Expected neutrino rates from point-like astrophysical sources in Baikal-GVD

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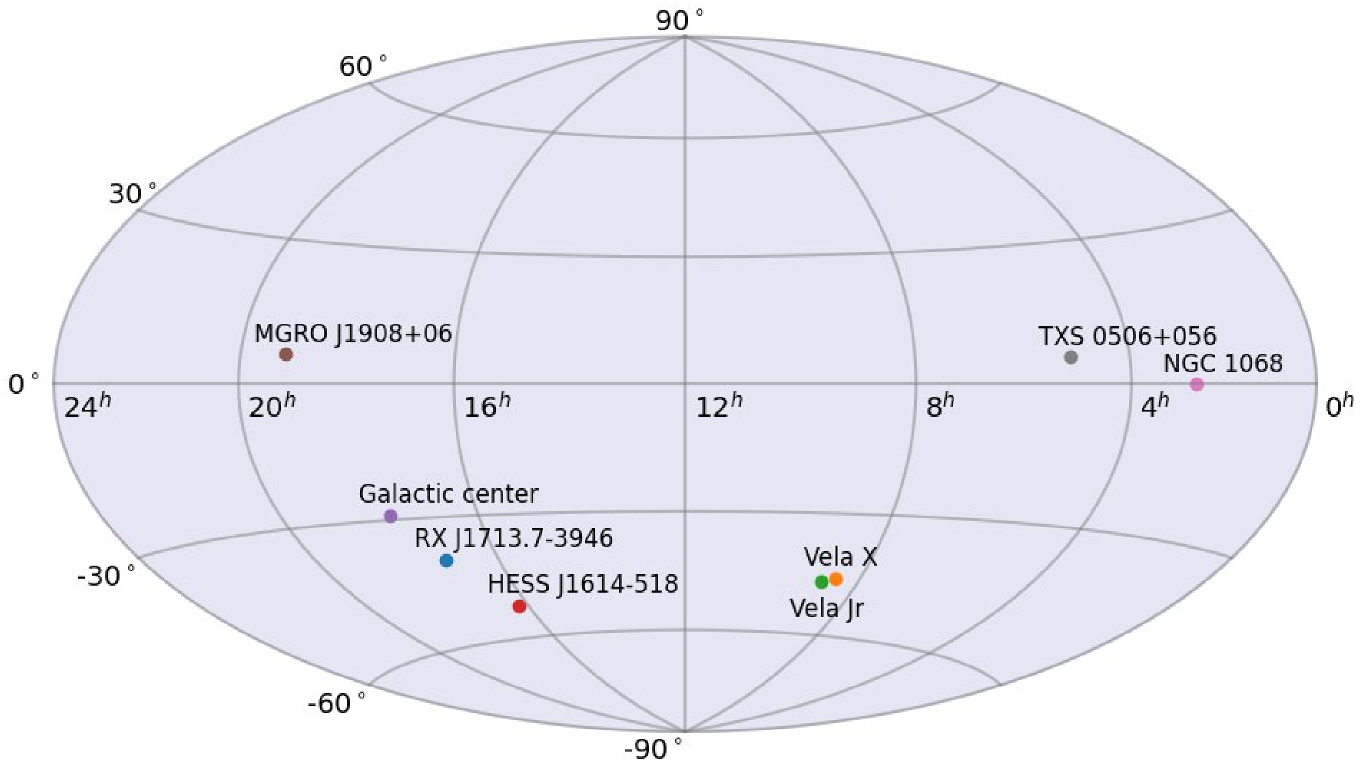
Outline

Neutrino sources	sources stellar coordinates and expected neutrino flux
Passage through the Earth	neutrino absorption in the Earth and its calculation
Baikal-GVD	detector description and its registration properties
Comparison with KM3Net	trigger-level comparison with the European telescope
Baikal-GVD reconstruction	reconstruction effective area & average reconstruction rate
Conclusion	

I. Neutrino sources

Investigated sources



position of the sources on the celestial sphere (top) and their characteristics: declination and right ascension in the table (right)

Source	δ °	α	Type
RX J1713.7-3946	-39.77	17^h14^m	SNR
Vela X	-45.6	08^h35^m	PWN
Vela Jr	-46.36	08^h52^m	SNR
HESS J1614-518	-51.82	16^h14^m	SNR
Galactic center	-28.87	17^h45^m	–
MGRO J1908+06	6.27	19^h08^m	UNID
NGC 1068	0.00	02^h42^m	AGN
TXS 0506+056	5.89	05^h09^m	blazar

investigated by KM3Net
[S. Aiello et al., (2019)]

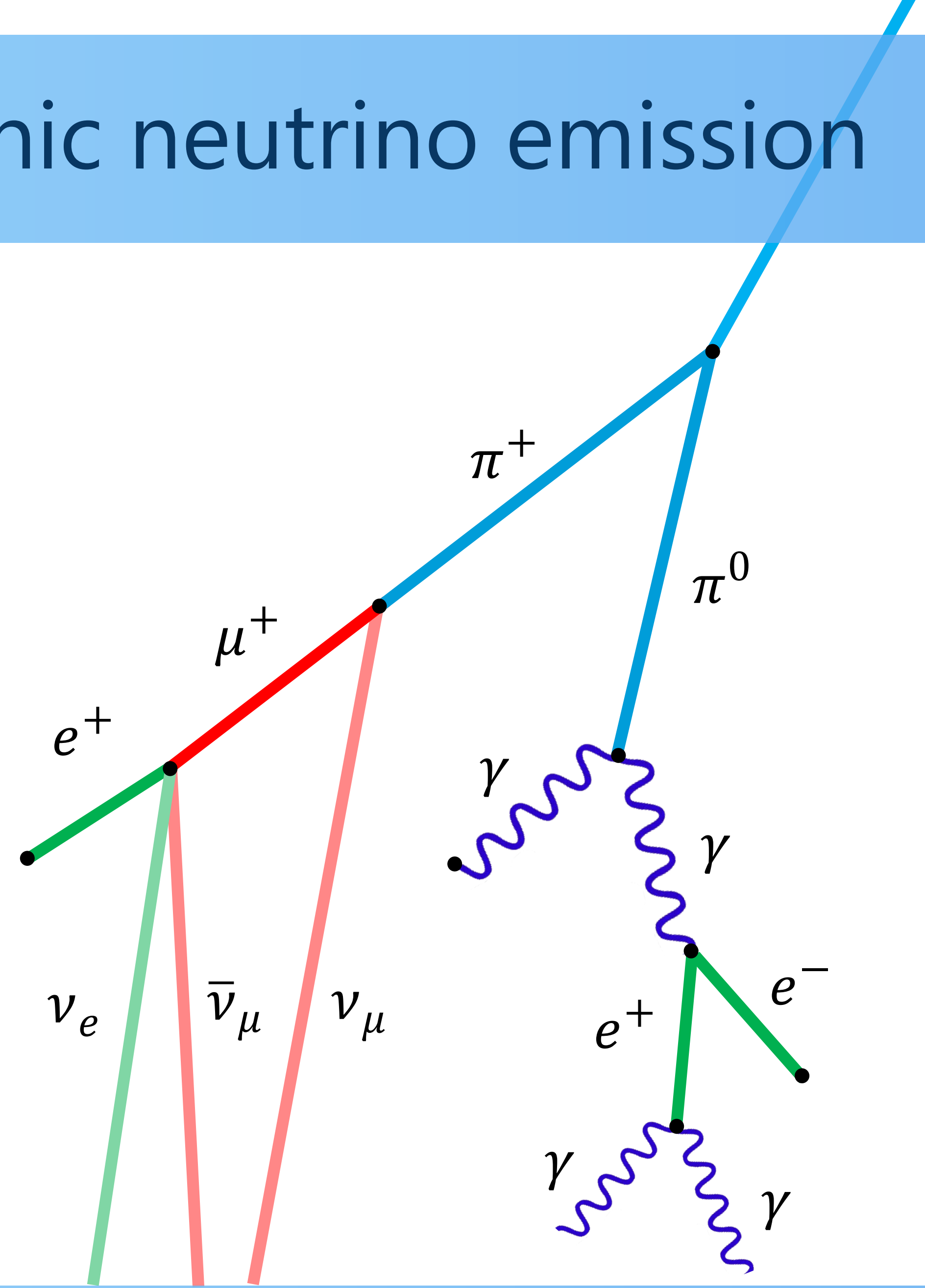
detected by IceCube
[IceCube Collaboration, (2018)]
[IceCube Collaboration, (2022)]

I. Neutrino sources

Hadronic neutrino emission

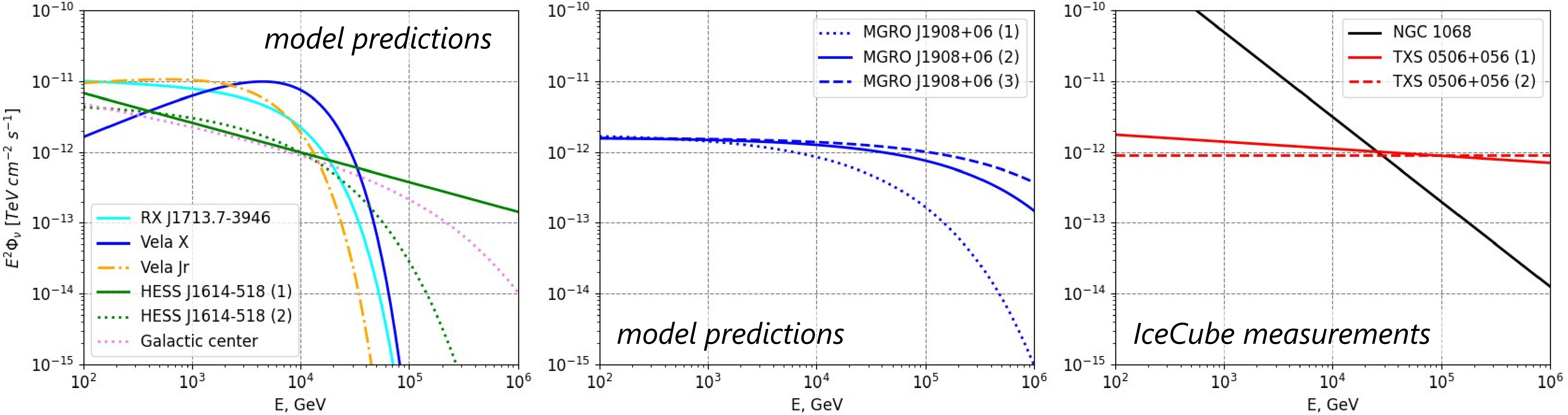
We assume that the selected sources produce neutrino with a hadronic mechanism:

- Something makes protons (or ions) accelerate
- Hadrons interact with medium or radiation
  in photon-reach environments
  $$p\gamma \rightarrow \pi$$
  in proton-reach environments
  $$pp \rightarrow \pi$$
- Pions decay with emission of neutrinos



I. Neutrino sources

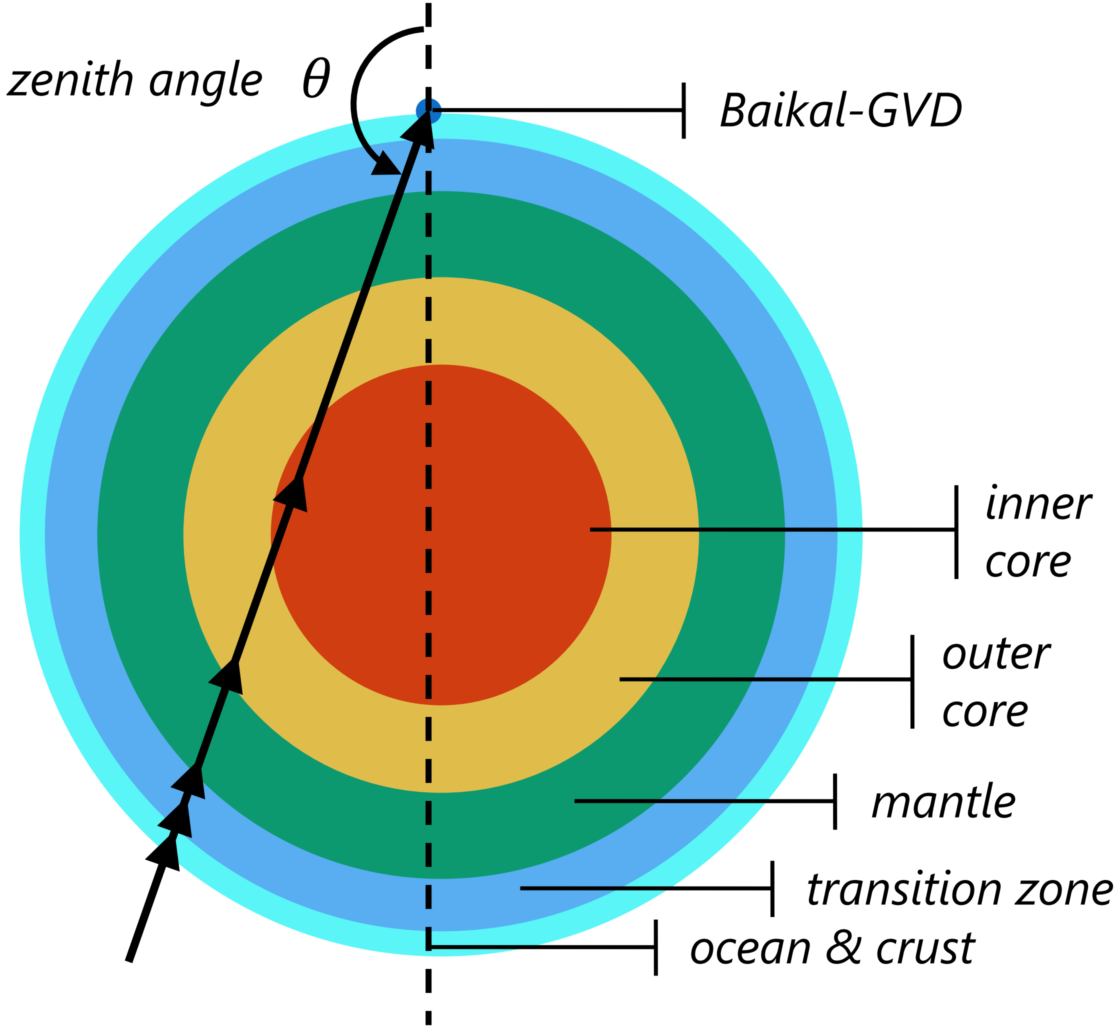
$$\phi_{\nu_l}(E) = k_0 \exp\left(\frac{E}{1\ TeV}\right)^{-\Gamma} \exp\left\{-\left(\frac{E}{E_{cut}}\right)^{\beta}\right\}$$



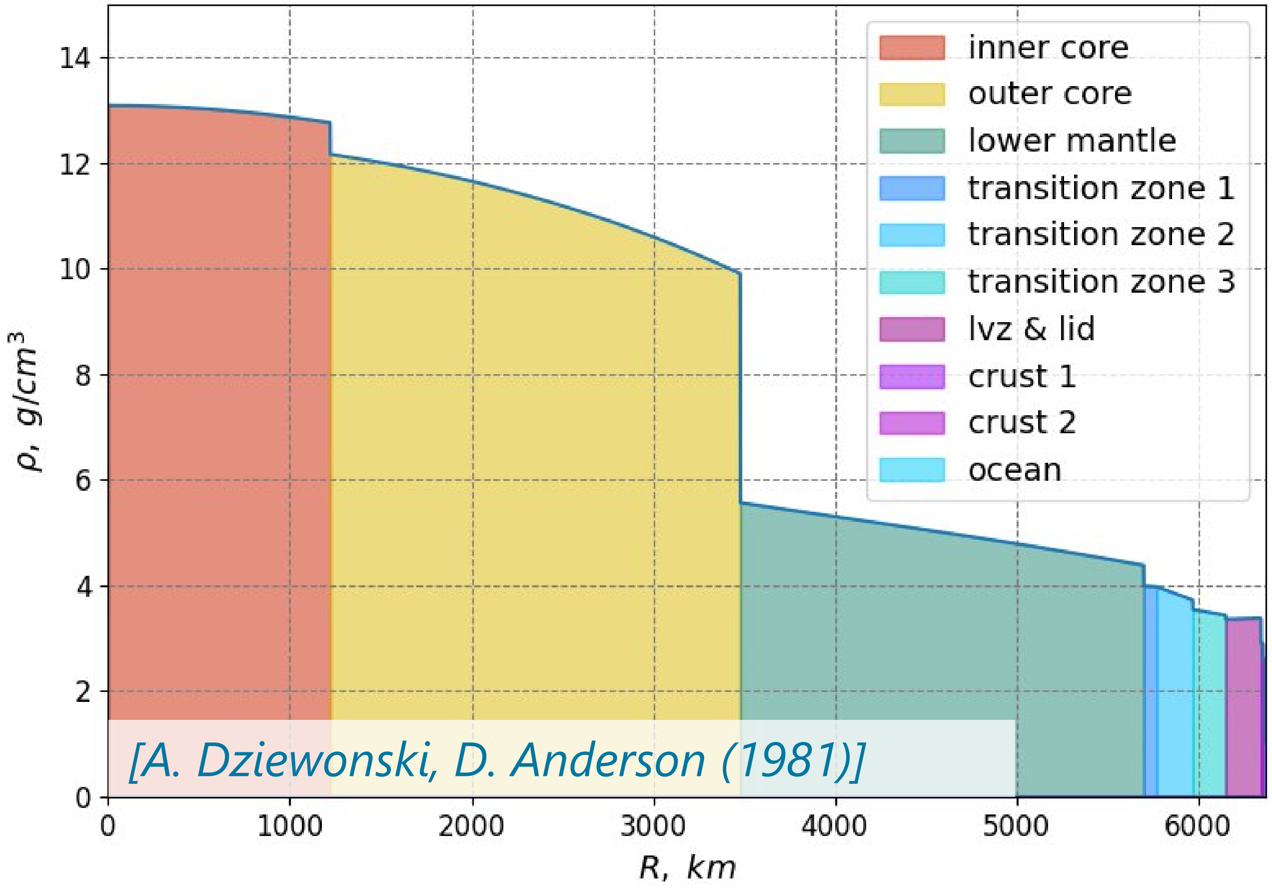
Source	δ	α	k_0	Γ	E_{cut}	β
RX J1713.7-3946	-39.77	17^h14^m	0.89	2.06	8.04	1
Vela X	-45.6	08^h35^m	0.72	1.36	7	1
Vela Jr	-46.36	08^h52^m	1.30	1.87	4.5	1
HESS J1614-518 (1)	-51.82	16^h14^m	0.26	2.42	–	–
HESS J1614-518 (2)	-51.82	16^h14^m	0.51	2	3.71	0.5
Galactic center	-28.87	17^h45^m	0.25	2.3	85.53	0.5

Source	δ	α	k_0	Γ	E_{cut}	β
MGRO J1908+06 (1)	6.27	19^h08^m	0.18	2	17.7	0.5
MGRO J1908+06 (2)	6.27	19^h08^m	0.16	2	177	0.5
MGRO J1908+06 (3)	6.27	19^h08^m	0.68	2	472	0.5
NGC 1068	0.00	02^h42^m	5.0	3.2	–	–
TXS 0506+056 (1)	5.89	05^h09^m	0.14	2.1	–	–
TXS 0506+056 (2)	5.89	05^h09^m	0.09	2.0	–	–

II. Passing the Earth



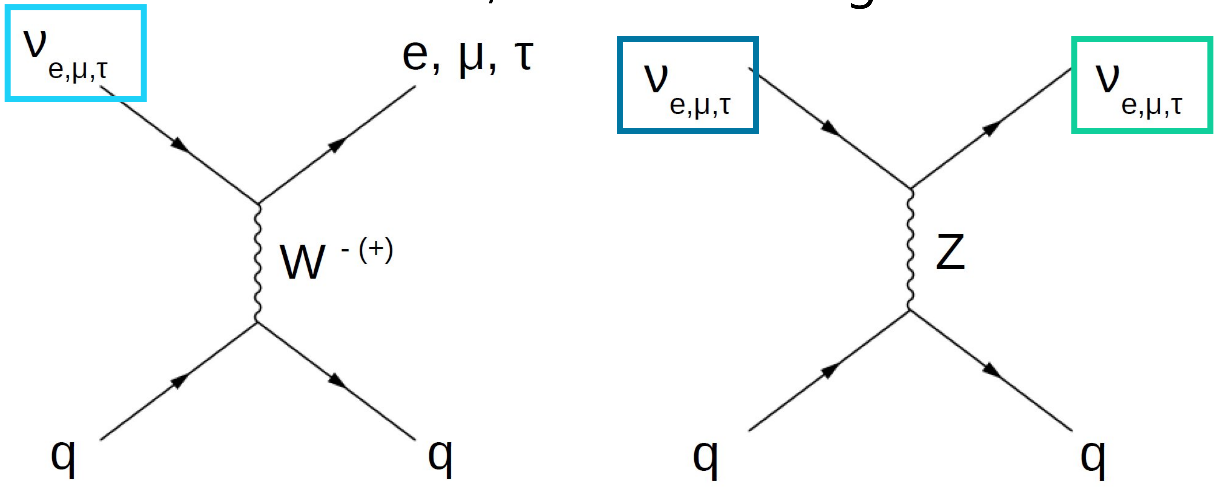
PREM Earth model



Earth's mean density vs. radius in PREM dependence

II. Passing the Earth   Neutrino flux attenuation

While neutrinos pass the Earth, they interact with matter there. Hence, total flux changes.

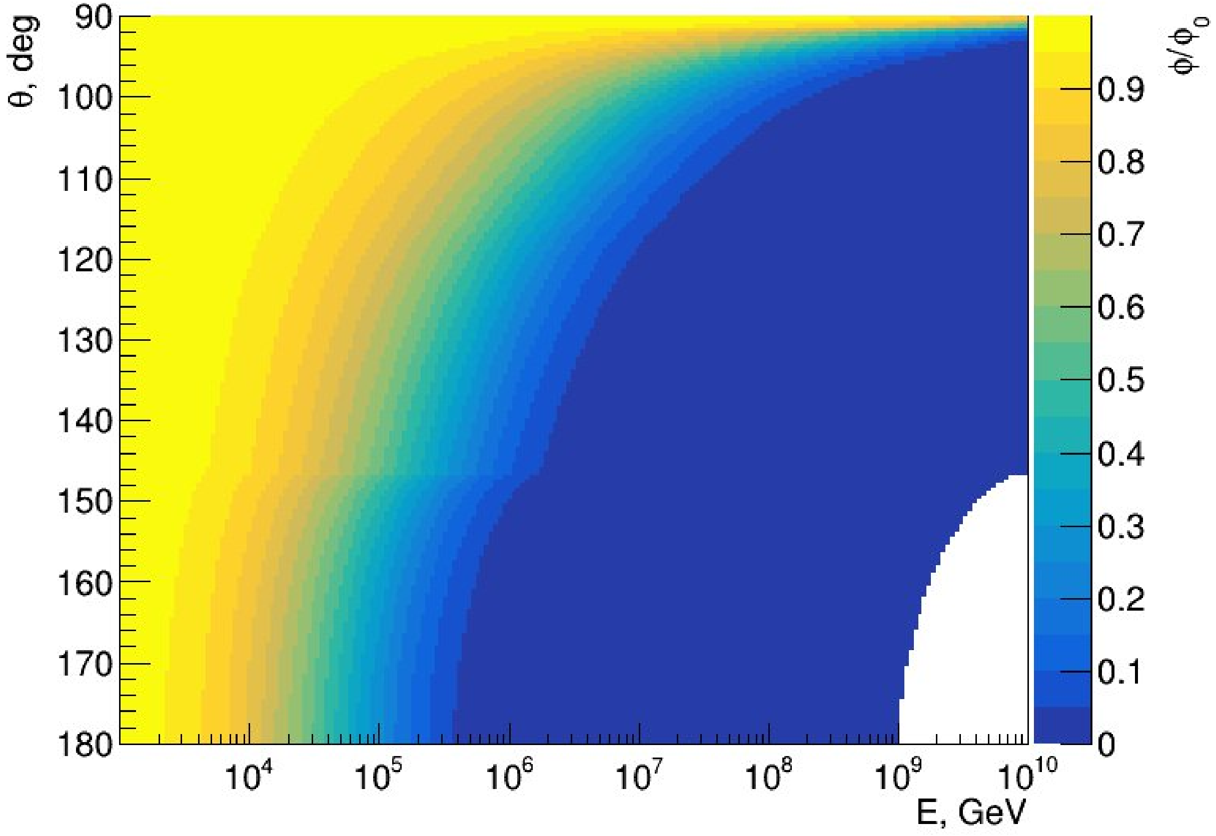


Charged-current (CC) and neutral current (NC) neutrino-nucleus interaction

$$\frac{\partial}{\partial x}\left(\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu}\right) = -\left(\sigma^{\rm NC}_{\nu_\ell}(E_\nu) + \sigma^{\rm CC}_{\nu_\ell}(E_\nu)\right)\frac{d\phi_{\nu_\ell}(E_\nu,x)}{dE_\nu} + \\ + \int_E^\infty d\tilde{E}\,\frac{d\sigma^{\rm NC}_{\nu_\ell}(E_\nu,\tilde{E}_\nu)}{dE_\nu}\,\frac{d\phi_{\nu_\ell}(\tilde{E}_\nu,x)}{d\tilde{E}_\nu}$$

To solve these equations, we use NUFATE

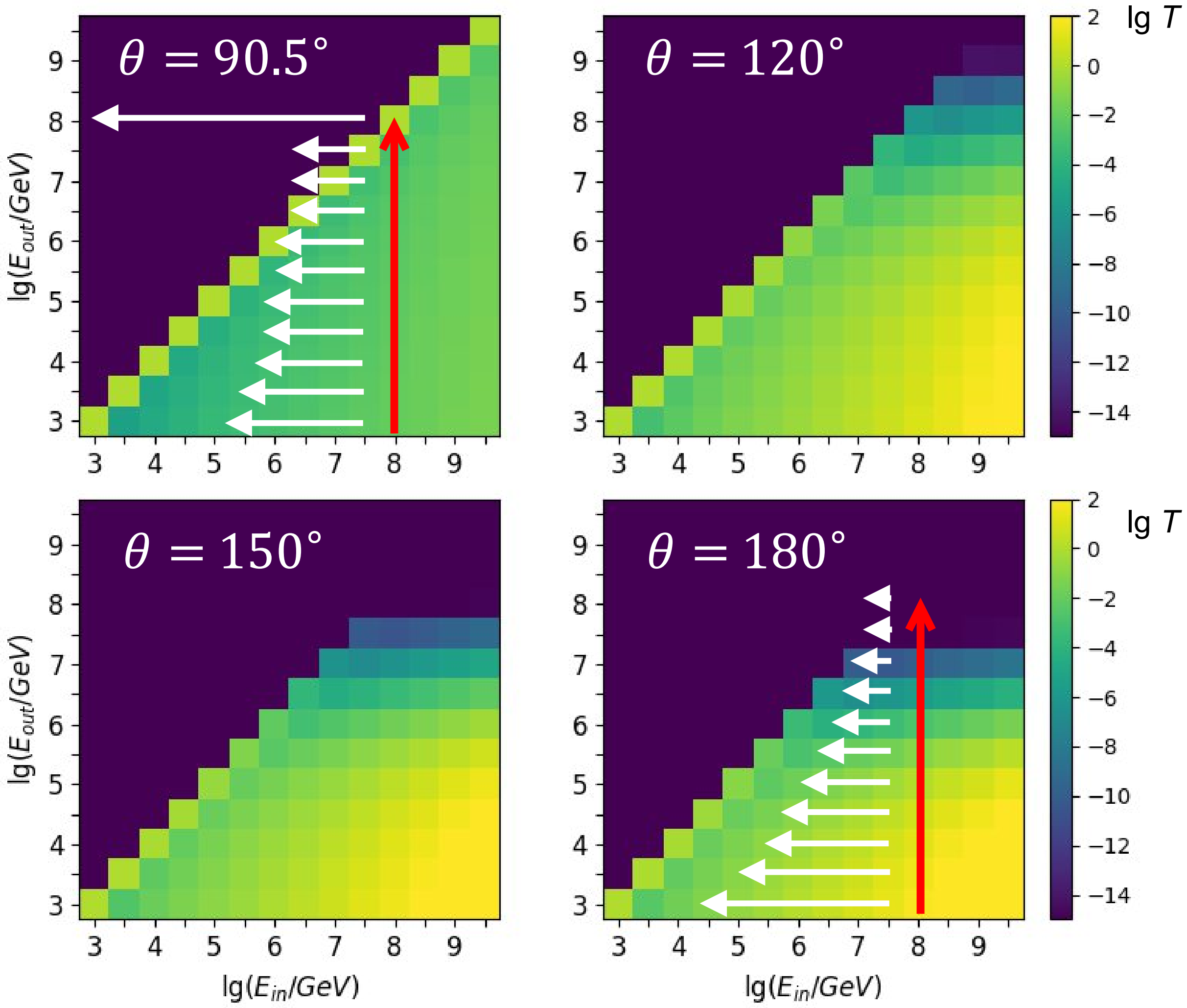
[A. Vincent, C. Argüelles and A. Kheirandish (2019)]



Transmission coefficient vs. zenith angle and energy

II. Passing the Earth

Transmission matrix



$\lg T_{ij}$ *elements for fixed zenith angles*

To accelerate the calculations, a transmission matrix T_{ij} was precomputed with the use of *νFATE*

We assume the flux to behave this way:

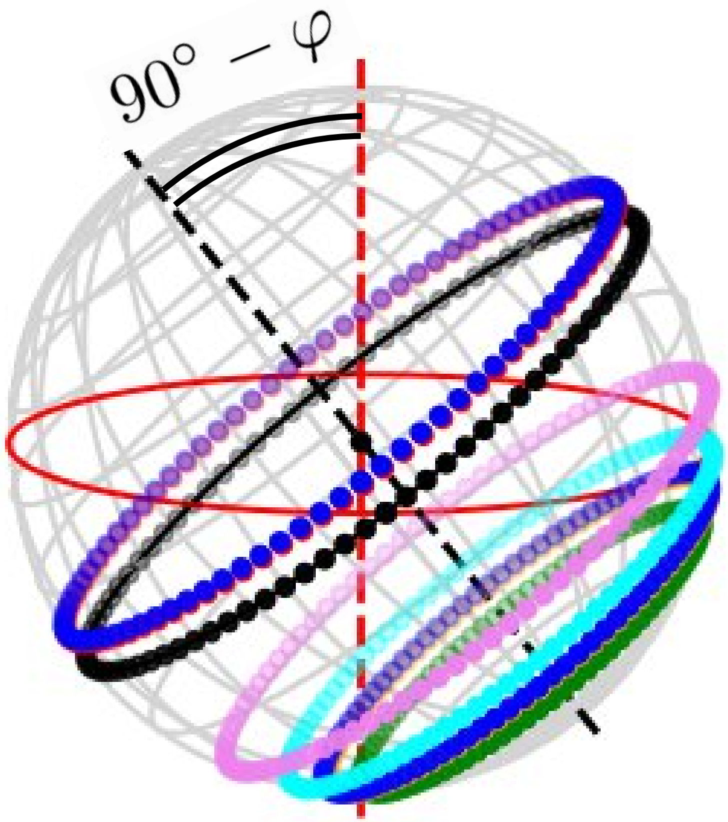
$$\phi(E_i,\theta) = \int_0^\infty dE' \phi_0(E',\theta) T(E',E_i,\theta) = \sum_{i,j} \phi_0(E_j,\theta) T_{ij}(\theta)$$

final flux spectral density — $\phi(E_i,\theta)$

initial flux spectral density — $\phi_0(E',\theta)$, $\phi_0(E_j,\theta)$

Thus, especially at high energies transfer to low-energy neutrinos is expected

II. Passing the Earth Celestial movement



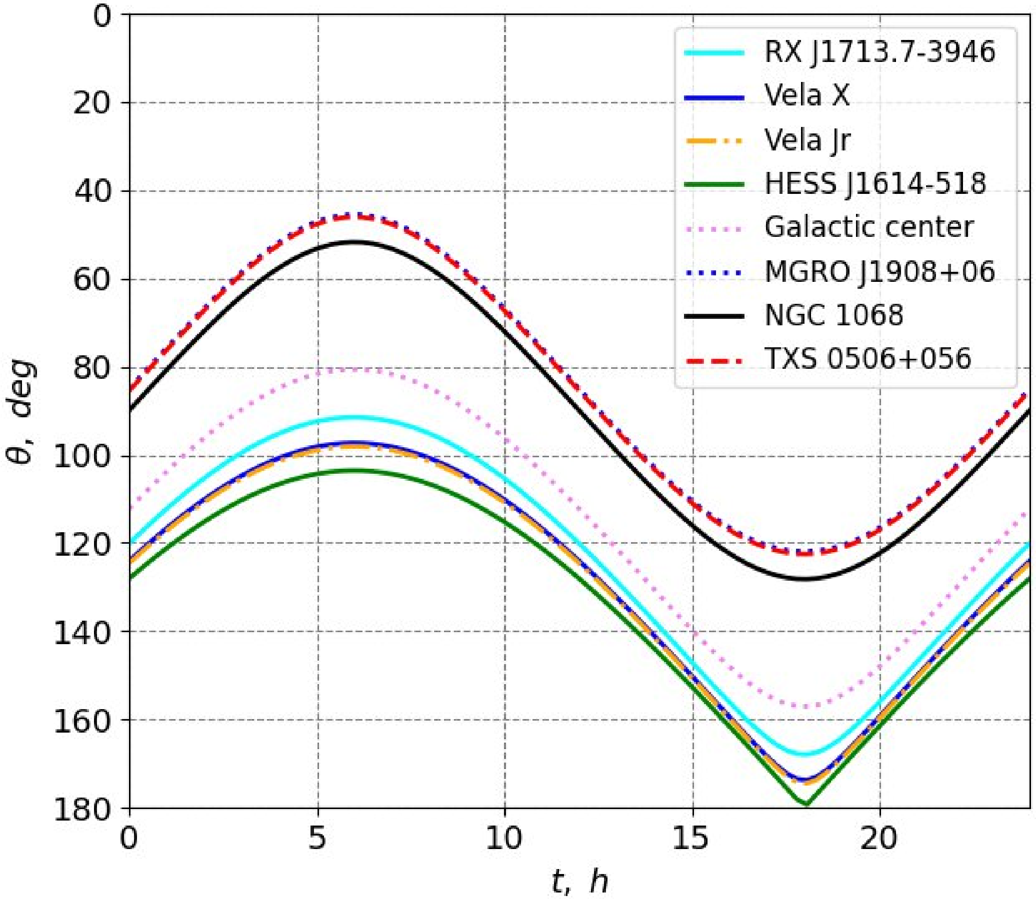
Sources tracks on the celestial sphere

The object's track for a polar viewer is defined by the following equation

$$\mathbf{r}(\delta, t) = \begin{pmatrix} \cos\delta\ \cos(\omega t) \\ \cos\delta\ \sin(\omega t) \\ \sin\delta \end{pmatrix}$$

For Baikal-GVD latitude $\varphi = 51^\circ 46'\, N$ the "polar" track is rotated at $90^\circ - \varphi$ around the X-axis

$$\mathbf{r}'(\delta, \varphi, t) = \begin{pmatrix} x'(\delta, \varphi, t) \\ y'(\delta, \varphi, t) \\ \cos\theta(t) \end{pmatrix}$$

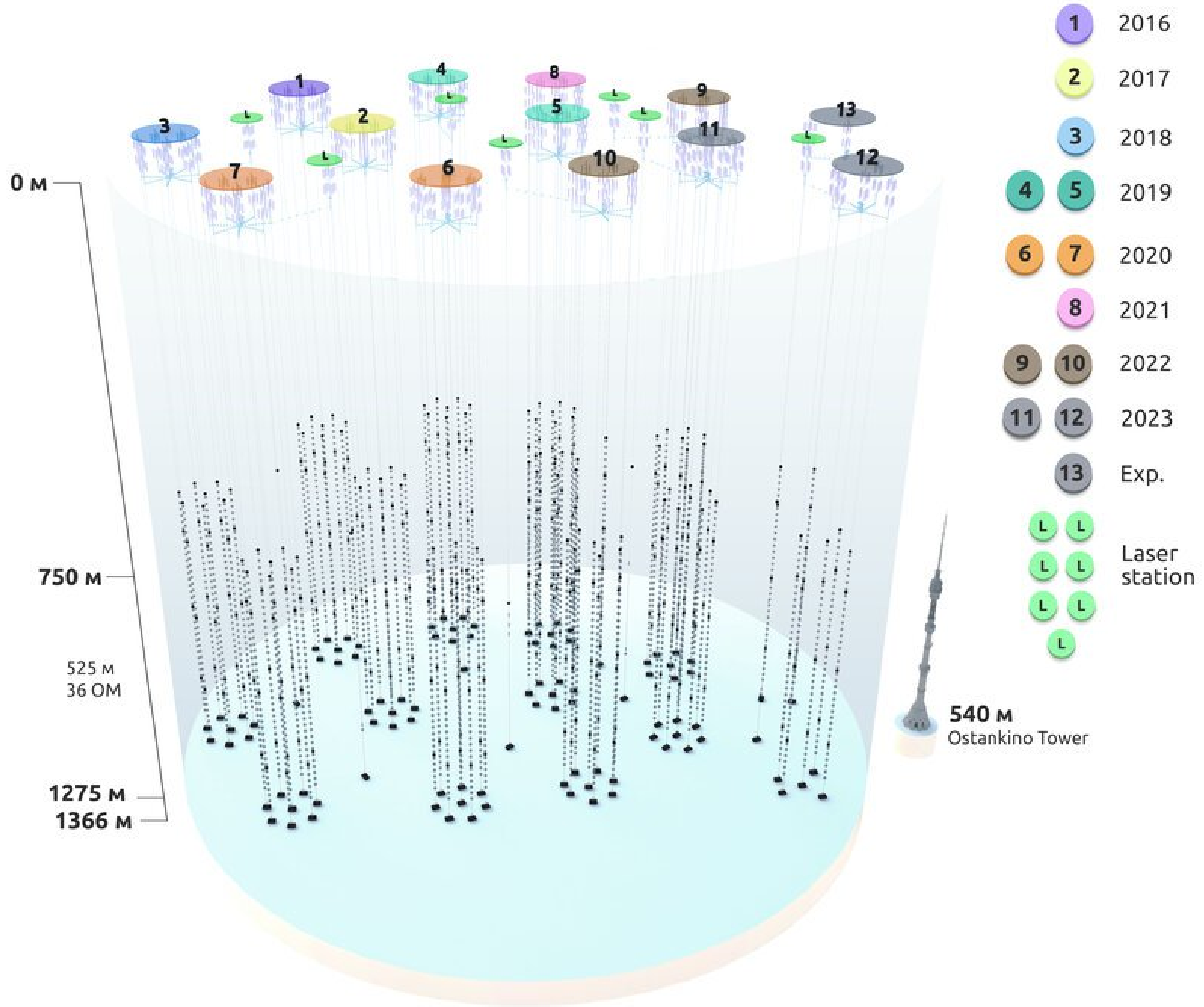


Sources' zenith angle θ vs. time without considering their right ascensions

Baikal-GVD
*(Baikal **G**igatone **V**olume **D**etector)*

- a neutrino observatory in Lake Baikal
- consists of 13* clusters
  8 strings per cluster, *36 modules per string*
- neutrino energy range
  from *100 GeV to 10 PeV*
- operating volume ≈ 0.5 km^3 *

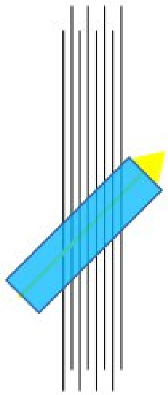
* *configuration 2023*



[https://baikalgvd.jinr.ru]
[R. Dvornický et al., ICRC-2023]

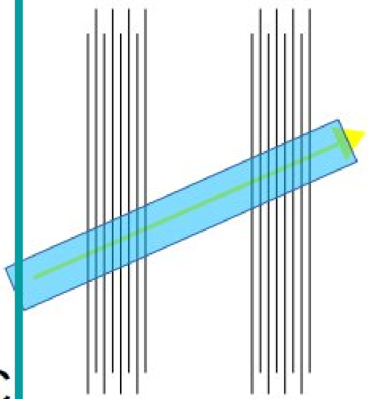
III. Baikal-GVD Tracks and cascades

Single-cluster tracks



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

Multi-cluster tracks

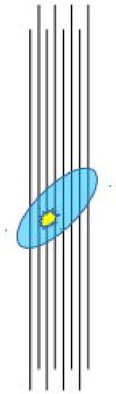


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- 10% of recorded track events

ν_μ CC

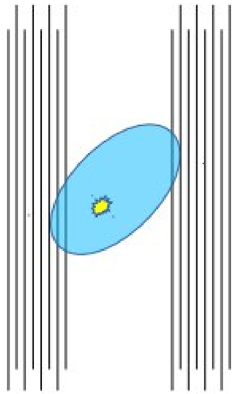
NC, ν_e ν_τ CC

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

Effective area at trigger level

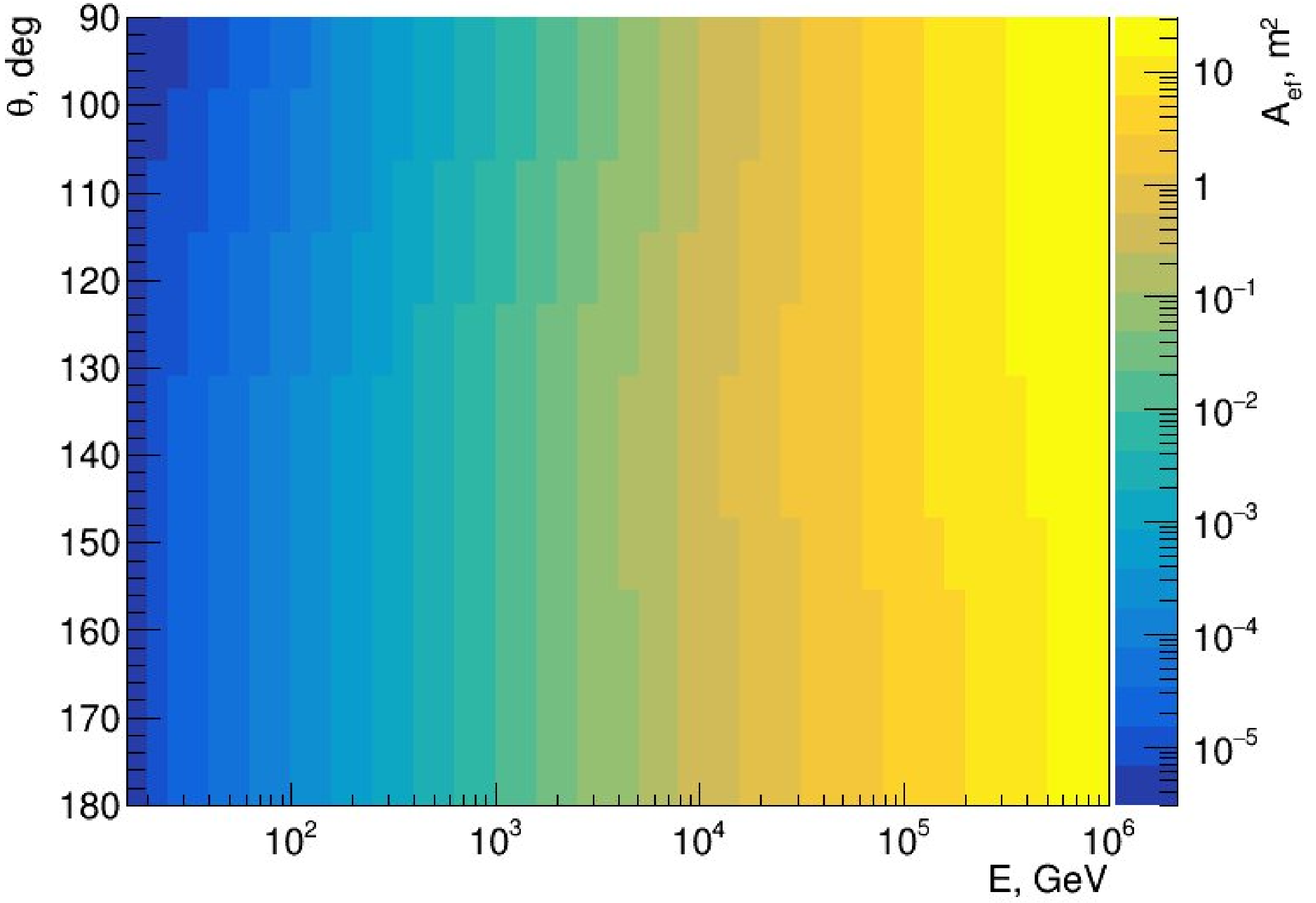
The integral neutrino flux through ***i**-th* energy bin and ***j**-th* zenith angle bin is expressed as follows

$$F_{ij} = \int_{\theta_j}^{\theta_{j+1}} d\Omega \int_{E_i}^{E_{i+1}} dE \, \frac{d\Phi_{\nu_\mu + \overline{\nu}_\mu}(E,\theta))}{dE \; d\Omega}$$

The effective area is a ratio between the registration rate in the *ij-bin* zenith angle bin and integral flux in this bin

$$A_{ij}^{ef} = R_{ij}/F_{ij}$$

Downward-going neutrinos are excluded from consideration due to high background of atmospheric muons



muon neutrino effective area at trigger level as function of neutrino energy and zenith angle for one GVD cluster (MC)

III. Baikal-GVD Three-step-processing

Trigger

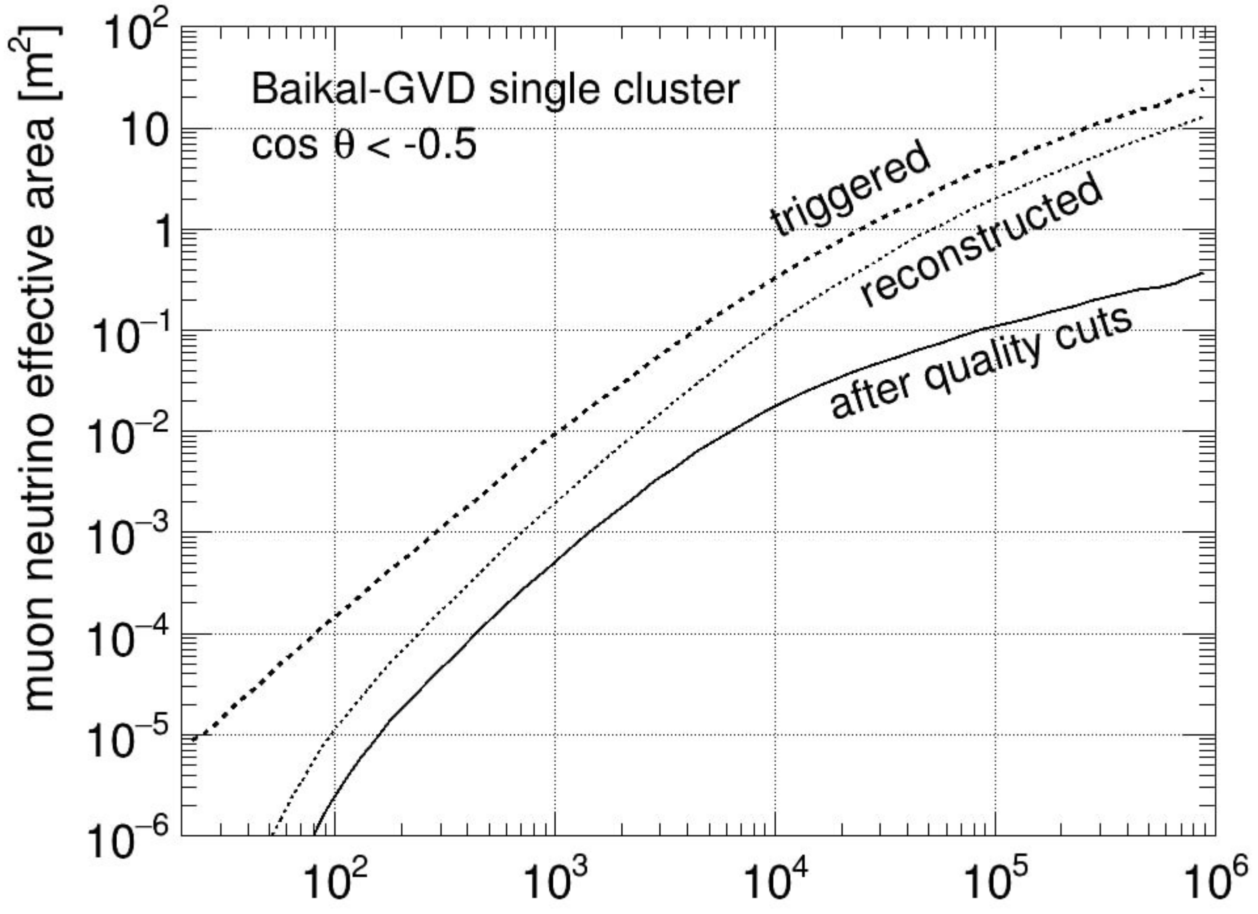
Activation of the two neighboring channels within the same *section* *(12 OMs)* within a *100 ns* time window and with amplitudes above certain threshold

Reconstruction

Atmospheric background suppression and track position reconstruction by minimization of the quality function

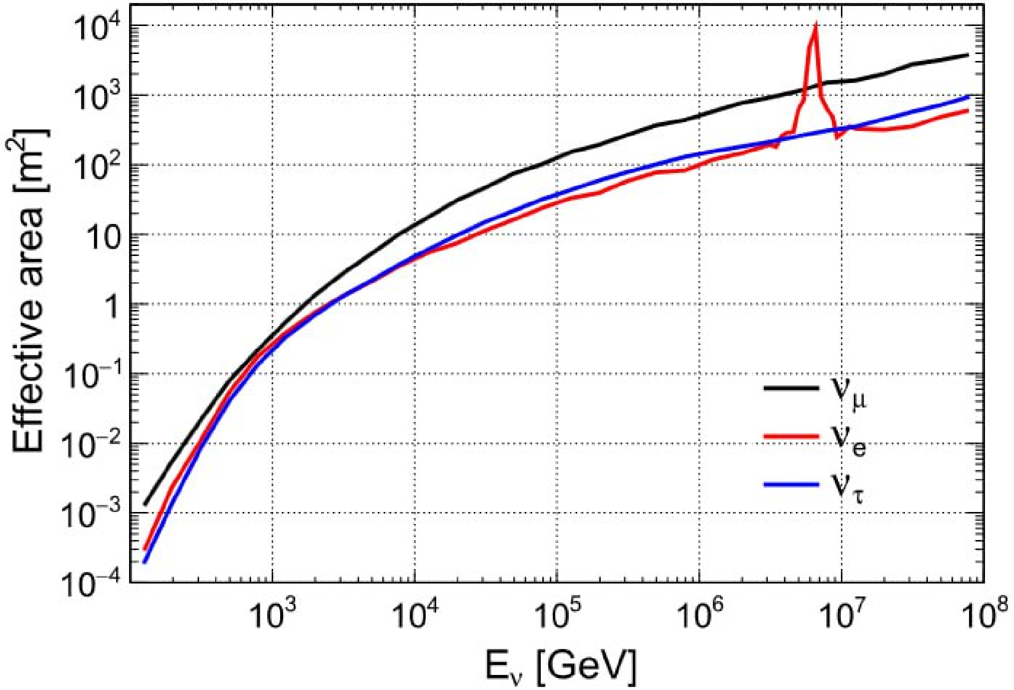
Quality cuts

Selection of the reconstructed events by quality parameters values



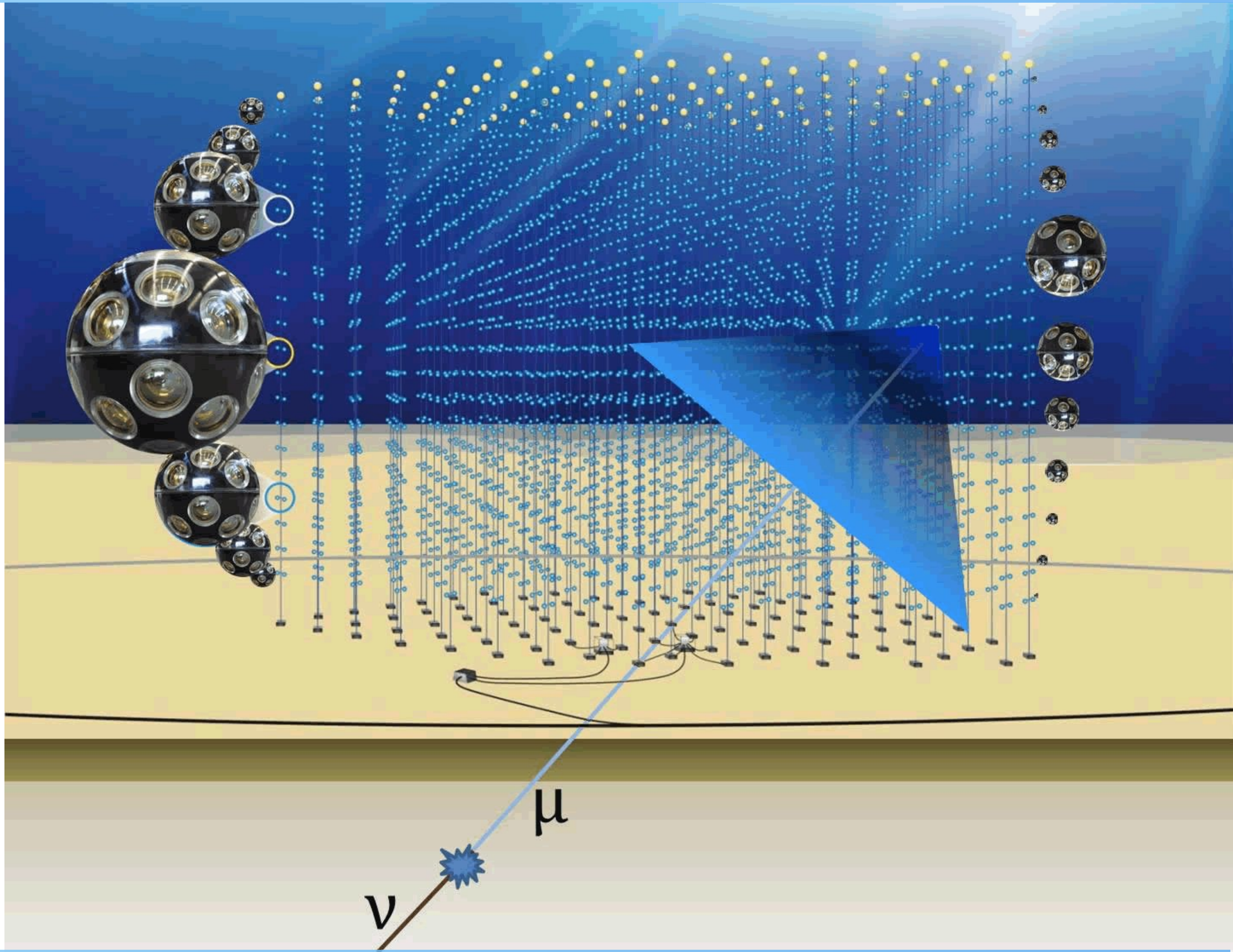
[V. A. Allakhverdyan et al., 2021]

KM3Net-ARCA

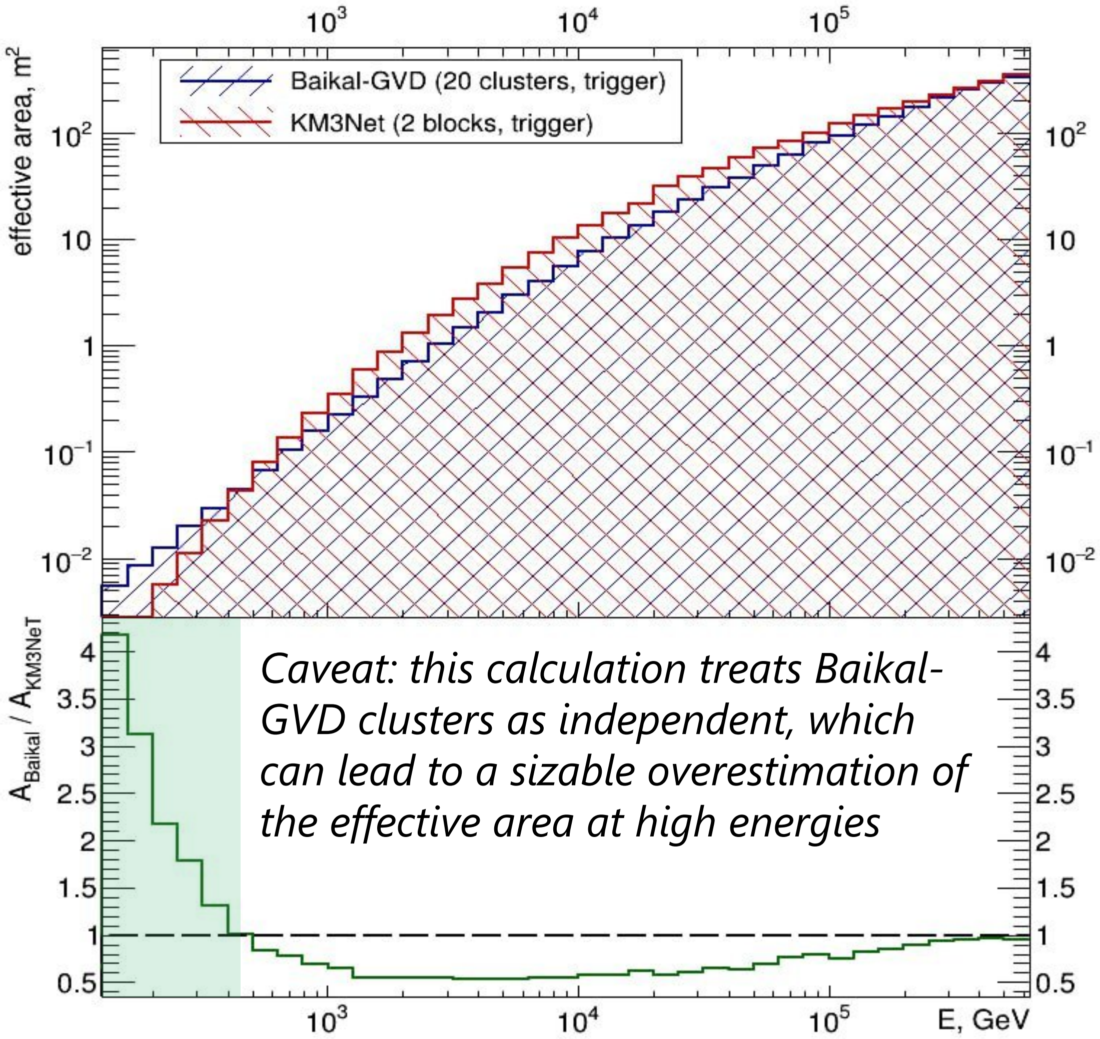


Trigger-level ARCA effective areas for two blocks, averaged for ν and $\bar{\nu}$ and includes both NC and CC interactions (top)
Scheme of the KM3Net-ARCA detector (right)

[https://www.km3net.org]



IV. Comparison Trigger effective area



Caveat: this calculation treats Baikal-GVD clusters as independent, which can lead to a sizable overestimation of the effective area at high energies

The designed volume for both detectors is about 1 km^3.

At Baikal-GVD such volume will be covered by 20 clusters. Two blocks of KM3NeT will also cover 1 km^3.

Baikal-GVD trigger effective area is higher than KM3Net trigger effective area at low energies *(< 500 GeV)* and almost equals it at high energies *(10^6 GeV)*.

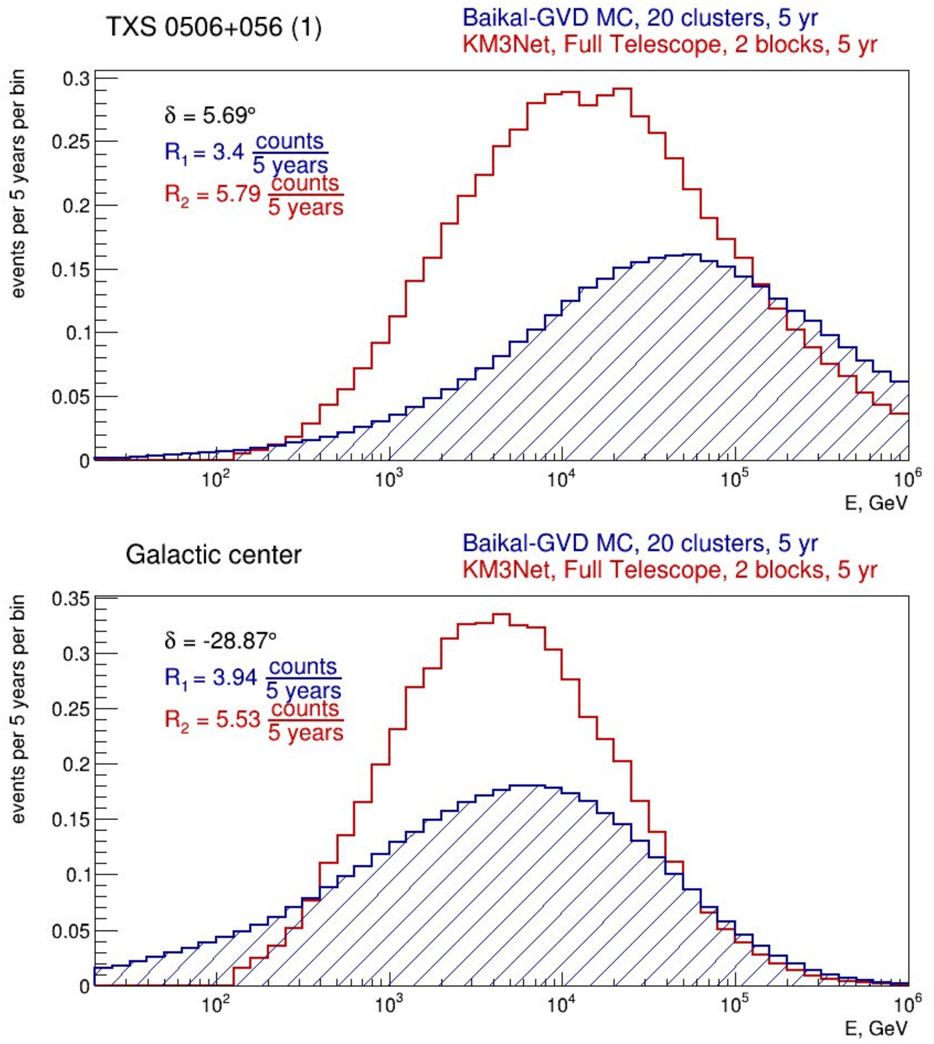
*20 clusters of Baikal-GVD and 2 blocks KM3Net detector effective area at the **trigger level** (above) and effective areas ratio (Baikal-GVD to KM3NeT)*

Trigger-level comparison

Registration rate (RR) is given in events / 5 years

Source	Baikal-GVD	KM3NeT (calc.)	KM3NeT (ref.)	ratio
RRX J1713.7-3946	11.42	17.92	20.0	0.64
Vela X	19.46	37.17	40.7	0.52
Vela Jr	13.64	23.7	25.6	0.58
HESS J1614-518 (1)	6.1	10.5	9.0	0.68
HESS J1614-518 (2)	5.19	9.1	8.37	0.62
Galactic center	3.94	5.53	7.0	0.71
MGRO J1908+06 (1)	1.62	3.52	4.1	0.46
MGRO J1908+06 (2)	3.11	5.79	7.1	0.54
MGRO J1908+06 (3)	3.78	6.7	8.3	0.56
NGC 1068	66.39	52.81	–	1.26
TXS 0506+056 (1)	3.4	5.79	–	0.59
TXS 0506+056 (2)	3.12	4.97	–	0.63

The developed method gives *10%* lower estimation than provided in literature. In this work we take into consideration only muon neutrinos, and KM3NeT researchers include tau- neutrinos into their calculations *[S. Aiello, 2019]*



IV. Comparison NGC 1068

Registration rate (RR) is given in events / 5 years

Source	Baikal-GVD	KM3NeT (calc.)	ratio
RRX J1713.7-3946	11.42	17.92	0.64
Vela X	19.46	37.17	0.52
Vela Jr	13.64	23.7	0.58
HESS J1614-518 (1)	6.1	10.5	0.68
HESS J1614-518 (2)	5.19	9.1	0.62
Galactic center	3.94	5.53	0.71
MGRO J1908+06 (1)	1.62	3.52	0.46
MGRO J1908+06 (2)	3.11	5.79	0.54
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NGC 1068	66.39	52.81	1.26
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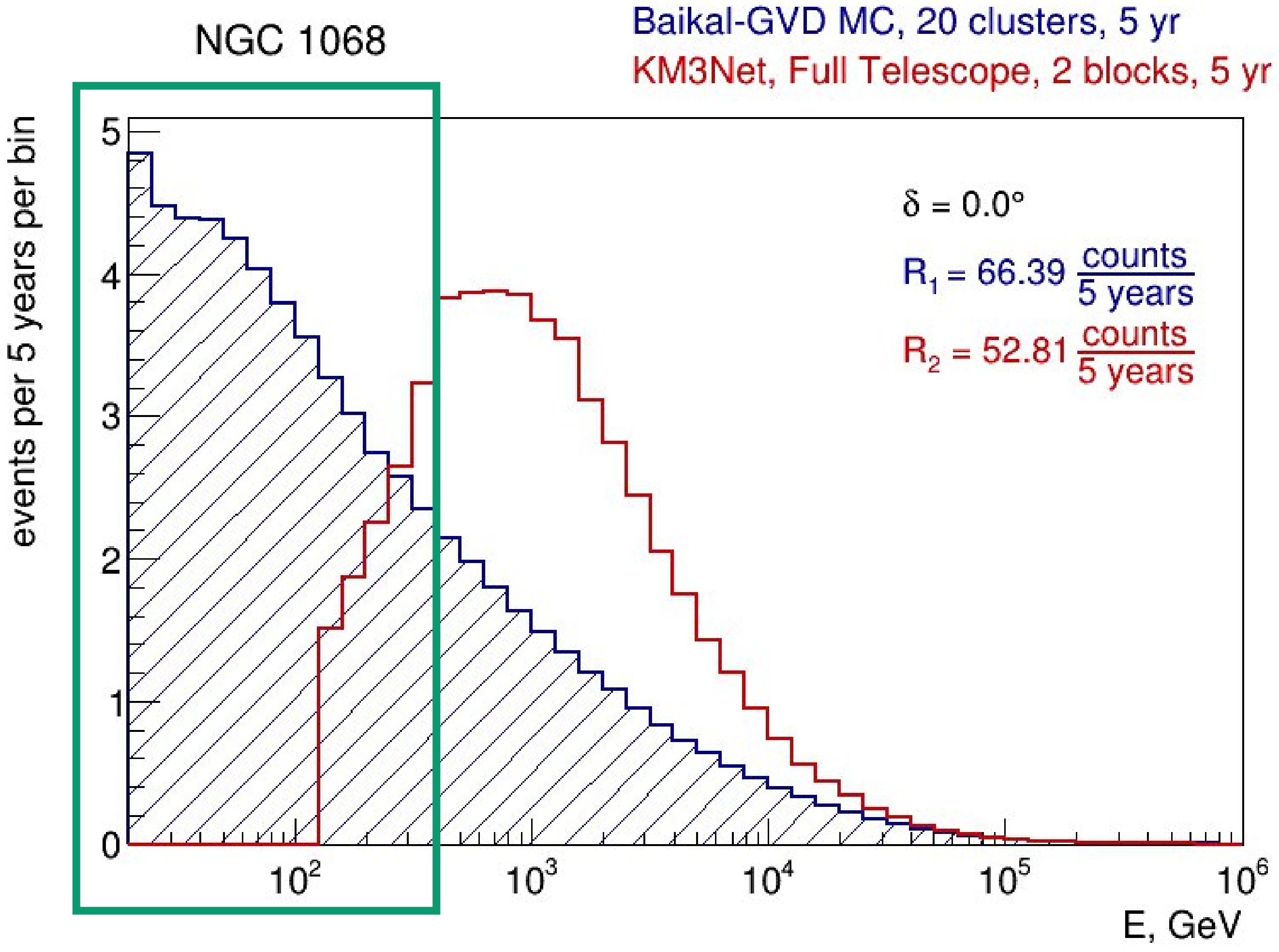


NB: events with E < 100 GeV can be ignored due to low reconstruction efficiency and high background

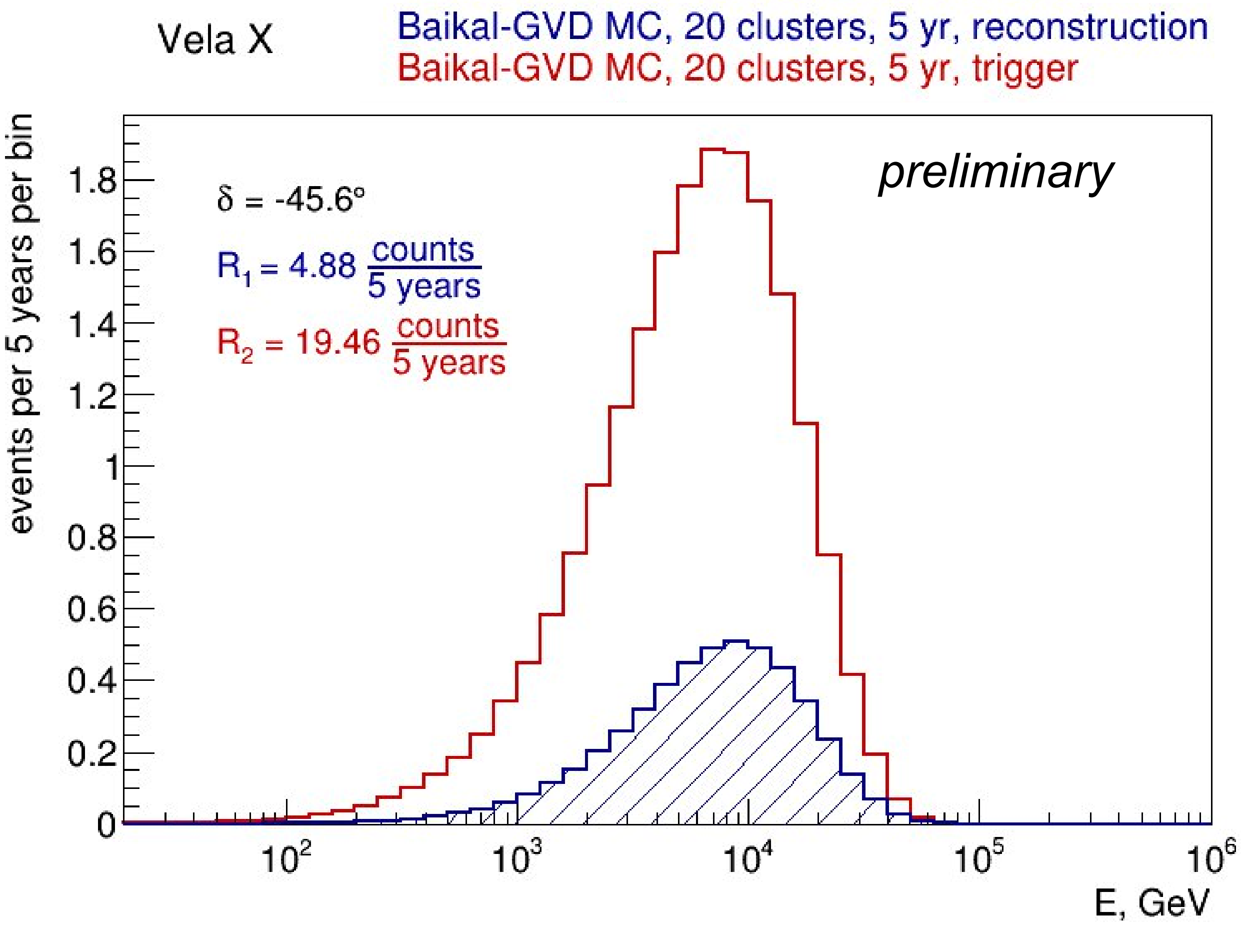
V. Reconstruction

Registration rate (RR) is given in events / 5 years

Source	RR, trigger	RR, reconstruction	ratio
RX J1713.7-3946	11.42	2.31	0.2
Vela X	19.46	4.88	0.25
Vela Jr	13.64	2.83	0.21
HESS J1614-518 (1)	6.1	1.53	0.25
HESS J1614-518 (2)	5.19	1.18	0.23
Galactic center	3.94	0.93	0.24

Reconstruction includes a hit selection procedure and a χ^2-like track fitter. As a result, contribution of noise hits to neutrino events is reduced to ~1%.

Reconstruction effective area is much lower than the trigger one, thus it leads to decrease in registration rate.



V. Reconstruction

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Vela X	19.46	4.88	0.25
Vela Jr	13.64	2.83	0.21
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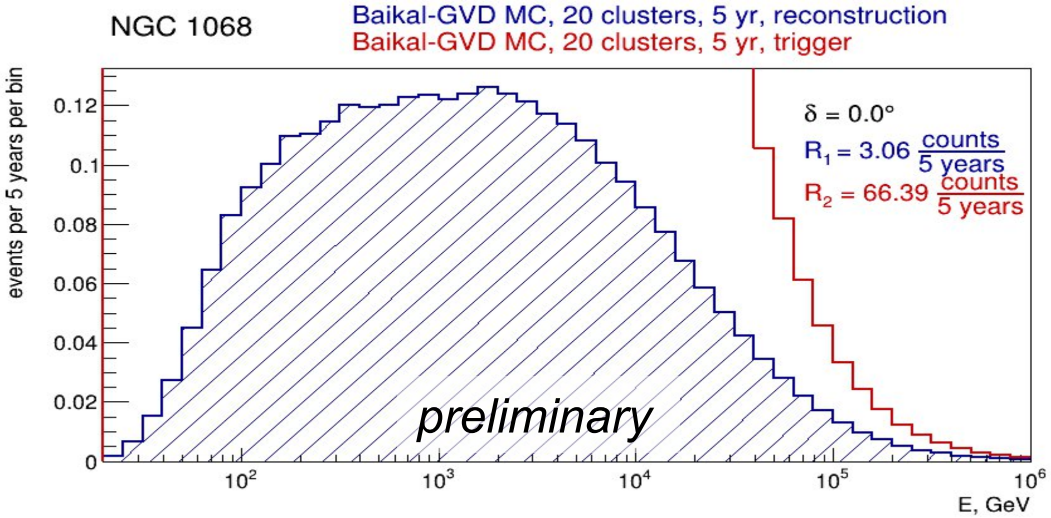
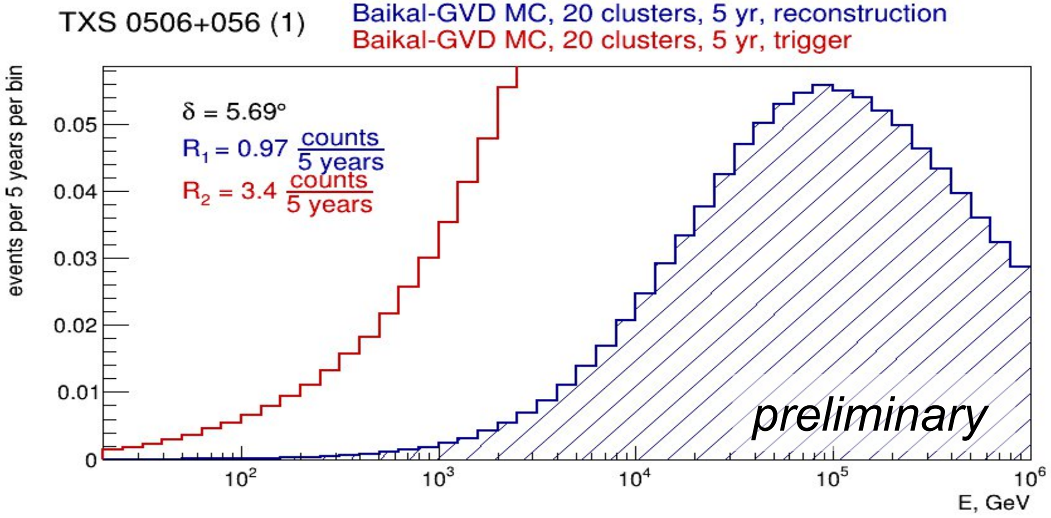
HESS J1614-518 (2)	5.19	1.18	0.23
Galactic center	3.94	0.93	0.24
MGRO J1908+06 (1)	1.62	0.31	0.19
MGRO J1908+06 (2)	3.11	0.8	0.26
MGRO J1908+06 (3)	3.78	1.04	0.28
NGC 1068	66.39	3.06	0.05
TXS 0506+056 (1)	3.4	0.97	0.29
TXS 0506+056 (2)	3.12	0.96	0.31





The reconstruction efficiency is on average better for harder spectrum sources (or for higher energy events)

VI. Conclusion

In this research we estimated neutrino registration rate from several point-like neutrino sources **assuming hadronic emission mechanism**.

- Neutrino transmission through the Earth
- Sources visibility
- Detector effective area

were taken into consideration

A **trigger-level comparison** with KM3NeT detector was performed and

- Registration rate in Baikal is expected to be approximately 40% lower than in KM3Net

A **reconstruction registration rate** was estimated and

- number of expected events with current reconstruction mechanism is in order of one event in every couple of years for the brightest sources

Main references

[1] V. A. Allakhverdyan et al. — Measuring muon tracks in Baikal-GVD using a fast reconstruction algorithm (2021)

[2] A. C. Vincent, C. A. Argüelles, A. Kheirandish — High-energy neutrino attenuation in the Earth and its associated uncertainties (2019)

[3] S. Aiello et al. — Sensitivity of the KM3NeT/ARCA neutrino telescope to point-like neutrino sources (2019)

[4] Ice Cube Collaboration — Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert (2018

[5] Ice Cube Collaboration — Evidence for neutrino emission from the nearby active galaxy NGC 1068 (2022)

[6] A. M. Dziewonski, D. L. Anderson - Preliminary reference Earth model (1981)

[7] J. A. Formaggio, G. P. Zeller — From eV to EeV: Neutrino cross-section across energy scales (2012)

[8] A. Connolly, R. S. Thorne, D. Waters — Calculation of high energy neutrino-nucleon cross sections and uncertainties using the Martin-Stirling-Thorne-Watt parton distribution functions and implications for future experiments

Thank you for attention!

Questions?

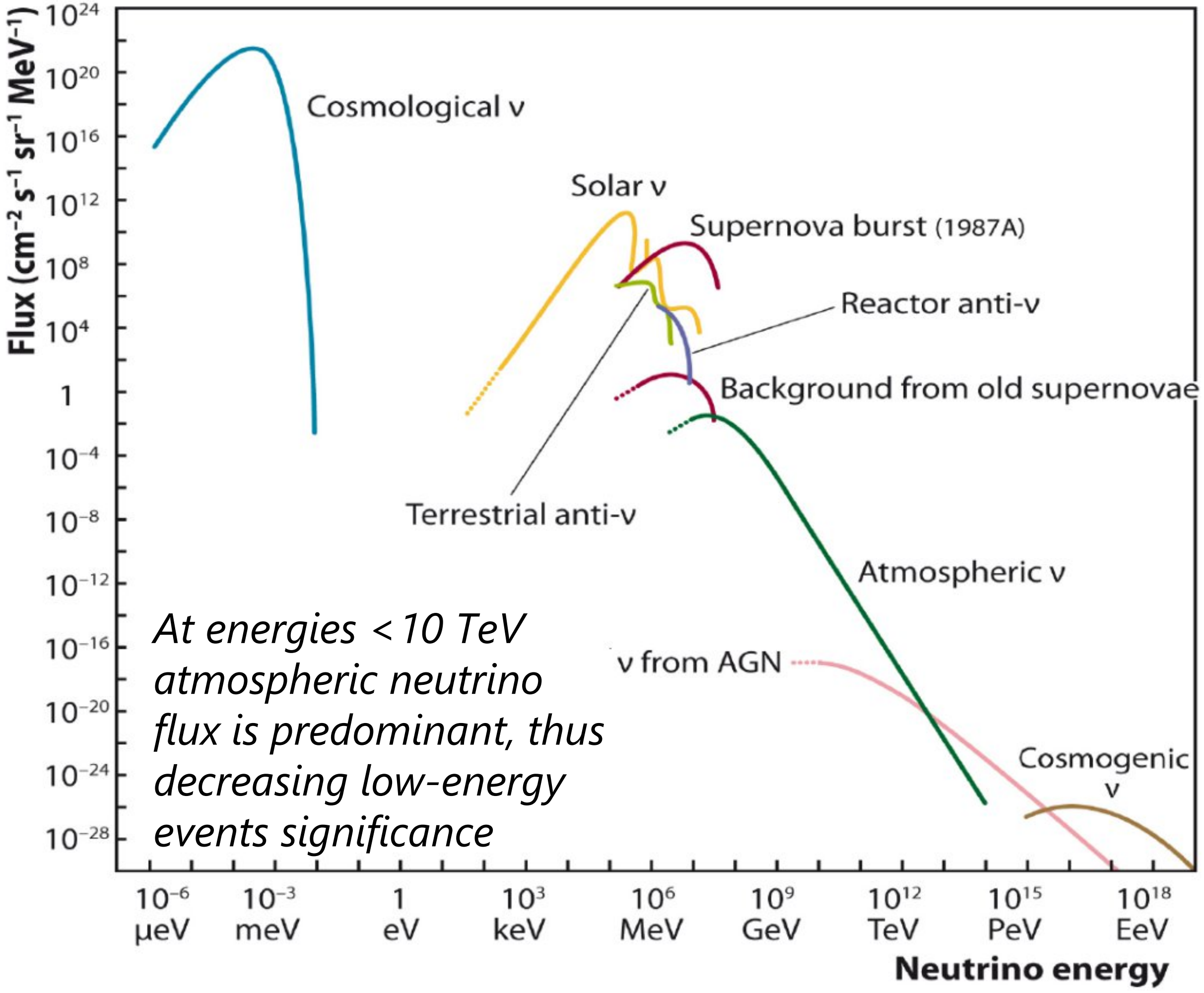
We estimate **the total neutrino detection rate** from several possible particle sources, including *TXS 0506+056, NGC 1068, and the Galactic Center*, assuming a **hadronic emission scenario**.

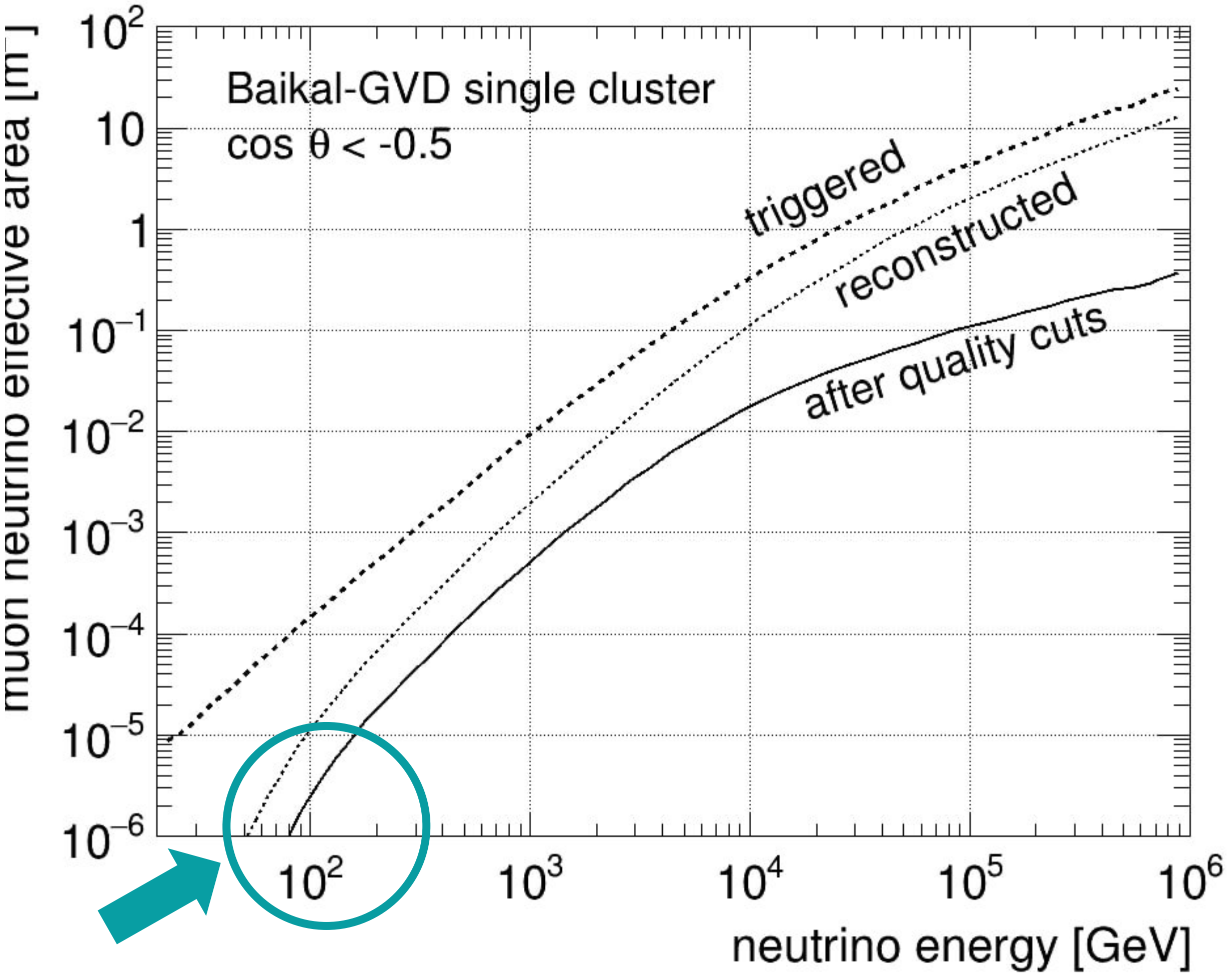
The neutrino rate is calculated using a precomputed detector effective area **for reconstructed track-like events**. The **daily source movement** across the sky and the **detector's registration efficiency** as a function of energy and zenith angle are taken into account.

The attenuation of the neutrino flux in the Earth is modeled using the *νFATE* package and is also incorporated into the neutrino detection rate calculations.

Additional slides

Atmospheric background





Transmission extrapolation

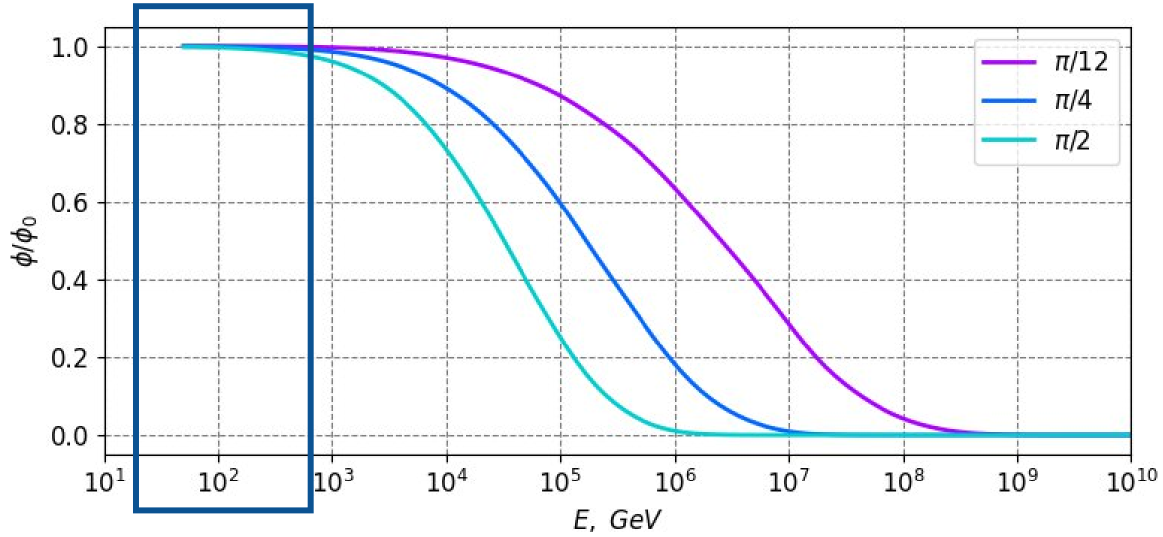
νFATE analysis energies | *Baikal-GVD energies*

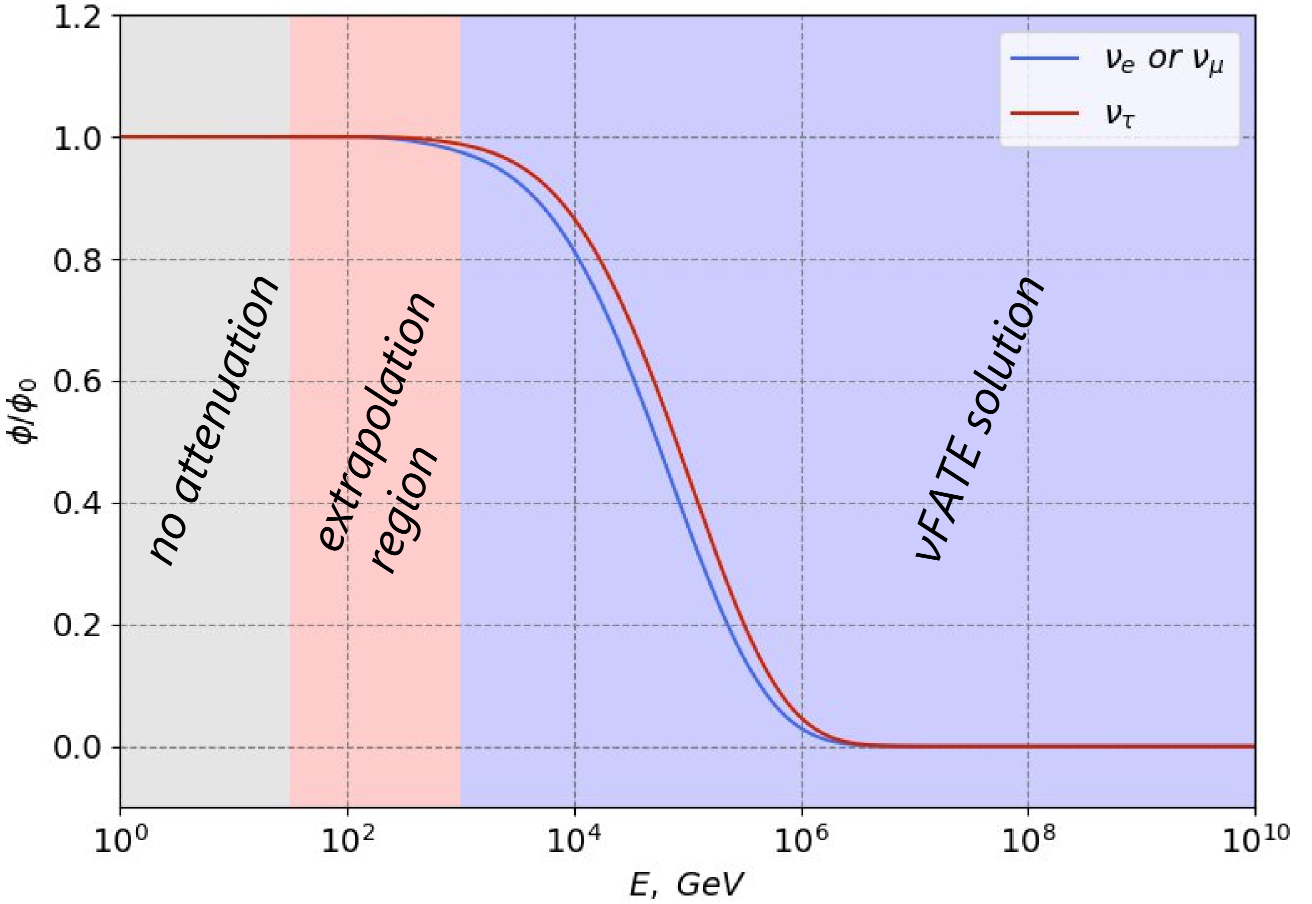
$10^3\ GeV < E < 10^{10}\ GeV$ | $10^1\ GeV < E < 10^6\ GeV$

A rough estimation to extrapolate:

$$\left.\frac{d\,\phi_{\nu_l}(E_\nu,\theta)}{d\,E_\nu}\right|_{out} = \left.\frac{d\,\phi_{\nu_l}(E_\nu)}{d\,E_\nu}\right|_{in} \cdot \exp\left\{-\sigma(E) N_A \int_{L(\theta)} d\boldsymbol{l}\, \rho\,(r(\boldsymbol{l}))\right\}$$

$$\sigma(E) = \sigma_{CC}(E) + \sigma_{NC}(E)$$





Hermitian interpolation down to low energies for $\Gamma = 2,\ E_{low} = 3 \cdot 10^1\ GeV,\ \theta = \pi/3$

Registration rate

The Source

- ***neutrino flux*** *estimation based on gamma radiation properties*
- *fixed* ***source's position on the celestial sphere***

The Earth

- *registration rate dependent on its direction and energy with the use of Baikal-GVD* ***single cluster effective area***

- ***neutrino transmission*** *based on the Earth's inner structure and neutrino cross-sections for charged- and neutral-current interactions*
- *source visibility (celestial movement)*

The Telescope

Additional slides

Attenuation in the Earth (1)

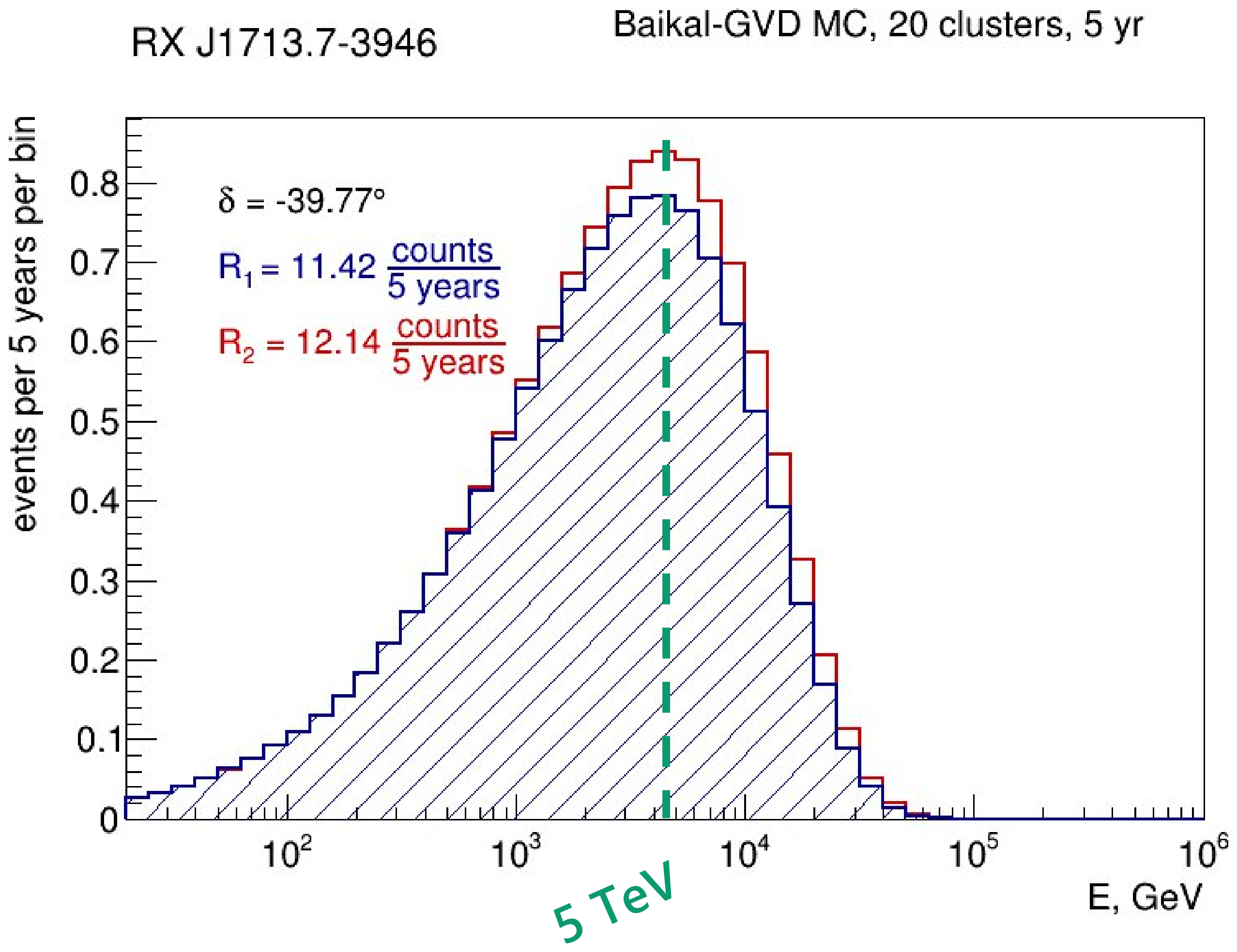
Registration rate (RR) is given in events / 5 years

Source	RR, no at.	RR, with at.	ratio
RX J1713.7-3946	12.14	11.42	0.94

Registration rate in assumptions

- *without attenuation (left column, red plot)*
- *with attenuation (middle column, blue plot)*

For RX J1713.7-3946, a supernova remnant registration rate peak is at *5 TeV*, which results in an insignificant *(6% only)* decrease in total registration rate due to attenuation in the Earth



Attenuation in the Earth (2)

Registration rate (RR) is given in events / 5 years

Source	RR, no at.	RR, with at.	ratio
RX J1713.7-3946	12.14	11.42	0.94
Vela X	21.67	19.46	0.90
Vela Jr	14.44	13.64	0.94
HESS J1614-518 (1)	7.28	6.1	0.84
HESS J1614-518 (2)	5.68	5.19	0.91
Galactic center	4.43	3.94	0.89
MGRO J1908+06 (1)	1.74	1.62	0.93
MGRO J1908+06 (2)	3.55	3.11	0.88
MGRO J1908+06 (3)	4.40	3.78	0.86
NGC 1068	66.87	66.39	0.99
TXS 0506+056 (1)	4.03	3.40	0.84
TXS 0506+056 (2)	3.78	3.12	0.83

For TXS 0505+06, a blazar with a high energy spectrum *(RR peak at 50 TeV),* one can see a significant *(>15%)* decrease in the flux