Сессия –конференция секции ядерной физики ОФН РАН, посвященная

70-летию В.А.Рубакова

Астрофизические результаты Байкальского нейтринного телескопа

Ж. Джилкибаев, Коллаборация Байкал, Москва, 20.02.2025

Outline

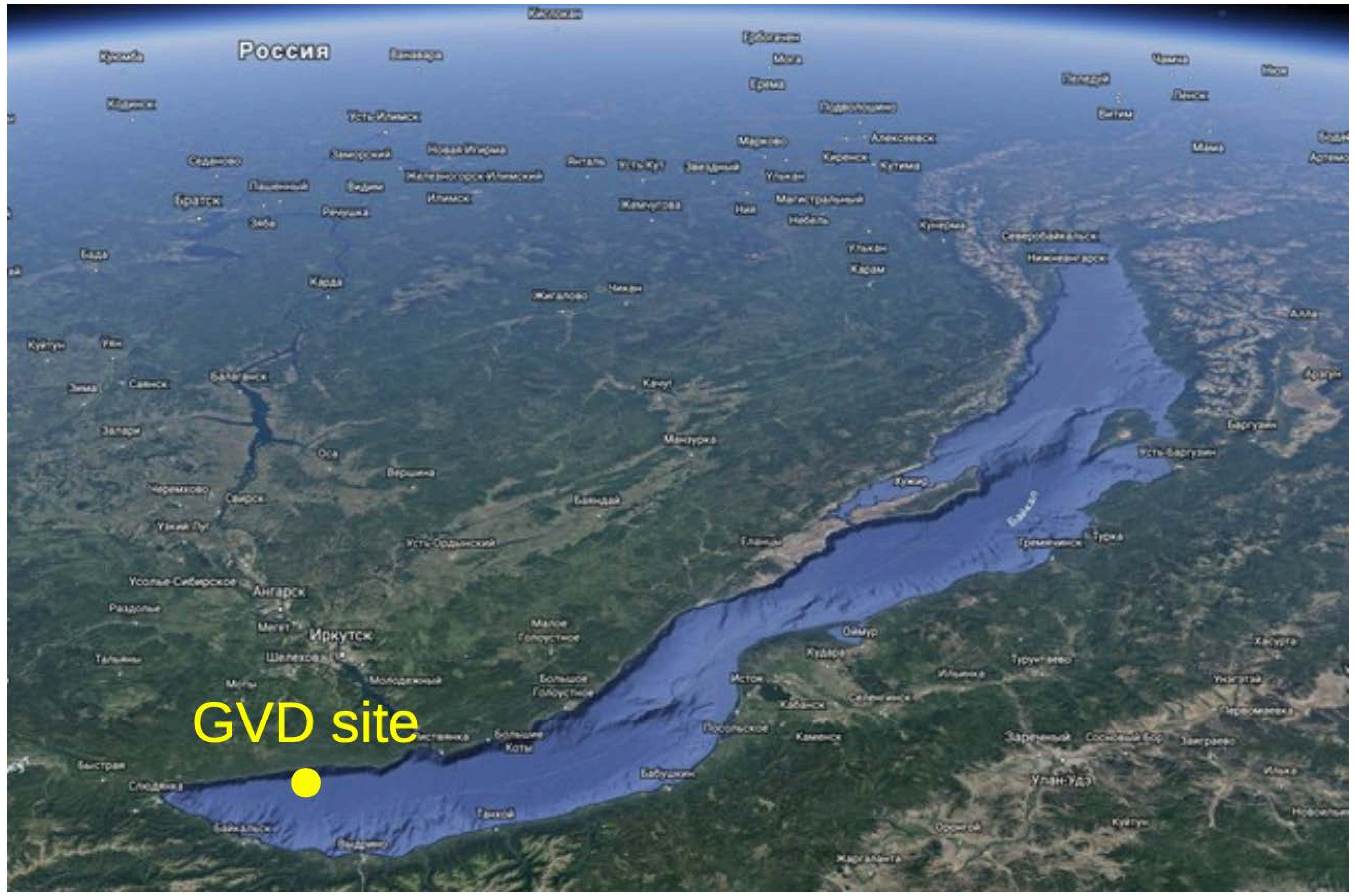
- Baikal-GVD Telescope Description and Status
- Recent Results:
  - Global diffuse astrophysical neutrino flux
  - Galactic diffuse neutrino flux
  - UHE diffuse flux limit
  - Search for astrophysical neutrino point sources
  - Follow-up activities

Baikal-GVD Collaboration

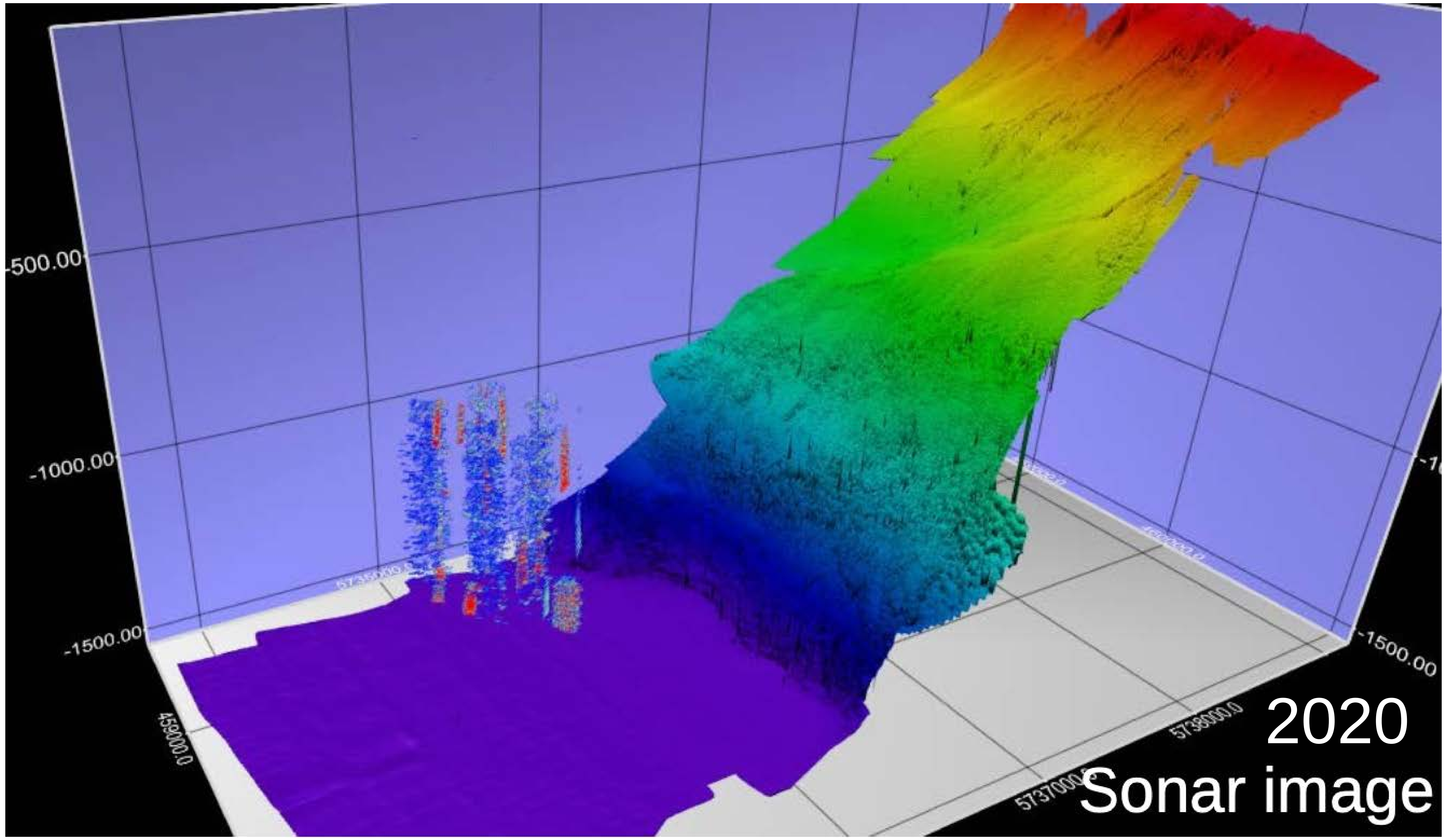
- Institute for Nuclear Research of the Russian Academy of Sciences, Russia
- Joint Institute for Nuclear Research, Russia
- Irkutsk State University, Russia
- Skobeltsyn Research Institute of Nuclear Physics, Russia
- St. Petersburg State Marine Technical University, Russia
- National Research Nuclear University MEPHI, Russia
- Comenius University, Slovakia
- Czech Technical University in Prague, Czech Republic
- Institute of Nuclear Physics ME RK, Kazakhstan

~ 65 physicists and engineers

Baikal-GVD Site



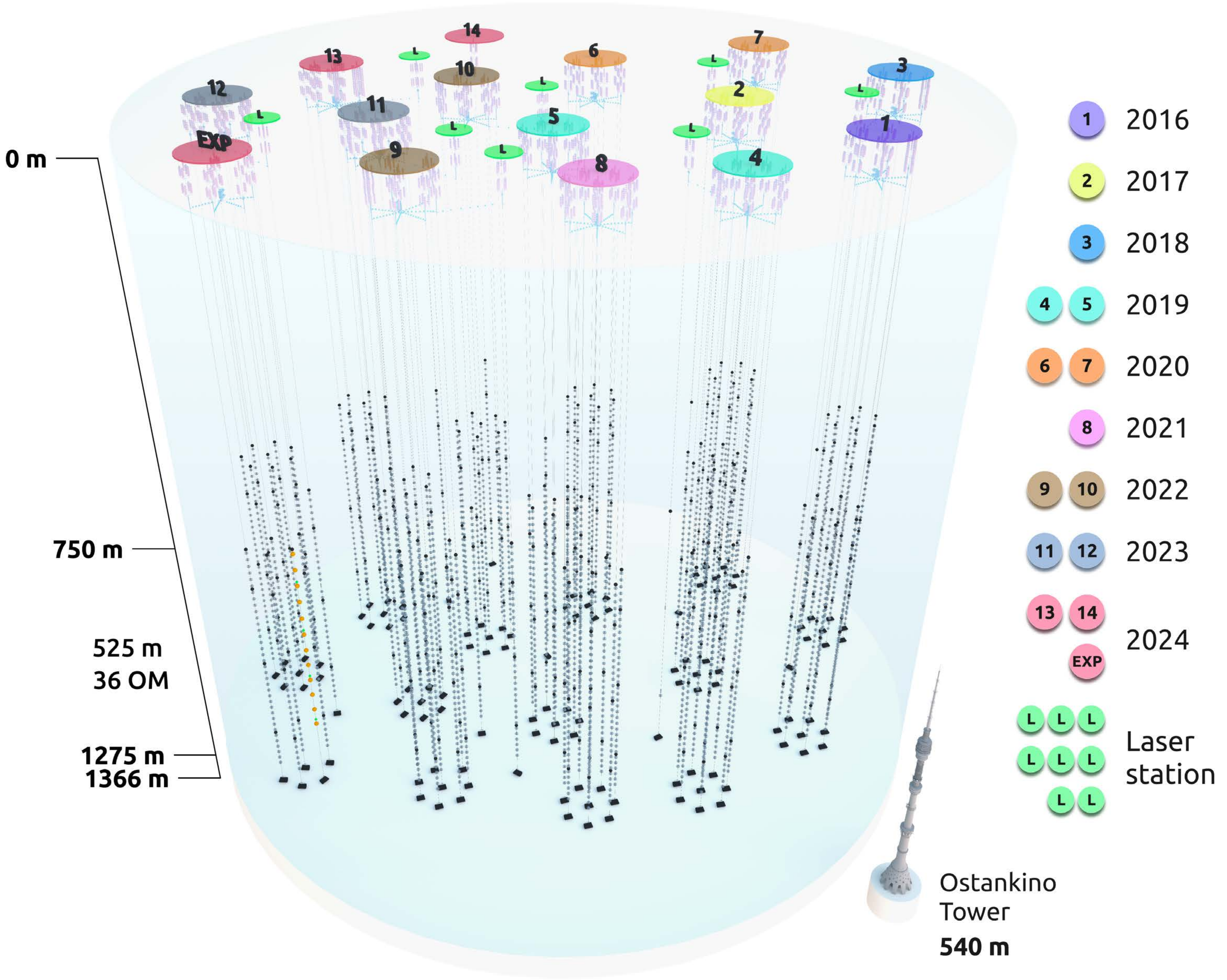
- Southern basin of the lake
- ~3.6 km offshore
- Flat area at depths 1366–1367 m
- High water transparency:
  - Absorption length: 22 m
  - Effective scattering length: 480 m
- Moderately low optical background: 15–50 kHz
- Deployment from the ice cover of the lake



Baikal-GVD Status

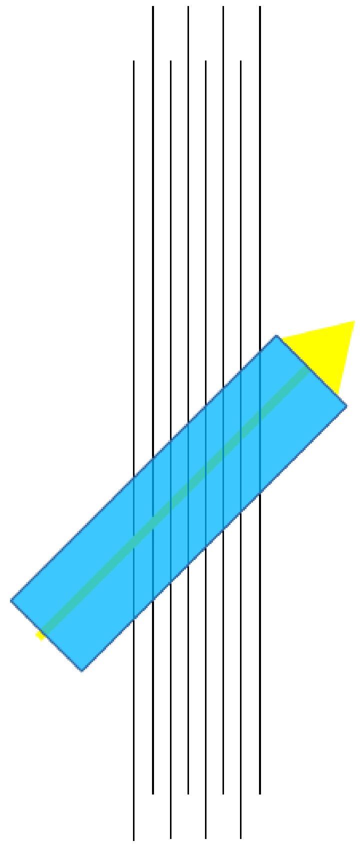
April 2024

- 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 with the fibre-optic DAQ for testing of new equipment
- Prototype string for the next-generation telescope (12 new OMs)



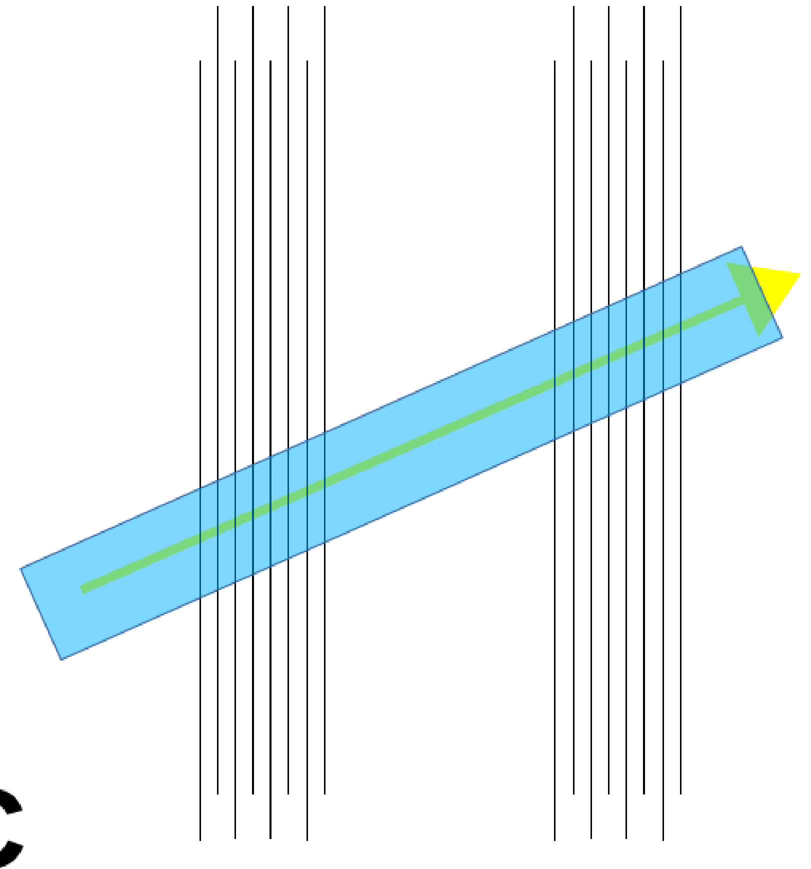
Event Topologies

Single-cluster tracks



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

Multi-cluster tracks

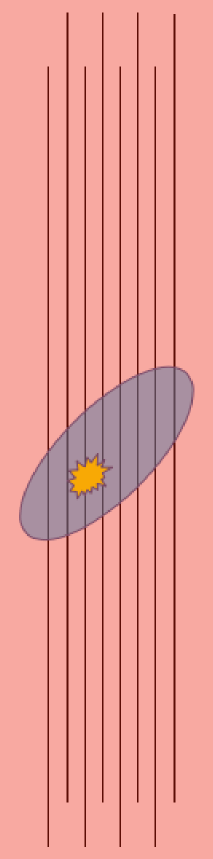


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

NC, ν_e ν_τ CC

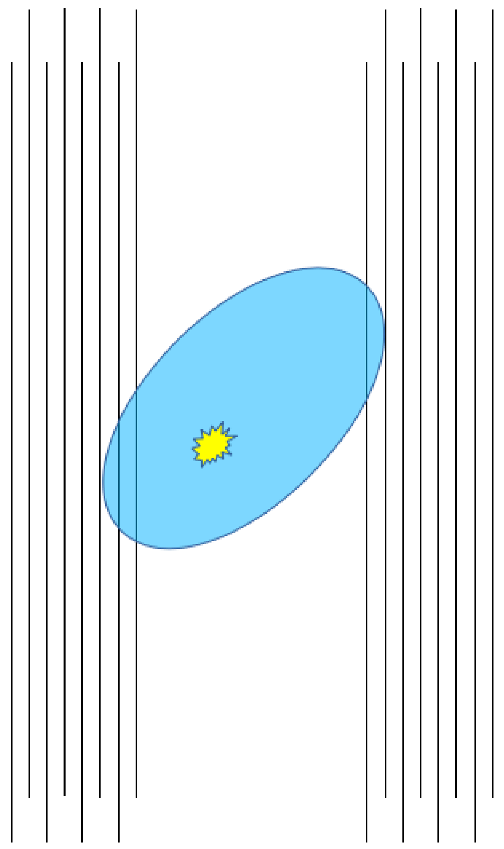
Single-cluster cascades



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

Main results for today

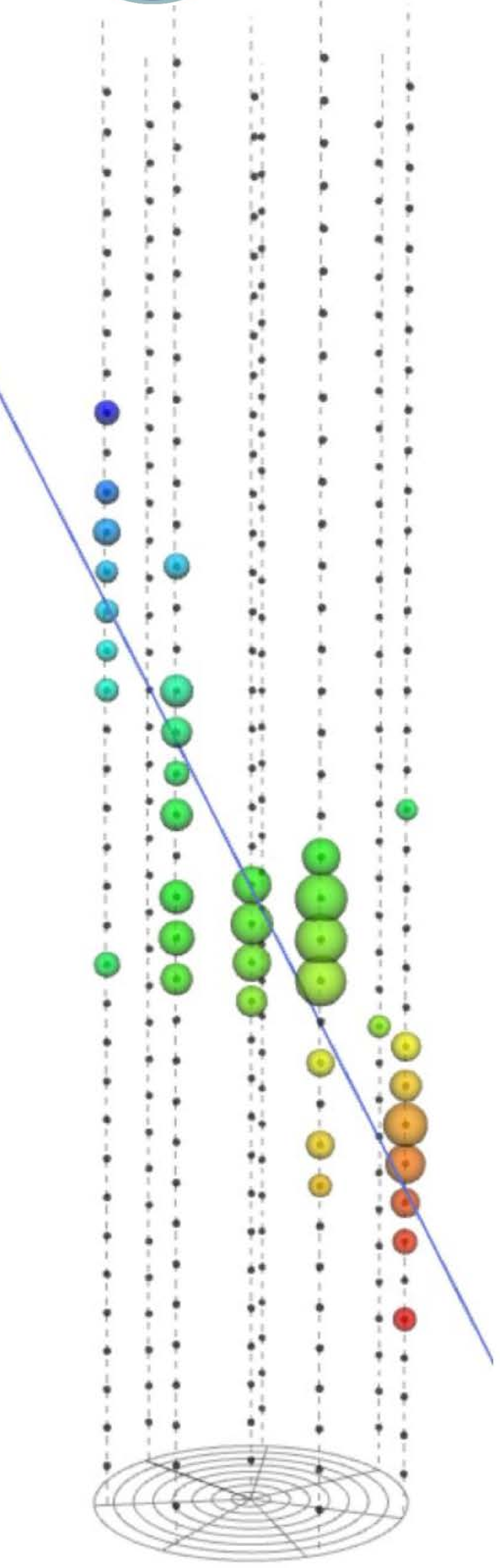
Multi-cluster cascades



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

Track analysis

- In tracks analysis seasons 2019-2023 were processed in single-cluster regime
- Signal and background MC samples for these seasons are avaialble
- The work is ongoing characterisation of the obtained dataset
- Preliminary high-purity dataset of 1189 tracks from seasons 2019-2021 was demostrated in the report by Grigory Safronov (https://indico.inr.ac.ru/event/5/contributions/105/)

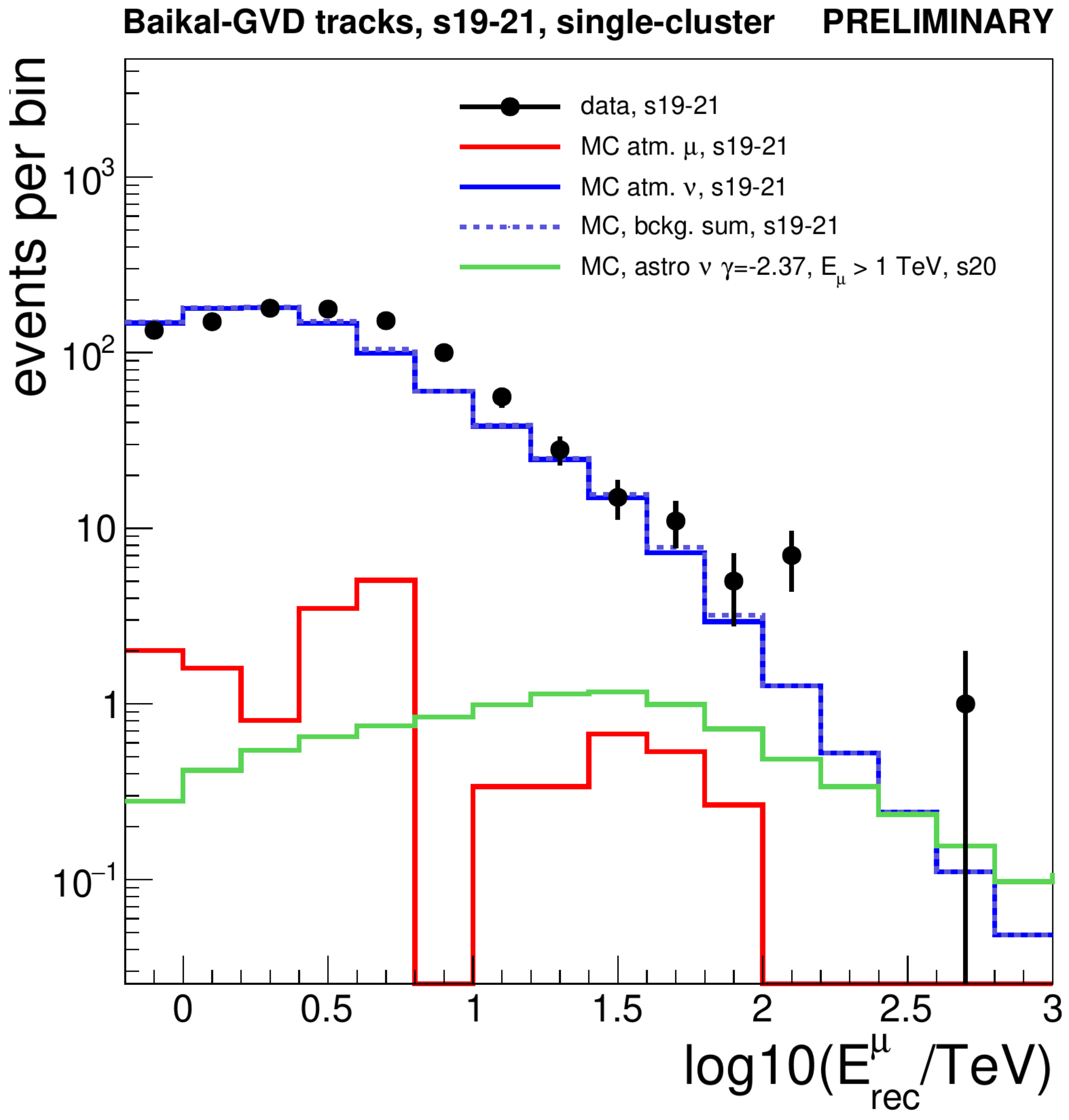


Season 2019, December

N_{hits}	36
E^{μ}_{rec}	62.1 ТэВ
θ_{rec}	153.1°
L_{track}	332.4 м

Angular precision:

50%:	0.5°
68%:	0.7°
90%:	1.0°

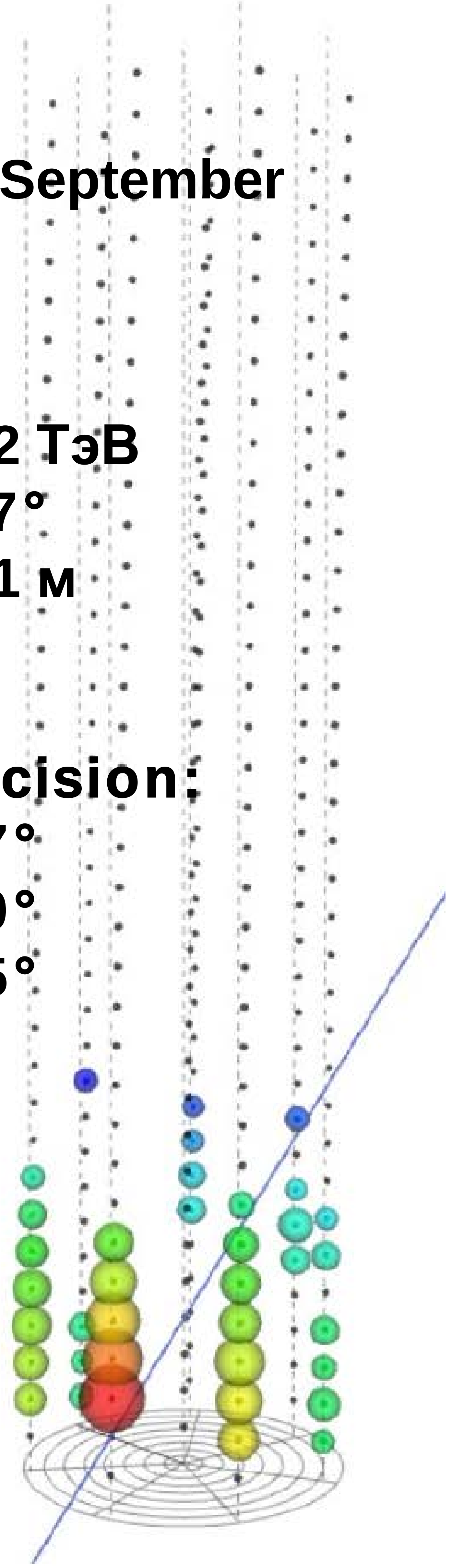


Season 2020, September
Cluster 5

N_{hits}	37
E^{μ}_{rec}	107.2 ТэВ
θ_{rec}	116.7°
L_{track}	140.1 м

Angular precision:

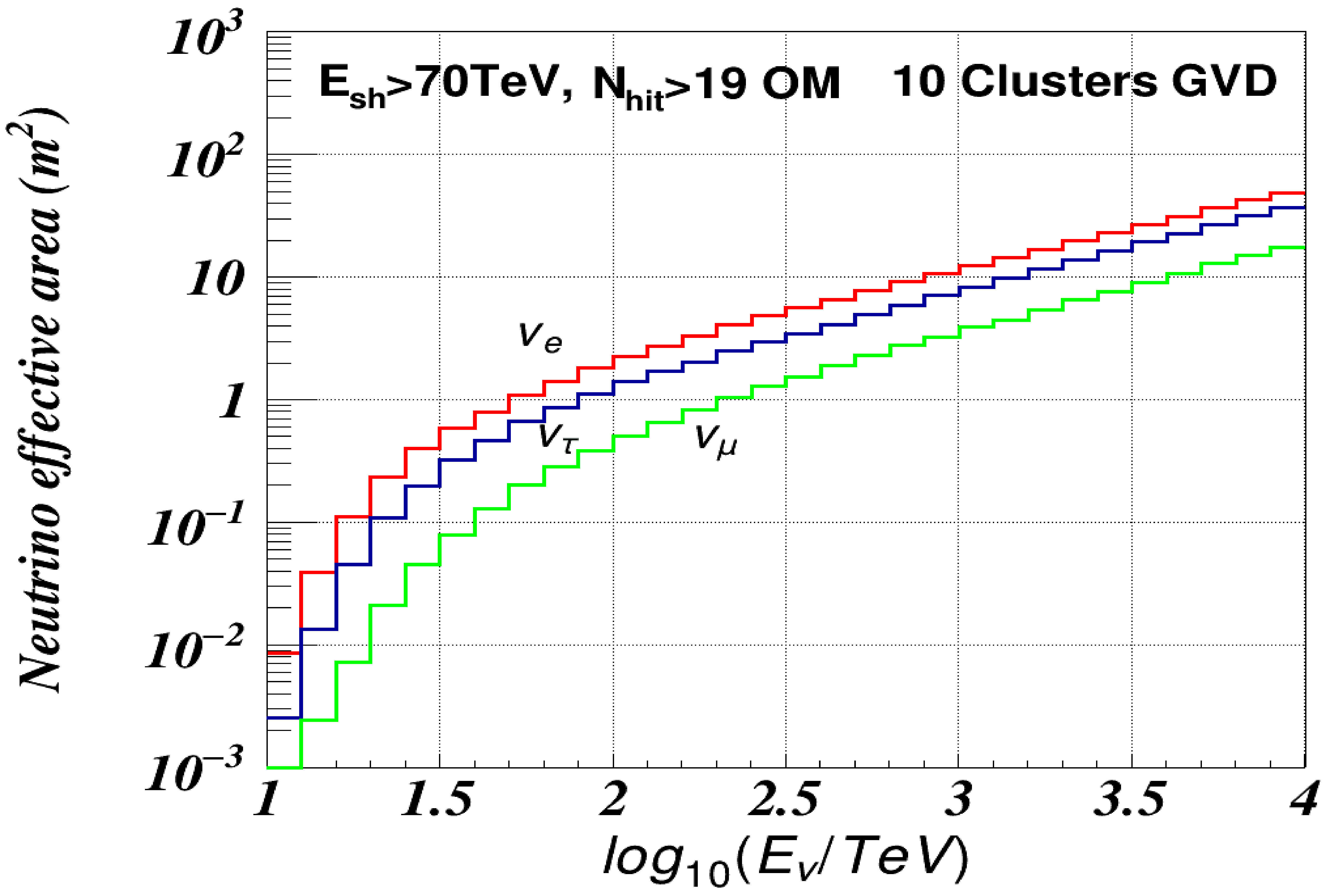
50%:	0.7°
68%:	1.0°
90%:	1.5°



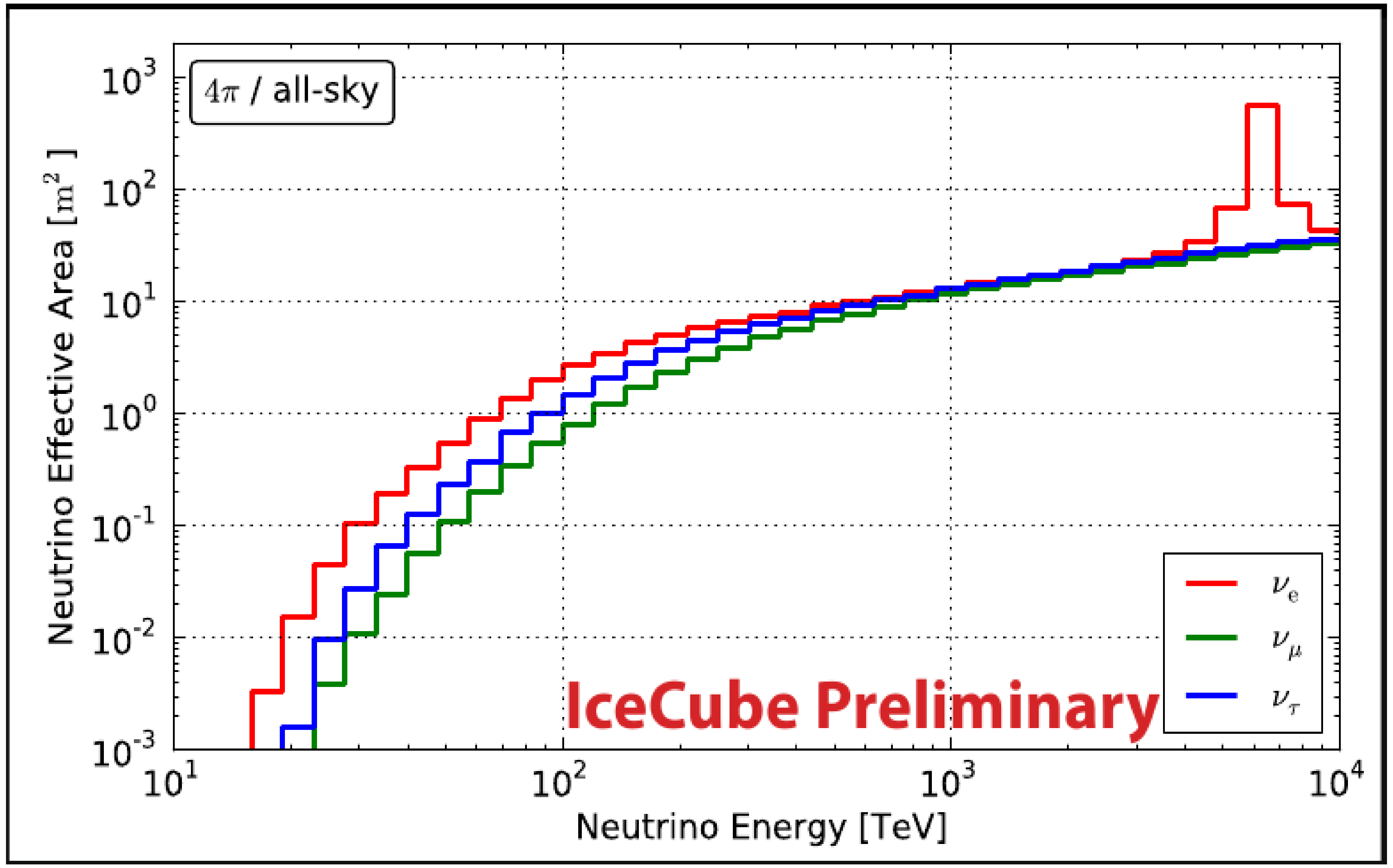
Effective neutrino area

IceCube (HESE) = 10 GVD Clusters

GVD 10 clusters



IceCube (HESE)

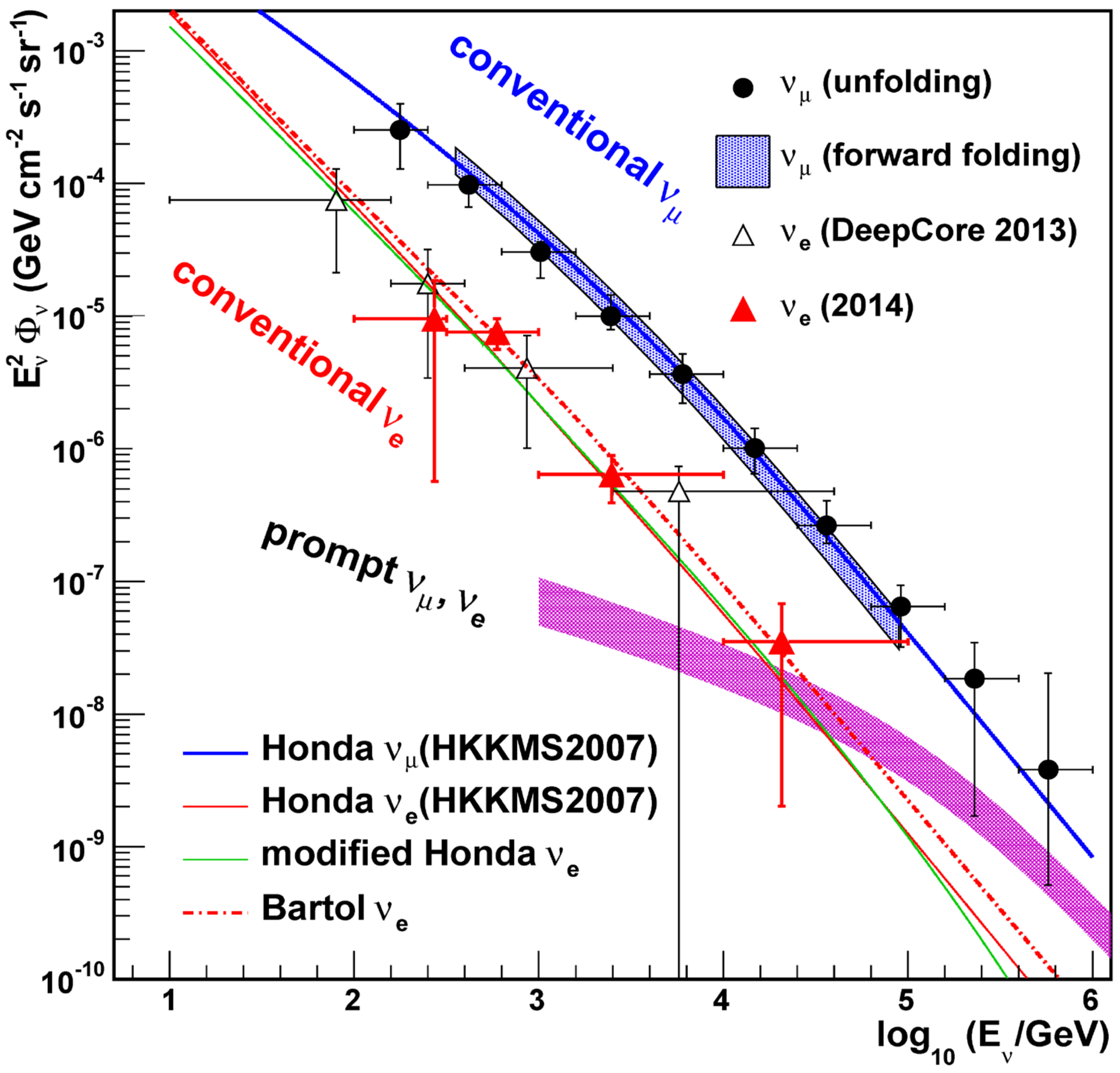


Search strategy for astrophysical neutrino flux

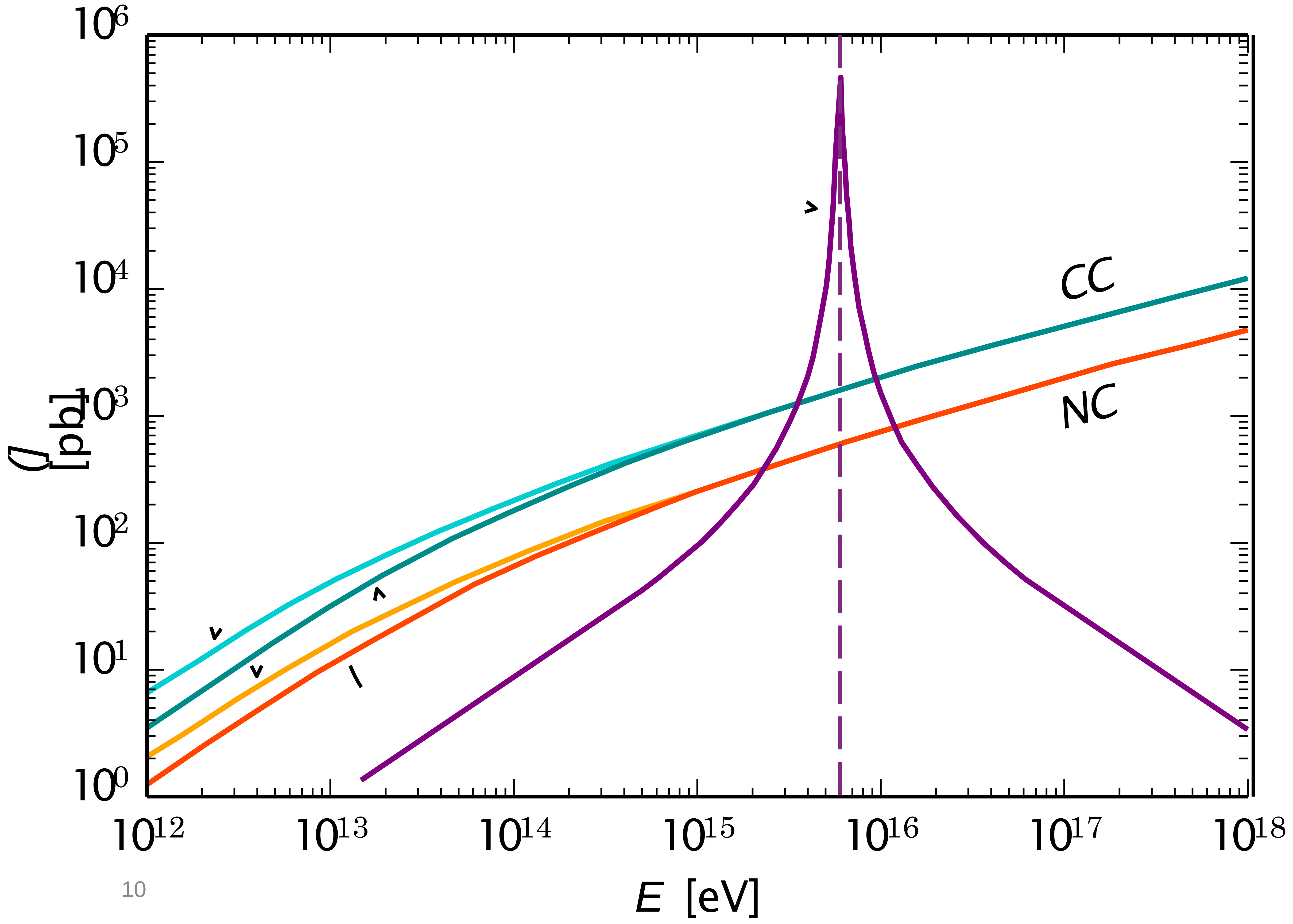
E < 1 PeV – from below the horizon

E> 1 PeV - from above the horizon

Atmospheric neutrino flux



Neutrino cross-sections



Astrophysical Diffuse Neutrino Flux

Data from 2018-2023:

effective livetime - 9778 days/eq.cluster (26.8 yr./cl.)

- **All-sky search for HE cascades:**

  threshold of E > 70 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)

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

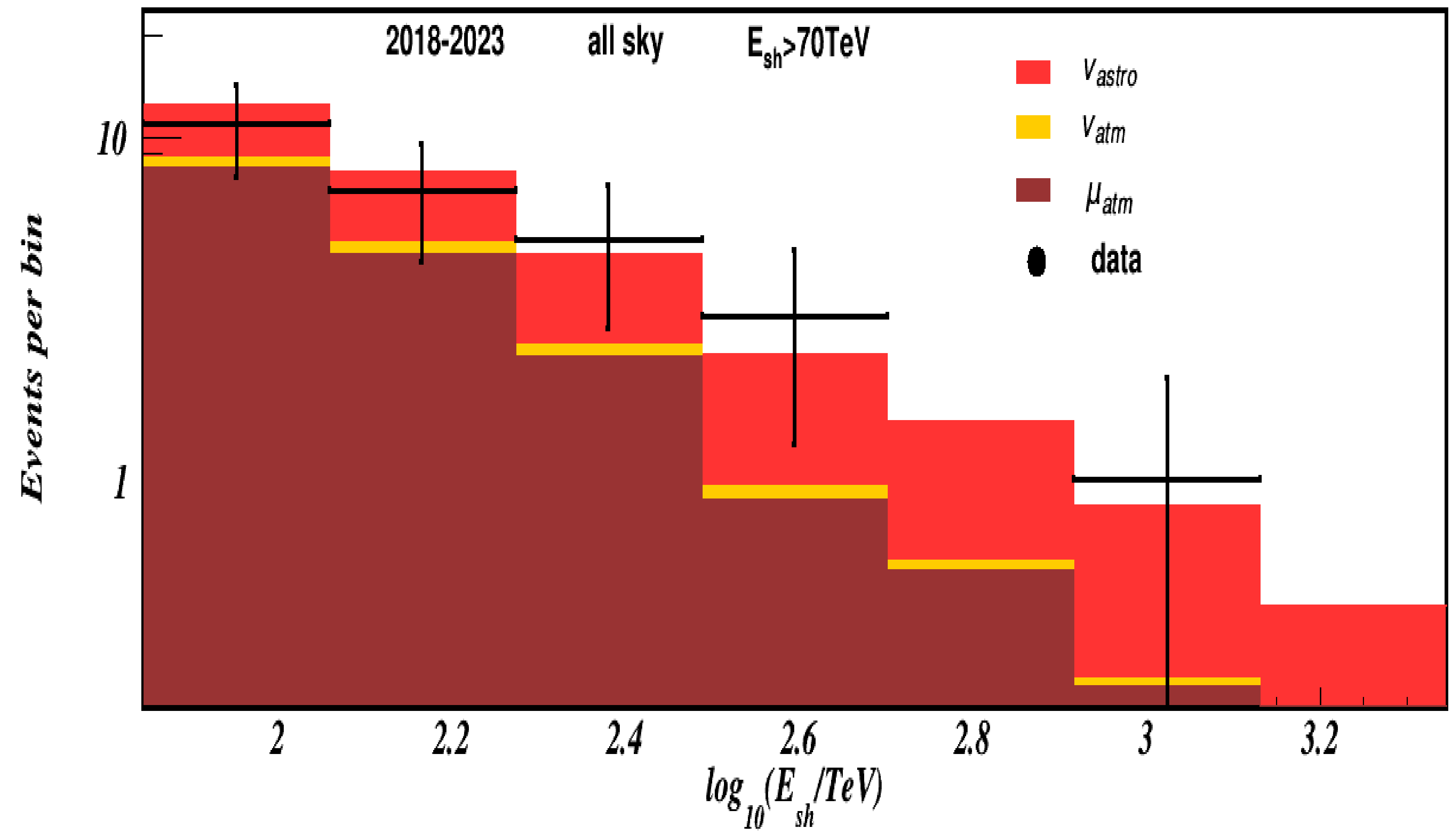
Expected:
14.7 events from atm. muons
1.0 events from atm. neutrinos
11.6 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

Phys.Rev. D107, 042005 (2023)

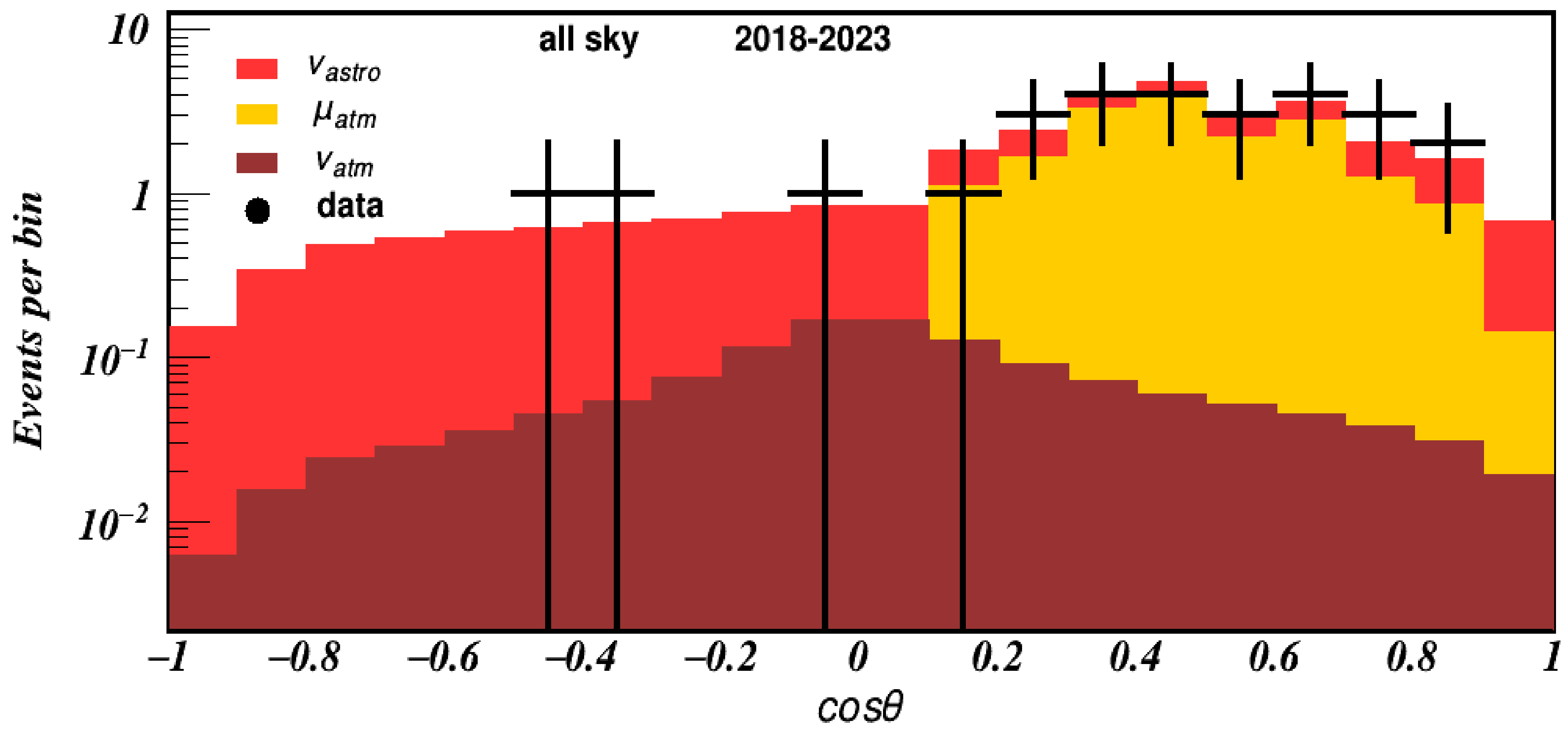
Found in real data: 28 events

Date	N_{data}	N_{bg}	P-value	Significance (no syst.)
18-21	16	8.2	2.09×10^{-2}	2.31σ
18-23	27	15.7	3.19×10^{-3}	**2.73σ**

Energy distribution (18-23)



Zenith distribution (18-23)



Search for upward moving events (2018-2023)

Selection requirements:

$E > 15$ TeV & $N_{hit} > 11$ & $\cos\theta < -0.25$

Expected:

1.0 events from atm. muons

5.3 events from atm. neutrinos

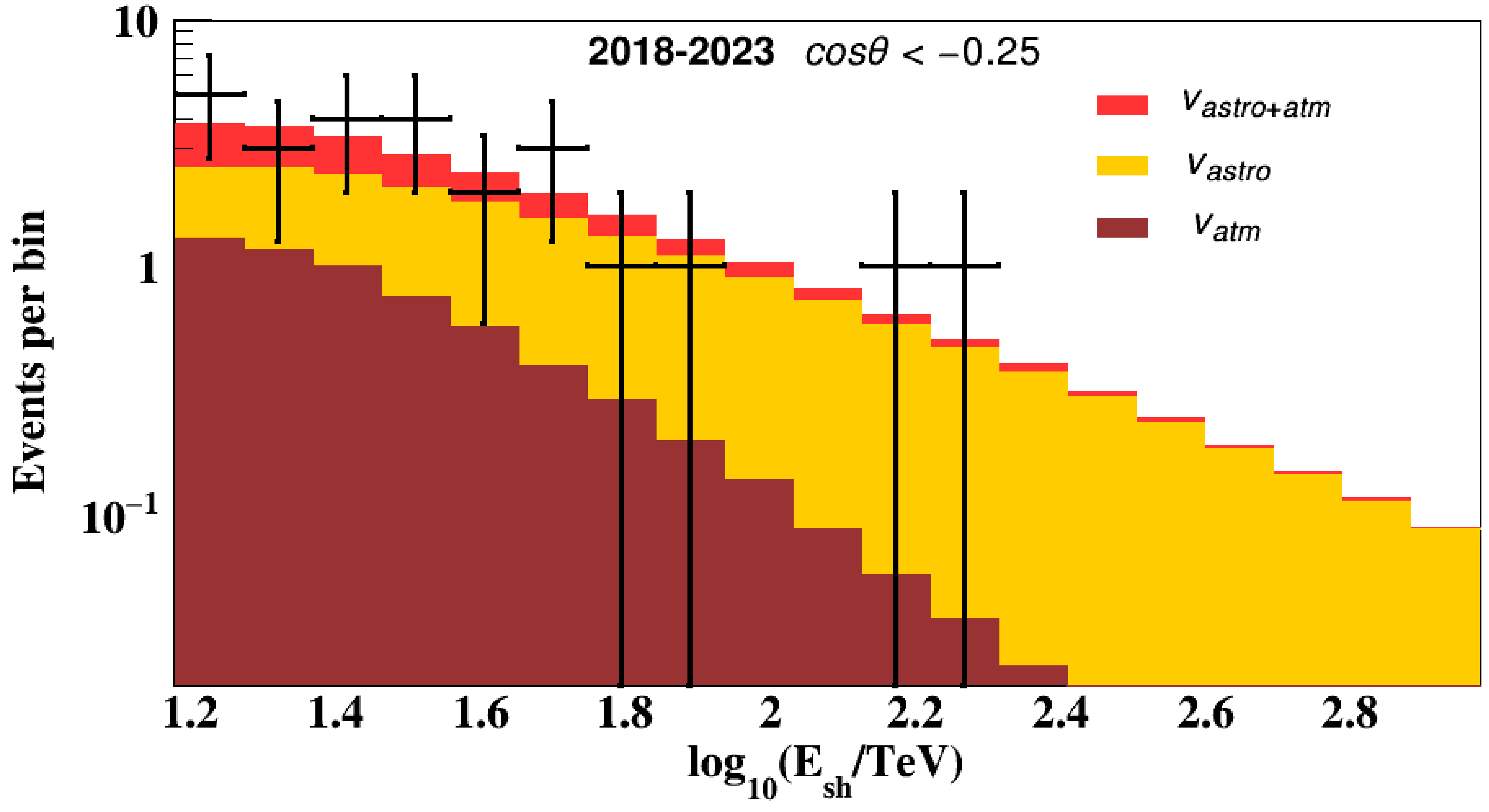
18.9 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

Found in data: 25 events

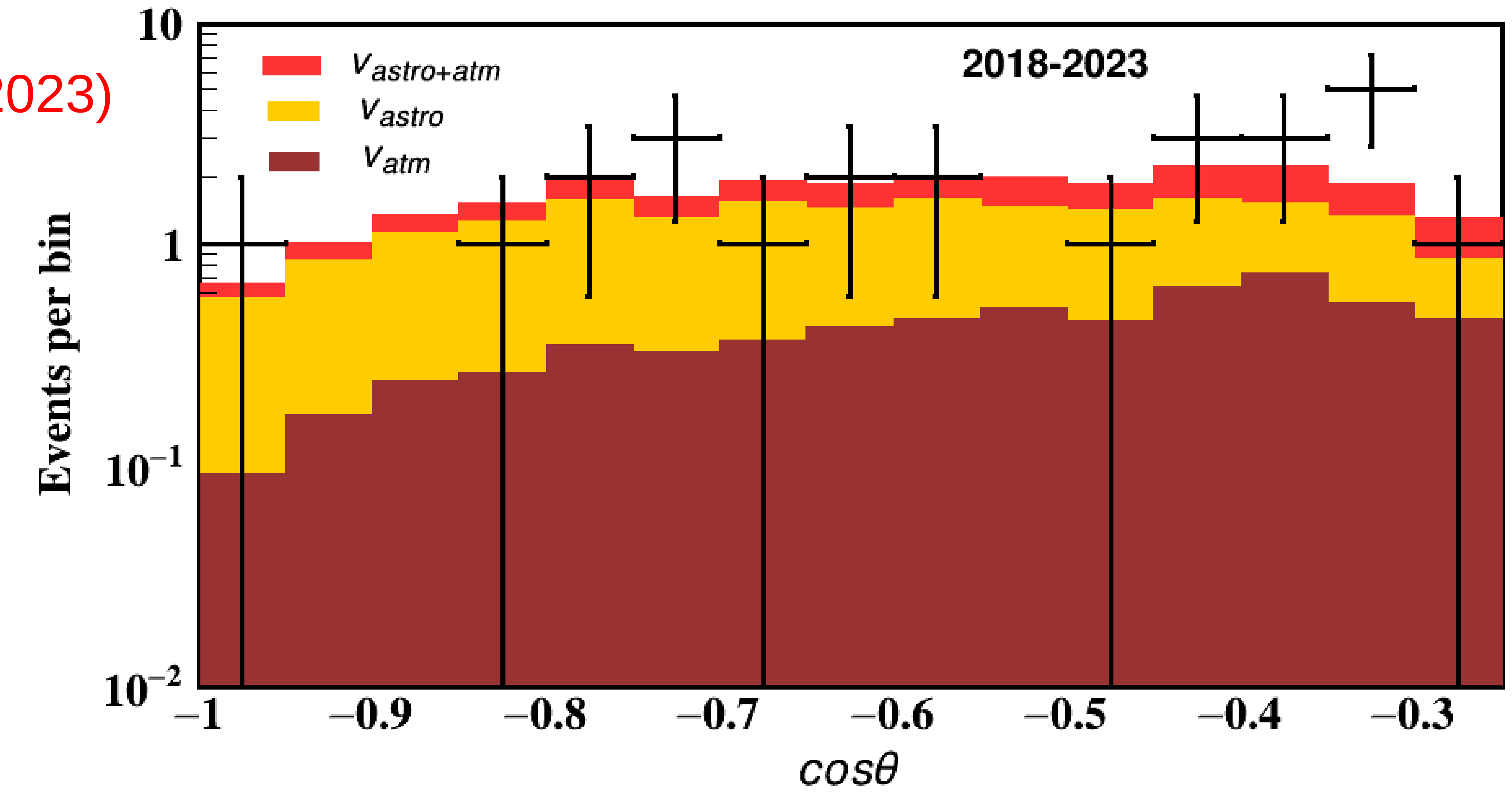
Phys.Rev. D107, 042005 (2023)

Date	N_{data}	N_{bg}	P-value	Significance (no syst.)
18-21	11	3.2	1.76×10^{-3}	3.13σ
18-23	25	6.3	1.5×10^{-8}	5.54σ

Energy distribution (18-23)



Zenith distribution (18-23)

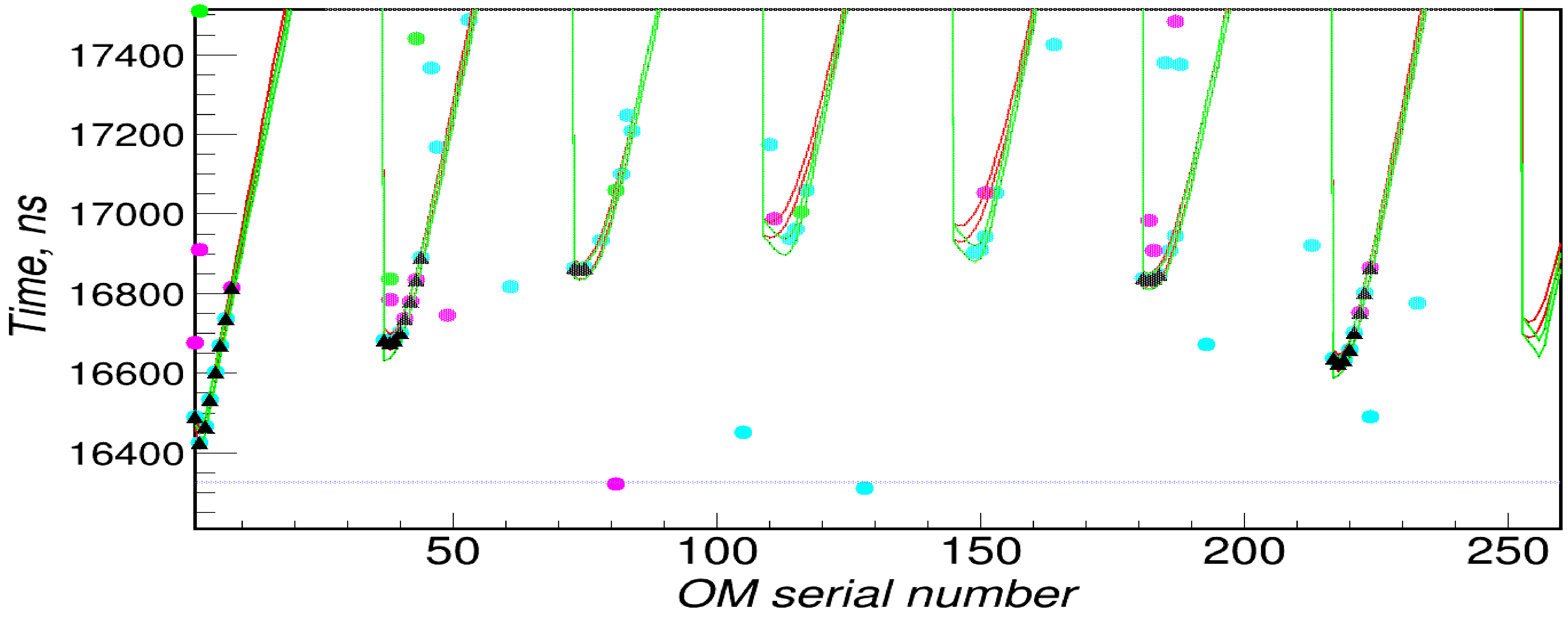


Event GVD200906

Track reconstruction

Cascade energy – 85 TeV; Zenith angle – 117°

OM hit arrival time



Season 2020, September Cluster 5

N_{hits}	37
E^{μ}_{rec}	107.2 ТэВ
θ_{rec}	116.7°
L_{track}	140.1 м

Angular precision:

50%:	0.7°
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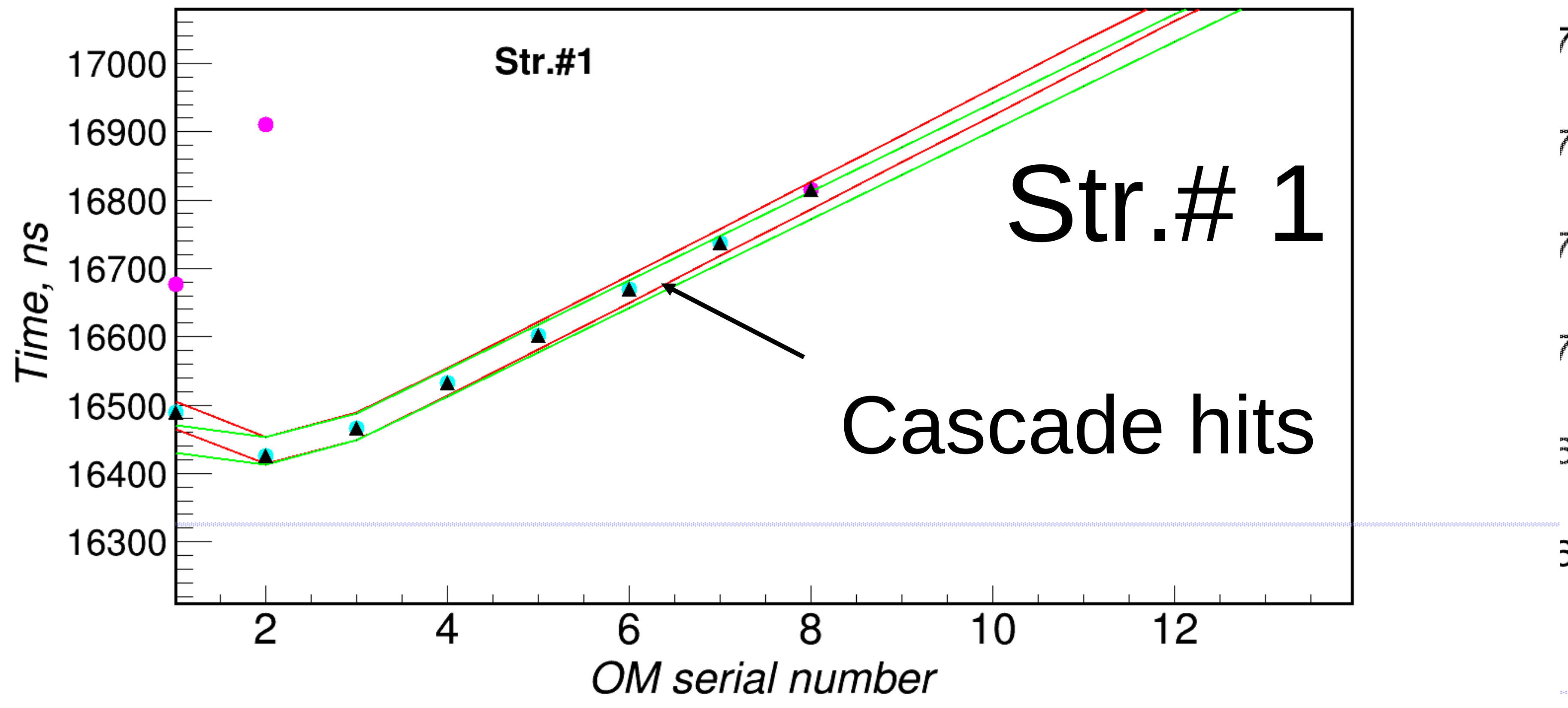
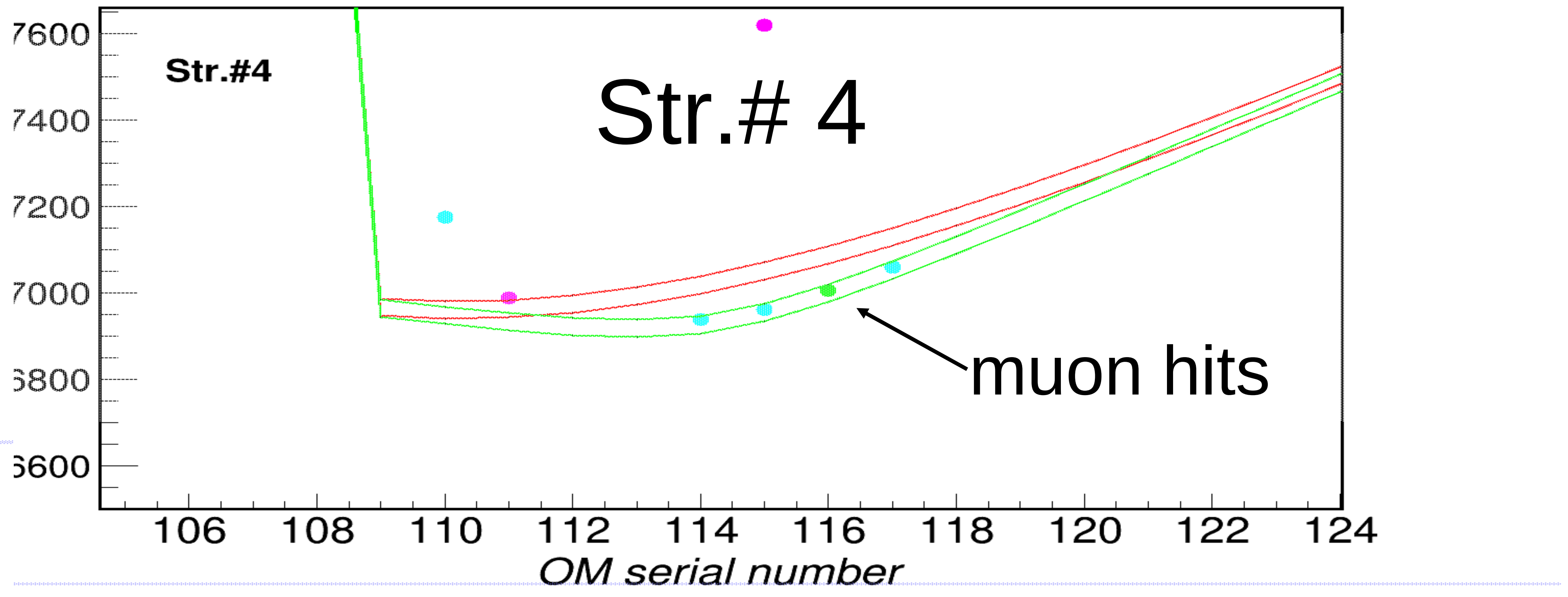
90%:	1.5°





Search for upward moving events (2018-2023)

Selection requirements:

$E > 15$ TeV & $N_{hit} > 11$ & $\cos\theta < -0.25$ $N_{hit\_\mu} < 2$

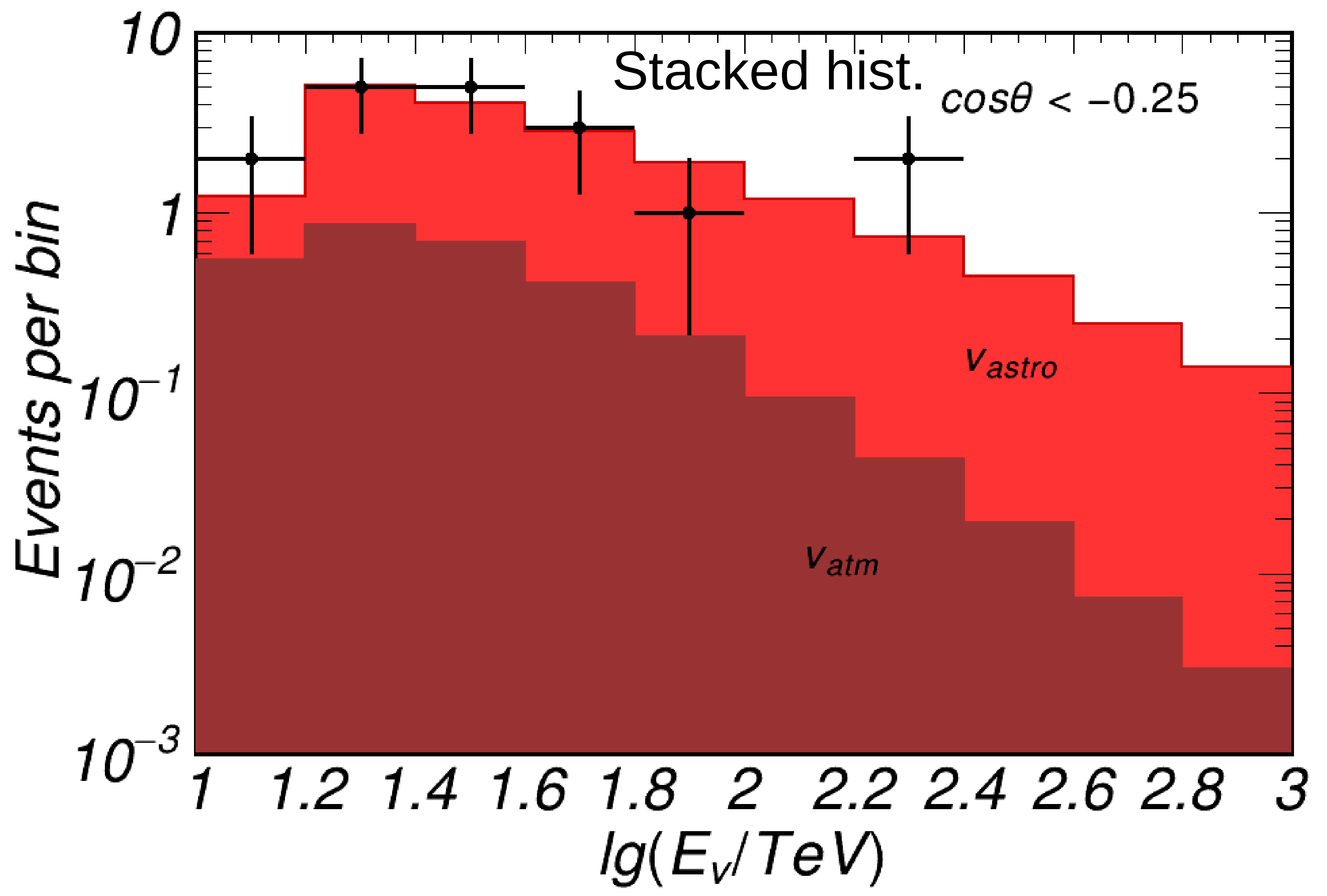
Expected:
0.4 events from atm. muons
2.1 events from atm. neutrinos
14.6 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

Found in data: 18 events

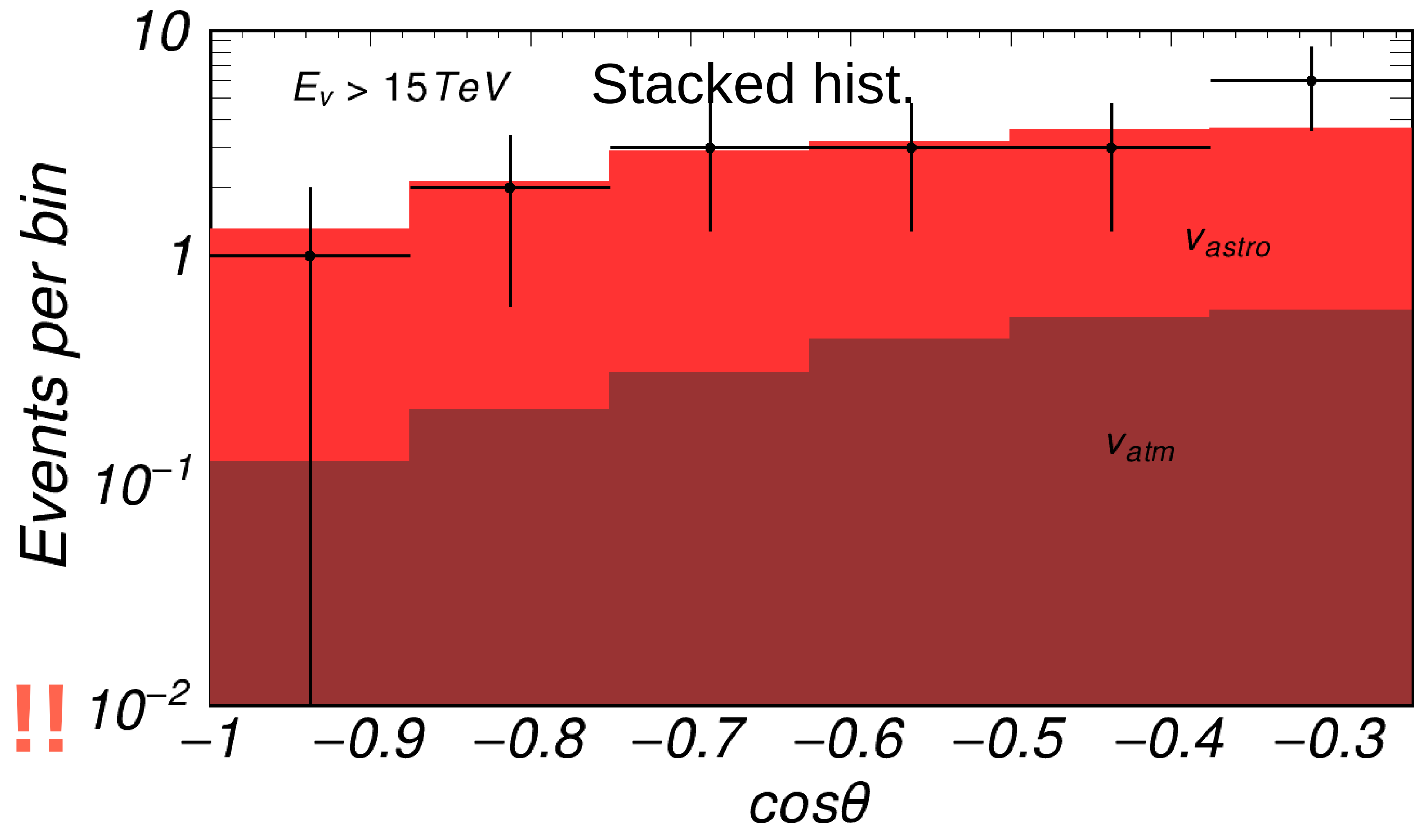
Date	N_{data}	N_{bg}	P-value	Significance (no syst.)	Significance (stat.&syst.)
18-23	18	2.5	2.15×10^{-10}	6.24σ	5.3σ !!!

Excess over the atmospheric background: 5.3σ!!!

Energy distribution (18-23)



Zenith distribution (18-23)



Single Power-Law Model of Astrophysical Flux

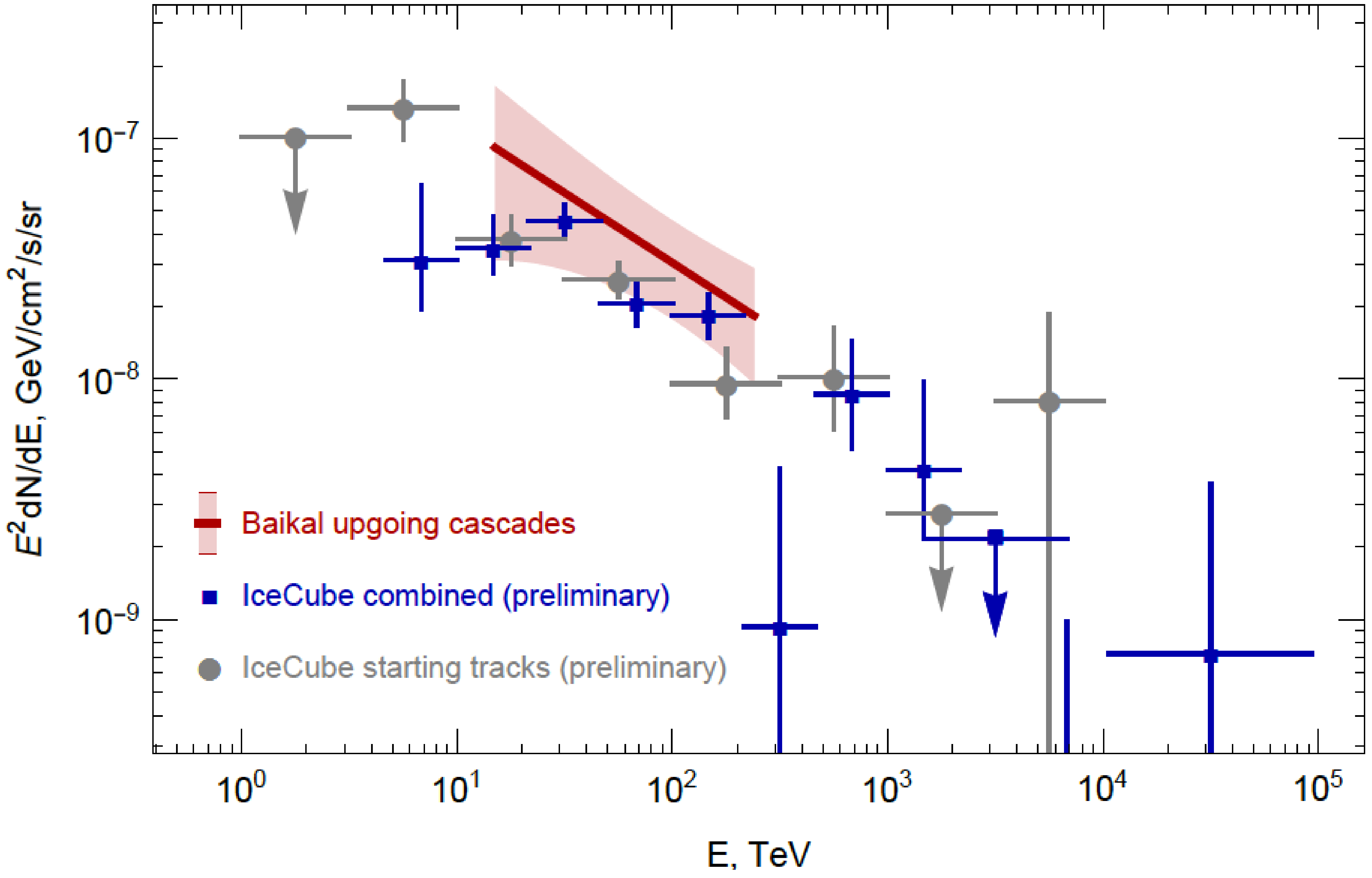
The best fit parameters for the single power law model:

$$\Phi^{\nu+\bar{\nu}}_{astro} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0}\right)^{-\gamma_{astro}} \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

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

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

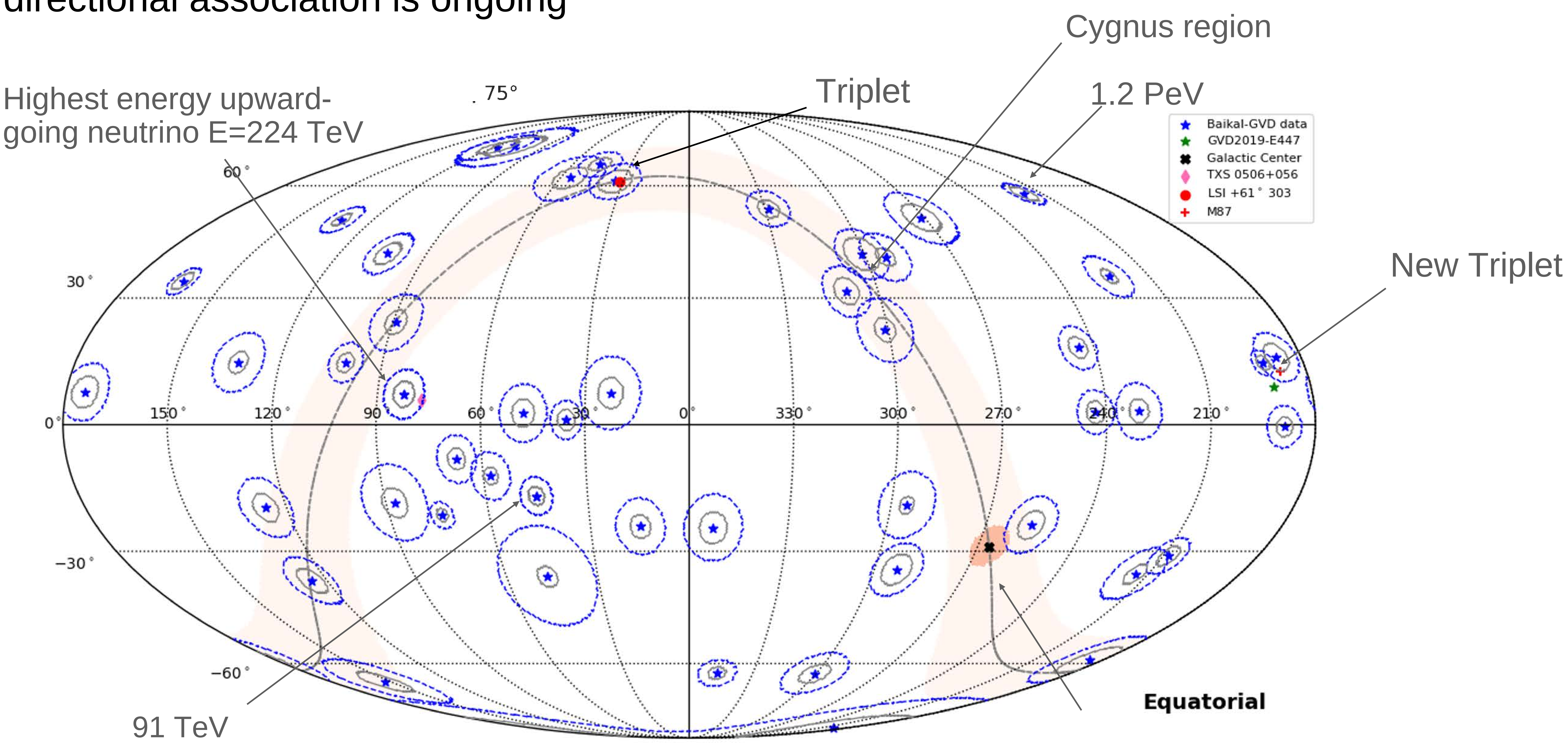
GVD diffuse flux



New High-Energy Cascade Sky Map

Data from April 2018 to March 2024

- Search for directional association is ongoing

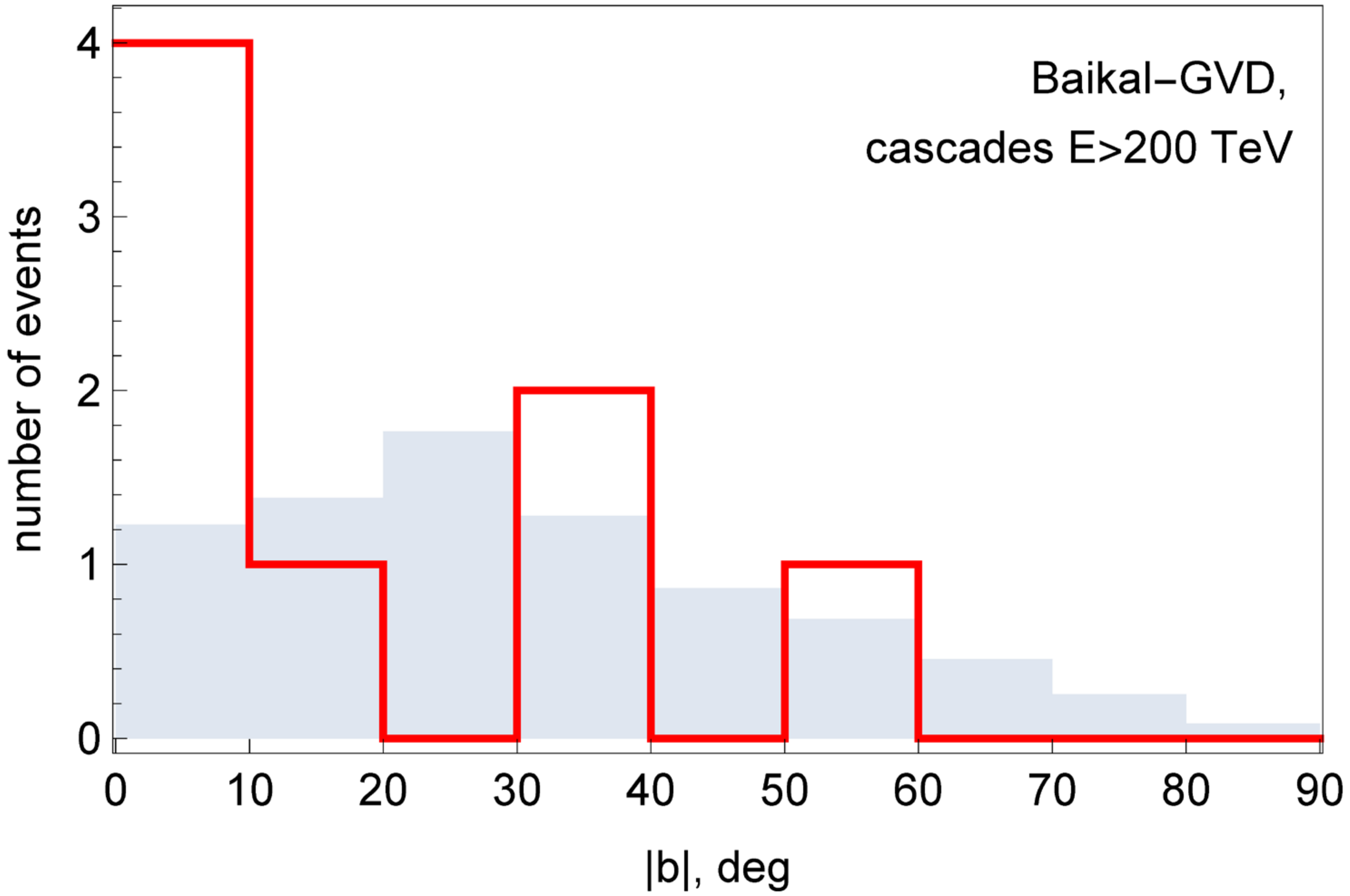


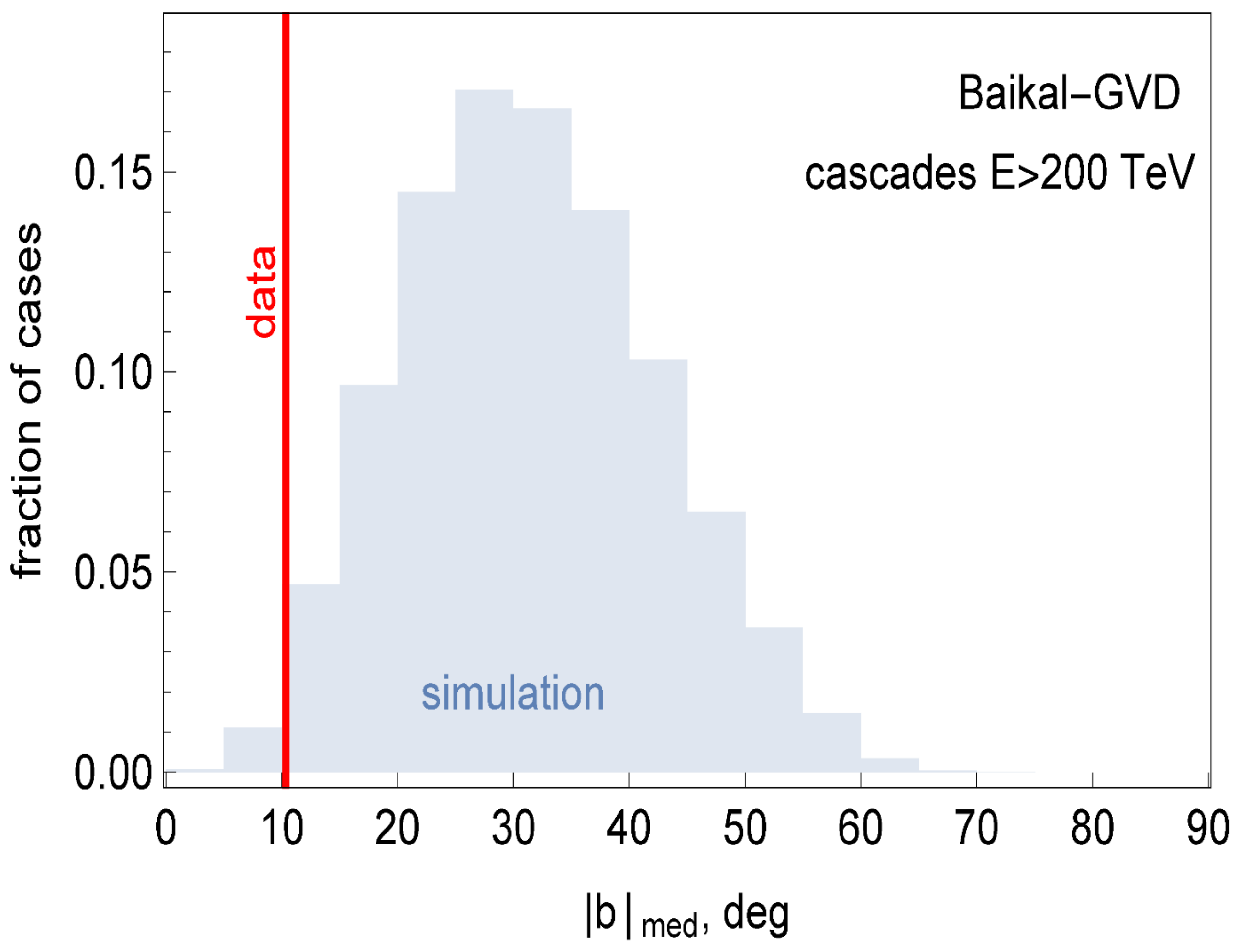
Best fit positions and 90% angular uncertainty regions

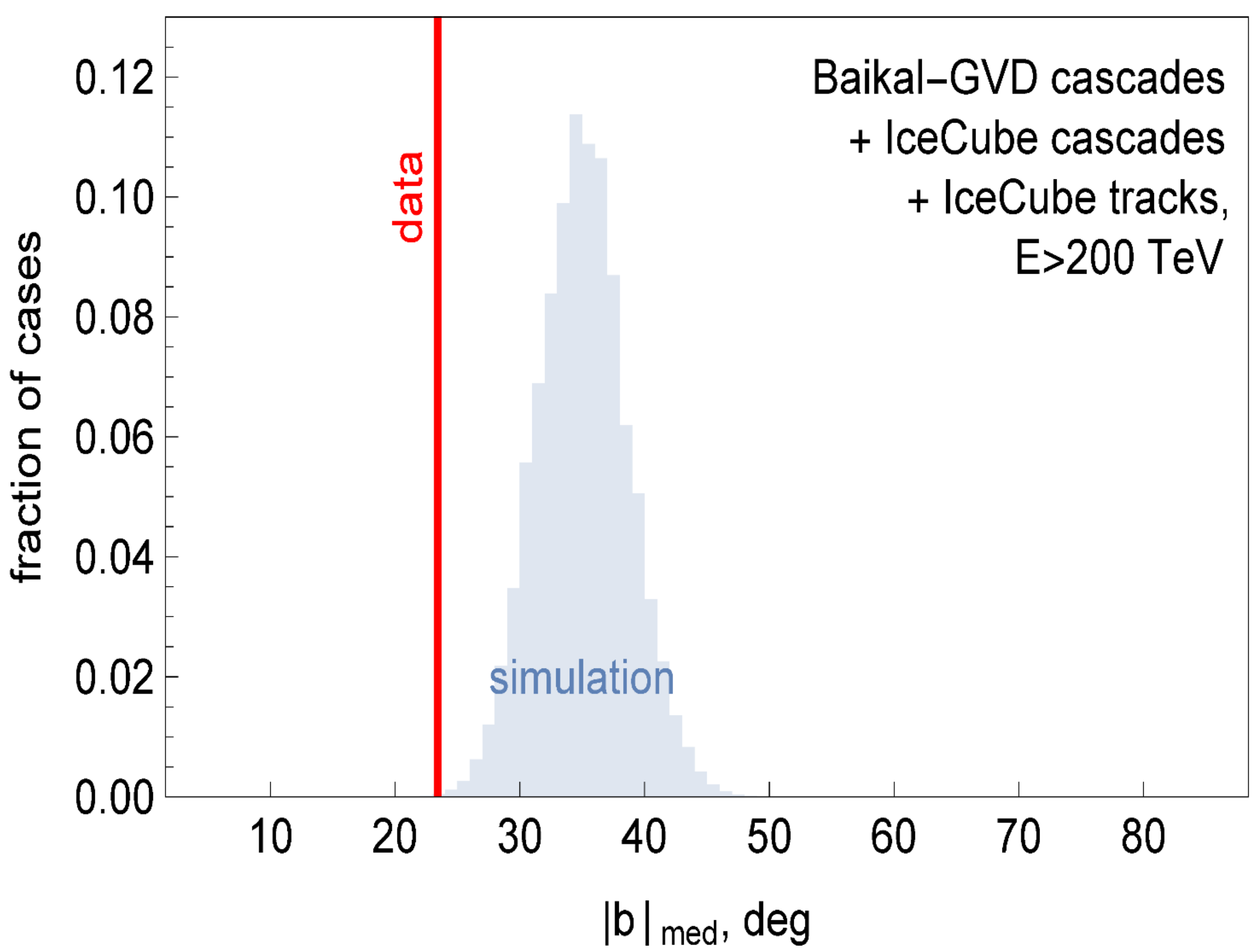
About half of the events are background from atmospheric muons and neutrinos

Galactic Neutrinos with the Highest Energies

- High-energy cascades April 2018- March 2024 (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



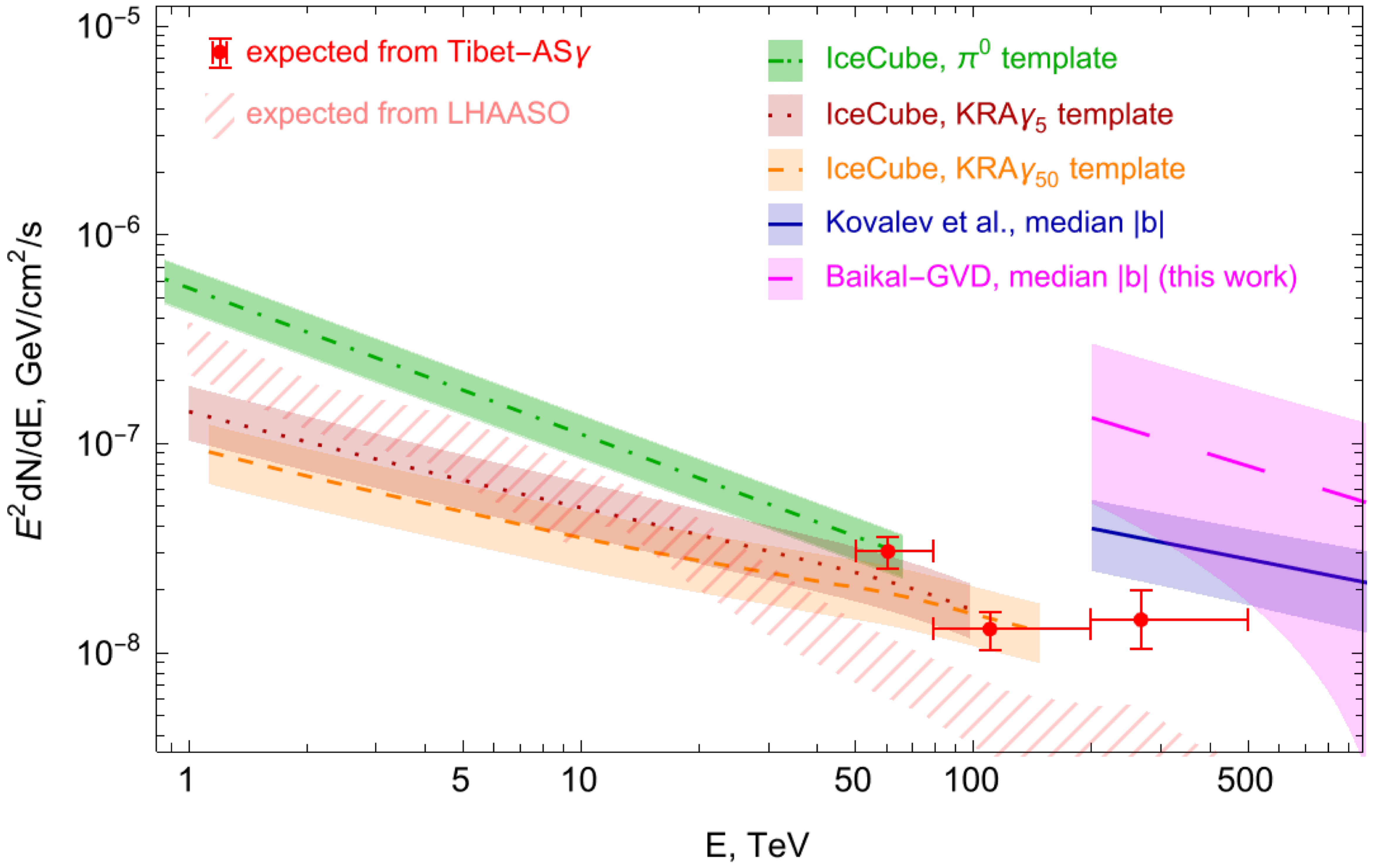


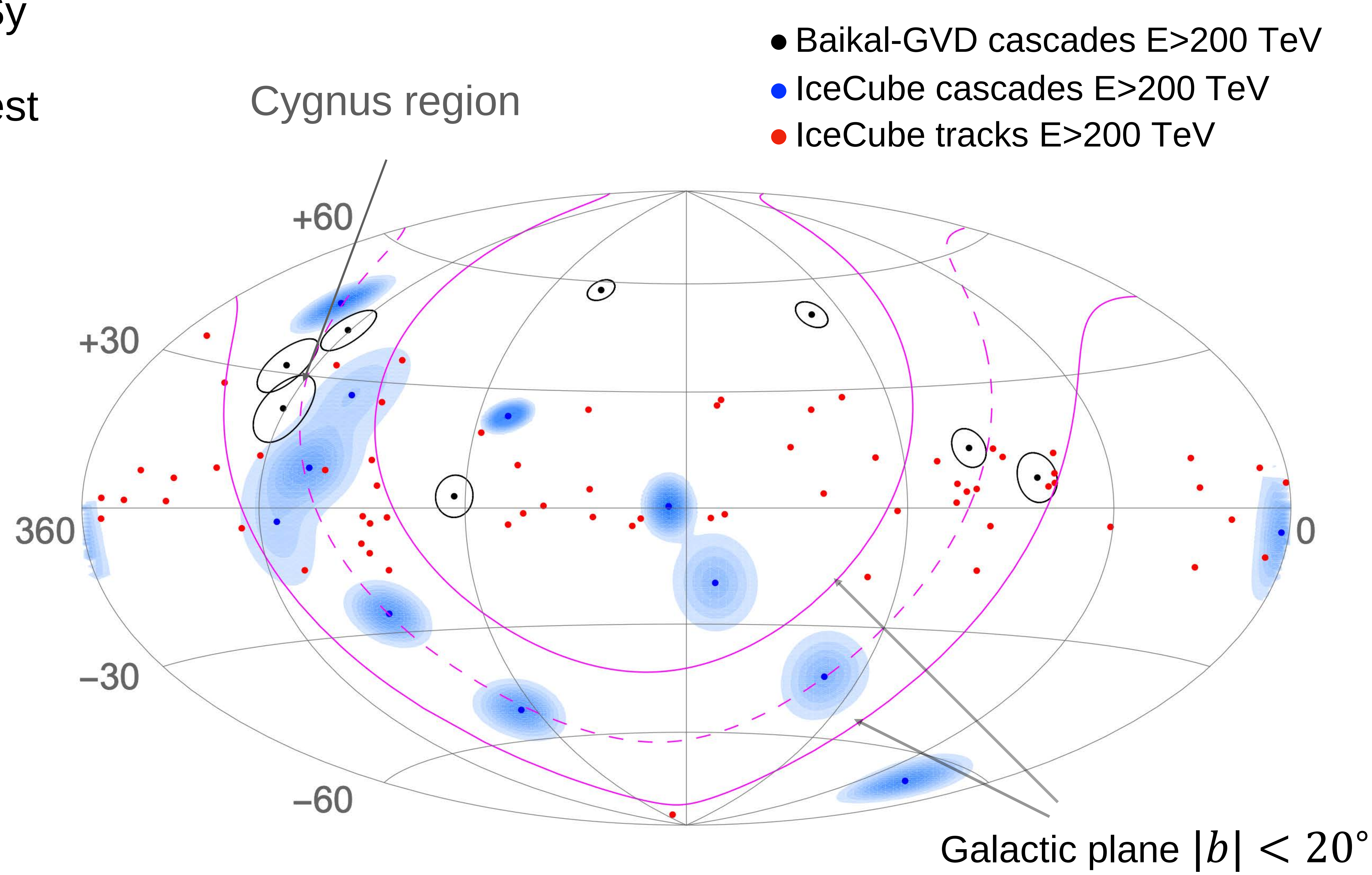


Sample	$\lvert b\rvert_{\rm med}$ observed	$\langle\lvert b\rvert_{\rm med}\rangle$ expected	p
Baikal-GVD cascades	10.4°	31.4°	$1.4 \cdot 10^{-2}$ (2.5σ)
IceCube cascades	12.4°	31.9°	$8.7 \cdot 10^{-3}$ (2.6σ)
combined cascades	12.4°	31.5°	$1.7 \cdot 10^{-3}$ (3.1σ)
IceCube tracks	24.7°	36.0°	$1.8 \cdot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

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)





ApJ (accepted);arXiv:2411.05608v2

Ultra High Energy neutrino flux limit *preliminary*

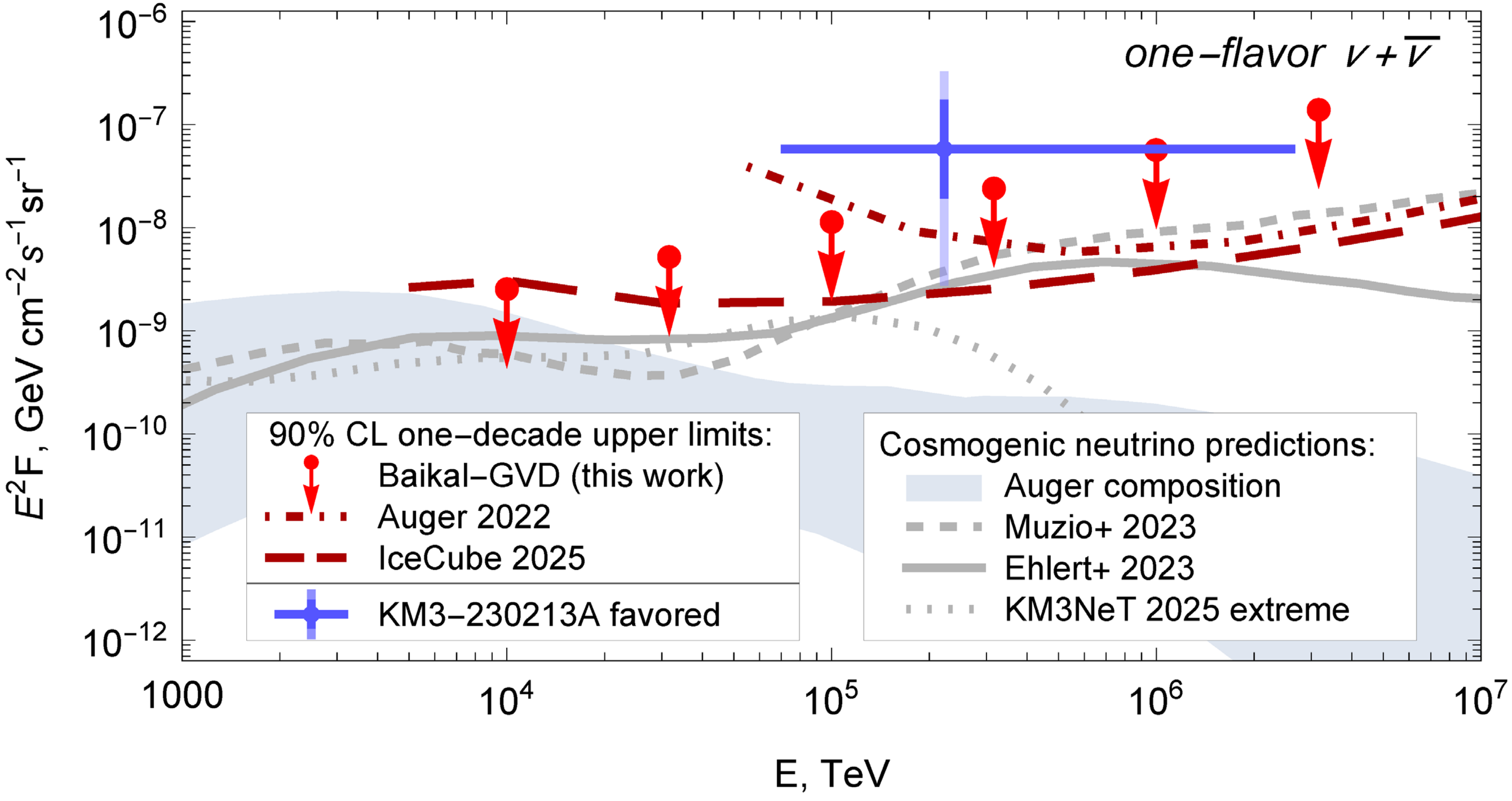
KM3-230213A:

Eν = 220 PeV,

Ra=94.3°, Dec=-7.8°

expected number of events

IC/NST:	0.014
IC/ESTES:	0.0034
IC/HESE:	0.00054
GVD:	0.006

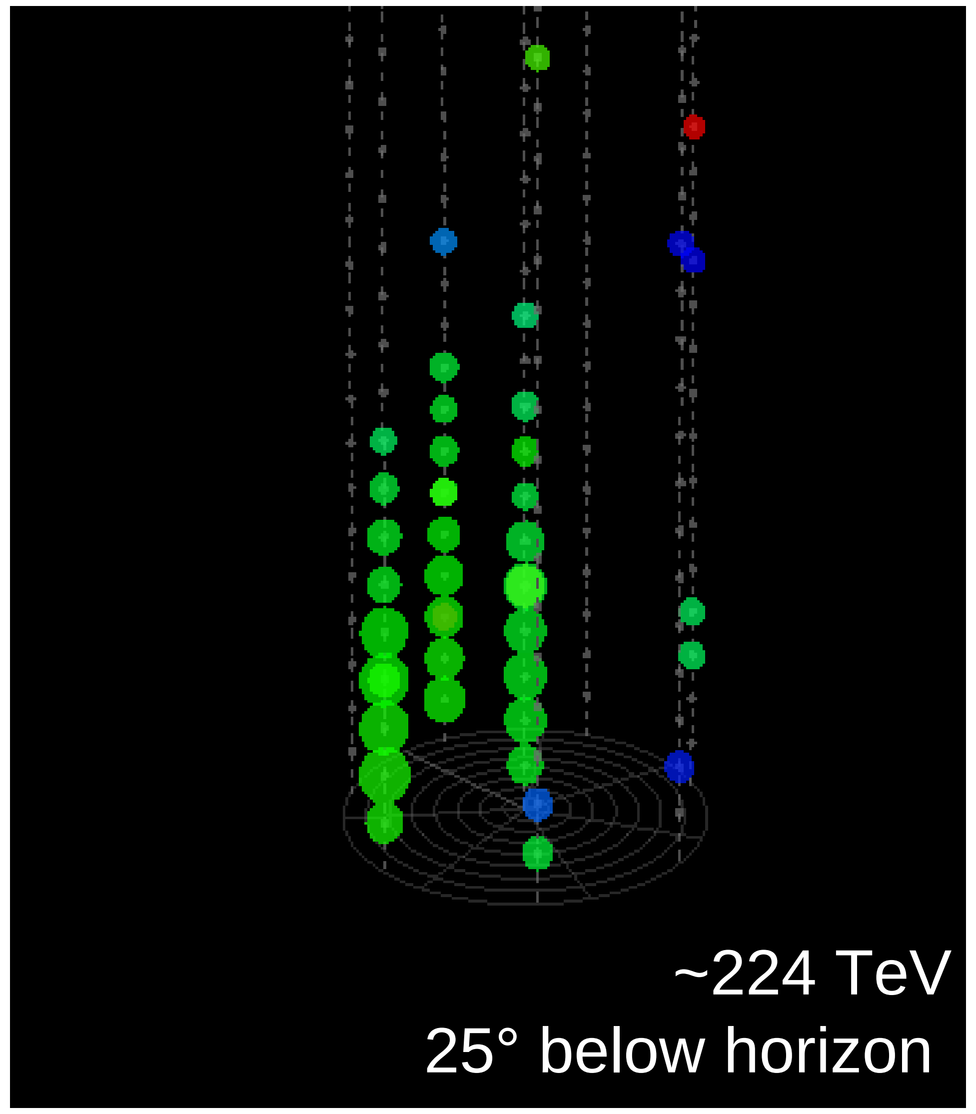


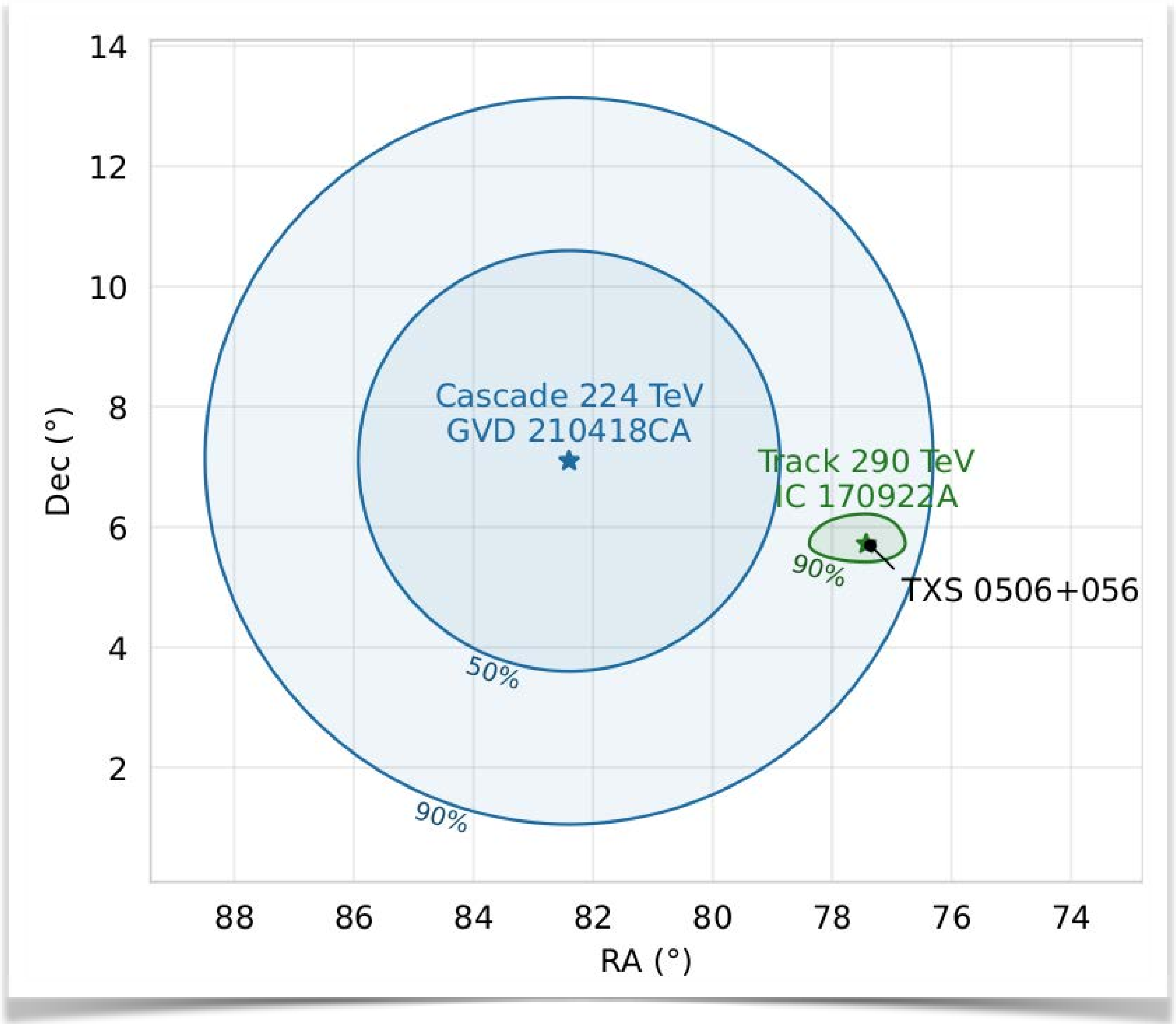
IceCube – track and cascade detection modes

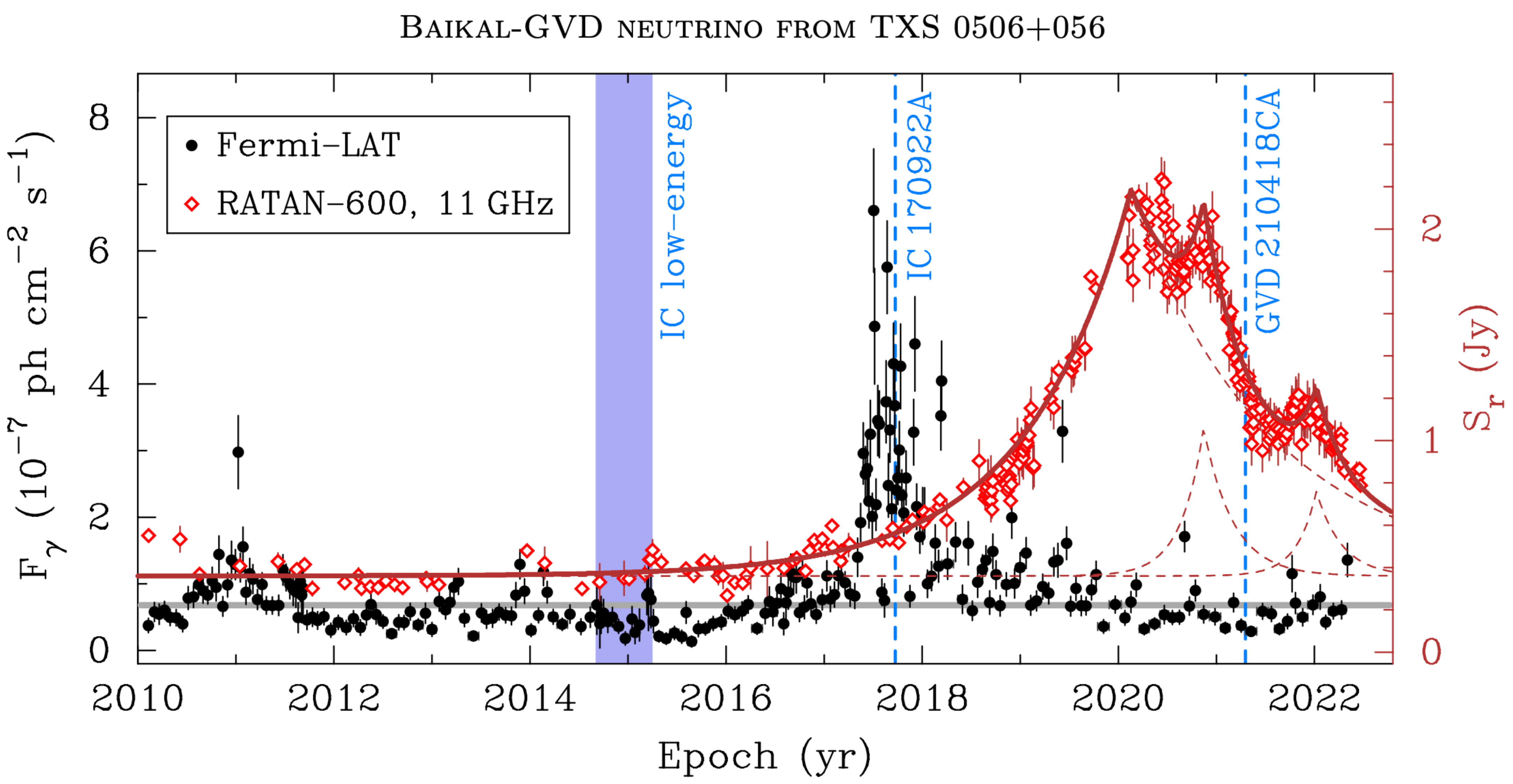
Baikal-GVD – cascade detection mode

Most energetic upgoing cascade event

Best candidate for neutrino events of astrophysical origin







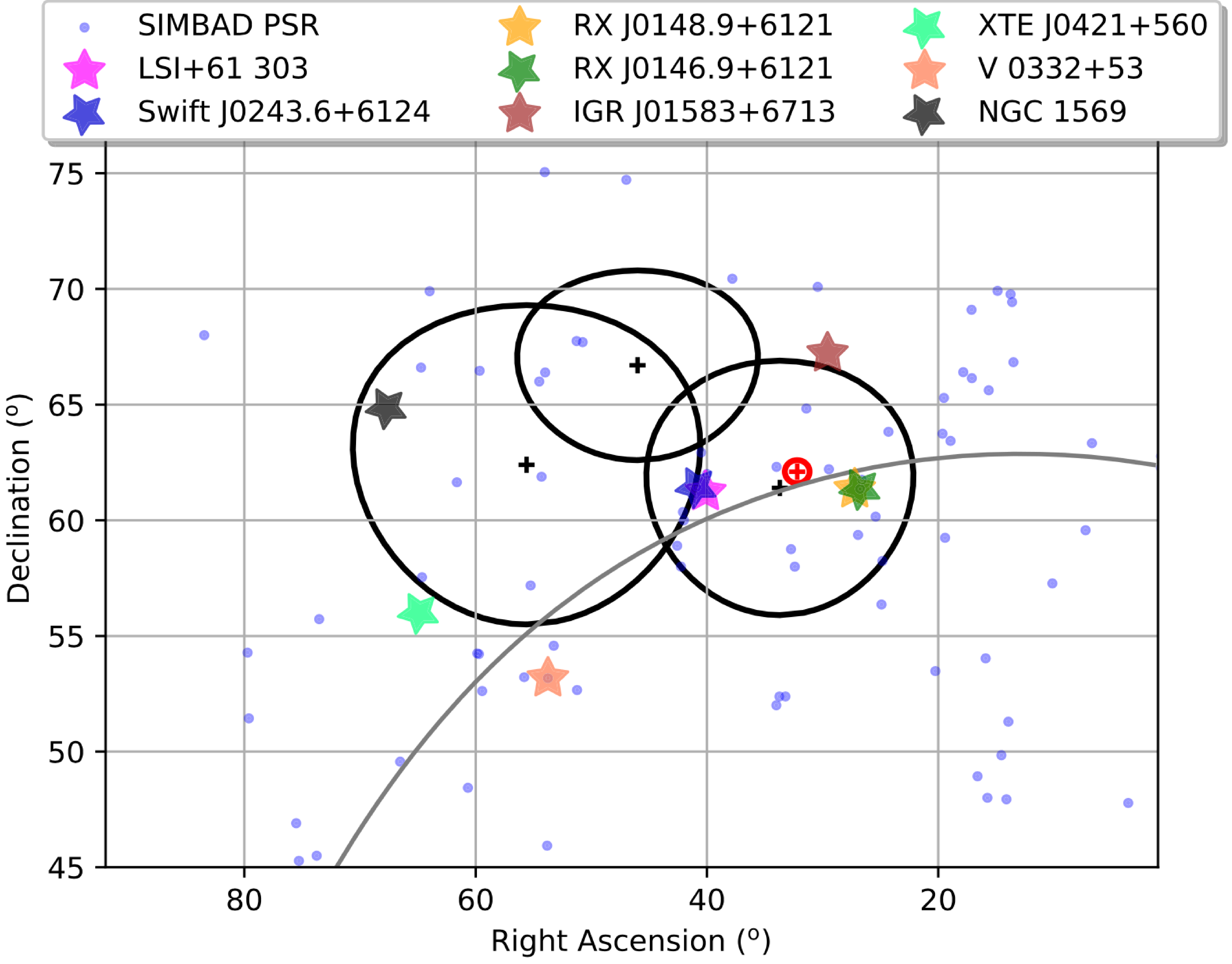
Closest sources (in 6 degrees):

- 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)

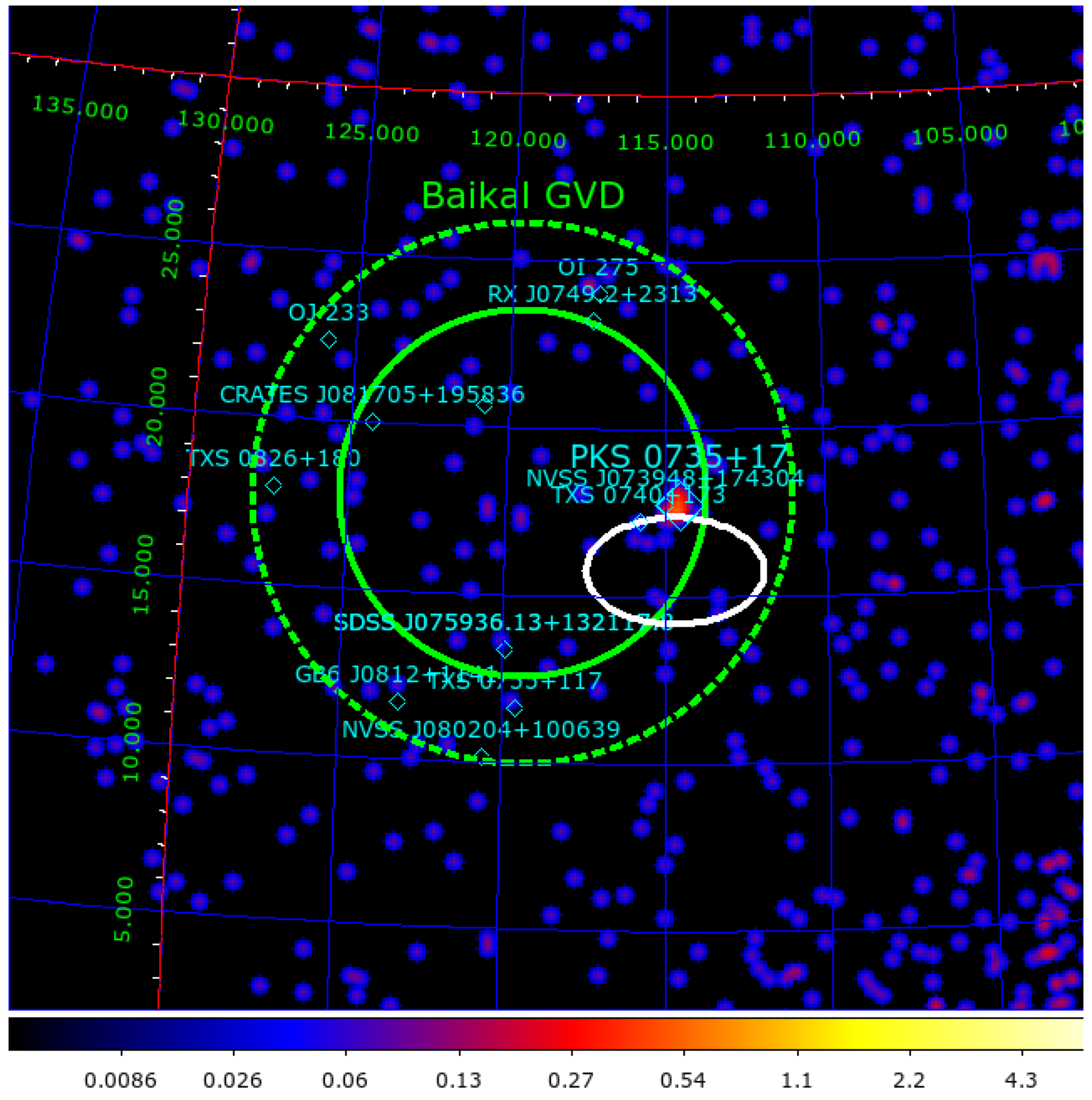
- γ-ray microquasar LS I +61 303 (very well known high energy Galactic source, only 2.6 kpc away) and the two Baikal-GVD events with 3.1° and 7.4° from the source (both are downgoing events)

- 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

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

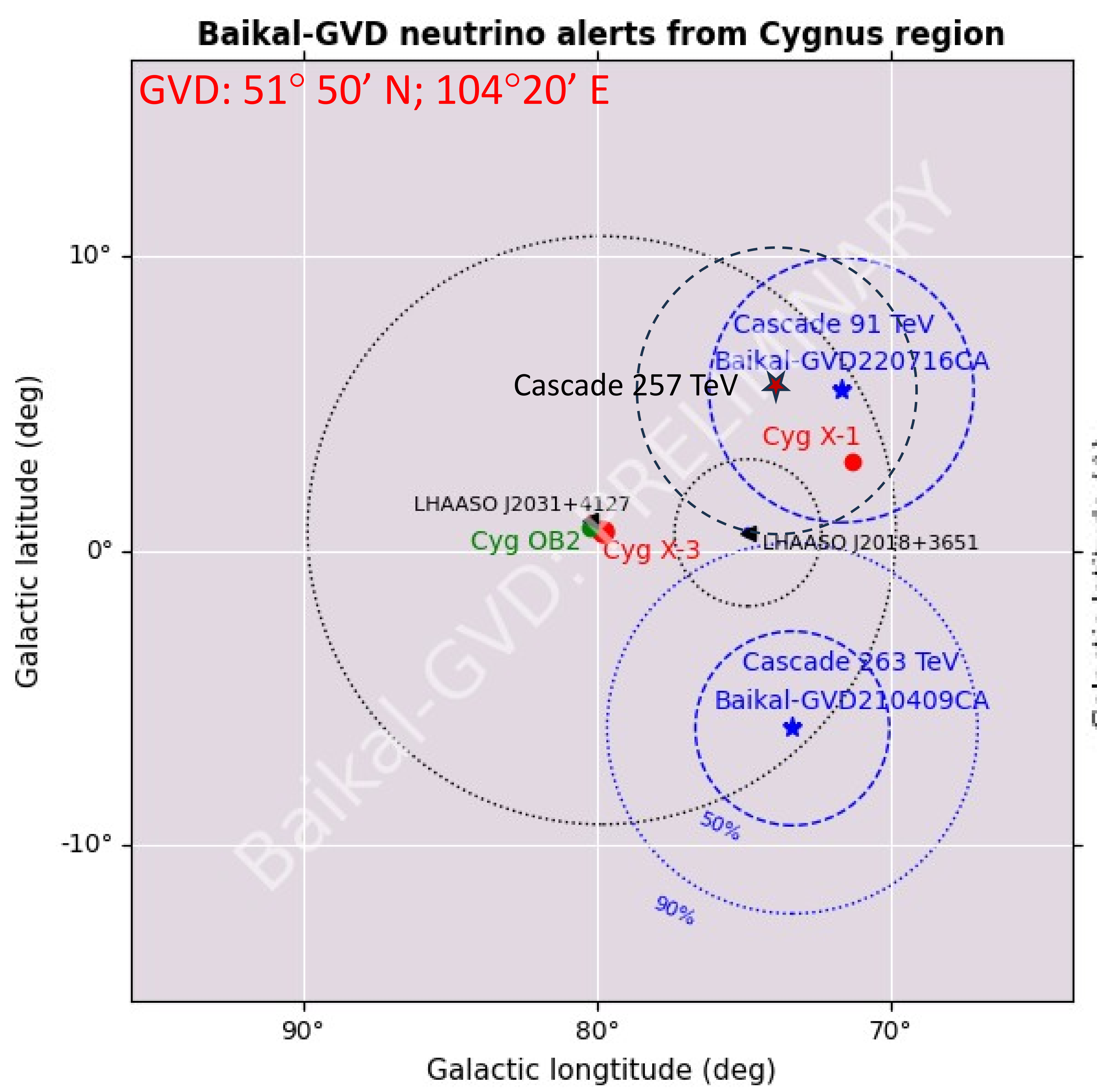
https://www.astronomerstelegram.org/?read=15112

Related

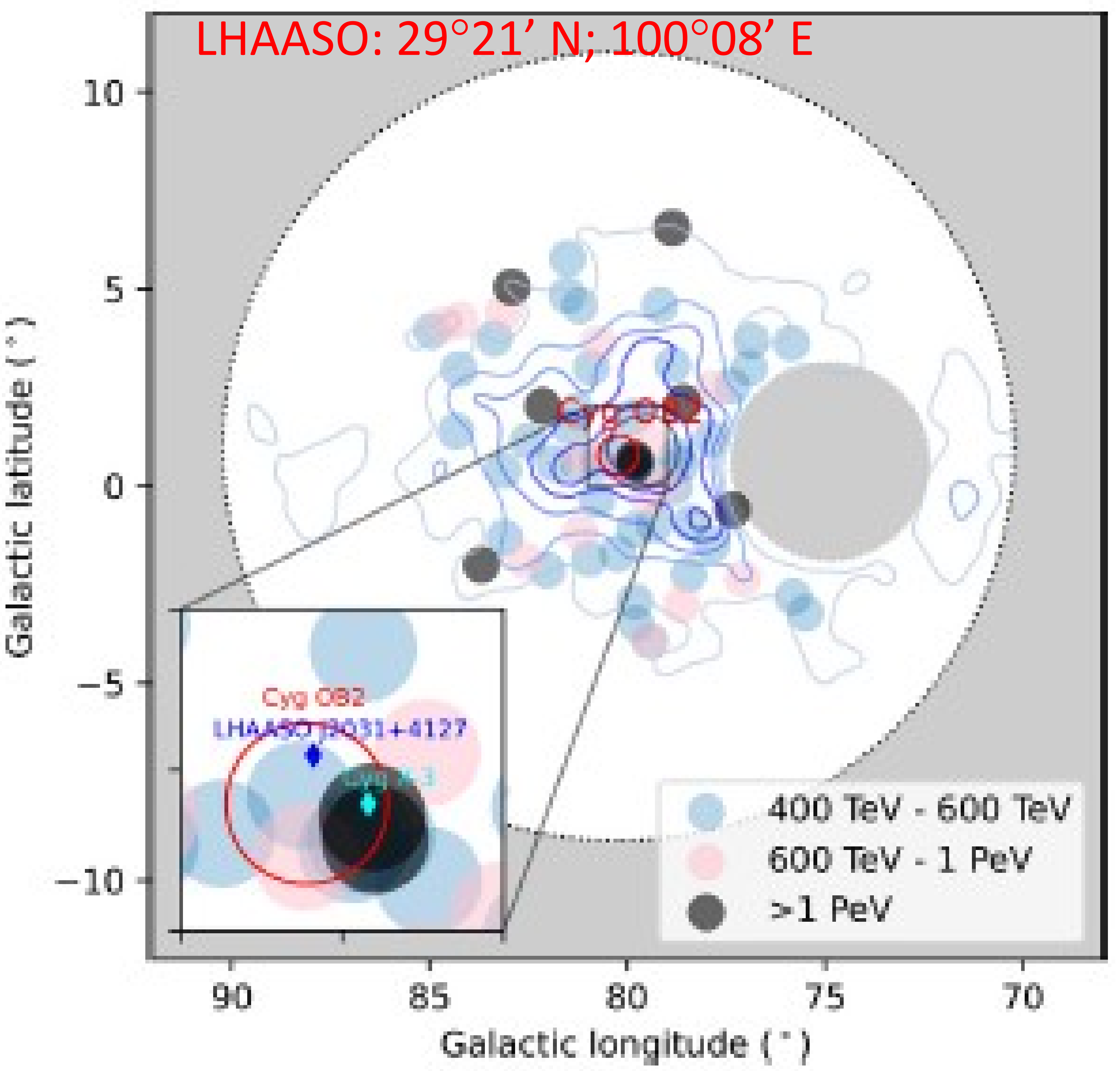
- **15290** Search for neutrino counterpart to the blazar PKS0735+178 potentially associated with IceCube-211208A and Baikal-GVD-211208A with the KM3NeT neutrino detectors.
- **15148** NIR followup of the Blazar PKS 0735+178
- **15143** Baksan Underground Scintillation Telescope observation of a GeV neutrino candidate event at the time of a gamma-ray flare of the blazar PKS 0735+17, a possible source of coinciding IceCube and Baikal high-energy neutrinos
- **15136** Optical and near-infrared observations of PKS 0735+178
- **15132** Optical view of neutrino emitter candidate PKS 0735 +178
- **15130** Re-brightening of the BL Lac object PKS 0735+178 observed by Swift
- **15129** Fermi-LAT observations of flaring activity from PKS 0346-27 and PKS 0735+178
- **15113** NuSTAR observations of the blazar PKS 0735+178
- **15112** Baikal-GVD observation of a high-energy neutrino candidate event from the blazar PKS 0735+17 at the day of the IceCube-211208A neutrino alert from the same direction
- **15109** Swift monitoring of the BL Lac object PKS 0735+178 during a bright state
- **15108** SRG/eROSITA observation of PKS 0735+17
- **15106** Search for counterpart to IceCube-211208A with ANTARES
- **15105** TELAMON, Metsahovi, Medicina, OVRO and RATAN-600 programs find a long-term radio flare in PKS0735+17 coincident with IceCube-211208A
- **15102** Swift-XRT observations of the blazar PKS 0735+178 in a flaring state
- **15100** Significant optical decay and brightening in blazar PKS 0735+17 coincident with IceCube-211208A
- **15099** Fermi-LAT Gamma-ray Observations of IceCube-211208A
- **15098** MASTER OT J073807.40+174219.2 brightening during IceCube-211208A observations
- **15021** BL Lac object PKS 0735+17 is bright in optical

GVD+ стратегия развития

- Увеличение эффективности регистрации нейтрино в области энергий 1 – 1000 ПэВ за счет увеличения детектирующего объема телескопа
- Повышение разрешающей способности в области энергий 1 – 100 ТэВ за счет оптимизации геометрии GVD (формирование плотного ядра детектора GVD+)
- Создание системы регистрации медленных частиц – монополь Рубакова и др., регистрации вспышек SN, поиск частиц темной материи за счет внедрения новой системы сбора и передачи данных
- Комплексное исследование галактических (Пэватроны) и внегалактических объектов в области энергий от сотен ТэВ и выше по данным GVD+, LHAASO,TAIGA



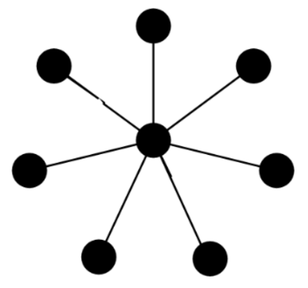
LHAASO- Science Bulletin 69 (2024) 449-457
We report the detection of a c-ray bubble spanning at least 100deg2 in ultra-high energy



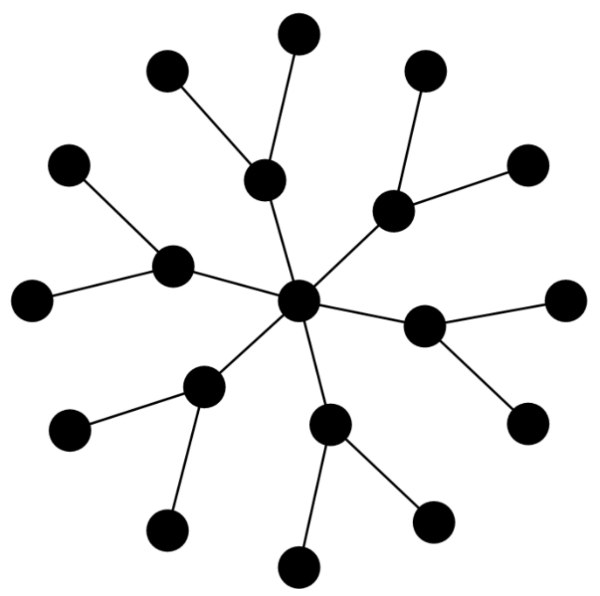
LHAASO: Science Bull. 69 (2024)

Toward Baikal project GVD+ / preliminary

Configuration



Cluster Baikal-GVD, 8 Strings
Distance between strings 60 m
D=120 m



Cluster GVD+, 19 Strings
Distance between strings ~80…100 m
D=300…380 m

$V_{GVD+/Cluster} / V_{GVD/Cluster}$ ~ 6…10

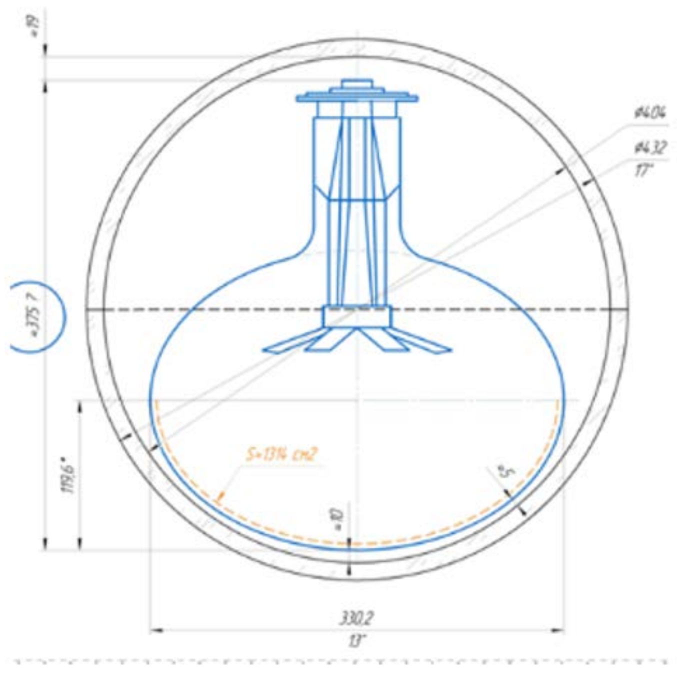
Data acquisition system

Architecture
Cluster-Strings-Sections.

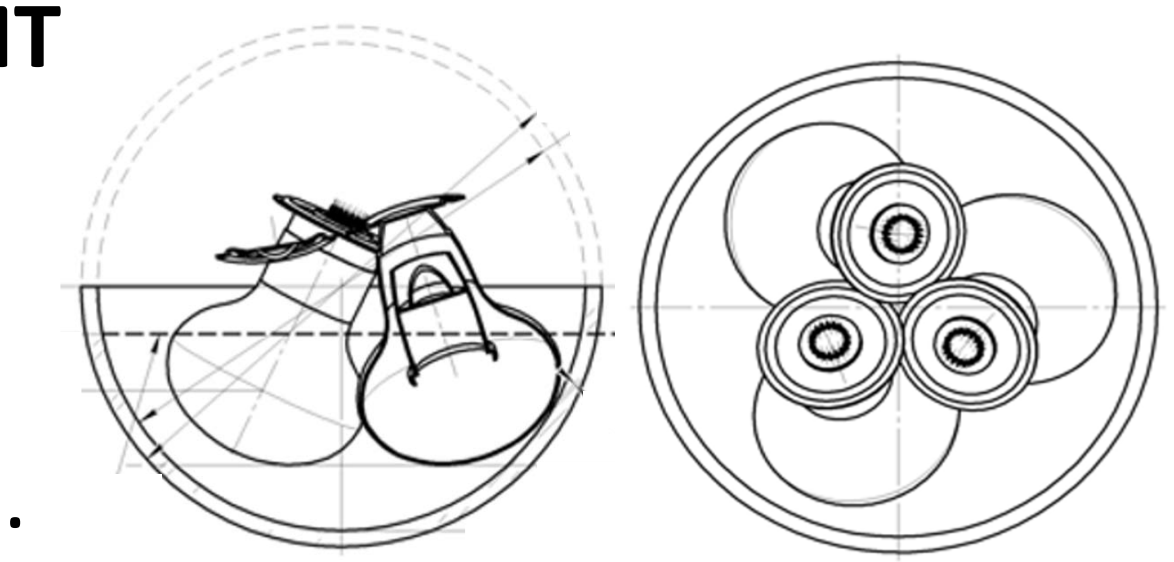
Implementation
- Fiber-optical DAQ.
- Data, Trigger and Synchro transmitted via a single optical line.
- The timing accuracy of the signals is better than 1 ns.
- OM outputs analog pulses (OM consumption less than 1 W).

Optical module

OM with one 13" PMT
- NEW PMT.
- Glass sphere 17".
- Expected parameters:
  QE > 26%, TTS < 4 ns.



OM with three 8" PMT
- PMT N6082.
- Glass sphere 20".
- Parameters:
  QE > 26%, TTS < 2 ns.



Detector design in progress

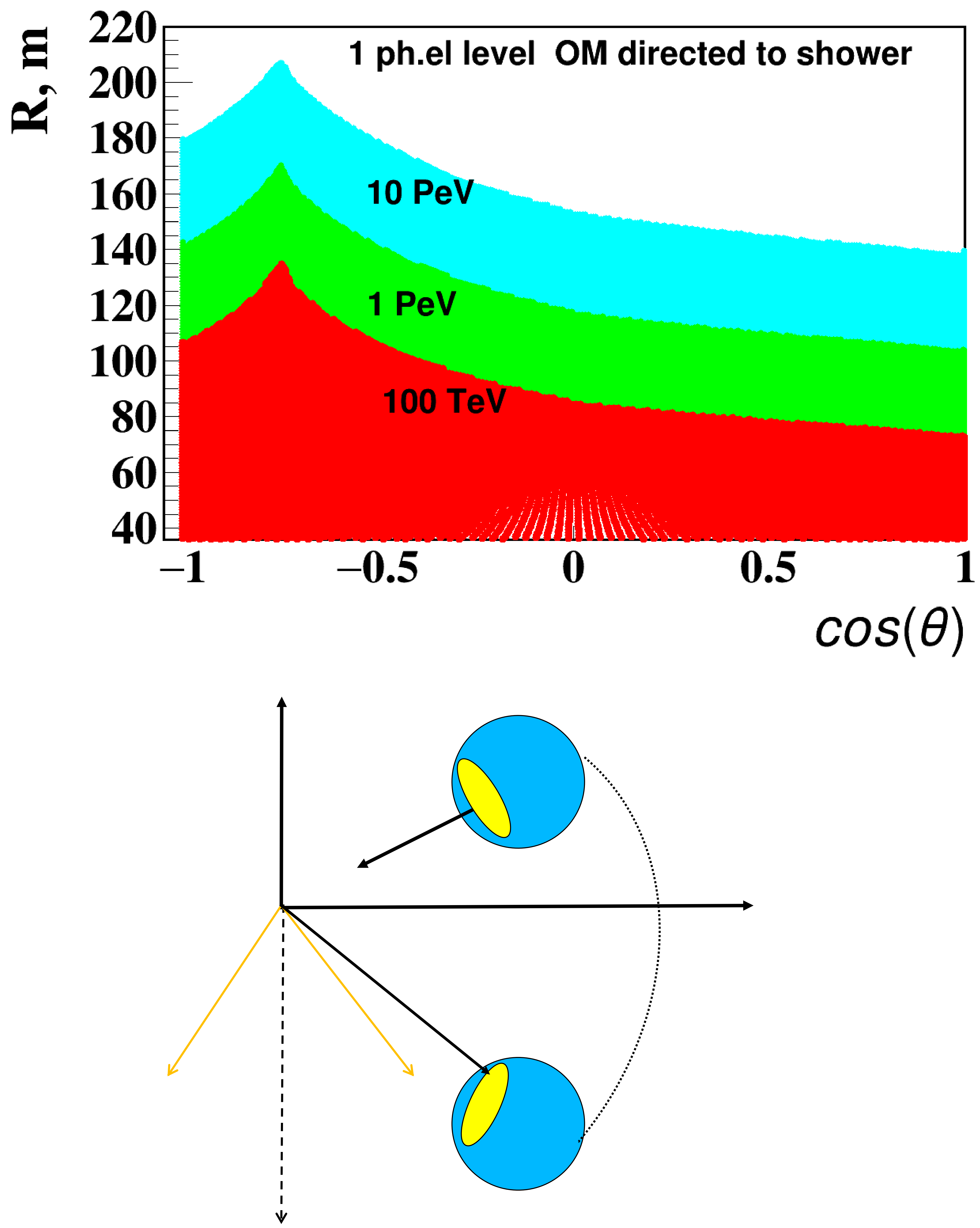
Conclusion

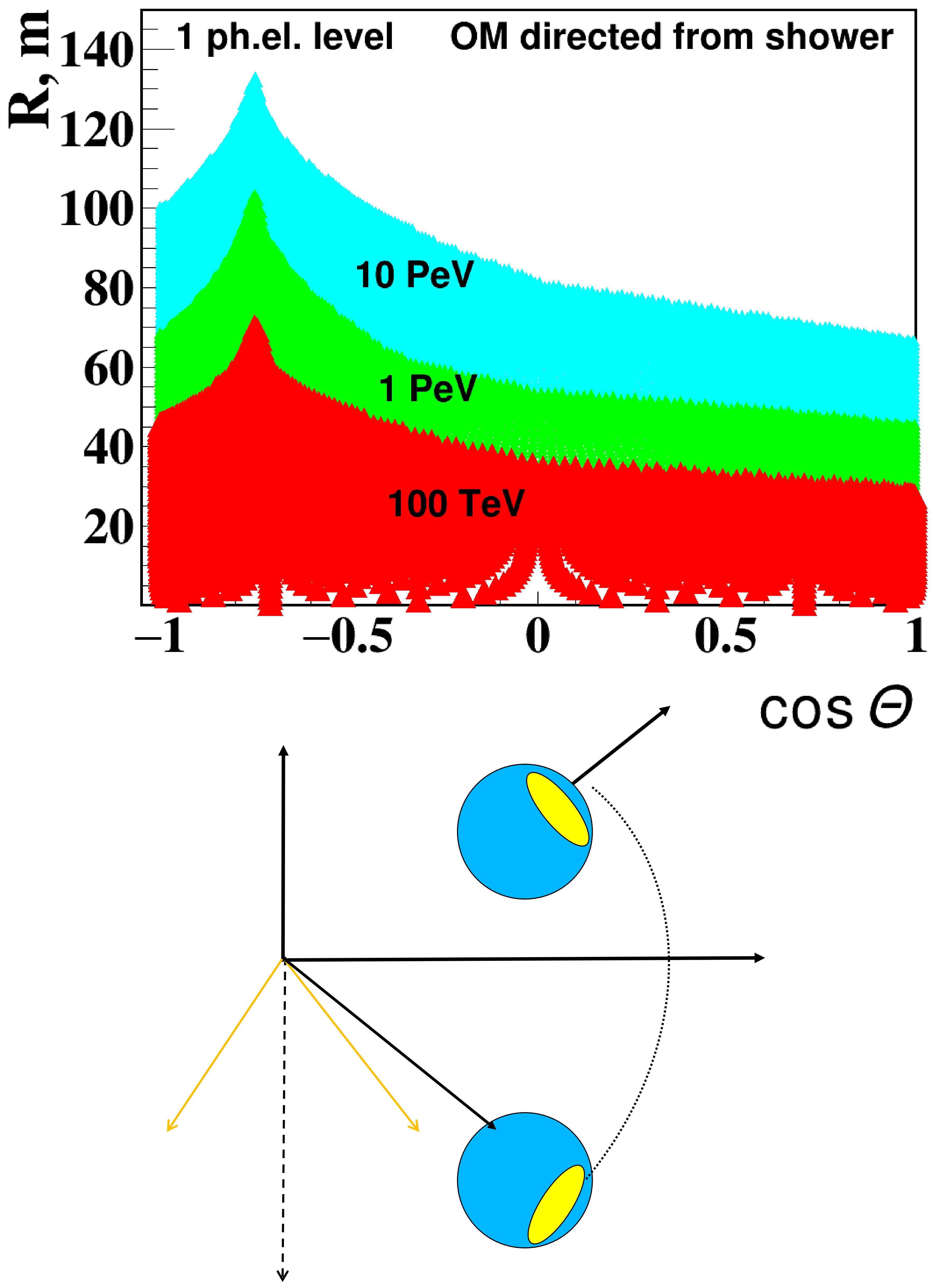
- Baikal-GVD is the largest neutrino telescope in the Northern hemisphere:
  - Volume approaching 0.6 km3 for high-energy cascades
  - Angular resolution better than 1° for tracks
  - Field of view complementary to IceCube
- Nearest plans:
  - Installation of two new clusters + full-scale string for the next-generation project (if the ice conditions are favorable to us)
- 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

Спасибо за внимание!

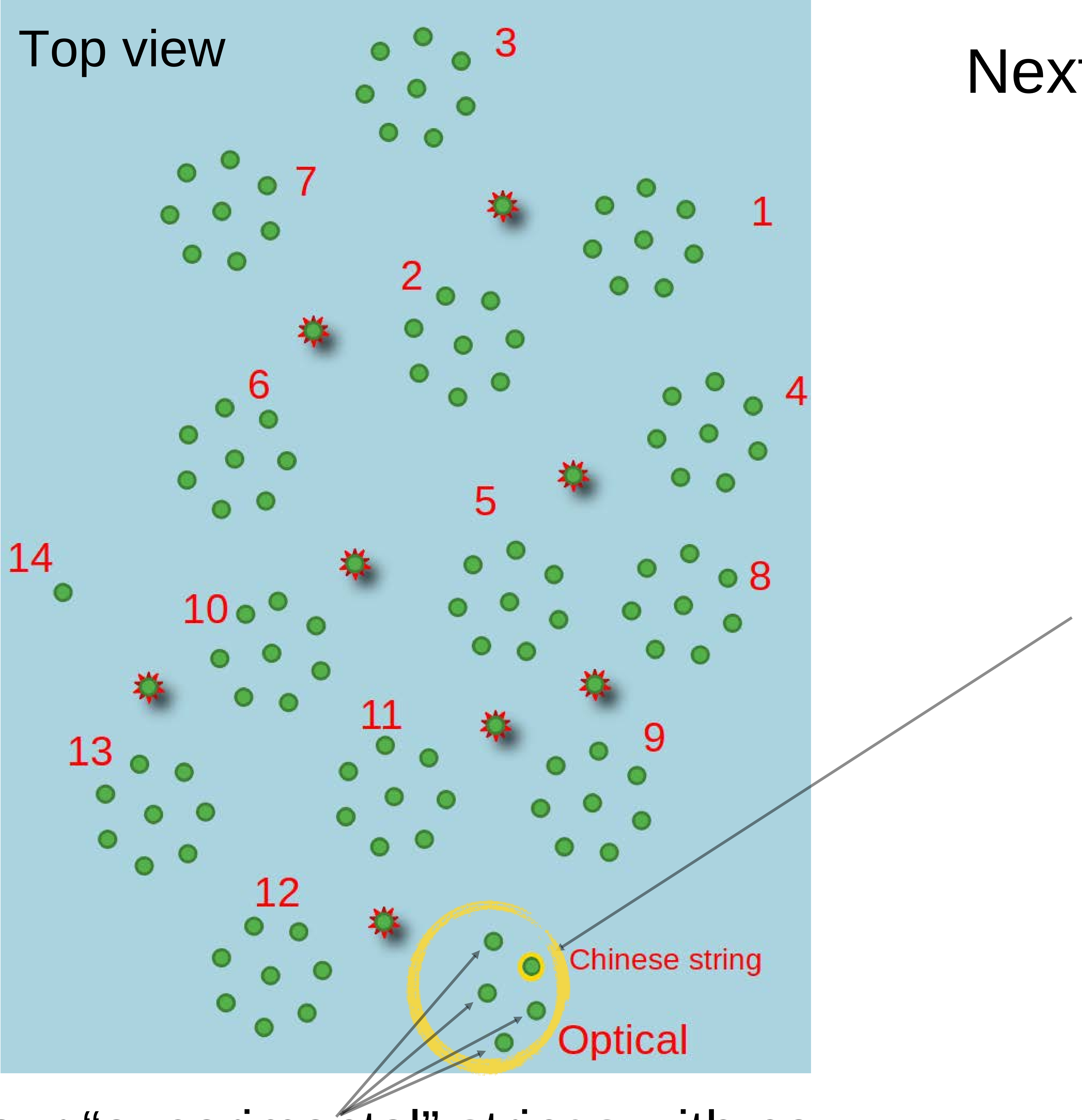
Back-ups

Sensitivity of OMs faced on and from cascade



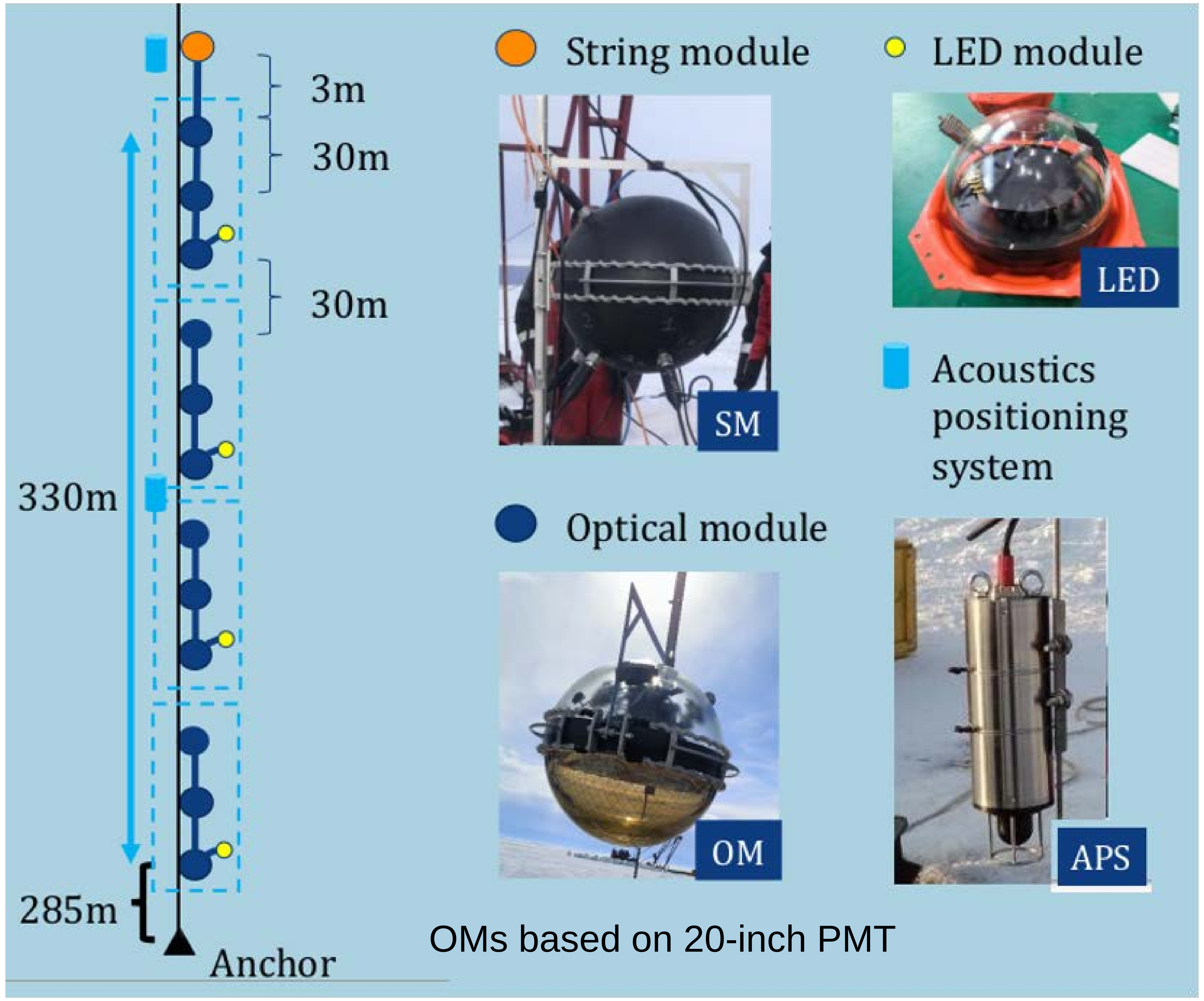


Technological prototype strings (2024)



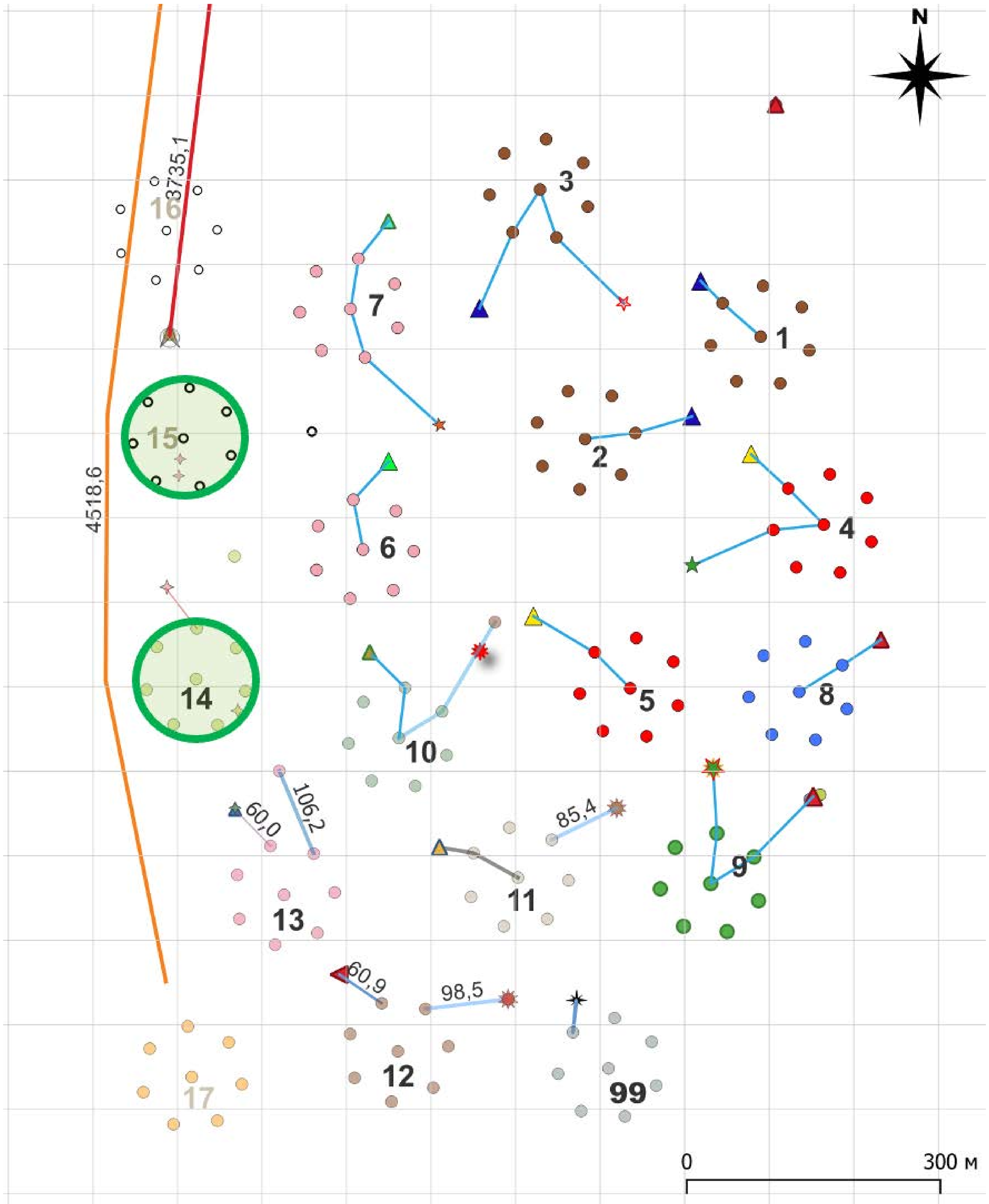
Four “experimental” strings with new fibre-optic technology for data transmission

Next-generation prototype string deployed in 2024
(IHEP (Beijing) & Baikal-GVD joint effort)



Next generation neutrino telescope project [PoS(ICRC2023)1080]

Next Expedition Plans (2025)



- Installation of new equipments:
  - Two new clusters: 14th and 15th
  - Two bottom cable lines
  - Full-scale string for the next-generation telescope
  - Cluster Center for cluster 17
- Repairing some parts
- But: autumn and winter in Siberia were warmer than usual
  - Challenging ice conditions