string deployed in 2024

(IHEP (Beijing) & Baikal-GVD joint effort)



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

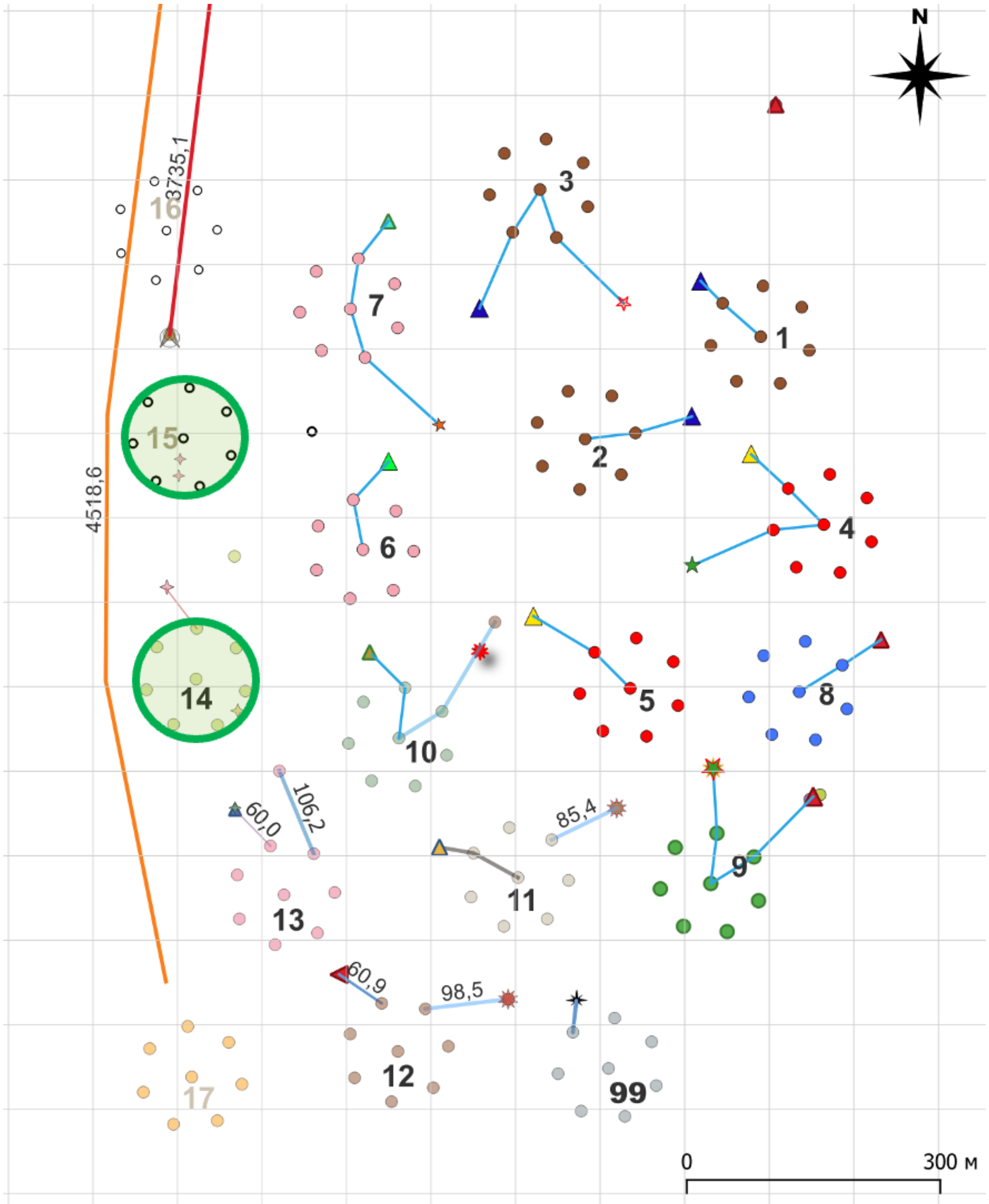
Data handling



Raw data are transferred from the Shore Center to JINR:

- Shore center ➙ Baikalsk: 300 Mbit/s radio-channel
- Baikalsk ➙ JINR: Internet
- Compressed data volume ~10-40 GB per day per cluster
- Full-scale reconstruction at JINR
- Delay due to shore - JINR data transfer < 1 min

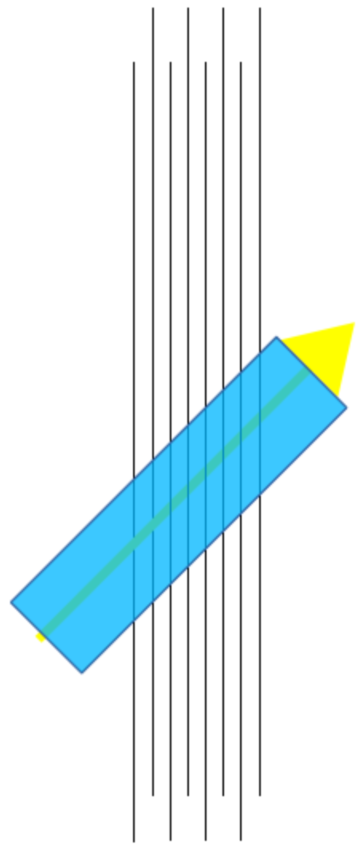
Next Expedition Plans (2025)



- Installation of new equipments:
  - Two new clusters: 14th and 15th
  - Two bottom cable lines
  - Full-scale HUNT string
  - Cluster Center for cluster 17
- Repairing some parts
- But: autumn and winter in Siberia was warmer, challenging ice conditions

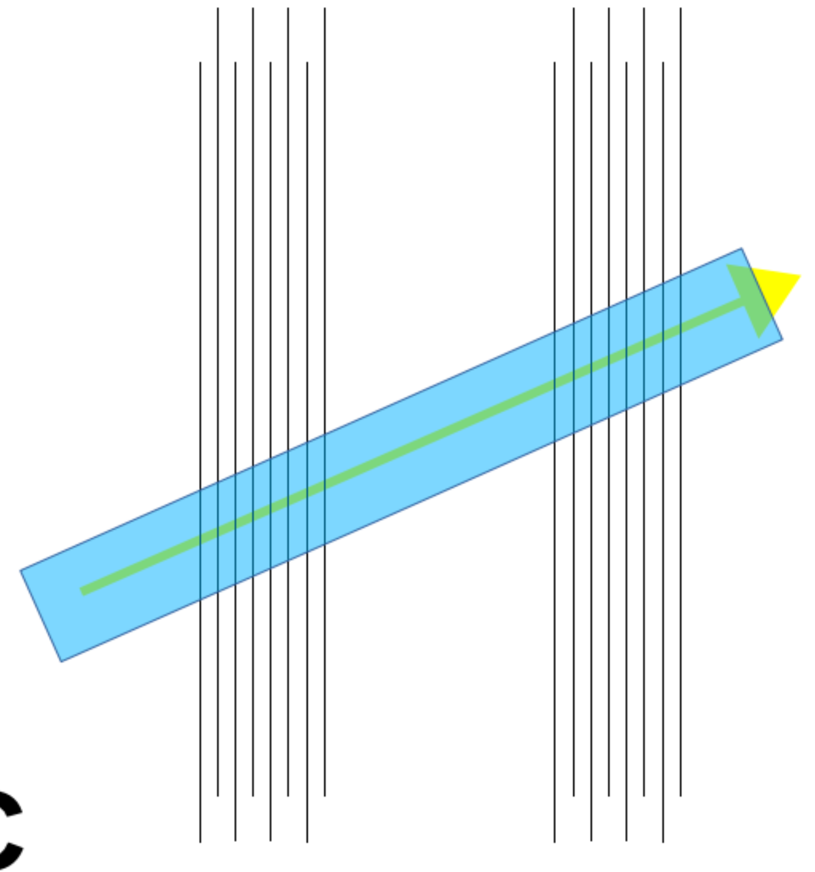
Event Types

Single-cluster tracks



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

Multi-cluster tracks

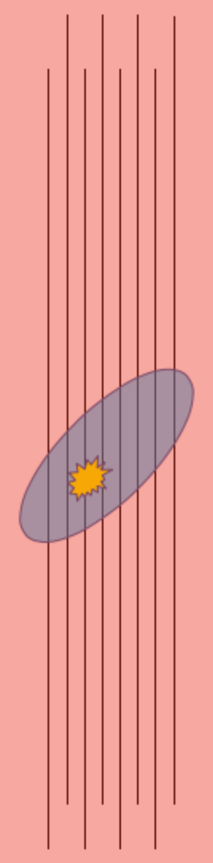


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

NC, ν_e ν_τ CC

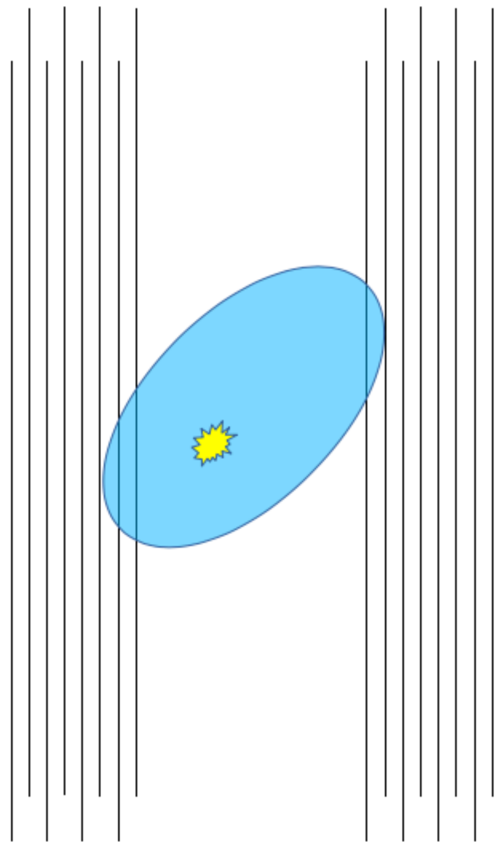
Single-cluster cascades



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

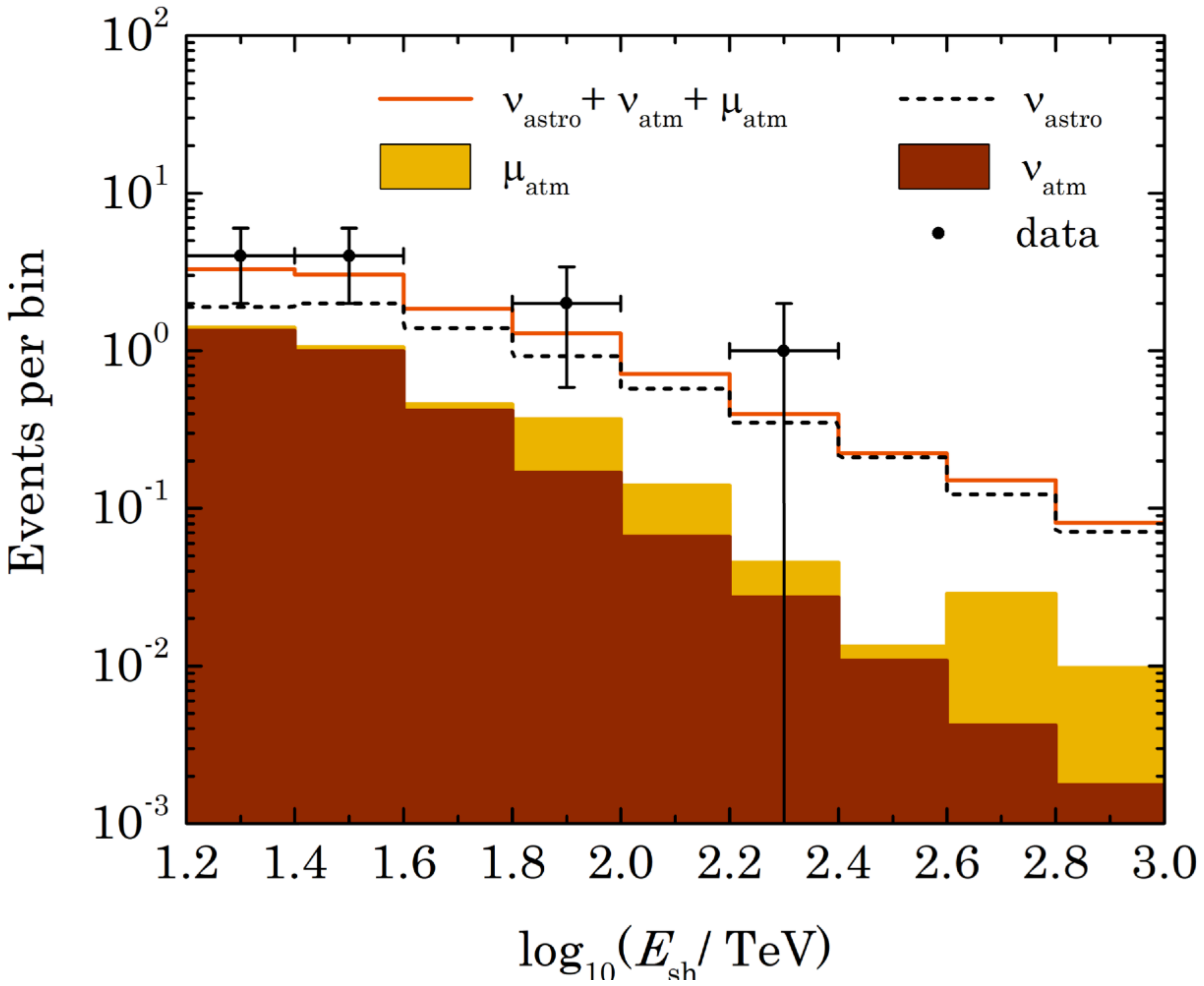
Main results for today

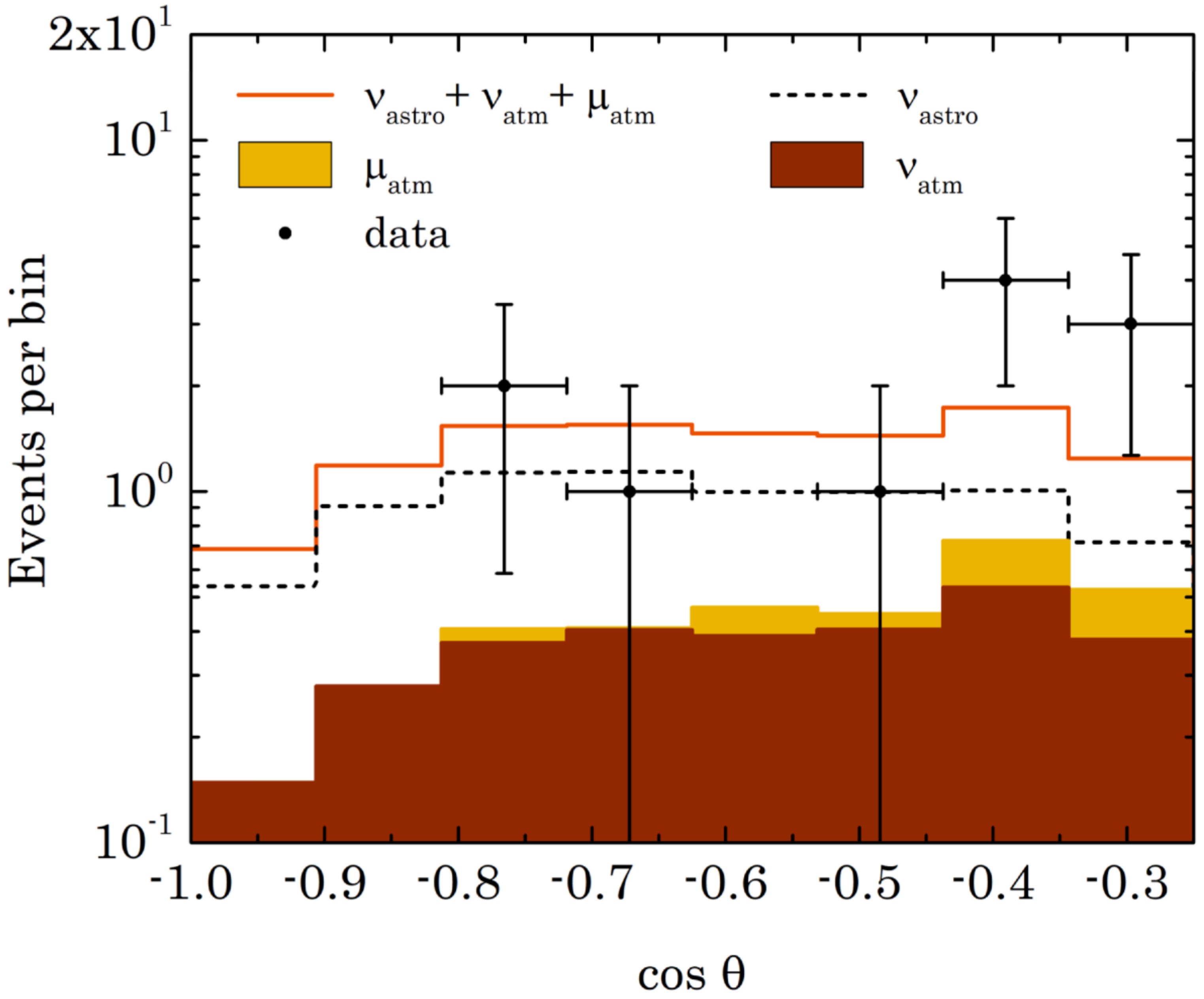
Multi-cluster cascades



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

Astrophysical Diffuse Neutrino Flux: Upward-Going Events





- Data analysed April 2018 - March 2022
- Less background from below:
  - Improving purity and lower energies
- Cascade energy >15 TeV

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

Excess over the atmospheric background: 3.05σ

Phys. Rev. D **107**, 042005, February 2023

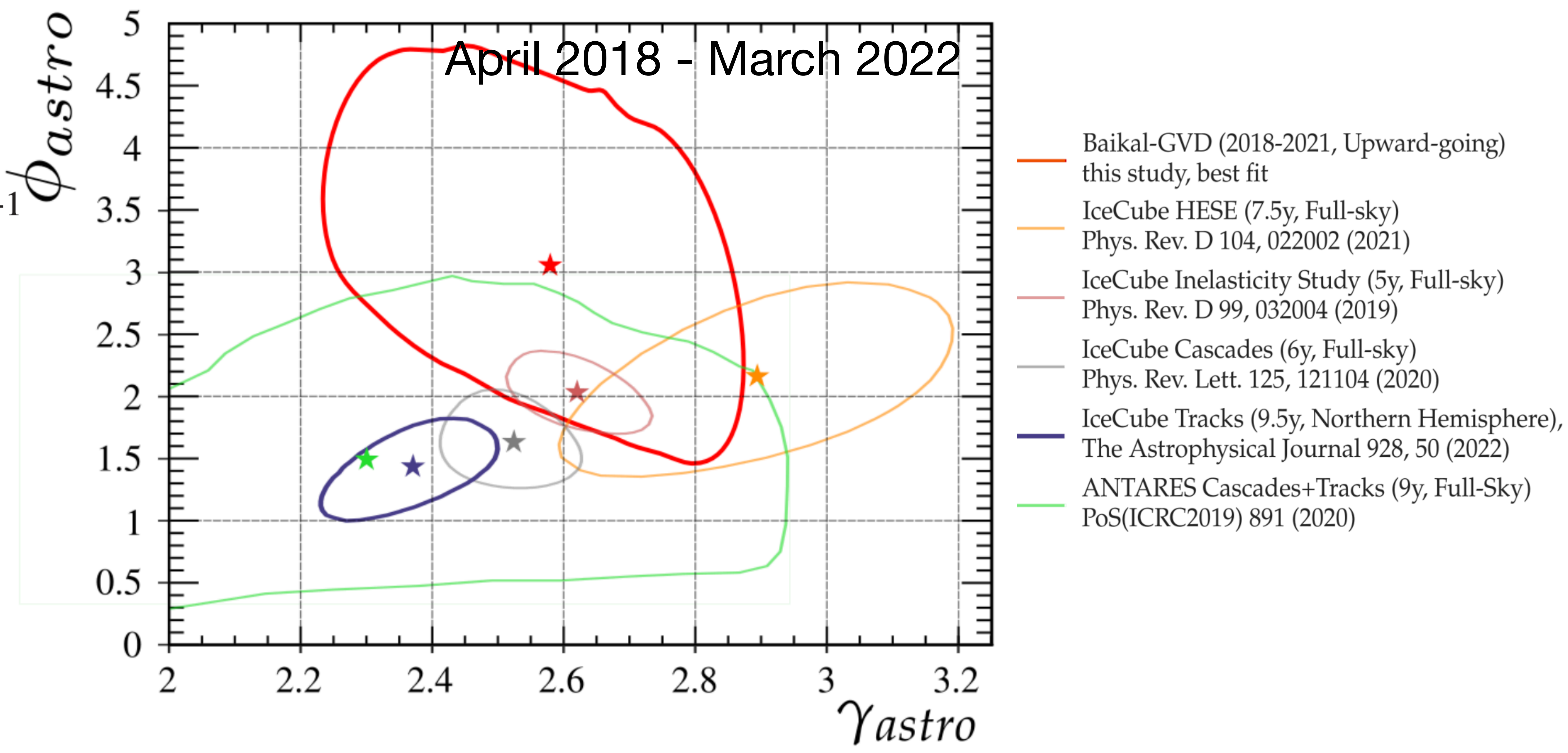
Single Power-Law Model of Astrophysical Flux

The best fit parameters for the single power law model:

$$\Phi^{\nu+\bar{\nu}}_{astro} = 3\times10^{-18}\phi_{astro}\left(\frac{E_\nu}{E_0}\right)^{-\gamma_{astro}} \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

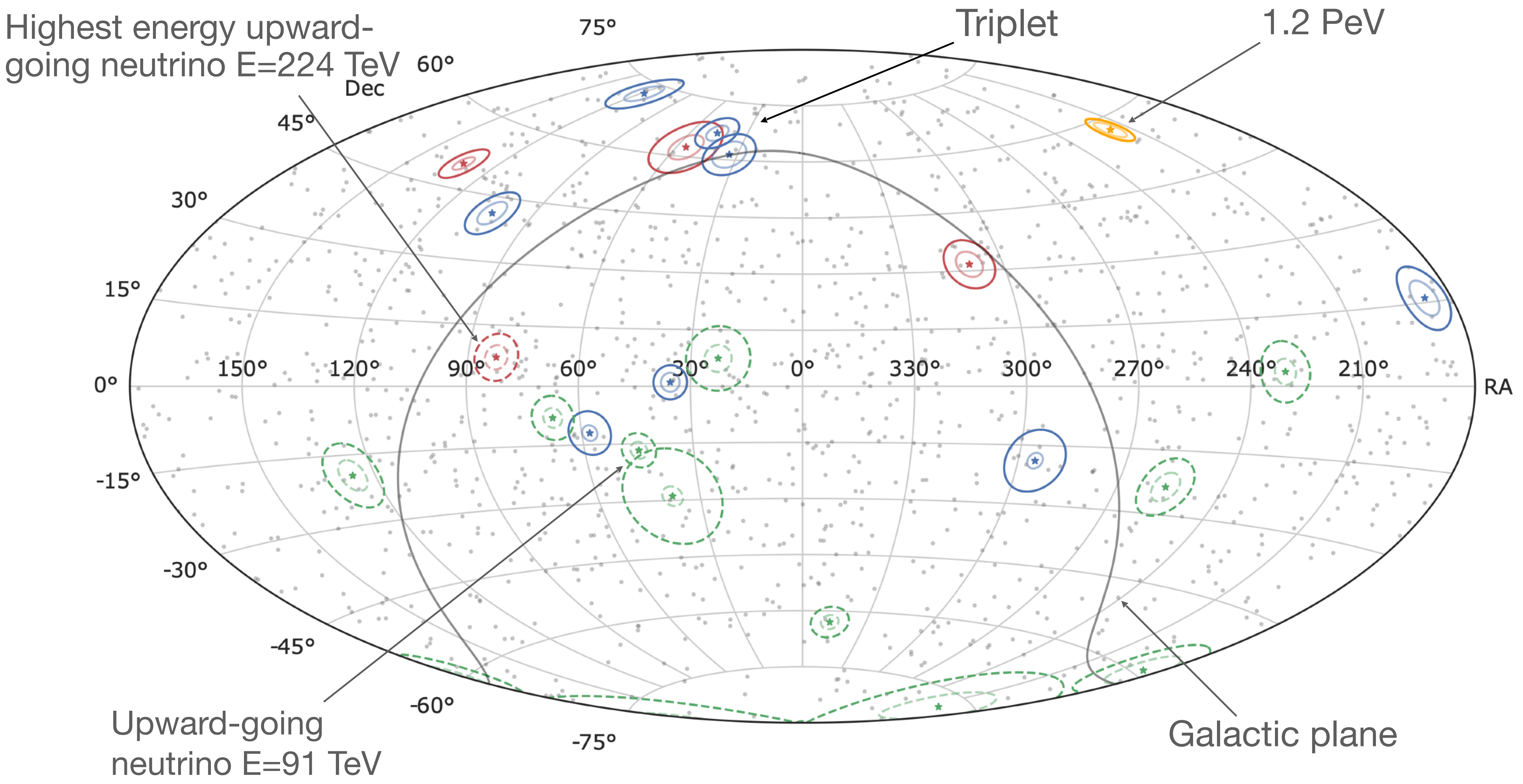
$$\gamma_{\text{astro}} = 2.58^{+0.27}_{-0.33}$$

$$\phi_{\text{astro}} = 3.04^{+1.52}_{-1.27}$$



High-Energy Cascade Sky Map

Opens a possibility to use the cascade channel for searches for neutrino point sources



Best fit positions and 90% angular uncertainty regions

Monthly Notices of the Royal Astronomical Society, Volume 526, Issue 1, November 2023, Pages 942–951

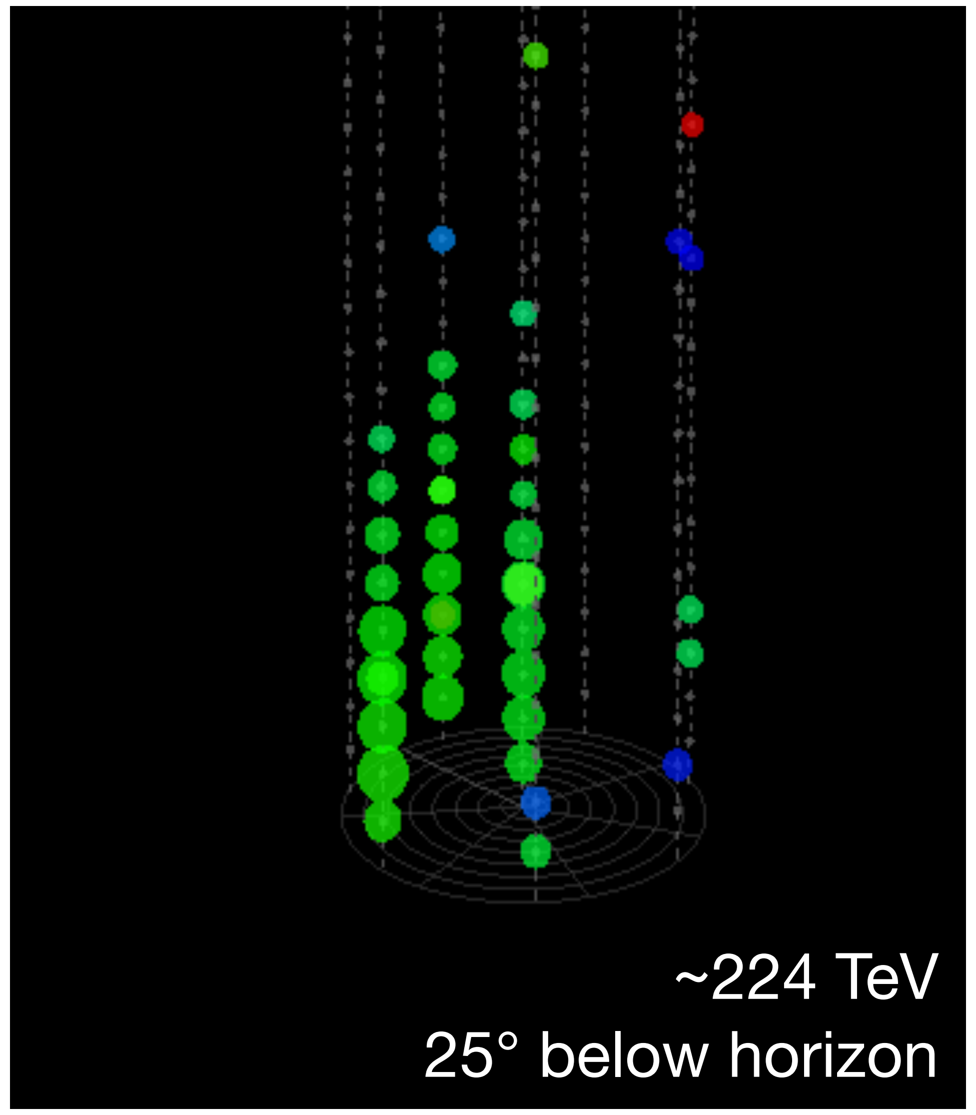
About half of the events are background from atmospheric muons and neutrinos

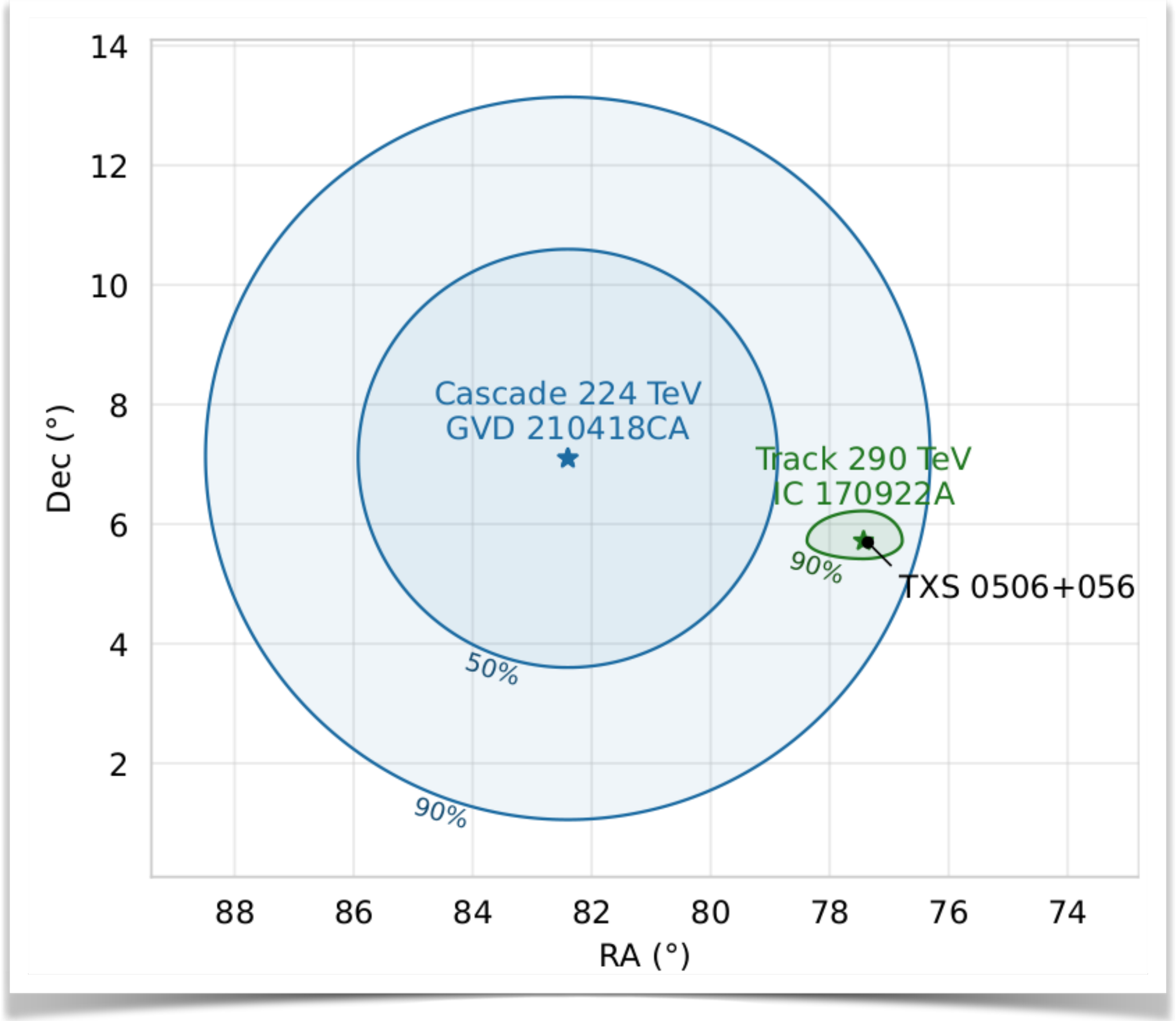
Grey dots: radio-bright blazars (3.6σ correlation with IceCube tracks with E > 200 TeV)

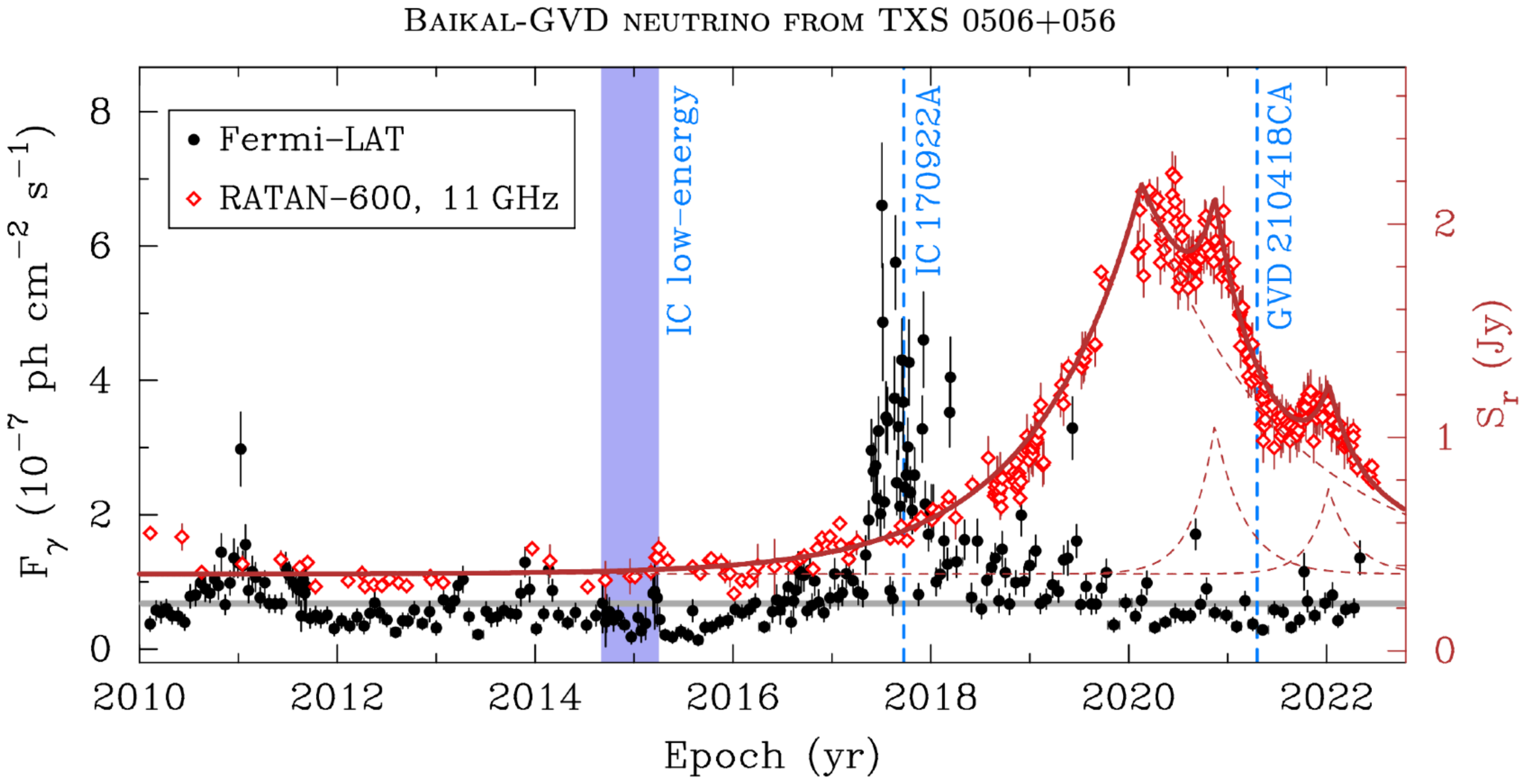
No significant correlation between Baikal-GVD cascades with E > 100 TeV and radio-bright blazars was found

Most energetic upgoing cascade event

Best candidate for neutrino events of astrophysical origin







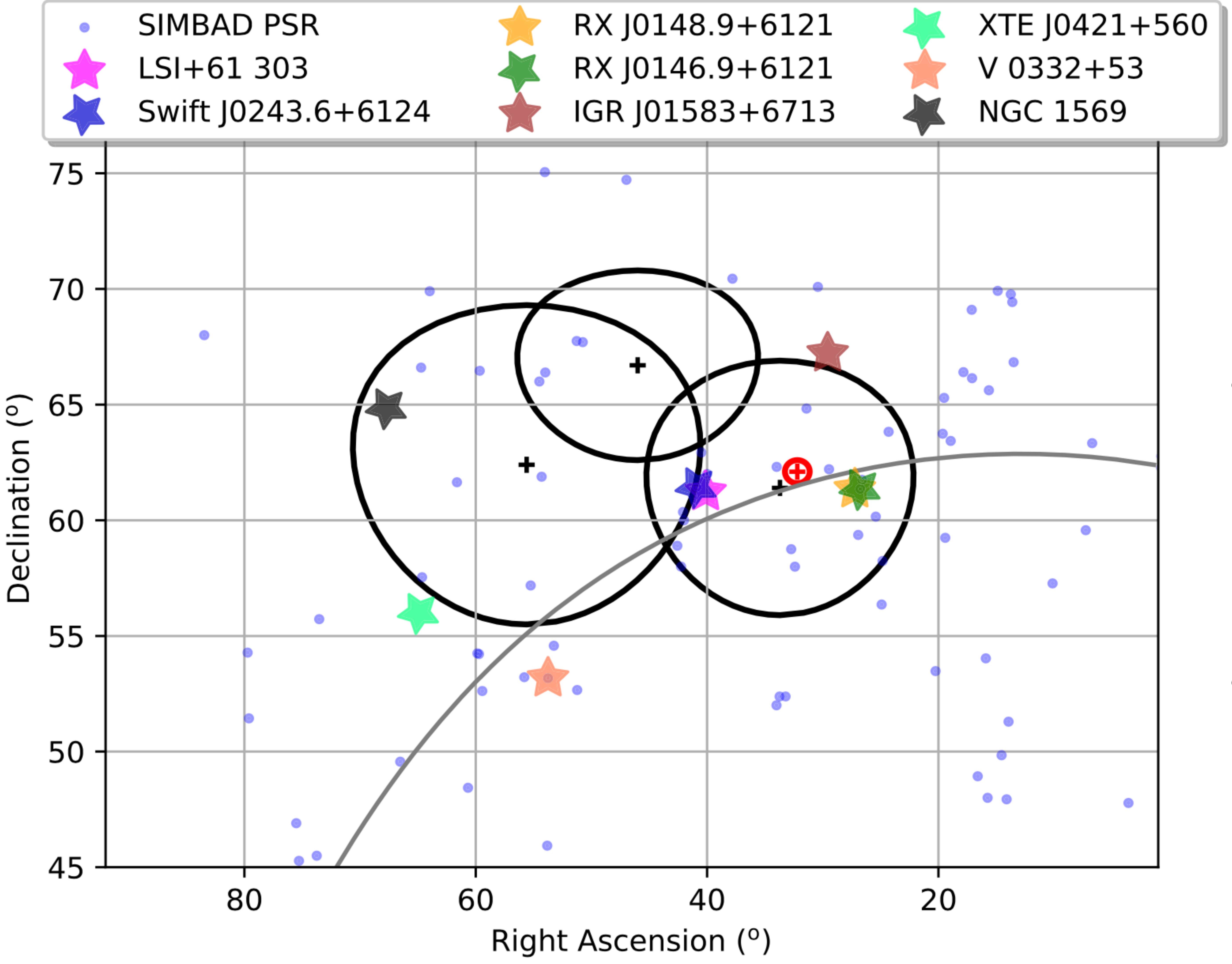
Closest sources (in 6 degrees):

- 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%).
- Chance probability of coincidence p=0.0074 (2.7σ)

Monthly Notices of the Royal Astronomical Society, Volume 527, Issue 3, January 2024, Pages 8784–8792

Event Triplet near Galactic Plane

Intriguing events



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

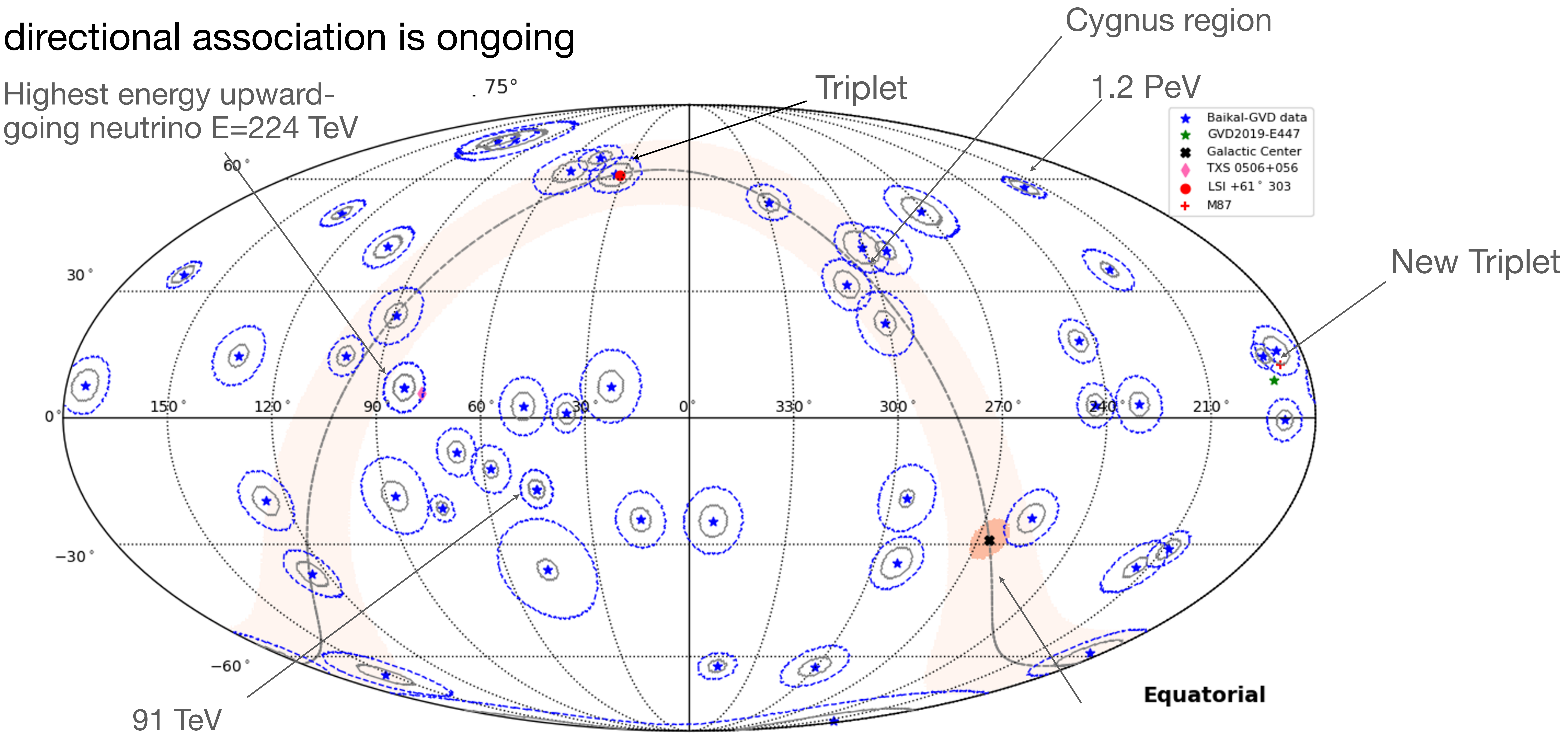
- γ-ray microquasar LS I +61 303 (very well known high energy Galactic source, only 2.6 kpc away) and the two Baikal-GVD events with 3.1° and 7.4° from the source (both are downgoing events)
- Highest significance IceCube persistent Northern hot spot (red plus and circle)

Monthly Notices of the Royal Astronomical Society, Volume 526, Issue 1, November 2023, Pages 942–951

New High-Energy Cascade Sky Map

Data from April 2022 to March 2024 double the statistics:

- Excess over the atmospheric background more than 5σ
- Search for directional association is ongoing

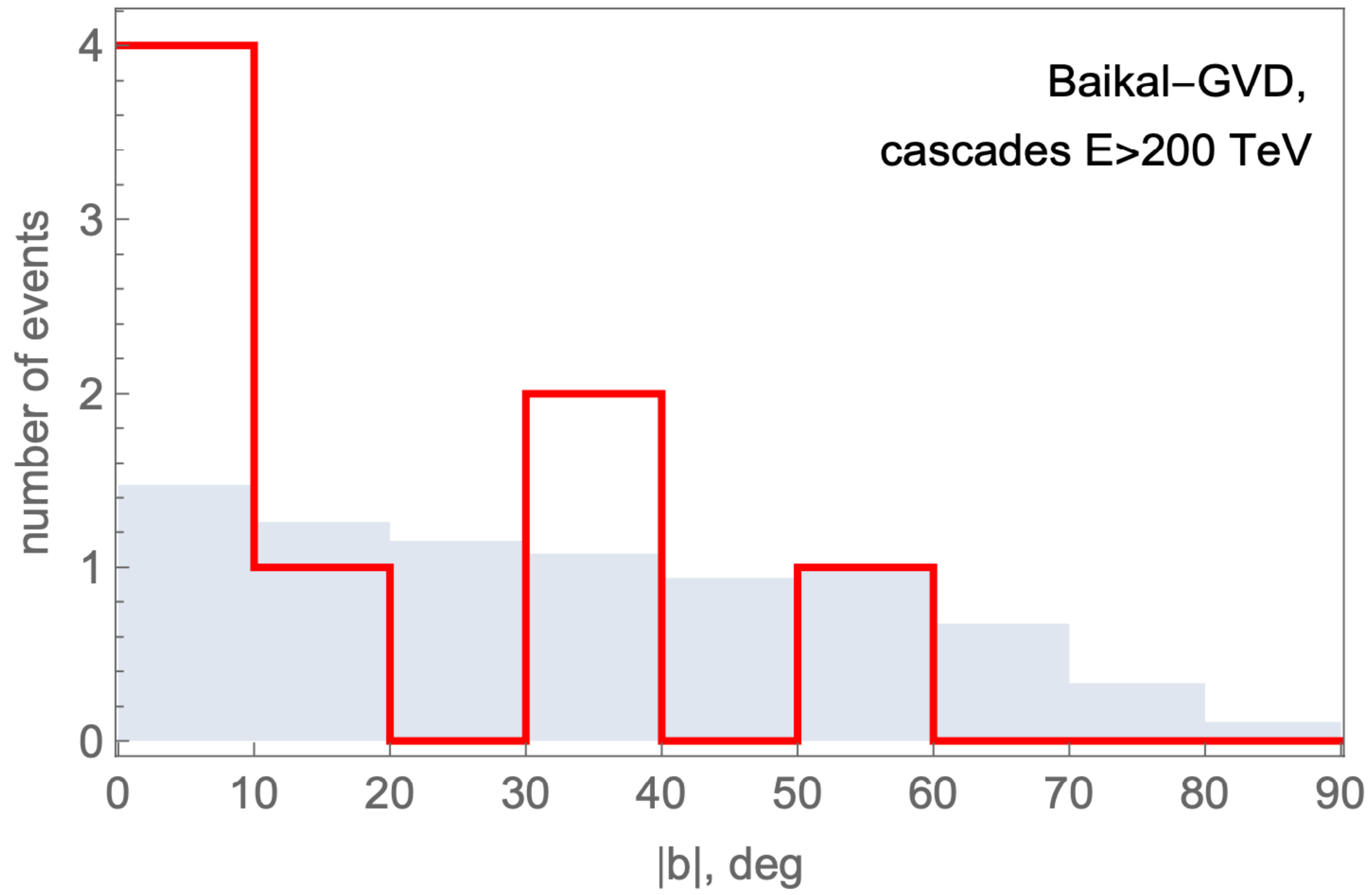


Best fit positions and 90% angular uncertainty regions

About half of the events are background from atmospheric muons and neutrinos

Galactic Neutrinos with the Highest Energies

- High-energy cascades 2018-2023 (6 years of operation)
- Test the Galactic excess at E>200 TeV (8 events, 64% of astrophysical origin)
- Simplest model-independent test using median of galactic latitude $|b|_{med}$
- Galactic component is visible with a significance of 2.5σ
- IceCube cascades and tracks also demonstrate the Galactic excess
- Fraction of Galactic events reaches several tens of percent at E>200 TeV disagreeing many theoretical predictions

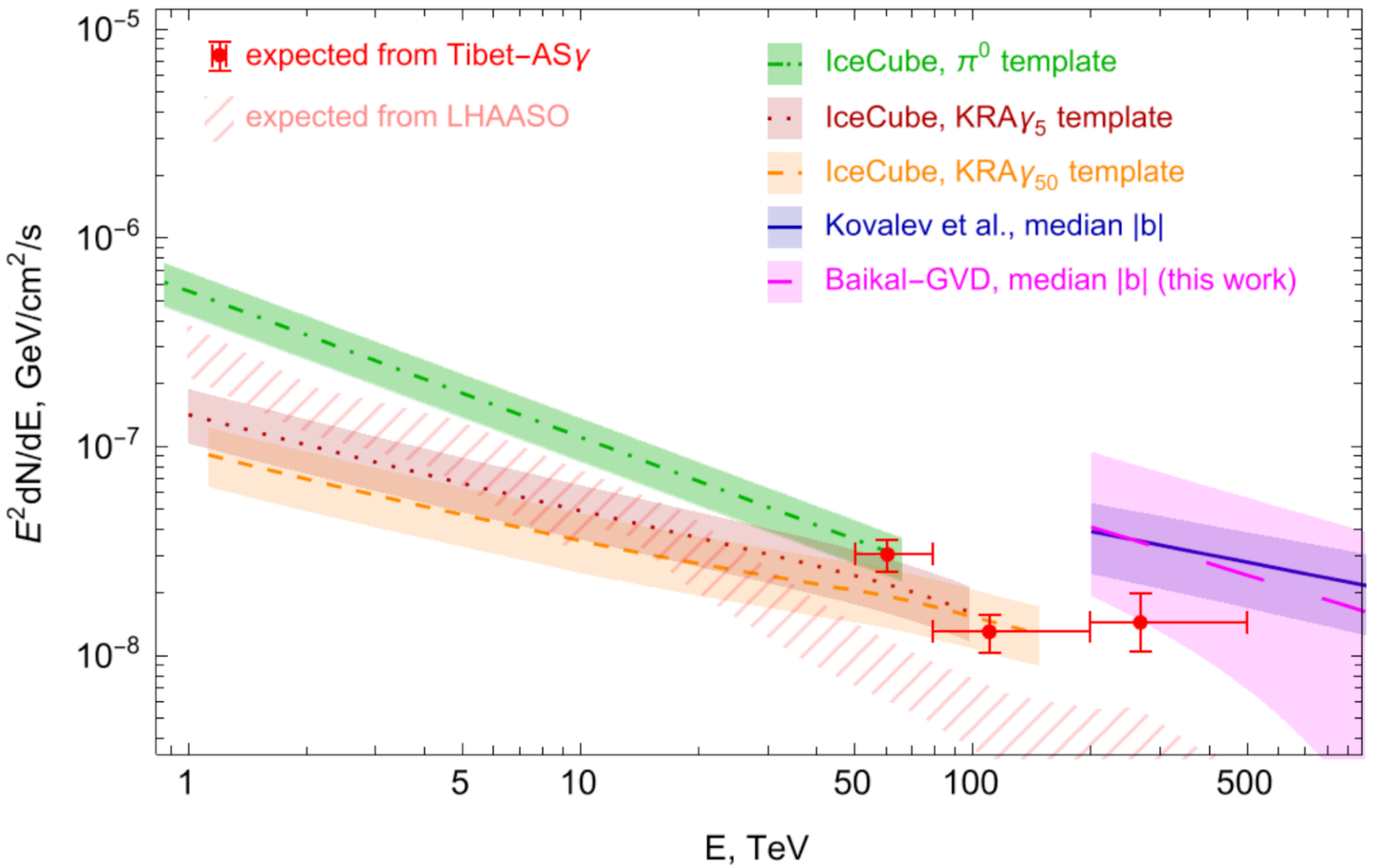


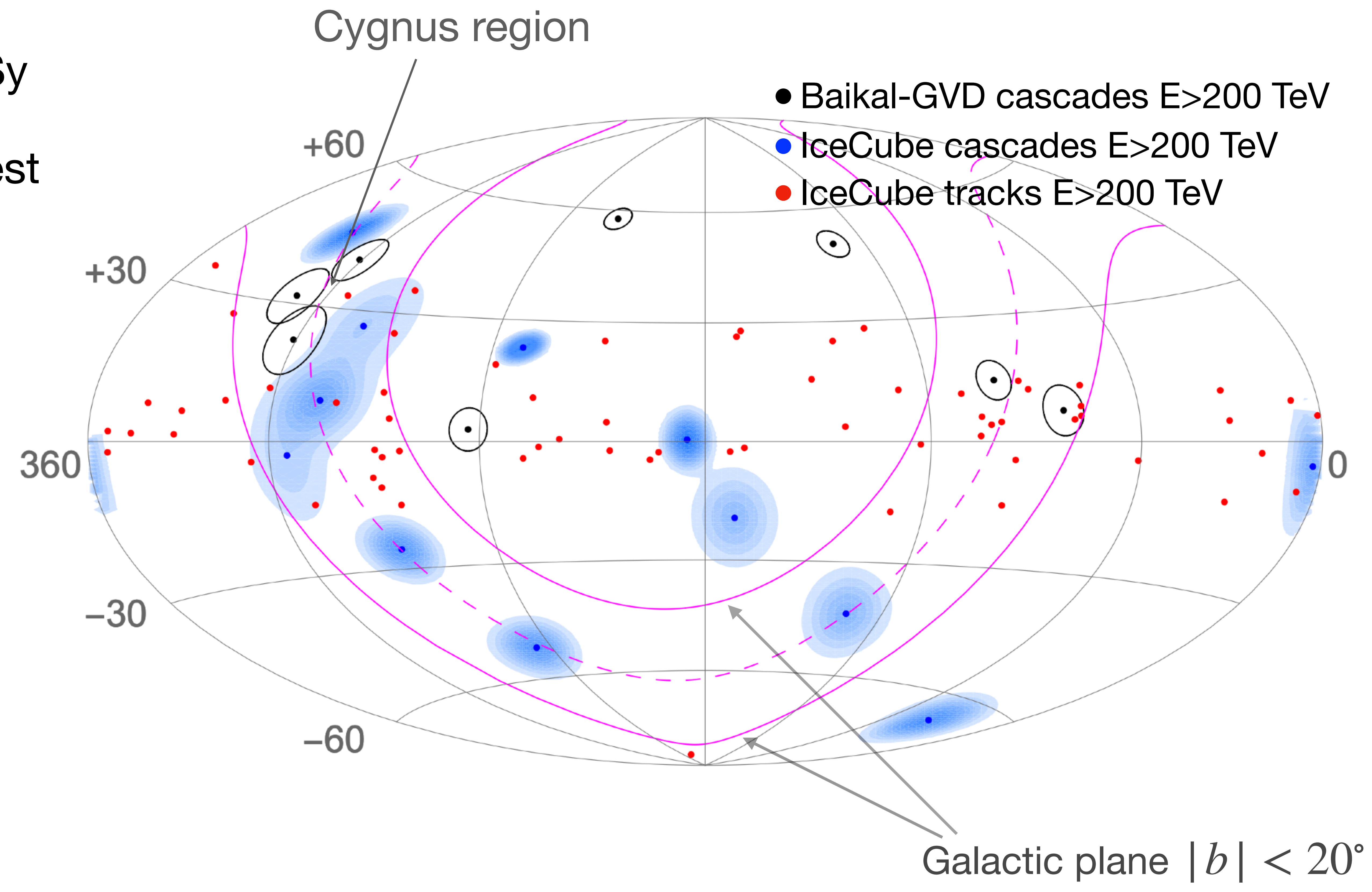
Sample	$\|b\|_{\mathrm{med}}$ observed	$\langle \|b\|_{\mathrm{med}} \rangle$ expected	p
Baikal-GVD cascades	10.4°	31.4°	$1.4 \cdot 10^{-2}$ (2.5σ)
IceCube cascades	12.4°	31.9°	$8.7 \cdot 10^{-3}$ (2.6σ)
combined cascades	12.4°	31.5°	$1.7 \cdot 10^{-3}$ (3.1σ)
IceCube tracks	24.7°	36.0°	$1.8 \cdot 10^{-3}$ (3.1σ)
all cascades+tracks	23.4°	35.0°	$3.4 \cdot 10^{-4}$ (3.6σ)

arXiv:2411.05608v1

Galactic Neutrinos with the Highest Energies

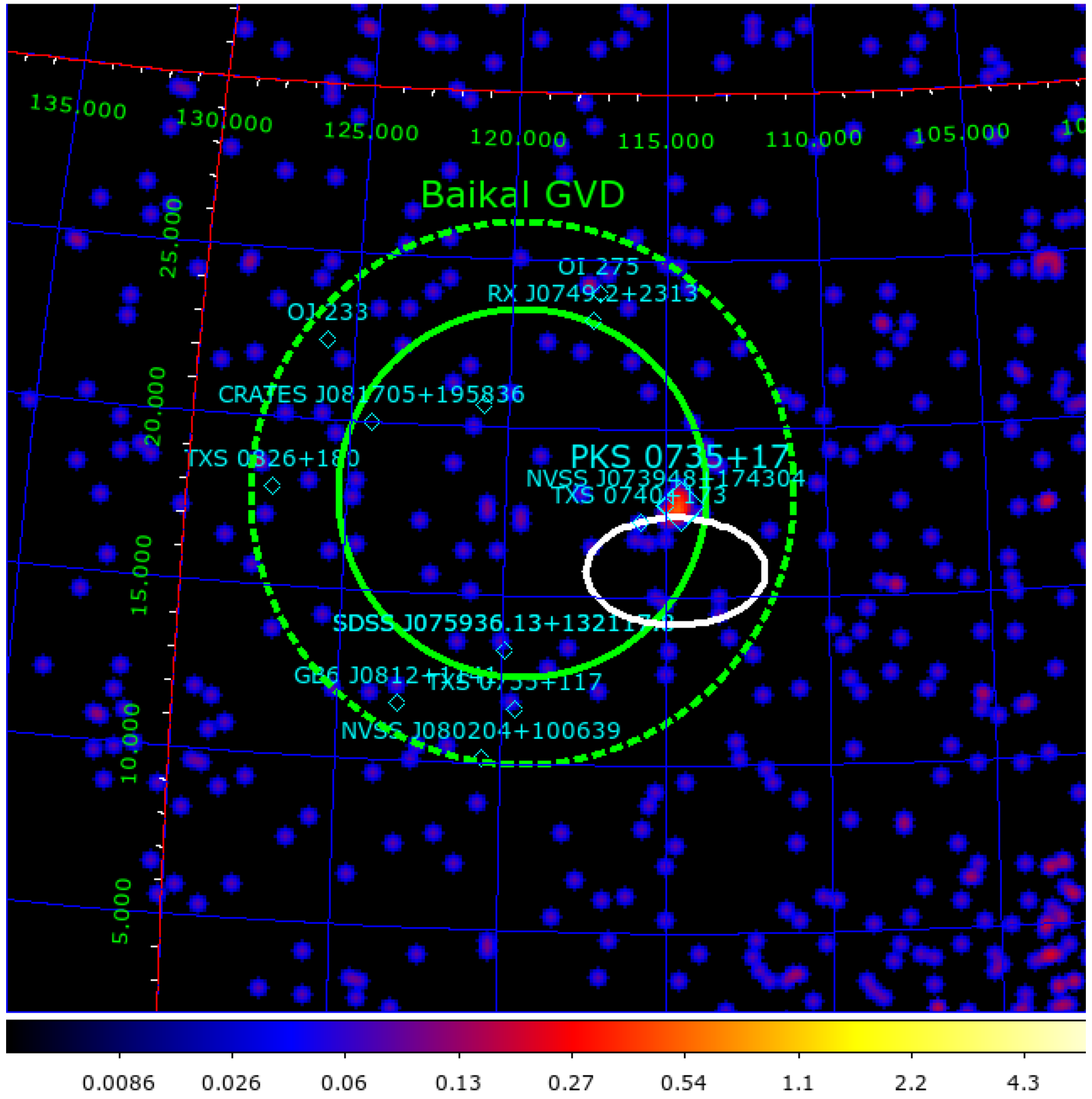
- Very rough estimate of the Galactic neutrino flux is obtained
- Agrees with Galactic gamma-ray diffuse emission by Tibet-ASγ
- Some event clustering towards the Cygnus region (the brightest region of diffuse γ-ray emission in the northern sky)





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

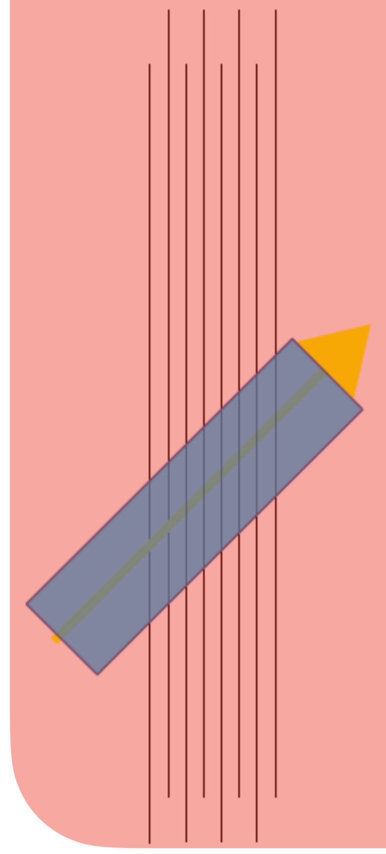
- Fast processing system for transient sources has been working since 2021
- Dec 8, 2021 20:02: IceCube “Astrotrack Bronze” neutrino event in the vicinity of the bright blazar PKS 0735+17
- Active state of PKS 0735+17 reported in optical (MASTER), HE gamma-rays (Fermi LAT), X-rays (Swift XRT) and radio
- 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 analysed)



Astronomy telegram ATeL 15112 was sent

Event Types

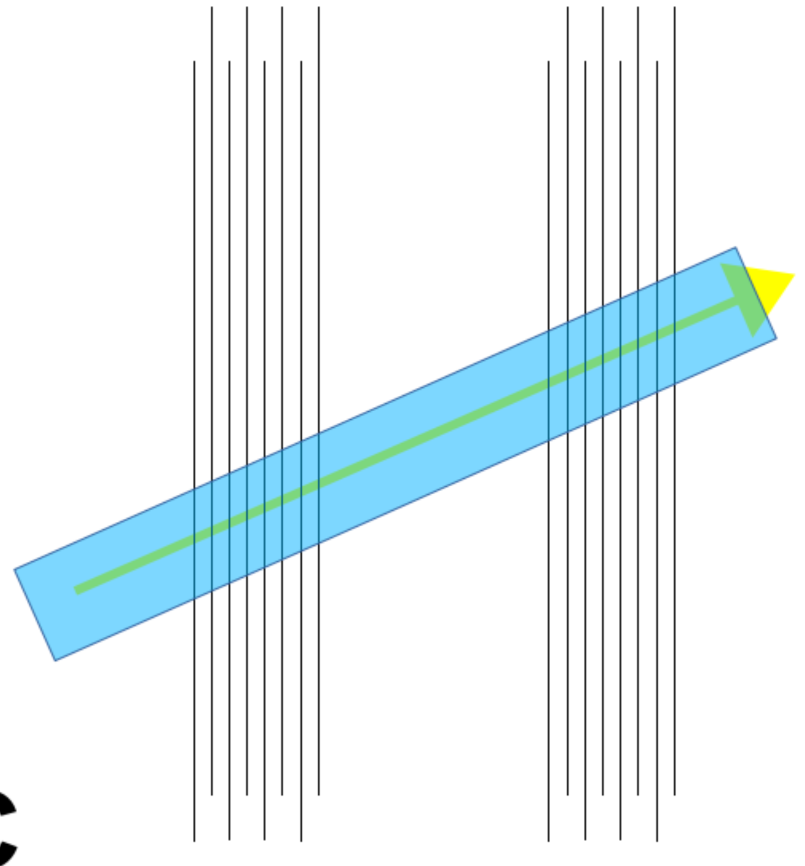
Single-cluster tracks



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

Results are coming

Multi-cluster tracks

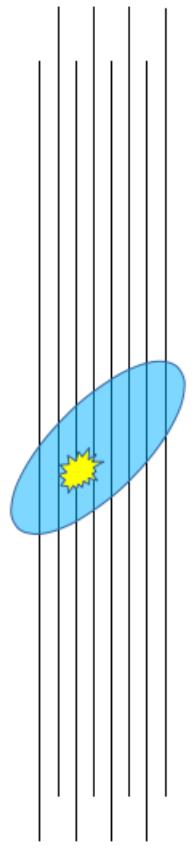


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

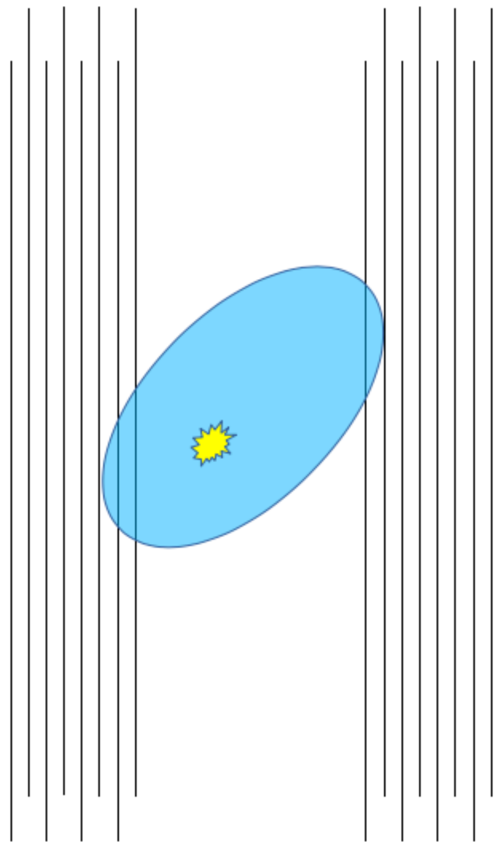
NC, ν_e ν_τ CC

Single-cluster cascades



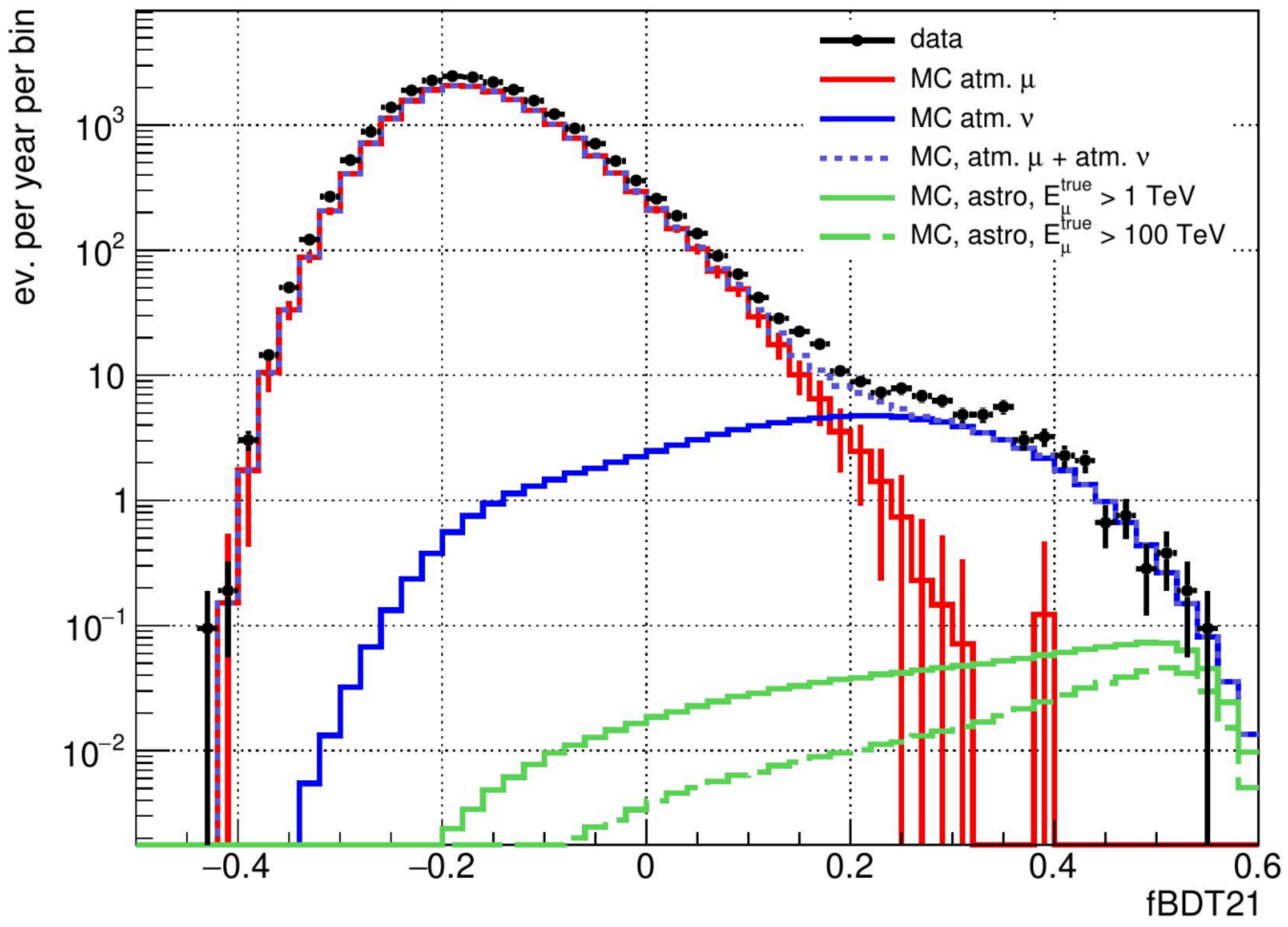
- High energy threshold
- Good energy resolution
- Relatively rare events

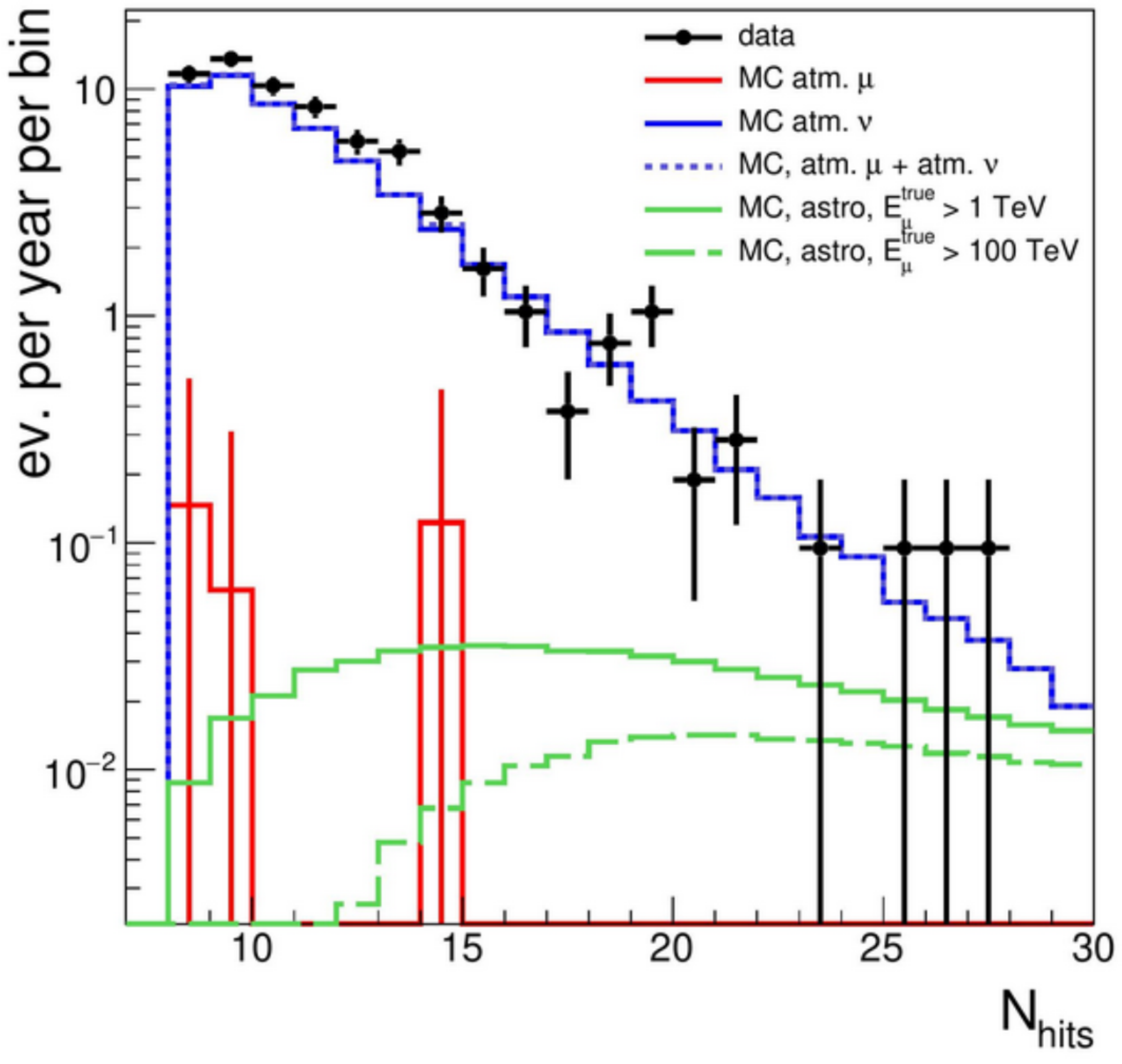
Multi-cluster cascades



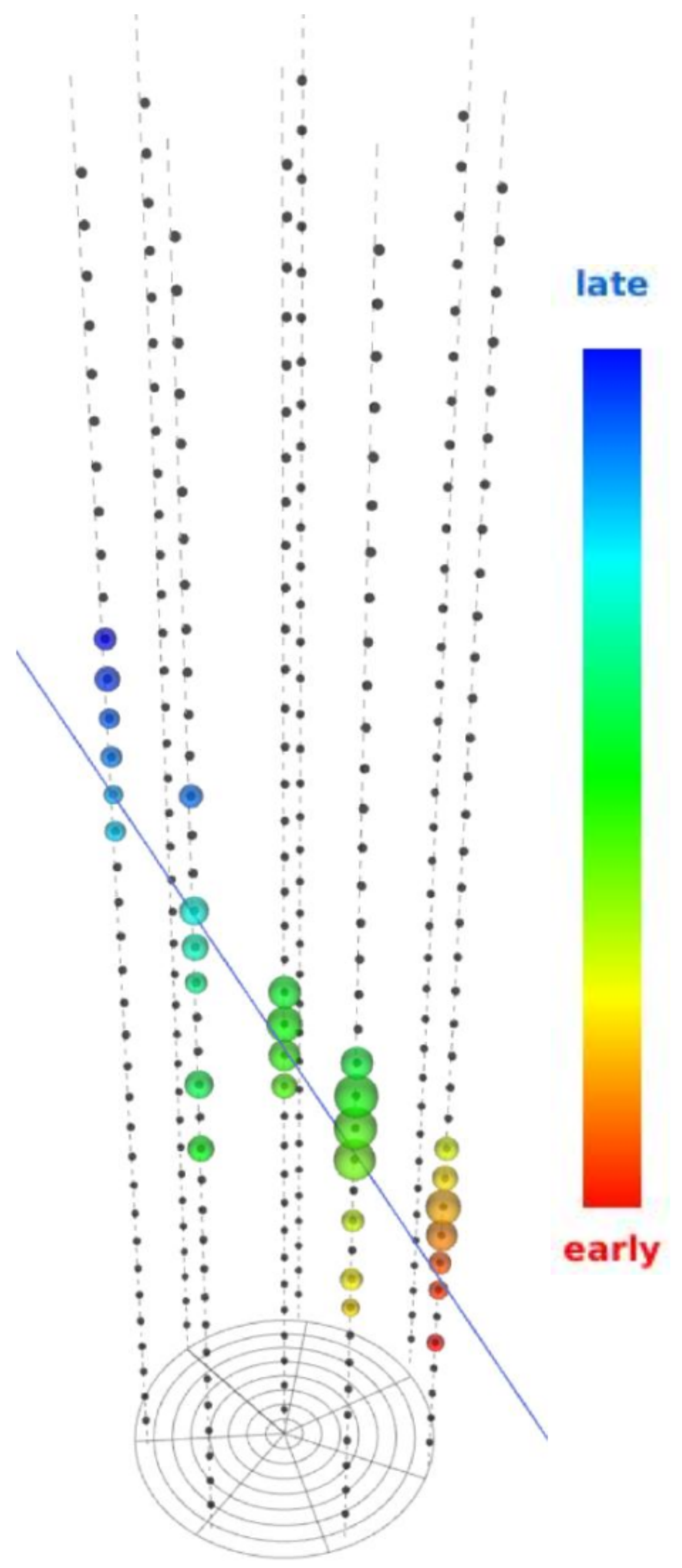
- Very high energy threshold
- Excellent energy resolution
- Very rare events

Muon-Track Analysis





Neutrino candidate example



E = 100 TeV

- Direction resolution: 0.3-1.0 degrees
- Energy resolution: factor of 3 or 2
- Good agreement with MC expectation

2613 neutrino candidates (2020-2023):

- 33 events E > 60 TeV
- 20 events E > 100 TeV

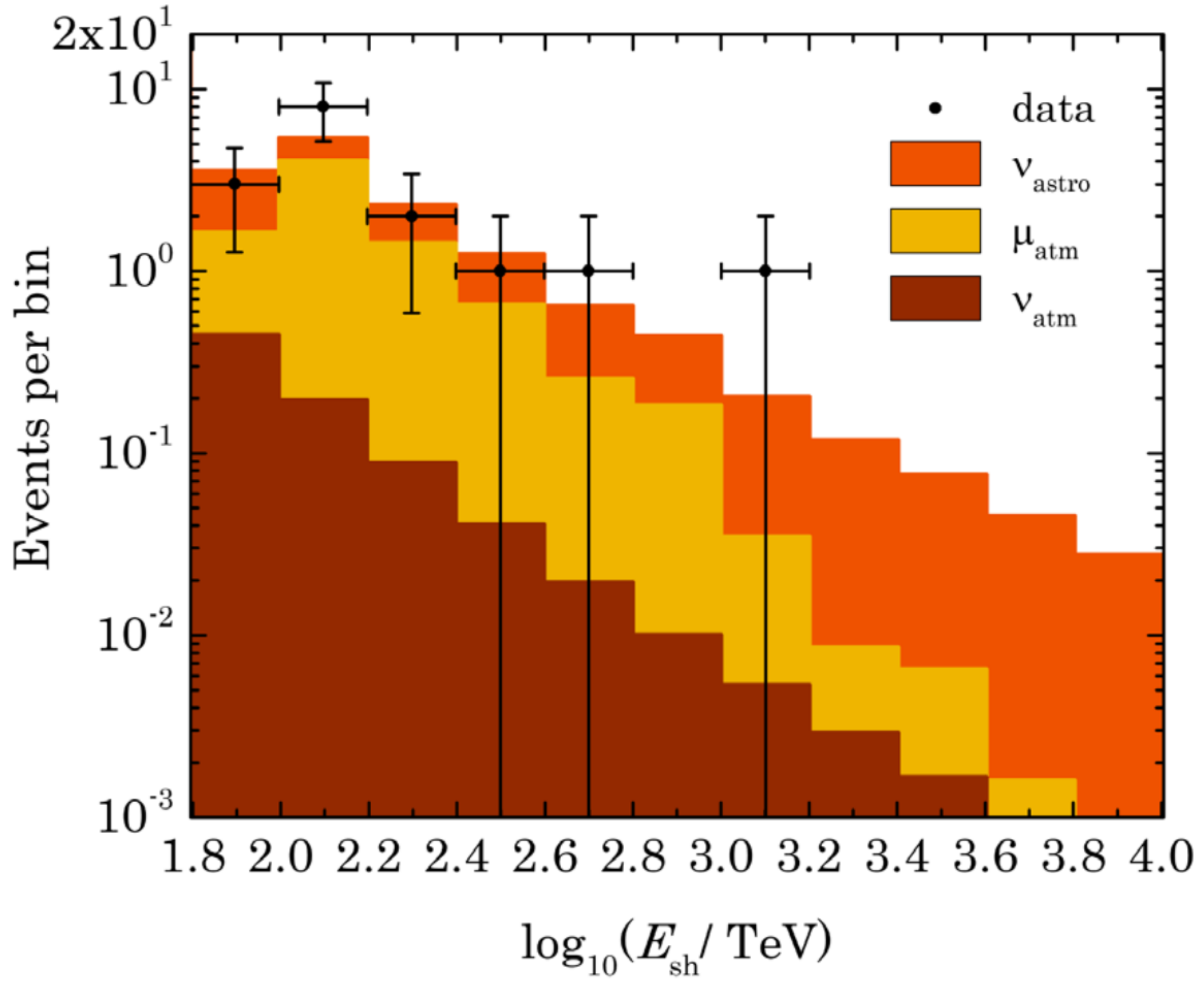
Work in progress…

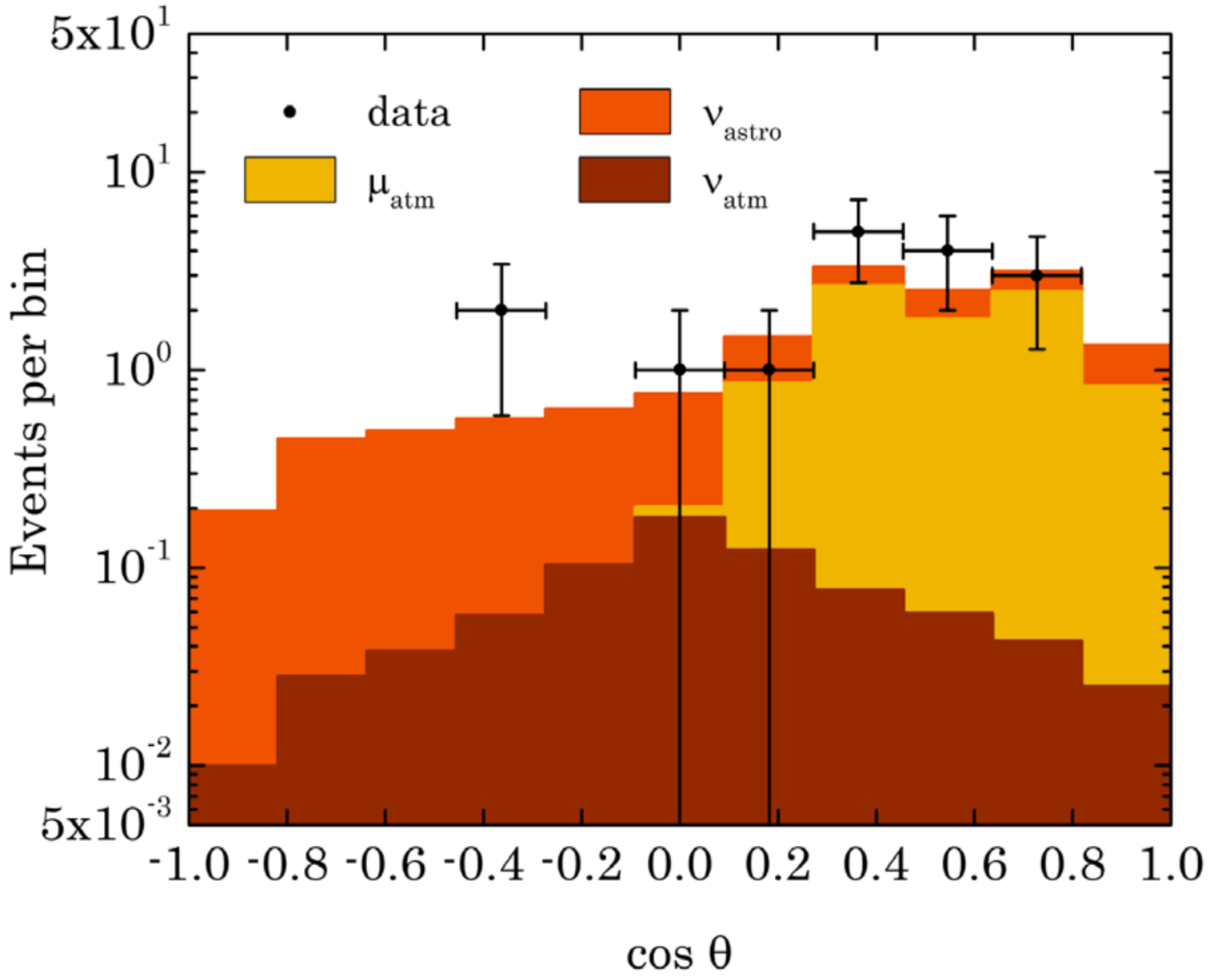
Conclusion

- Baikal-GVD is the largest neutrino telescope in the Northern hemisphere:
  - Volume approaching 0.6 km3 for high-energy cascades
  - Angular resolution better than 1° for tracks
  - Field of view complementary to IceCube
- Nearest plans:
  - Installation of two new clusters + full-scale string for HUNT project
- Partially installed telescope produces astrophysical results:
  - Diffuse neutrino flux is confirmed with > 5σ significance
  - Hints of Galactic and extragalactic neutrino sources are accumulating
- The completion of work on the creation of 1 km^3 Baikal-GVD detector with ~6000 OM is planned in 2027/2028

Back-ups

Astrophysical Diffuse Neutrino Flux: All-sky





- Data analysed April 2018 - March 2022
- 14328 cascades reconstructed with E > 10 TeV, N_{hit} > 11
- Cascade energy E >70 TeV and N_{hit} > 19

	Events
Atm. muons MC	7.4
Atm. neutrino MC	0.8
Astro neutrino MC best fit	5.8
Data	16

Excess over the atmospheric background: 2.22σ

Phys. Rev. D **107**, 042005, February 2023