Dark Ghosts

Granada, 31st March - 1st April 2022

3rd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes

BAIKAL-GVD

Dark Matter searches with Baikal NT&GVD

Olga Suvorova, Sergei Demidov

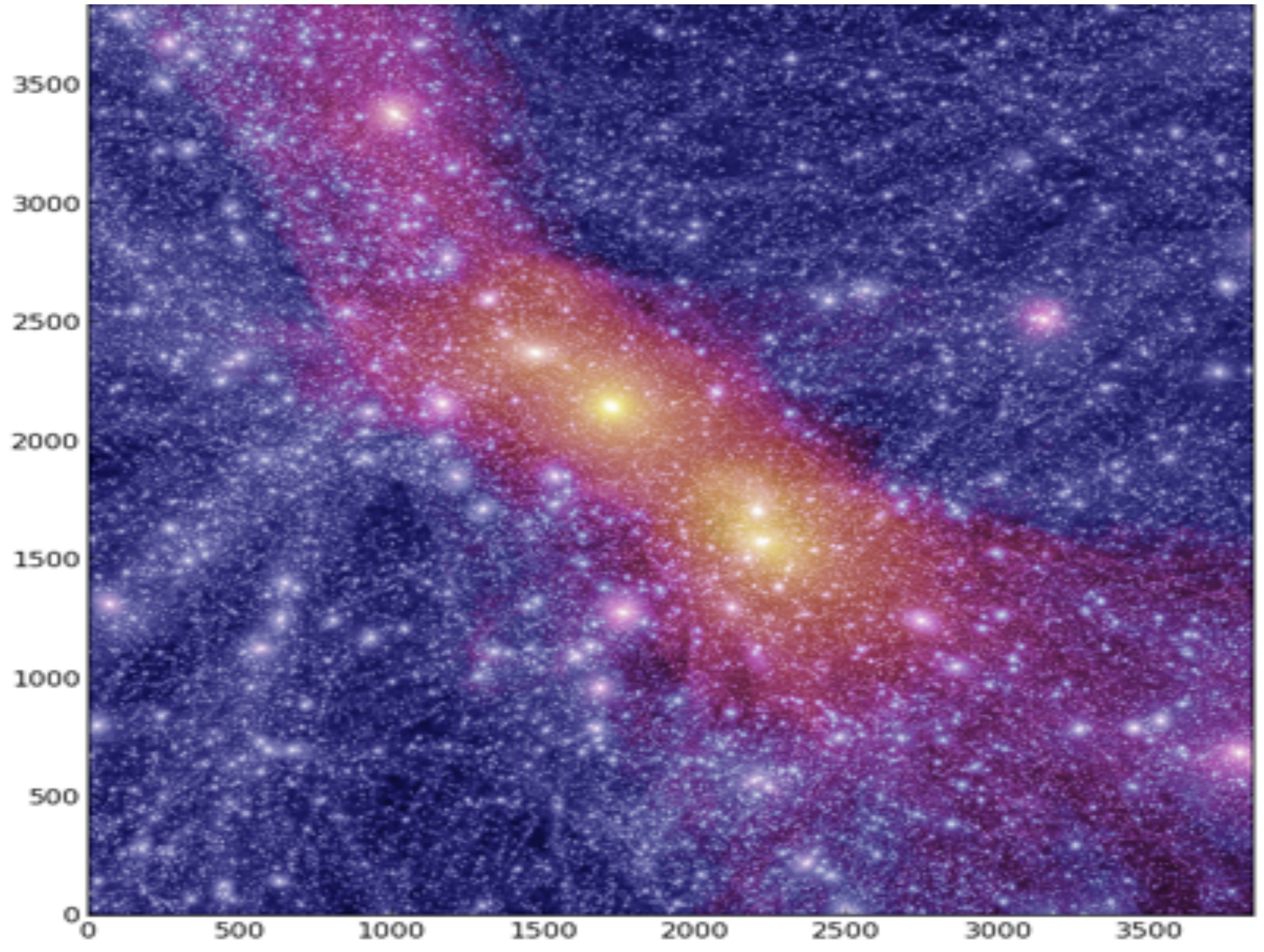
INR RAS, Moscow

for the Baikal-GVD collaboration

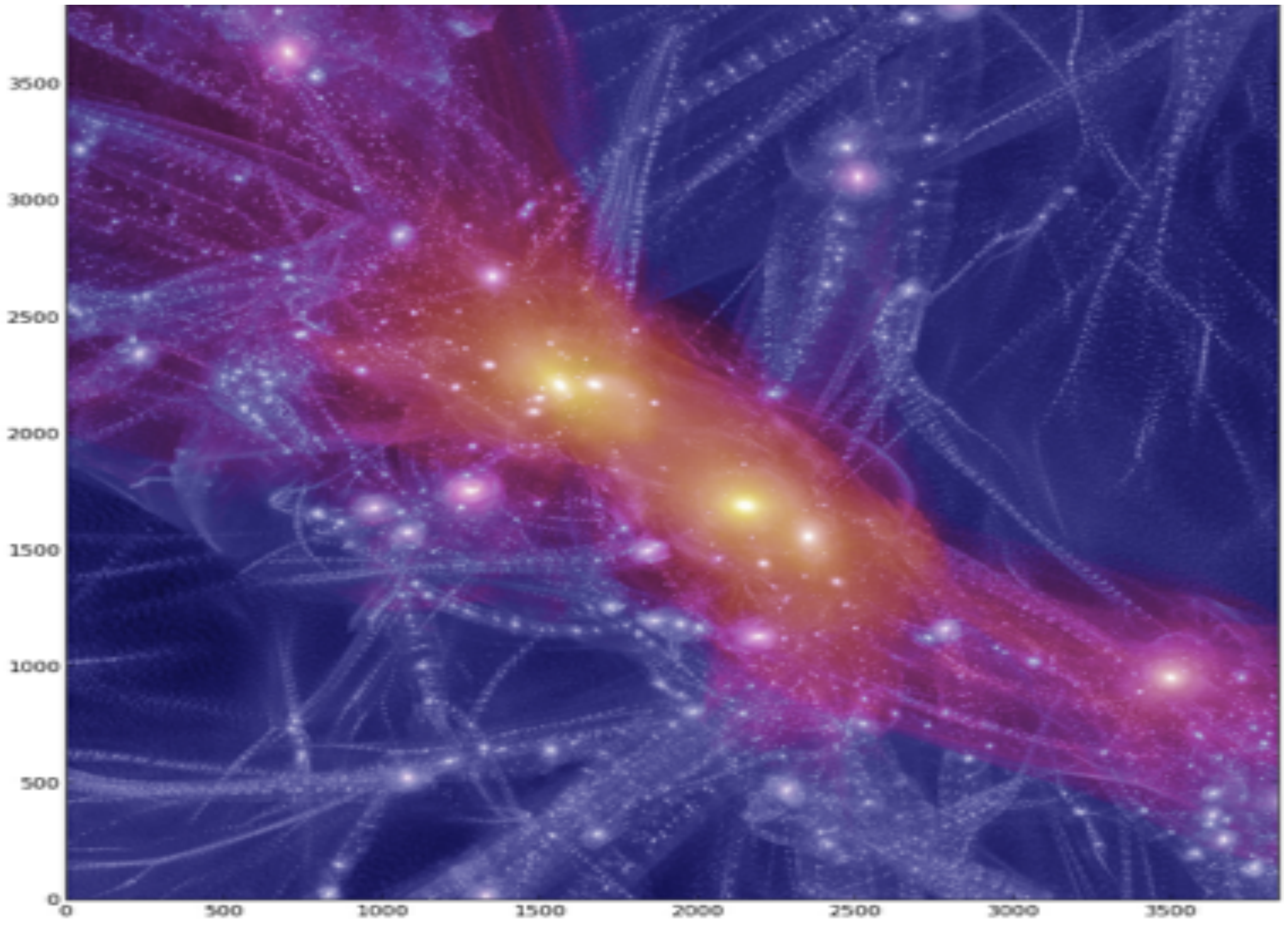
WIMPs are CDM candidates

Instead of Introduction

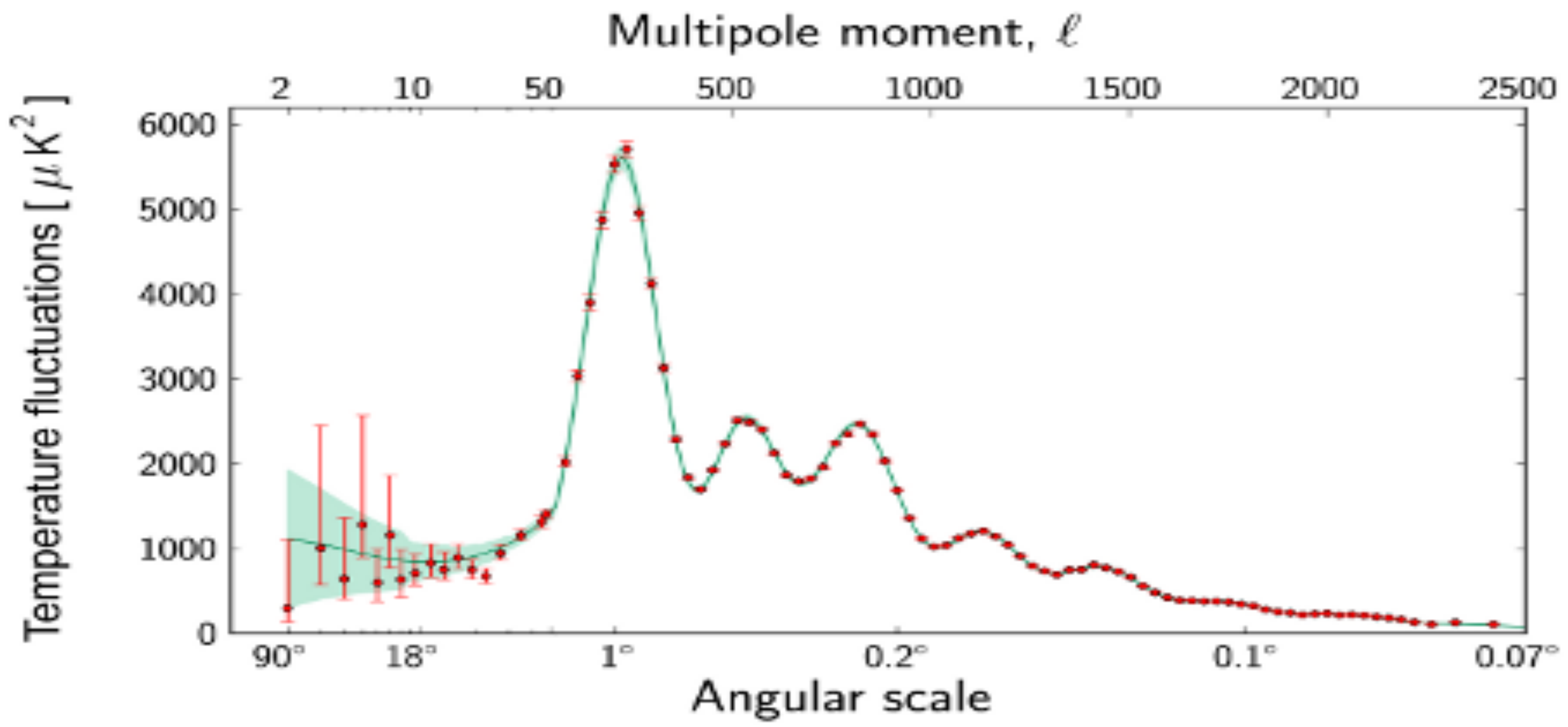
Simulation of what the Universe looks like



~ Simulation of what the Universe would look like without DM



CDM fit observations

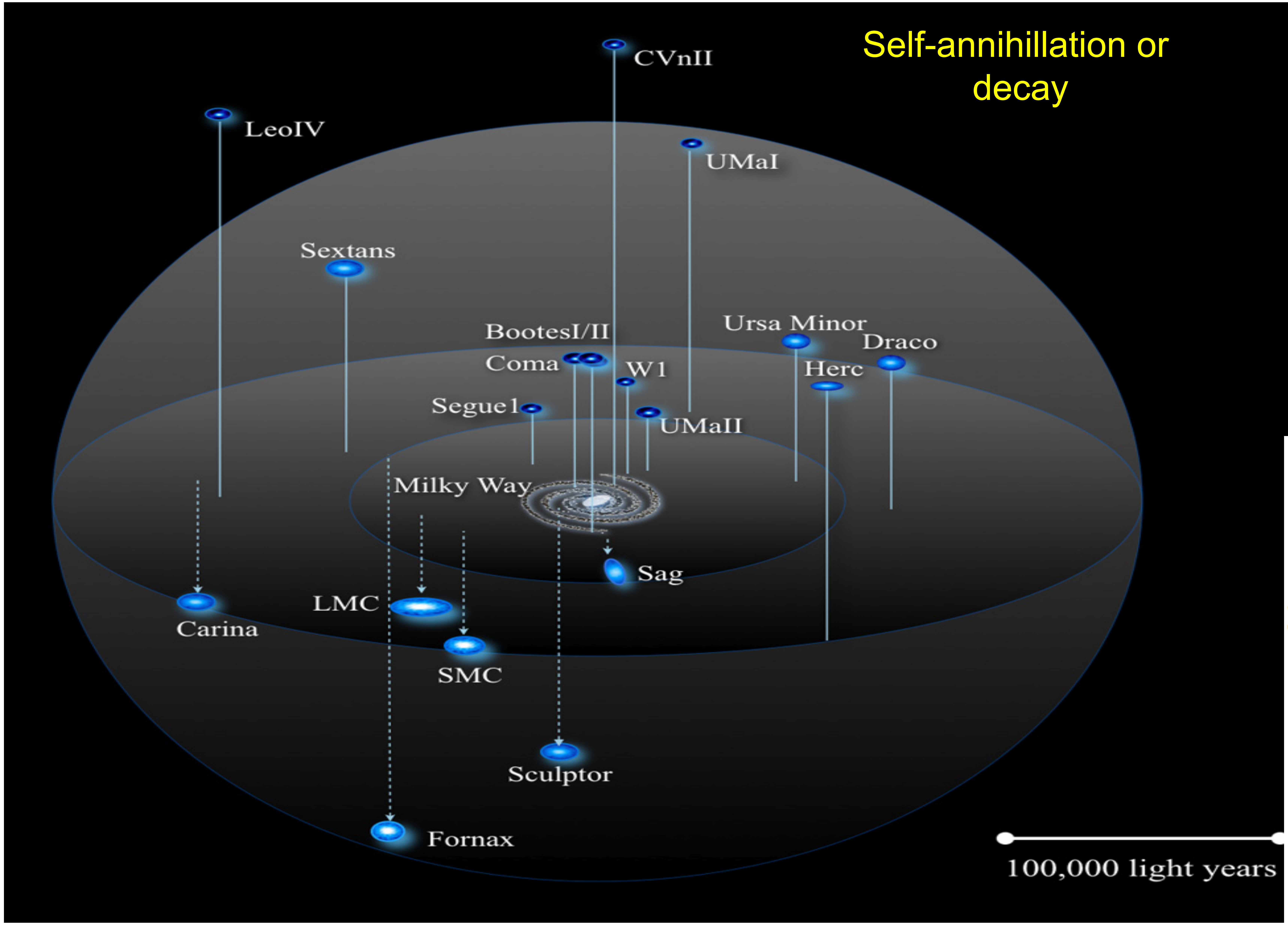


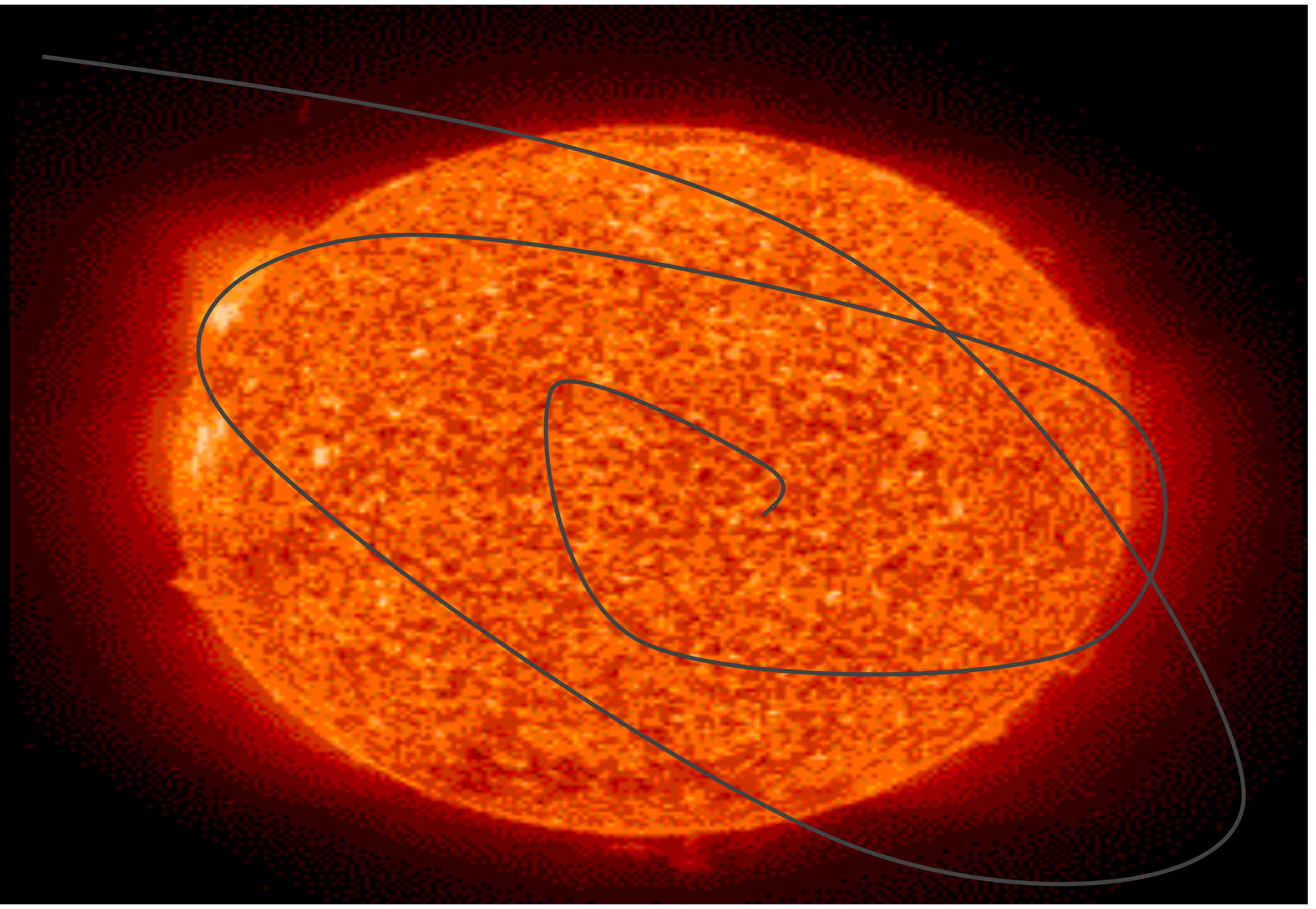
Directions in searches for DM. Upper Lim with NT-200 and GVD sensitivity, published early

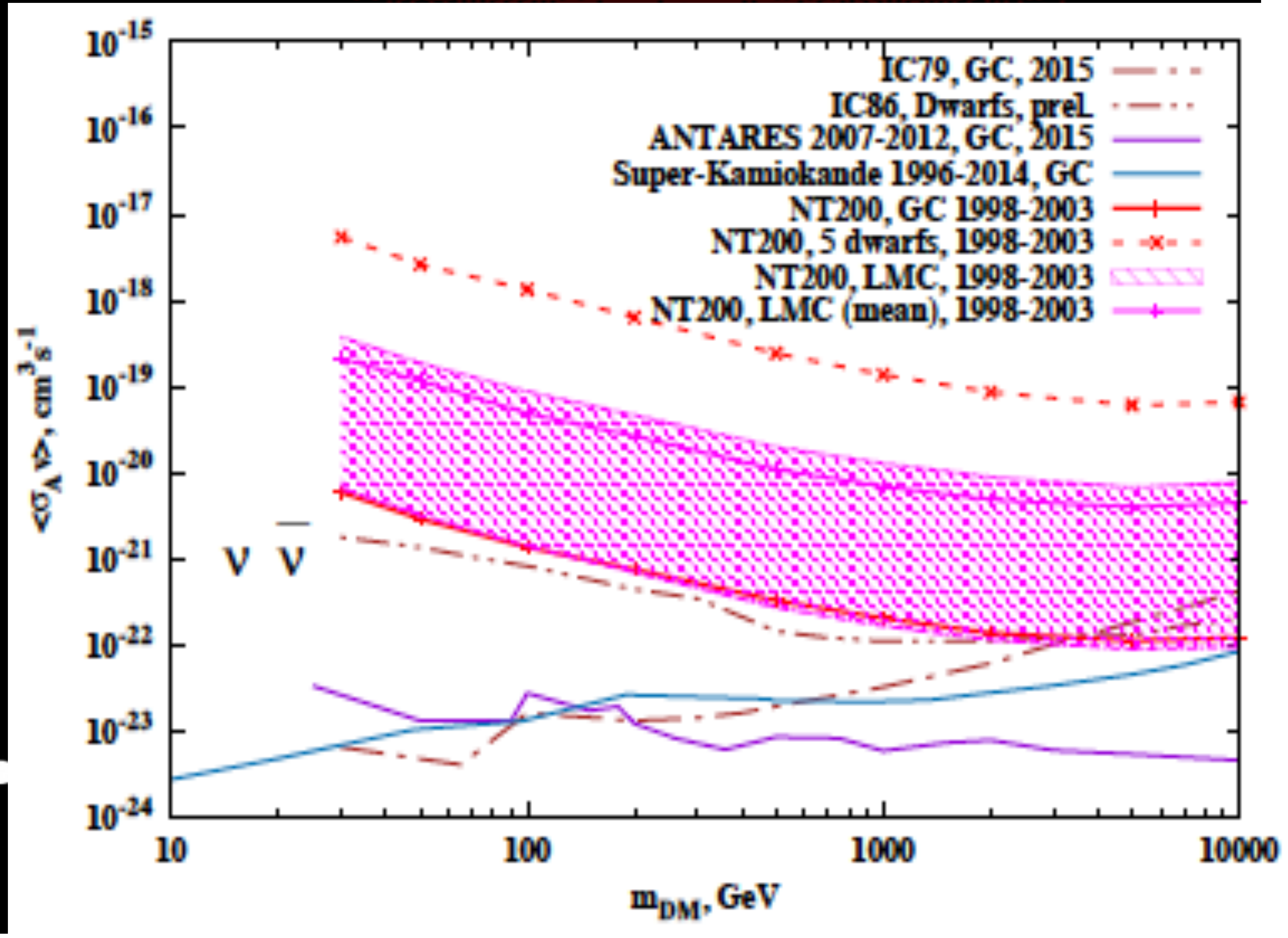
Baikal DM searches

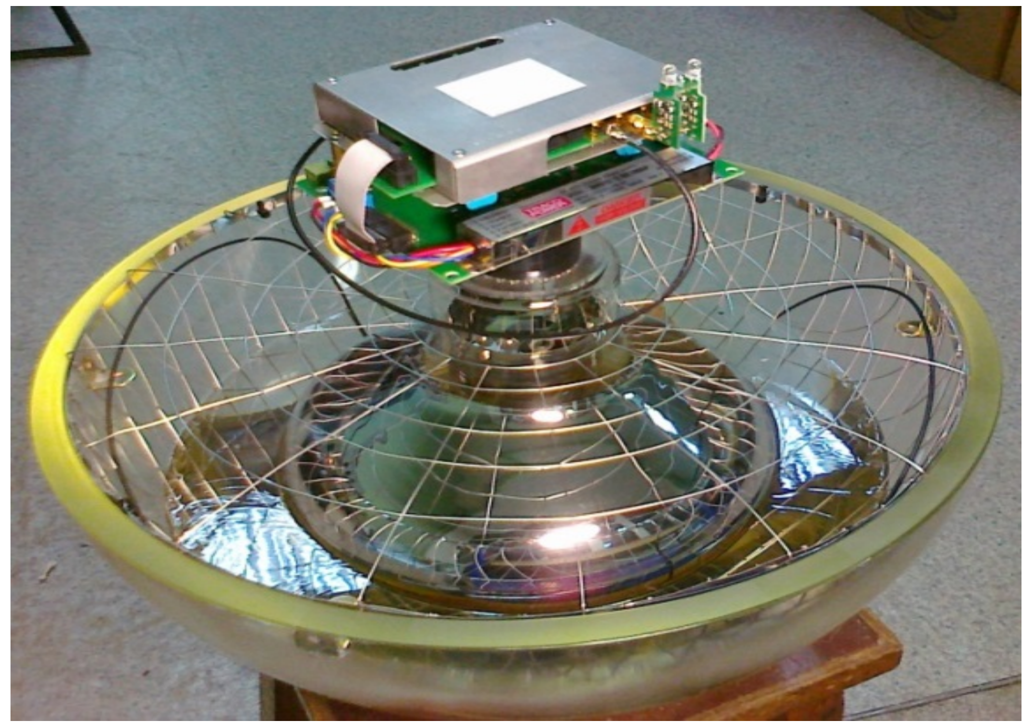
Capture and scattering

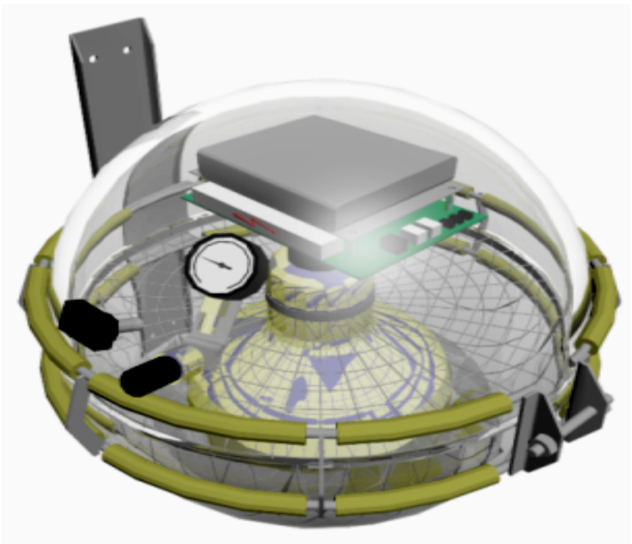
Self-annihillation or decay







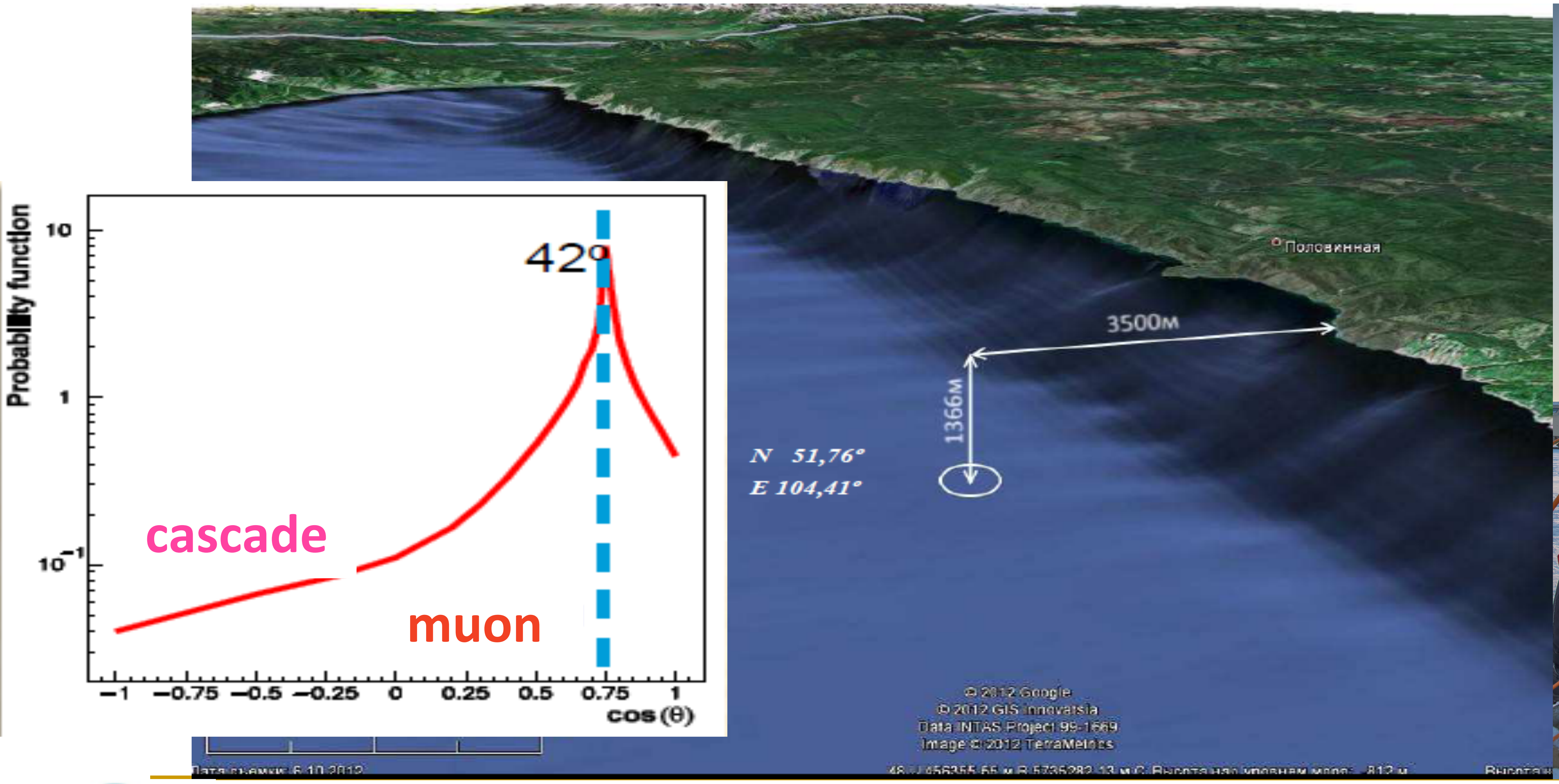


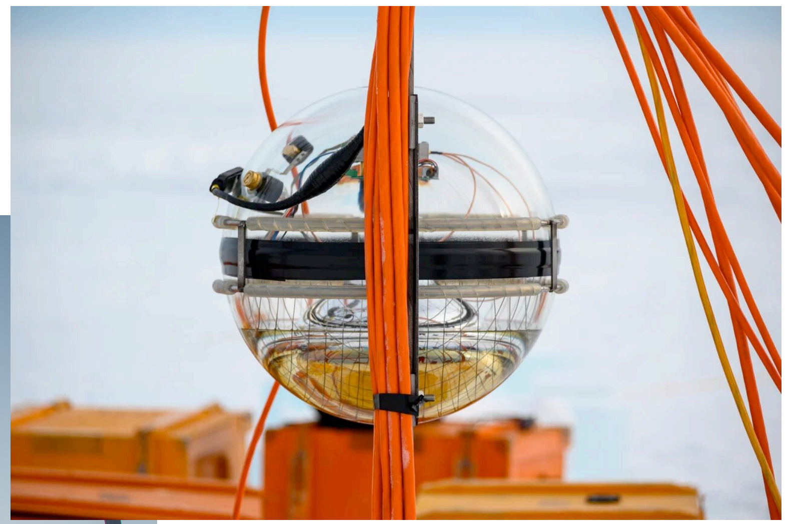


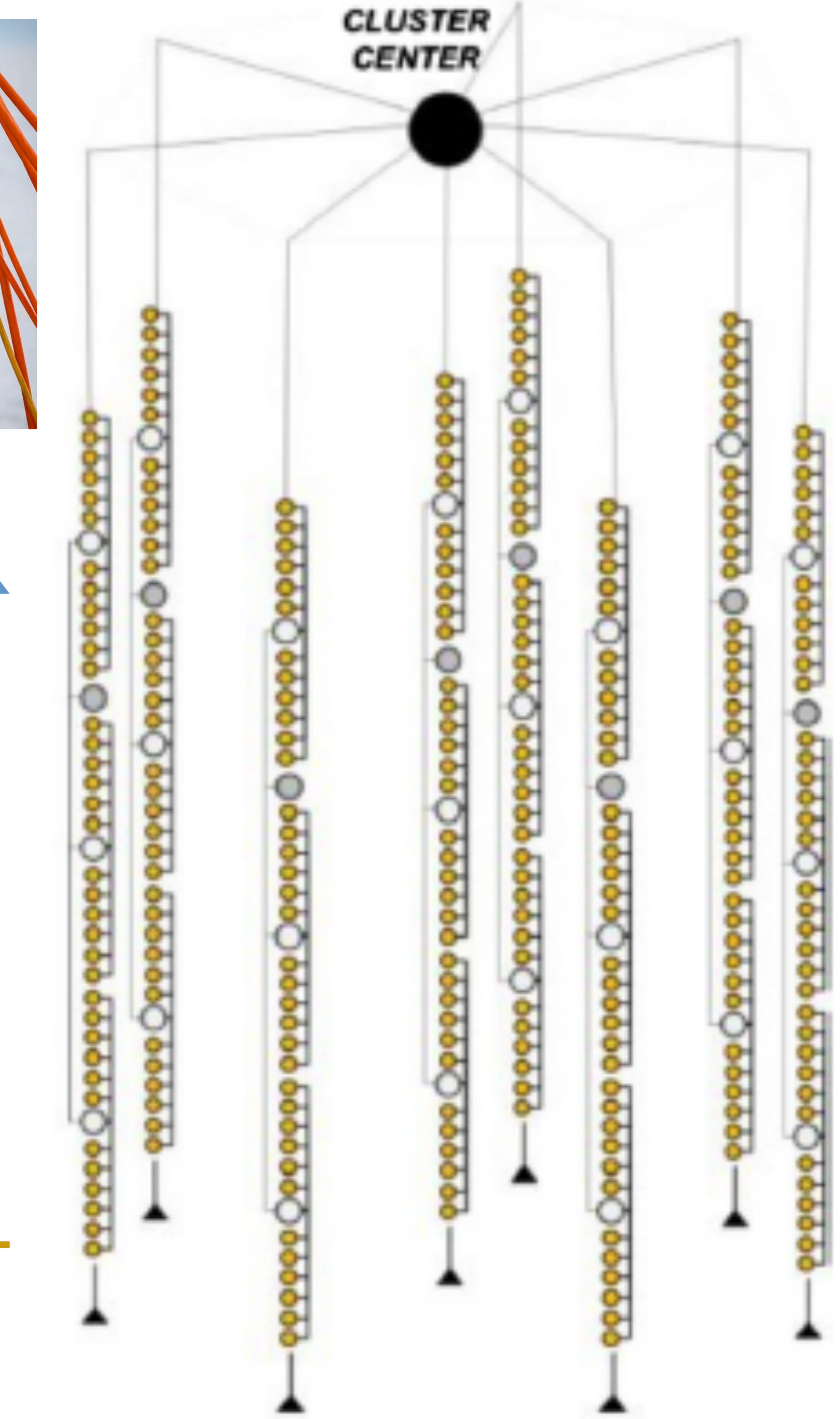
Optical module

PMT: R7081-100

Baikal-GVD

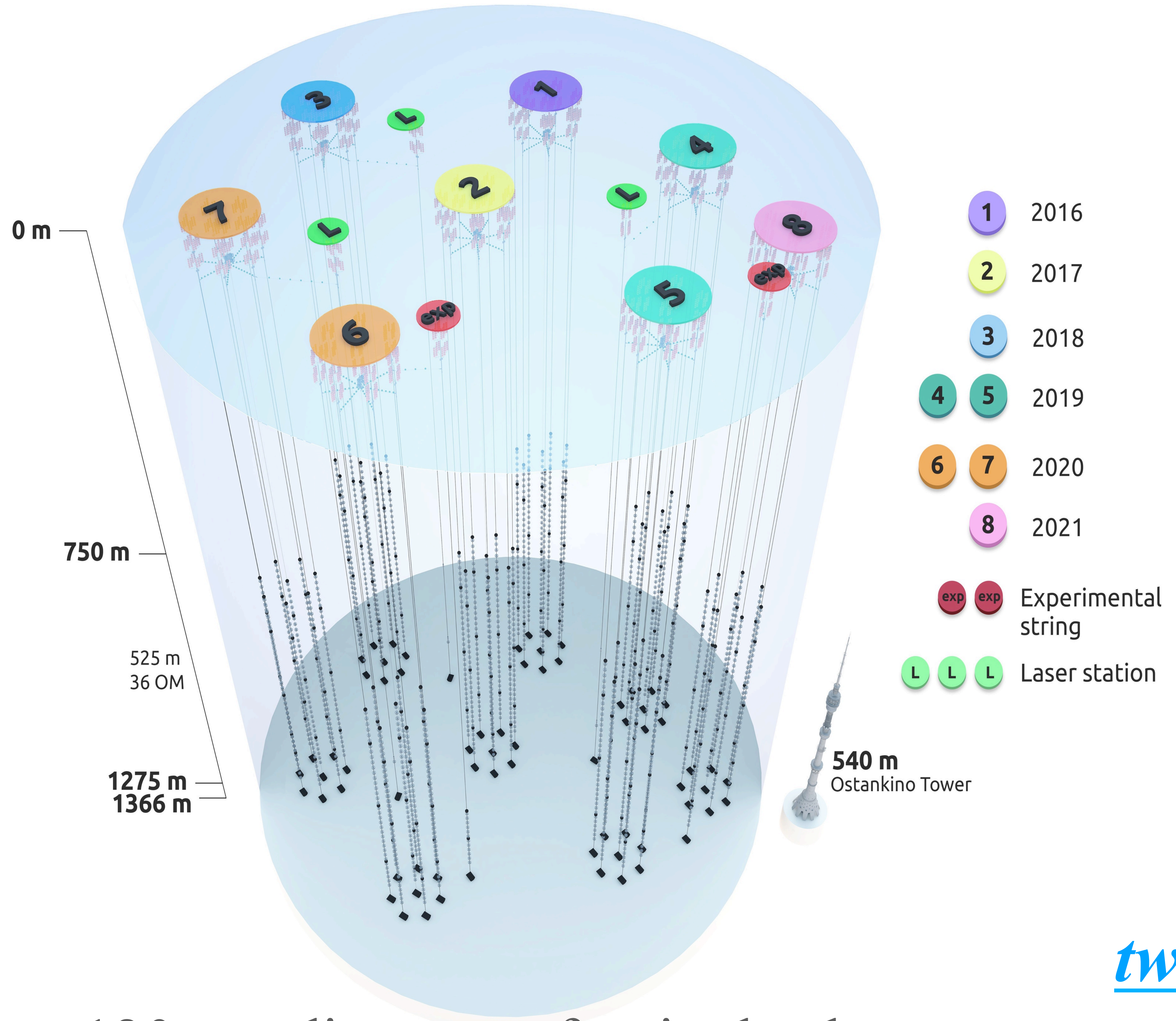






BAIKAL-GVD

Baikal-GVD of 2021yr: 2304 OMs/ 64 strings/ 8 clusters



120 m - diameter of a single cluster,
300 m - distance between clusters

0.4 km^3 for cascades of E>>100 TeV

Apr 2022:
two new clusters

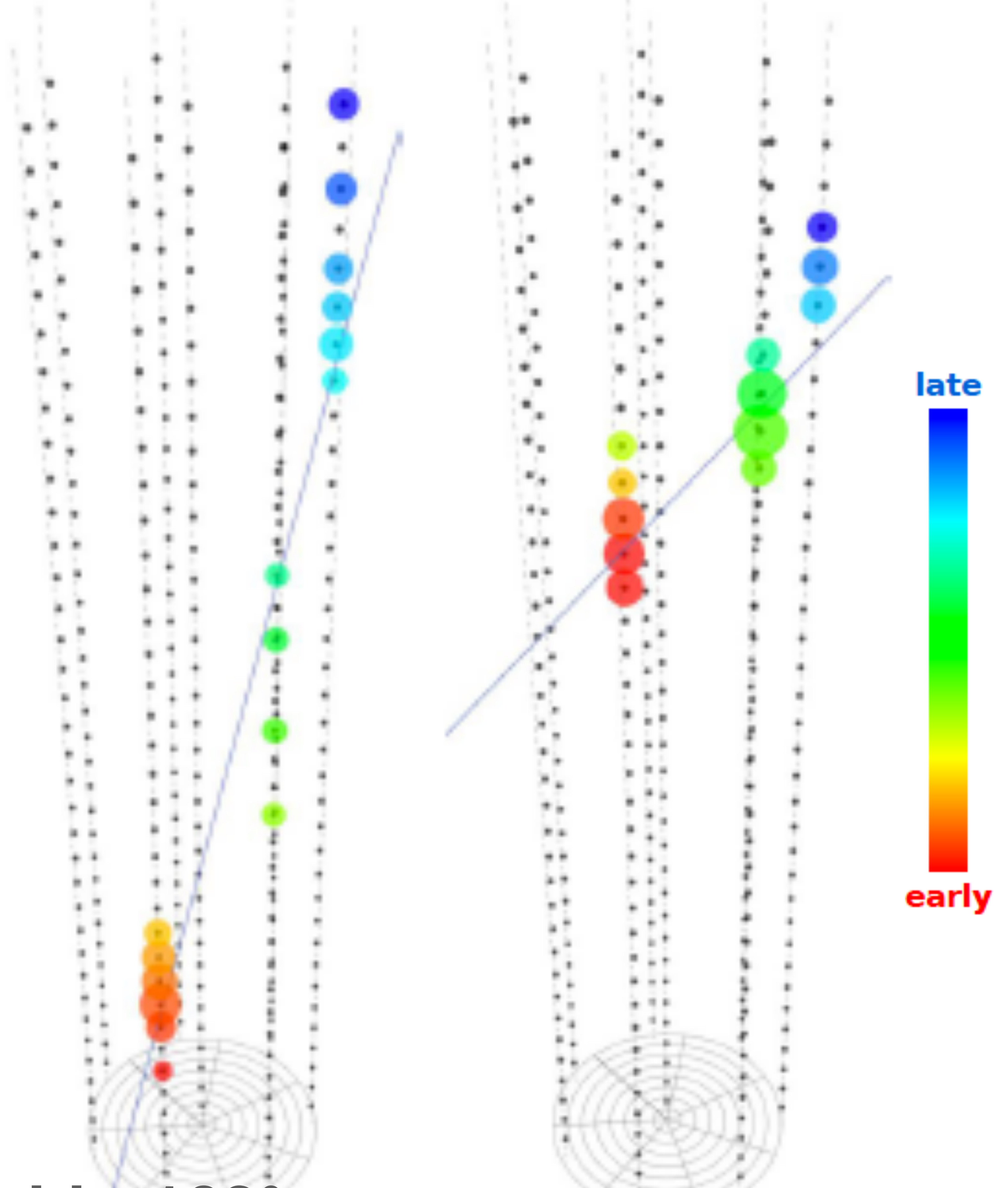
Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

ICRC2021, *Zh.-A.M. Dzhilkibaev and I.A.Belolaptikov;*
VLVnT2021, *V.M.Aynutdinov*

Data performance in fast /offline regimes

Upward going muon-like alert

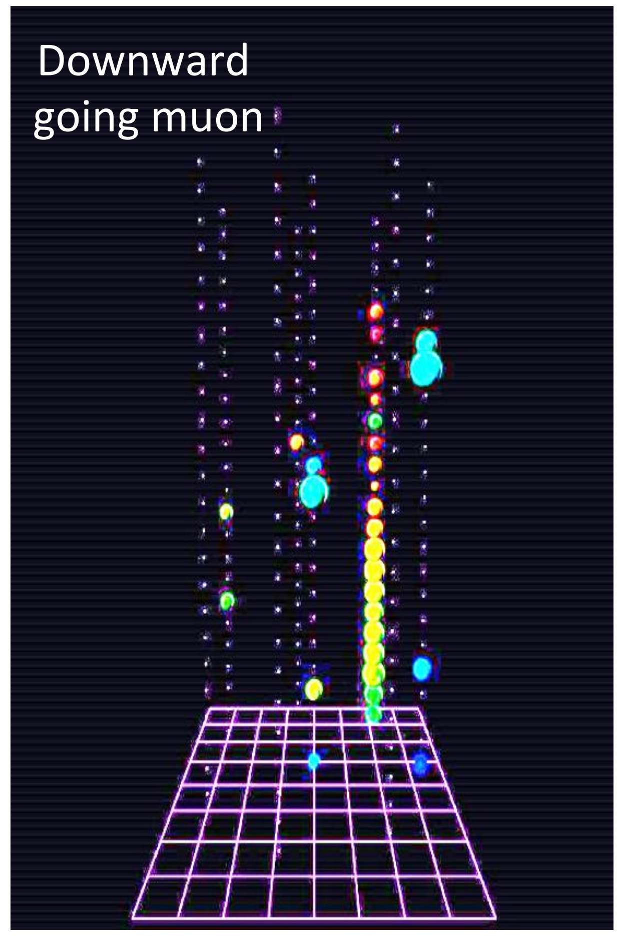


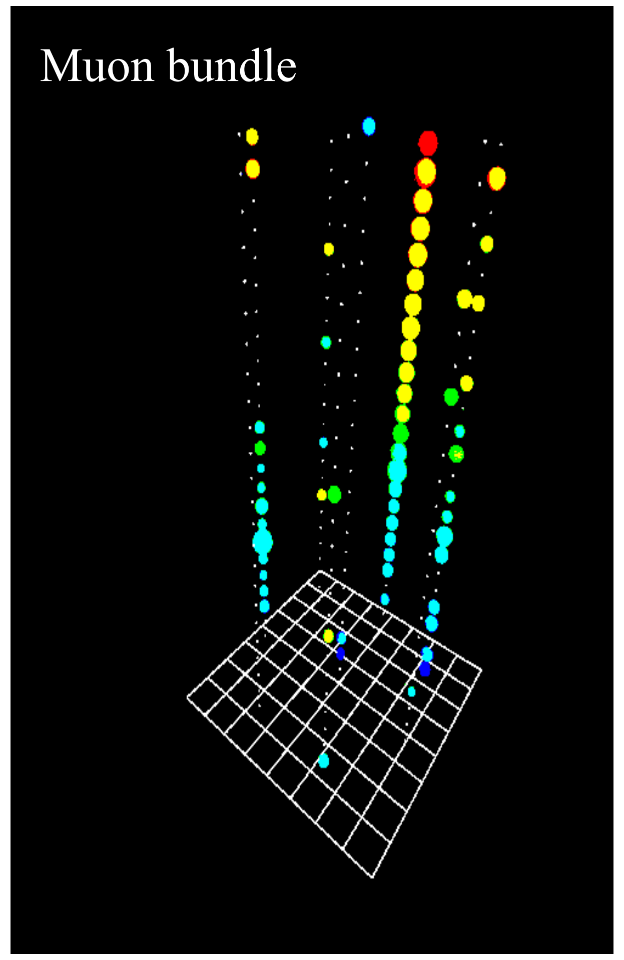
Zenith=163°   Zenith=127°

Fast algorithm of track reco in a single cluster events rejects a near horizon directions (<120°)

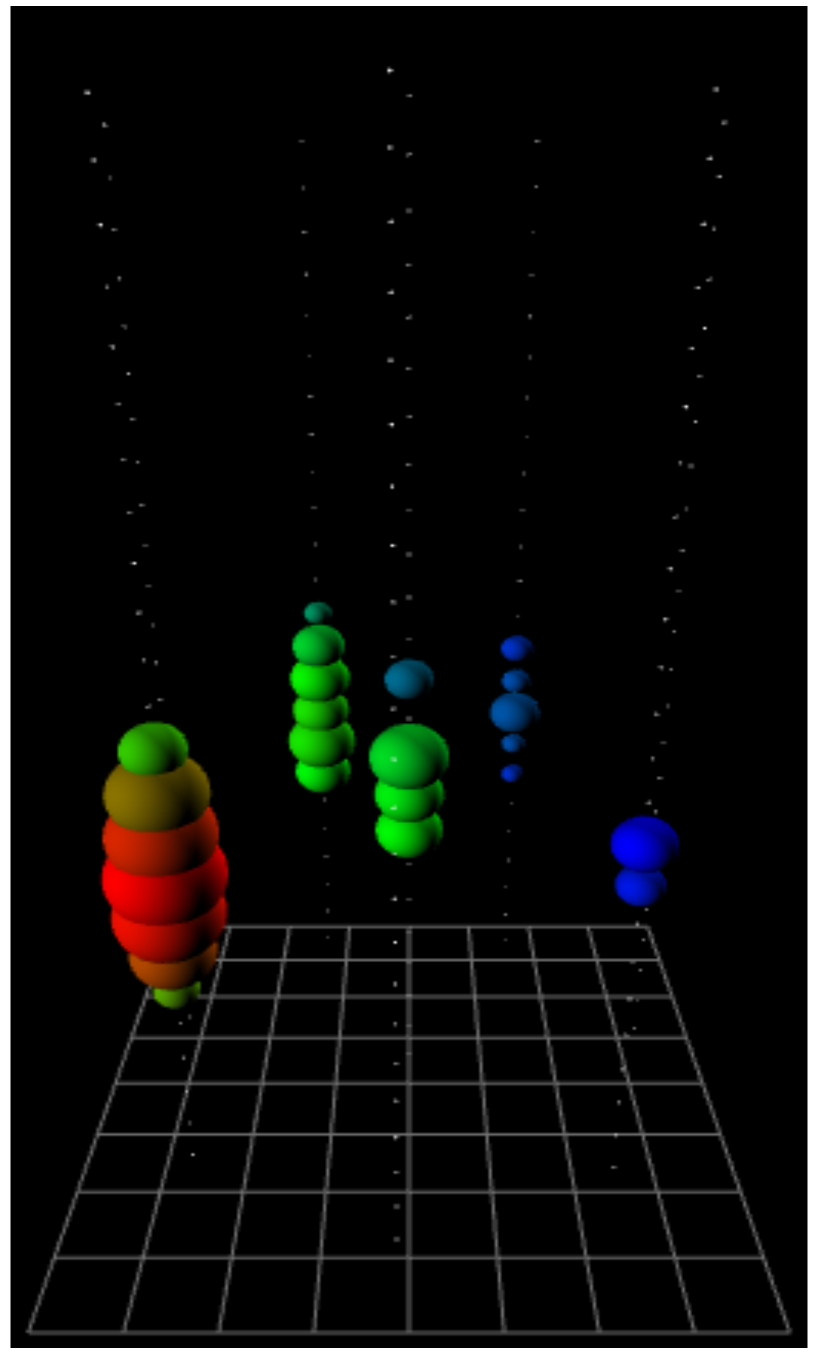
(ICRC2021, G.Safronov, D.Zaborov)

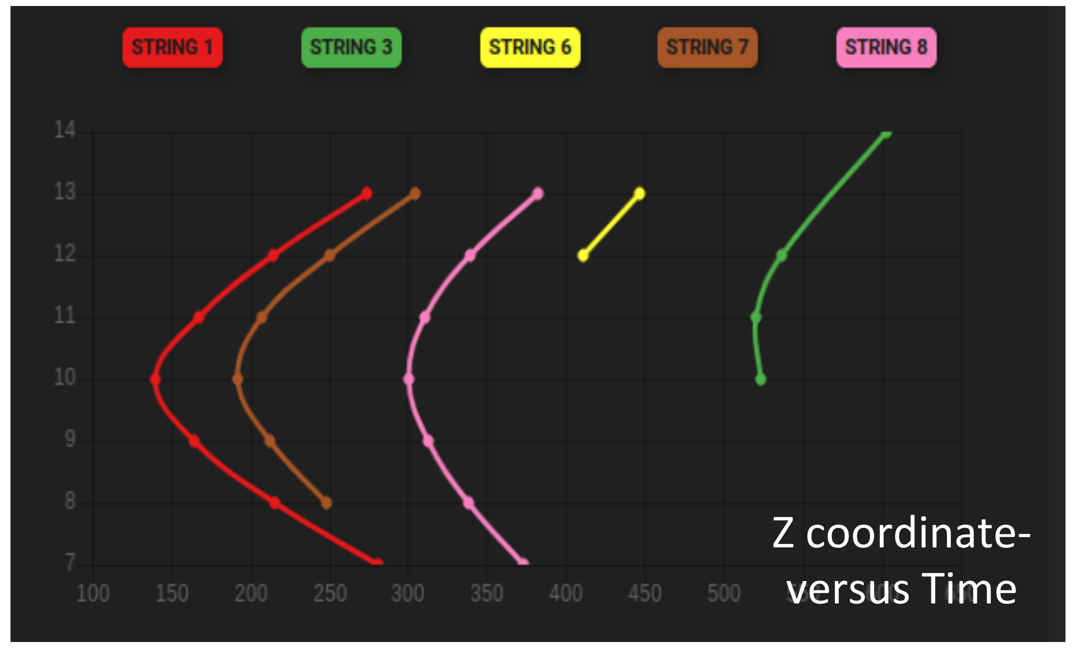
Background events



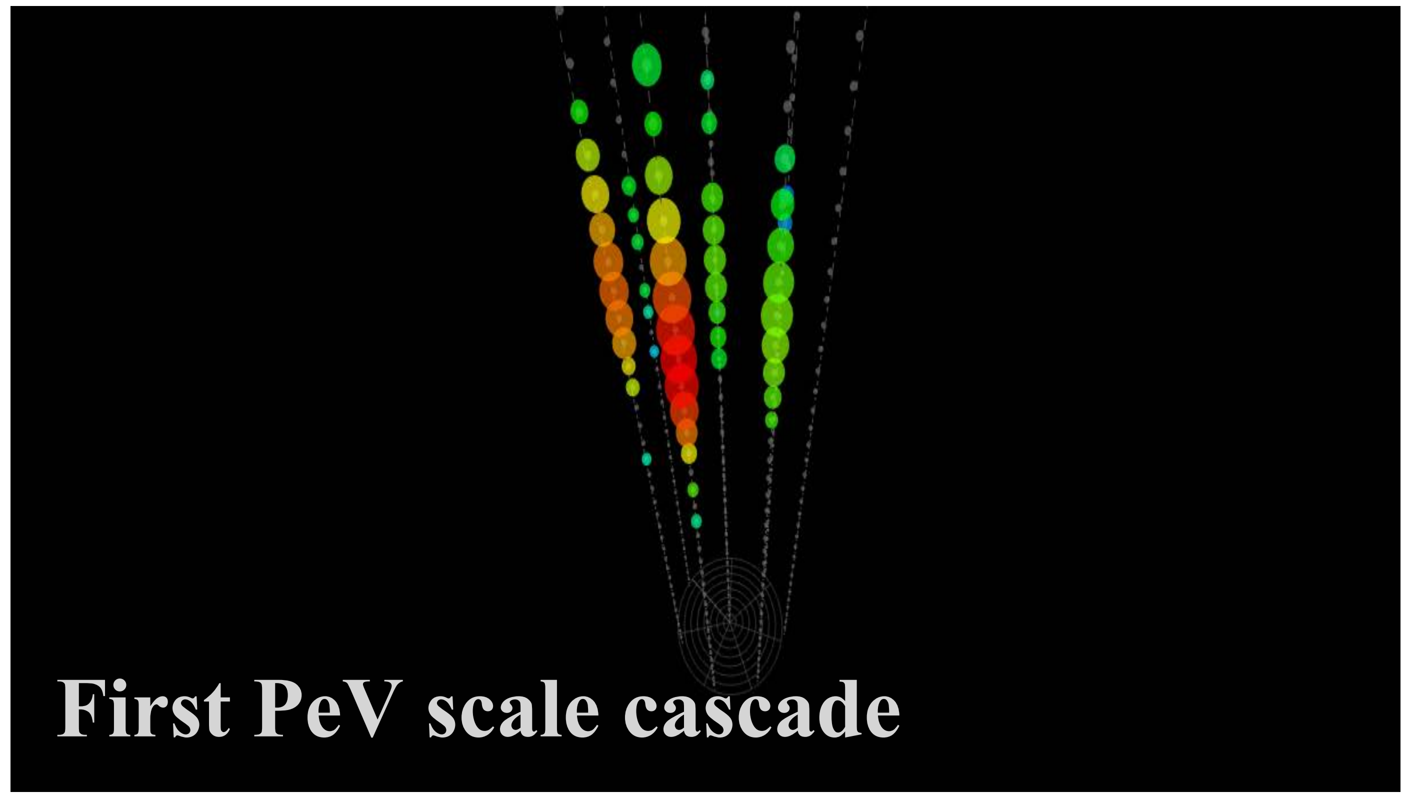


HE cascade-like alert

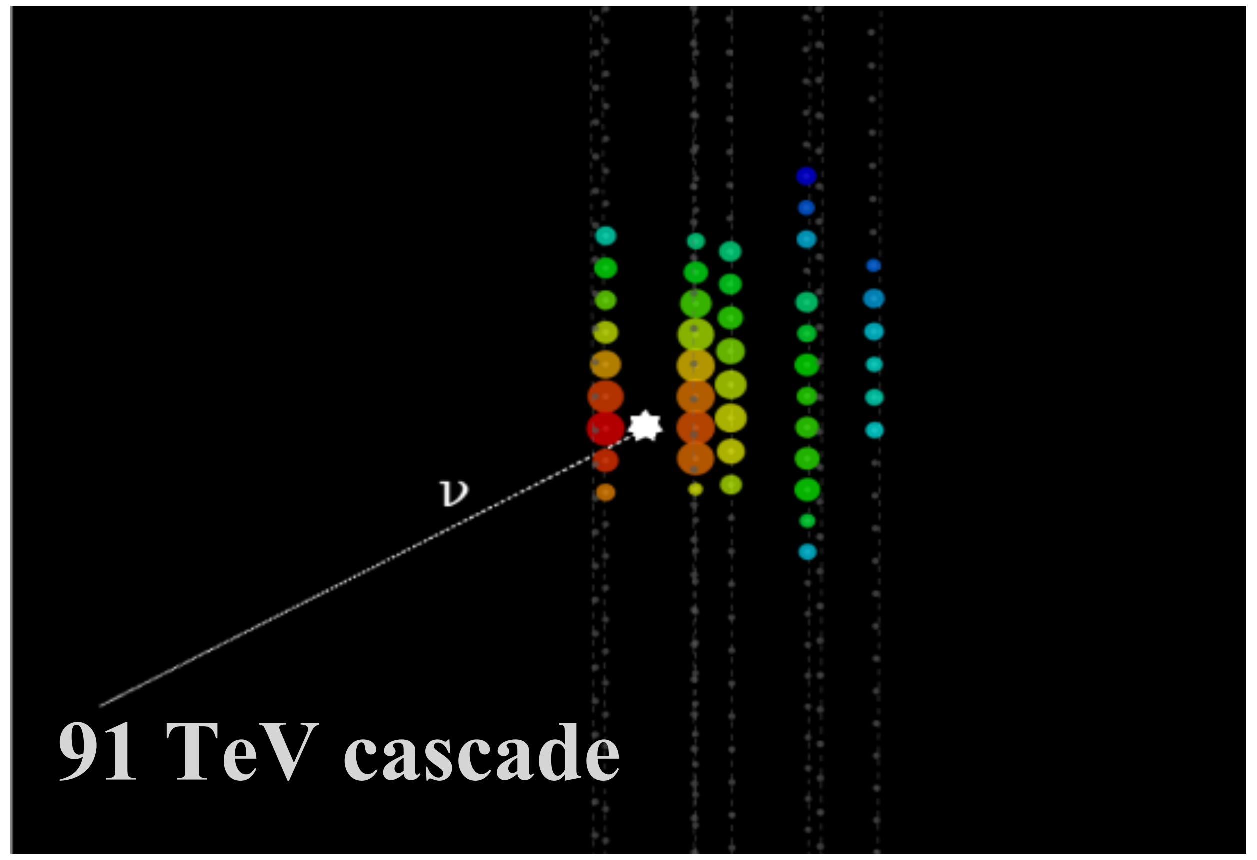




Downward going HE cascade-like alert



Upward going HE cascade-like alert

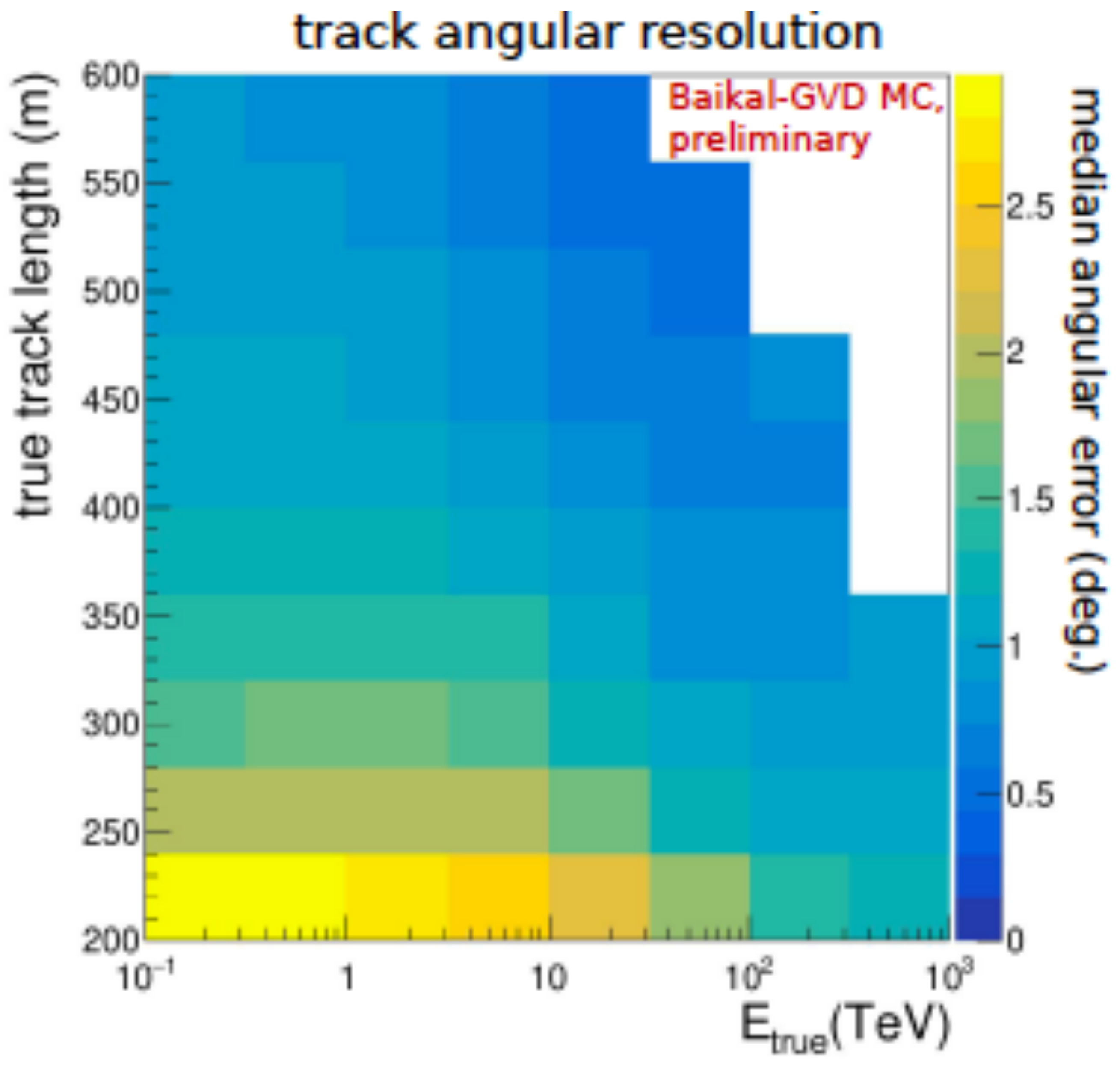


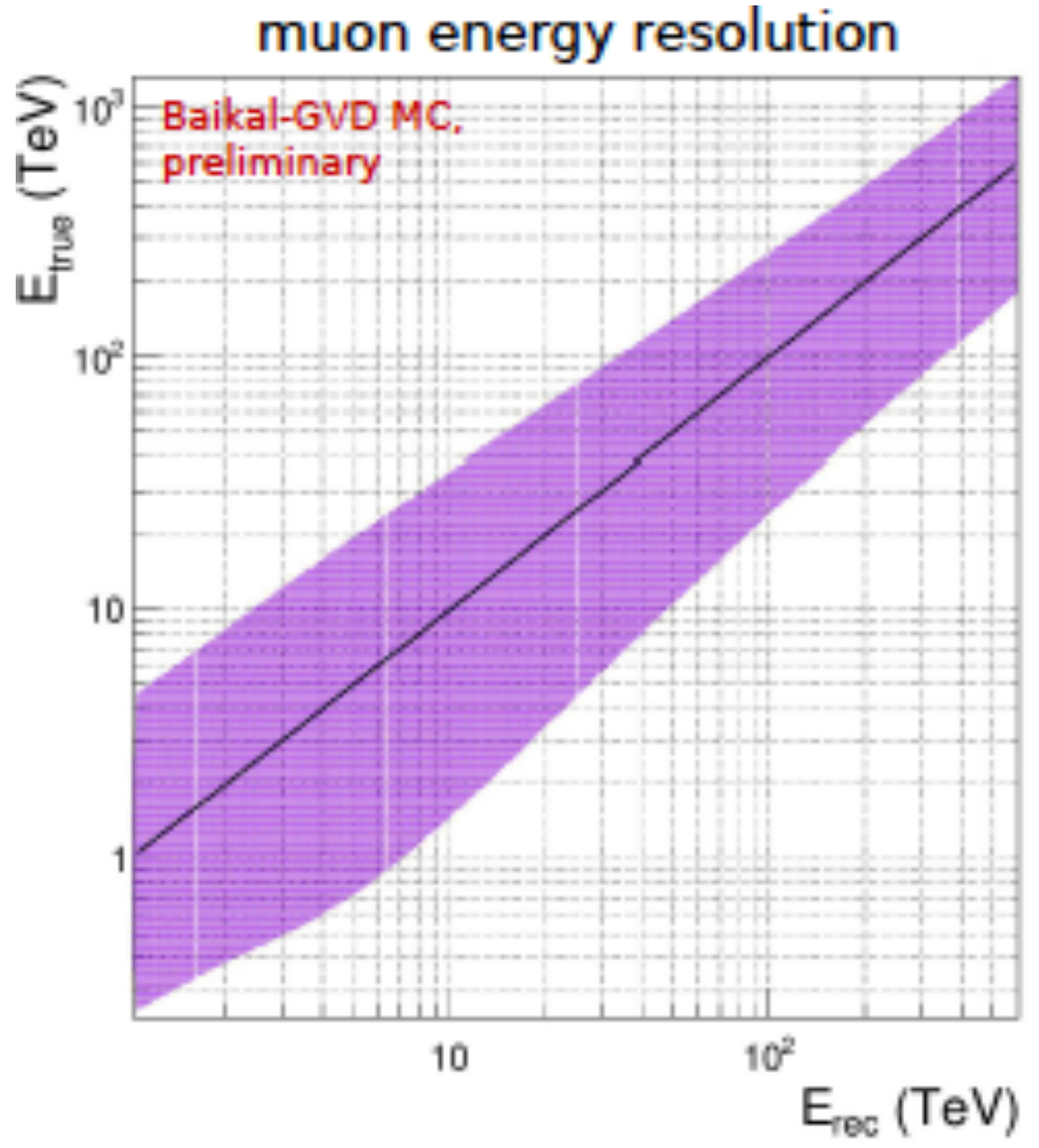
Cascades reco algorithm, selections and HE alerts

(ICRC2021, Zh.Dzhilkibaev; ICRC2021, L.Fajt)

Search for muon neutrinos

(analysis of **2019 data sample** –current ***iteration***)





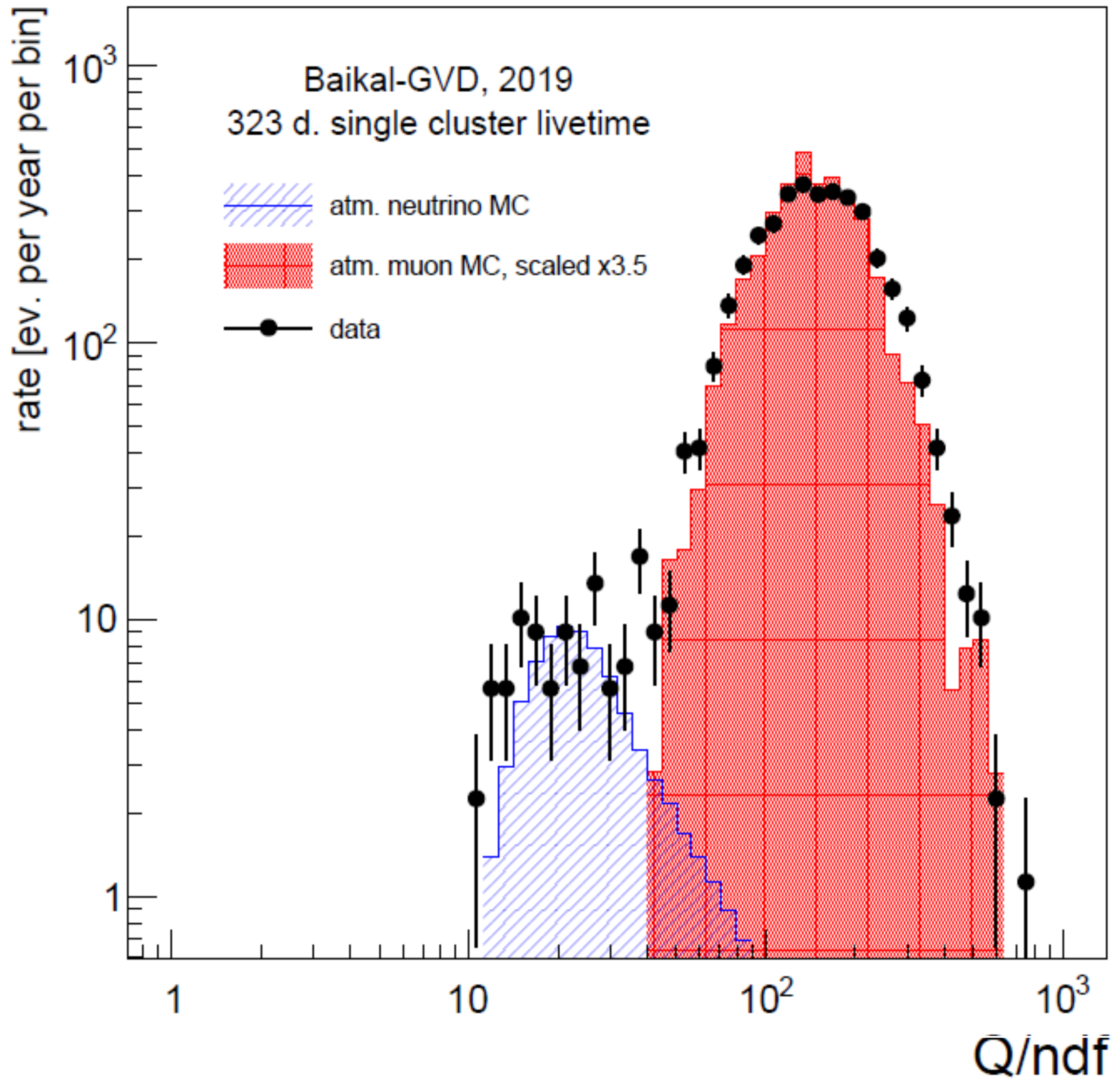
Muon neutrinos are detected as a muon tracks from bottom hemisphere.

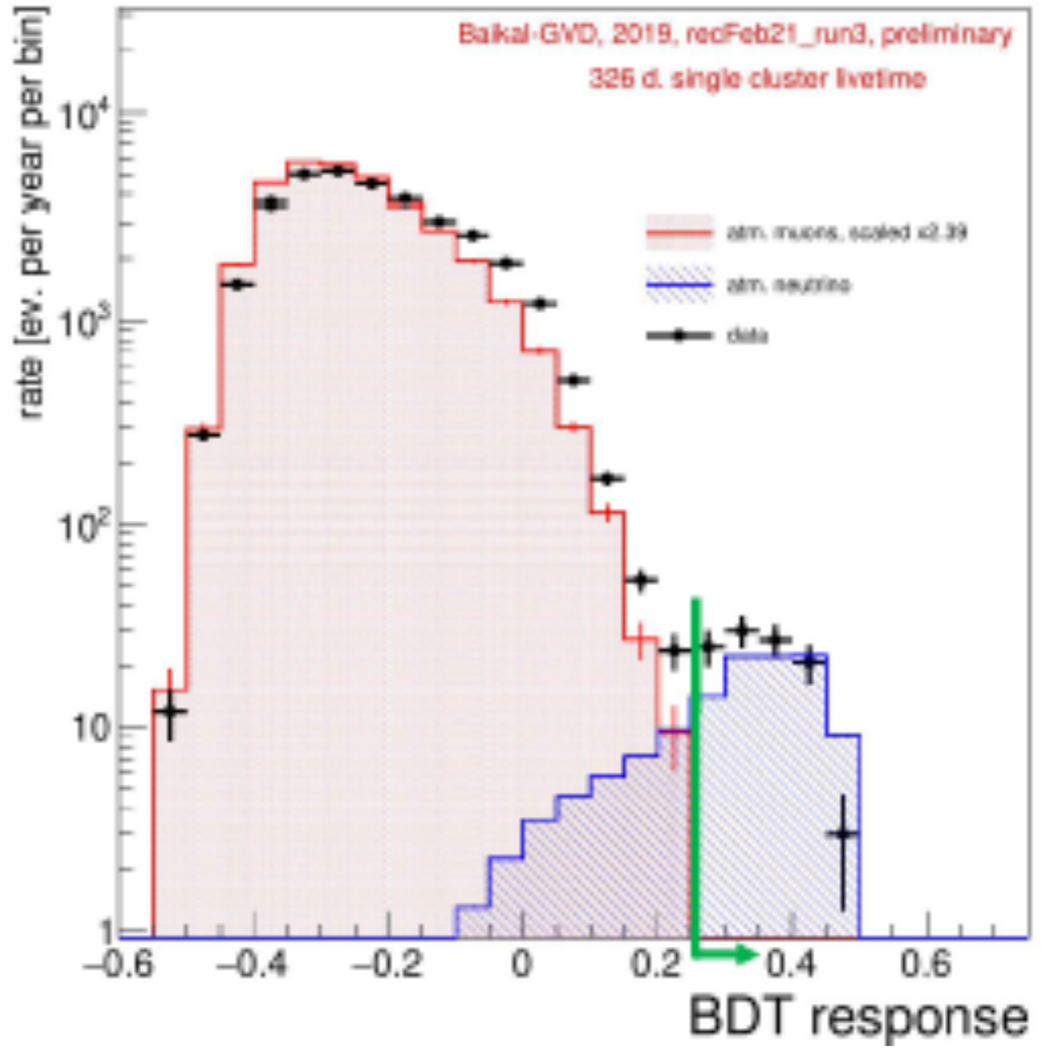
MC atmospheric muons - Corsika 7.74, SIBYLL 2.3c; MC atmospheric neutrinos – Bartol flux.

A single cluster reconstruction algorithms are developed, a multicluster reconstruction is in progress.

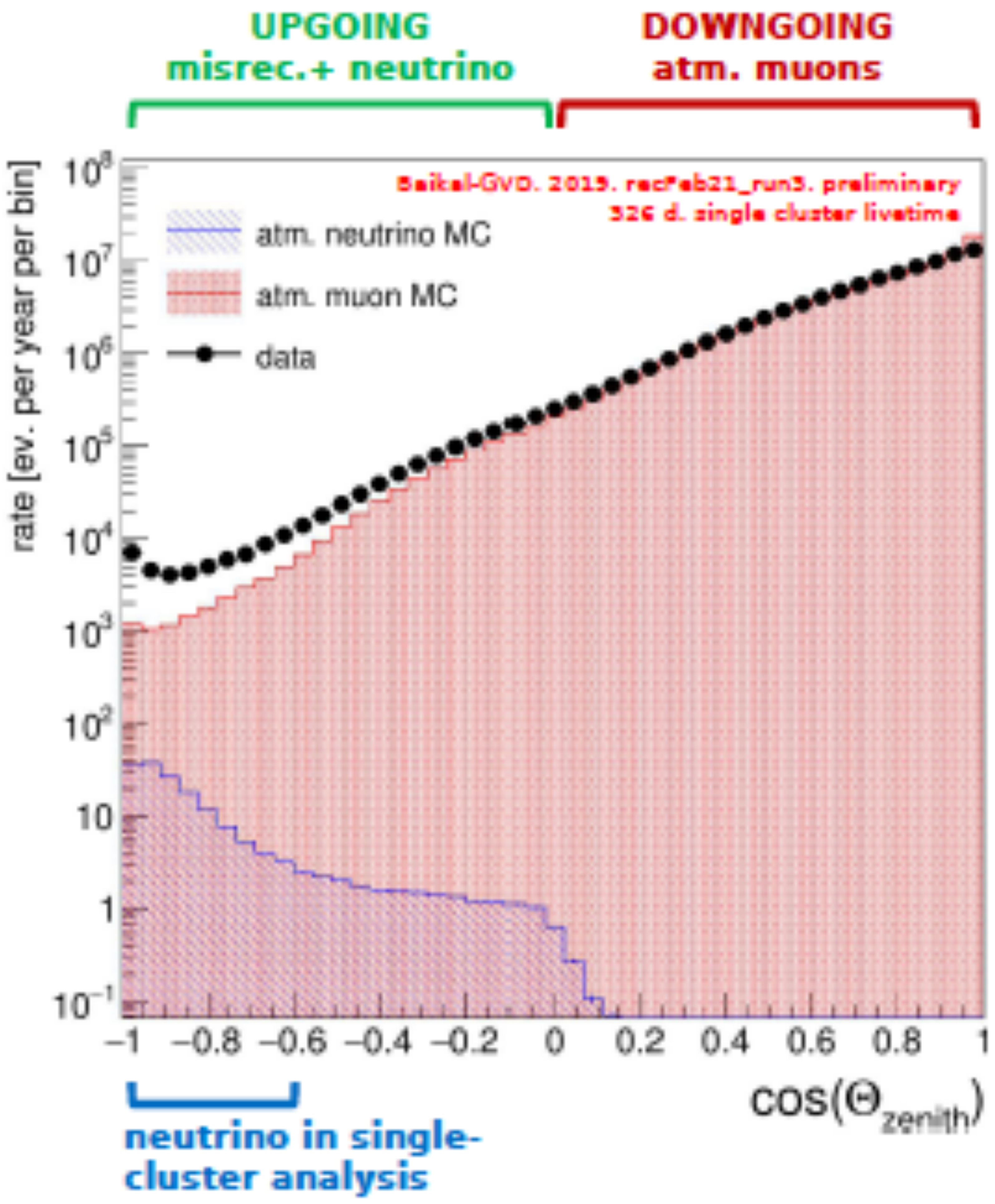
Two ways for neutrino selection were applied

- Cut-based (cuts on set of 13 variables)
- Mashine learning: Boosted Decision Tree (BDT) classifier (15 input variables)





Zenith angle distributions of muons



The median energy of the neutrino events 500 GeV

MC expected: 43.6 ±6.6 (stat.)

Observed: 44 for 323 l.d.(cls)

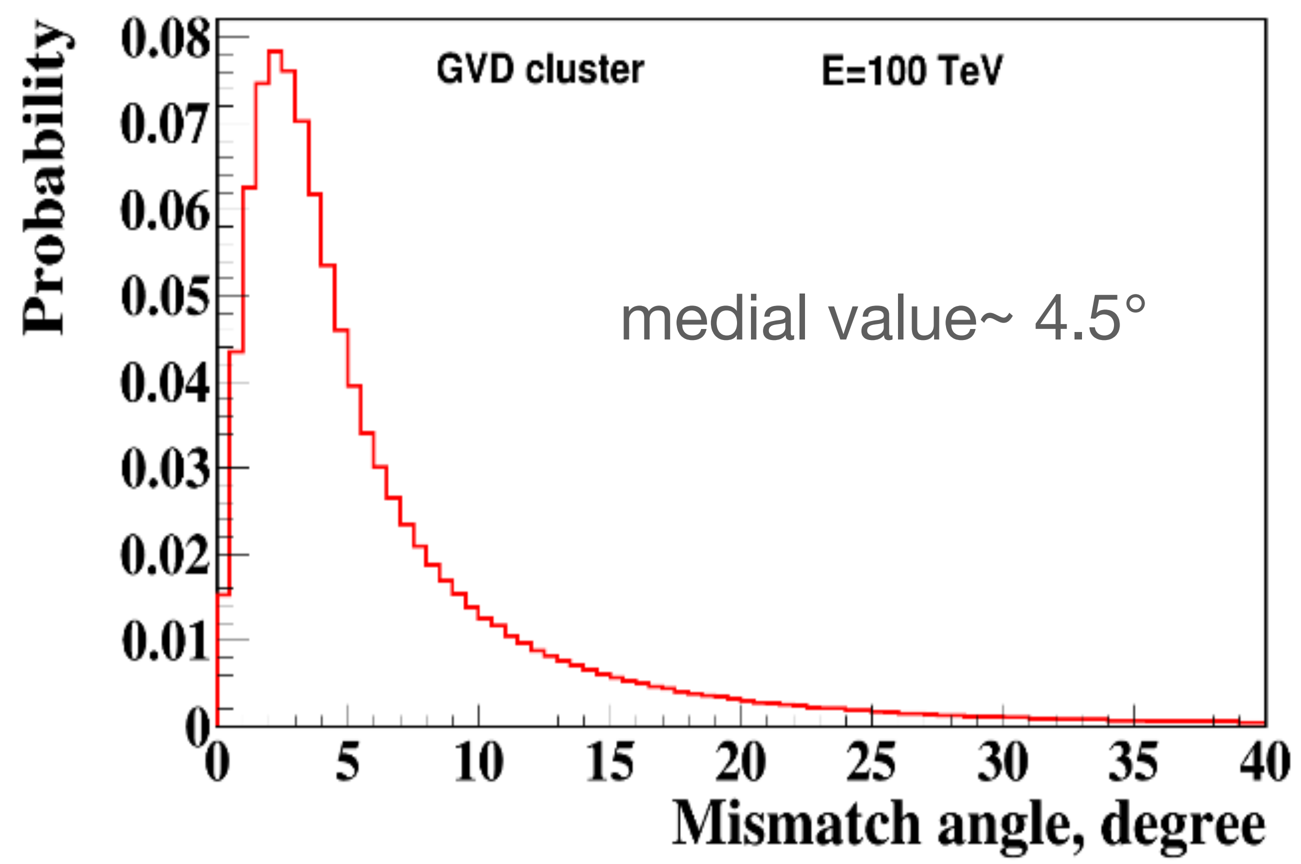
ICRC2021, A.Avrorin (PoS1063), G.Safronov (PoS1080), D.Zaborov (PoS1177)

Search for cascades of astroν (alert)

(estimates from MC analysis)

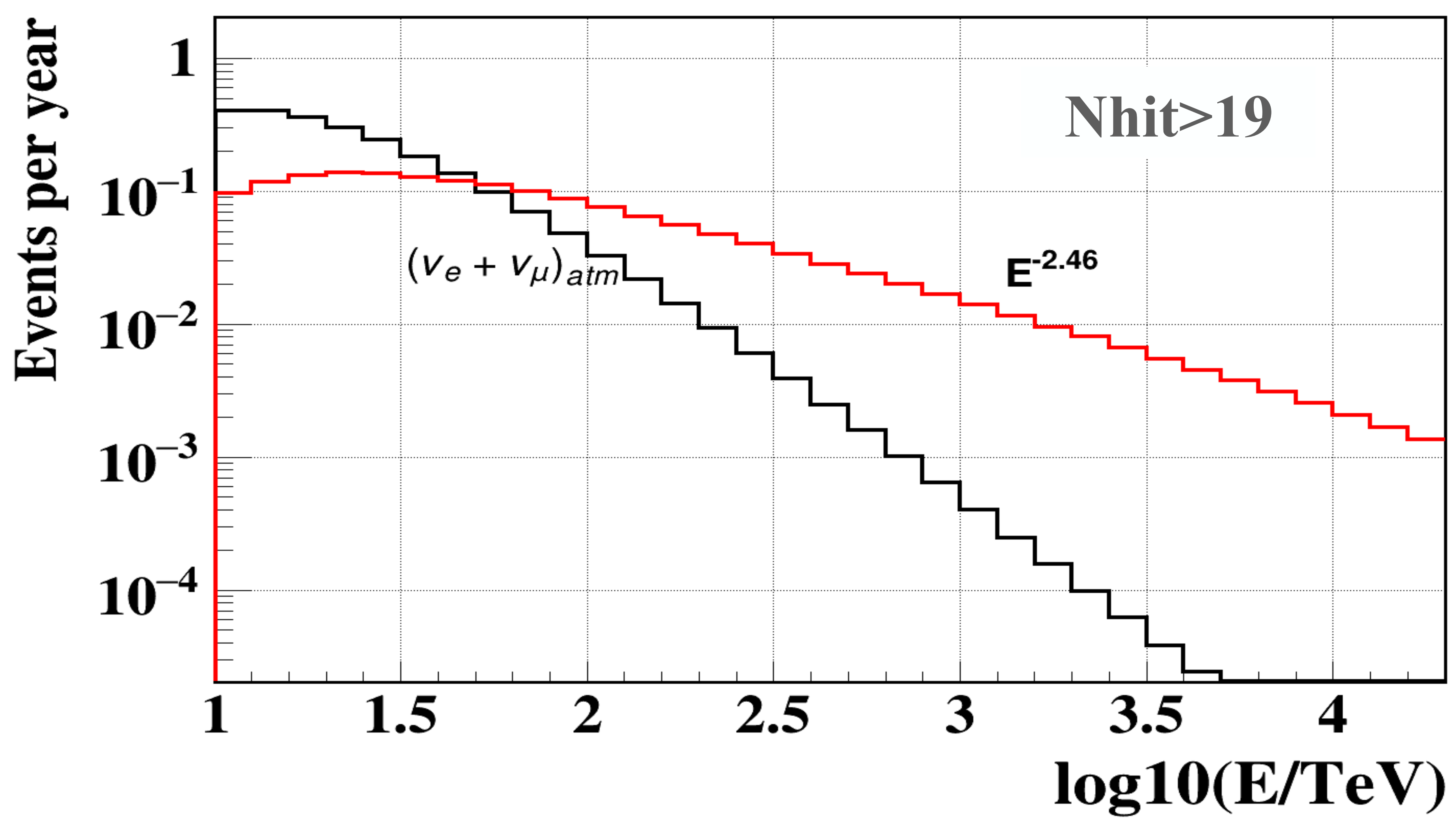
Expected ~0.3-0.5 astro-cascades/year for 1 GVD cluster for Esh>100 TeV & N_{hit}>19

Shower angular resolution

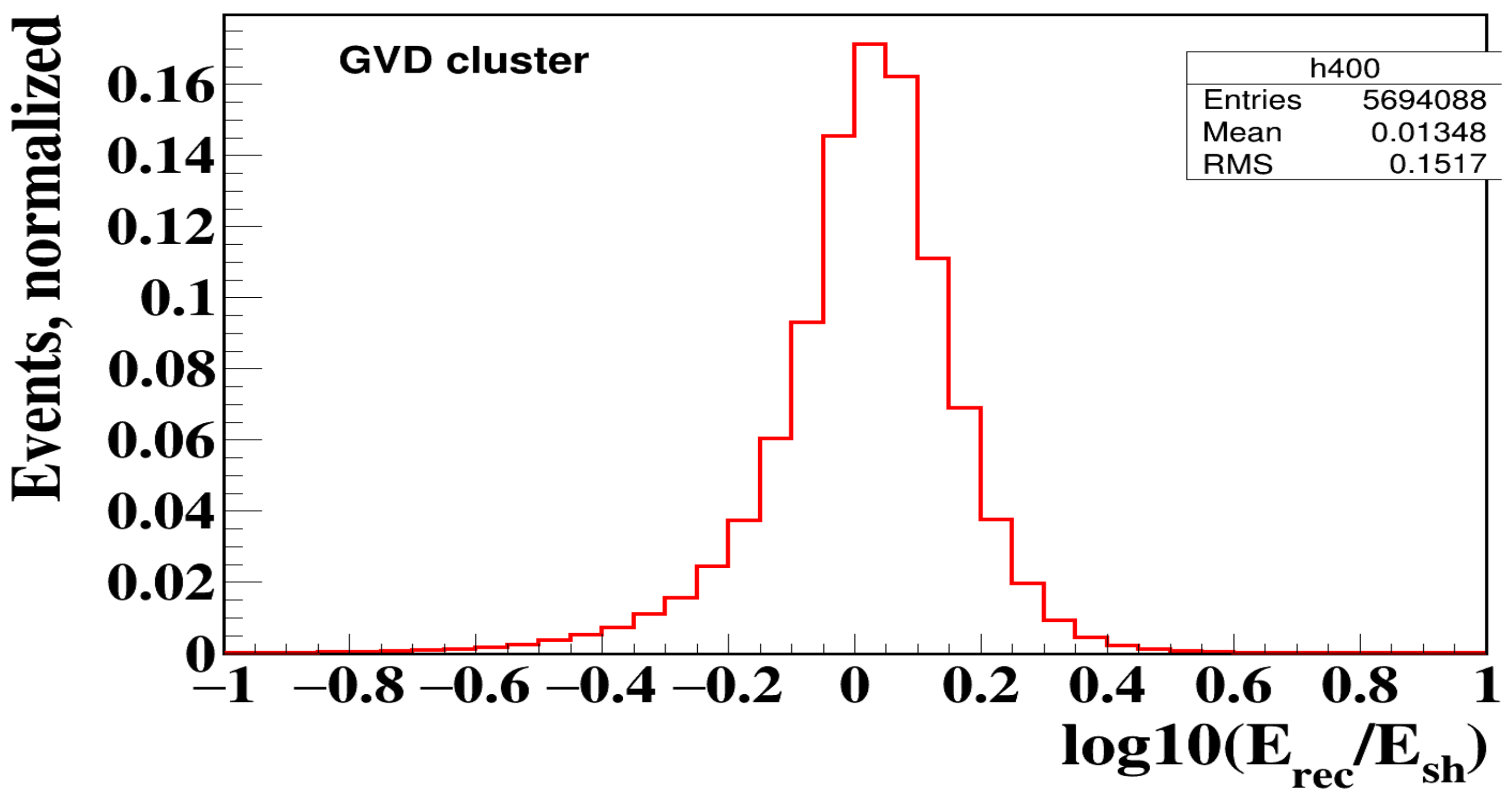


Cascade selection:

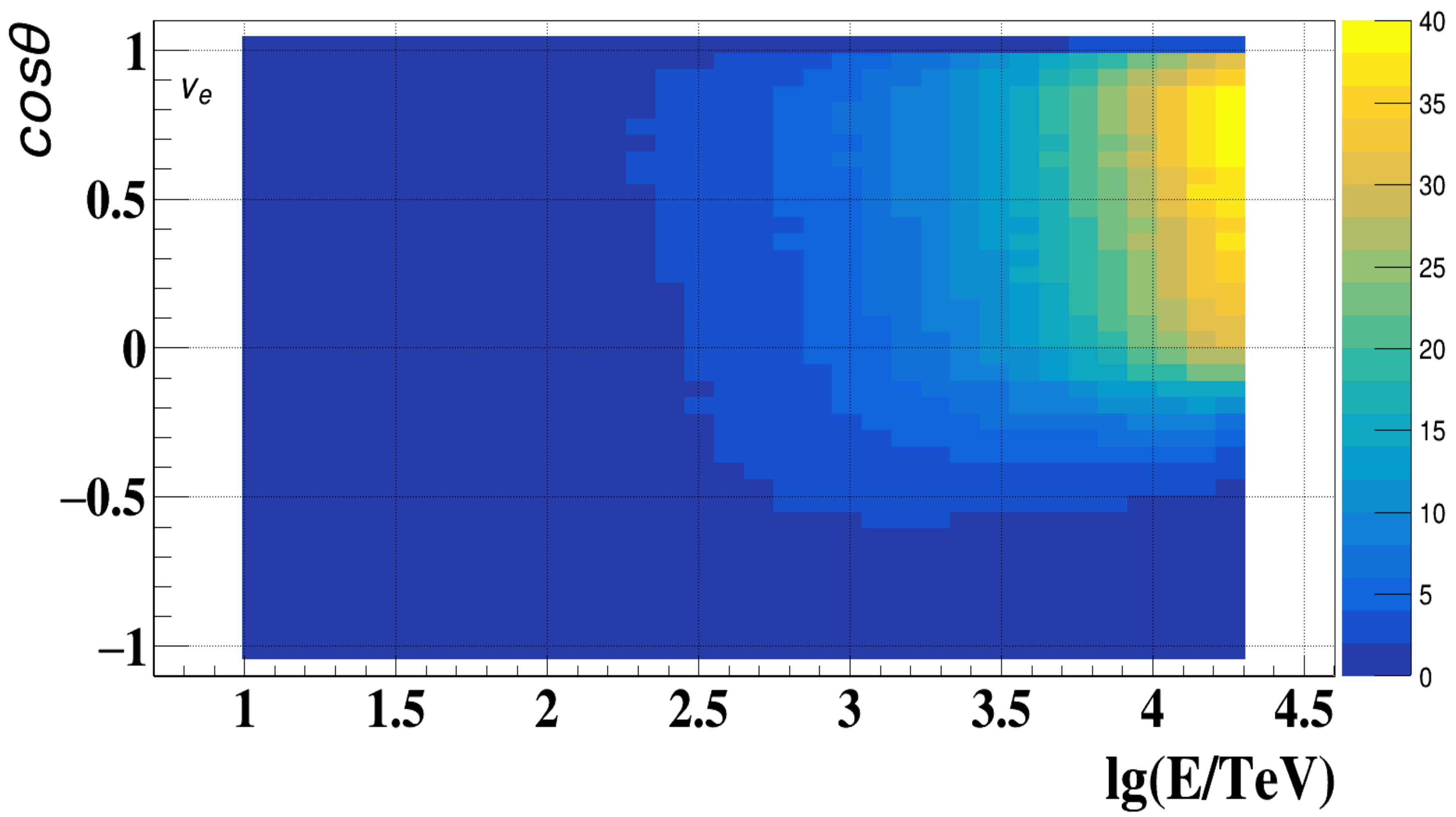
- Causality cuts (noise rejection);
- Reconstruction of cascade position direction and energy and cuts on quality parameters;
- $N_{hit} > 19$



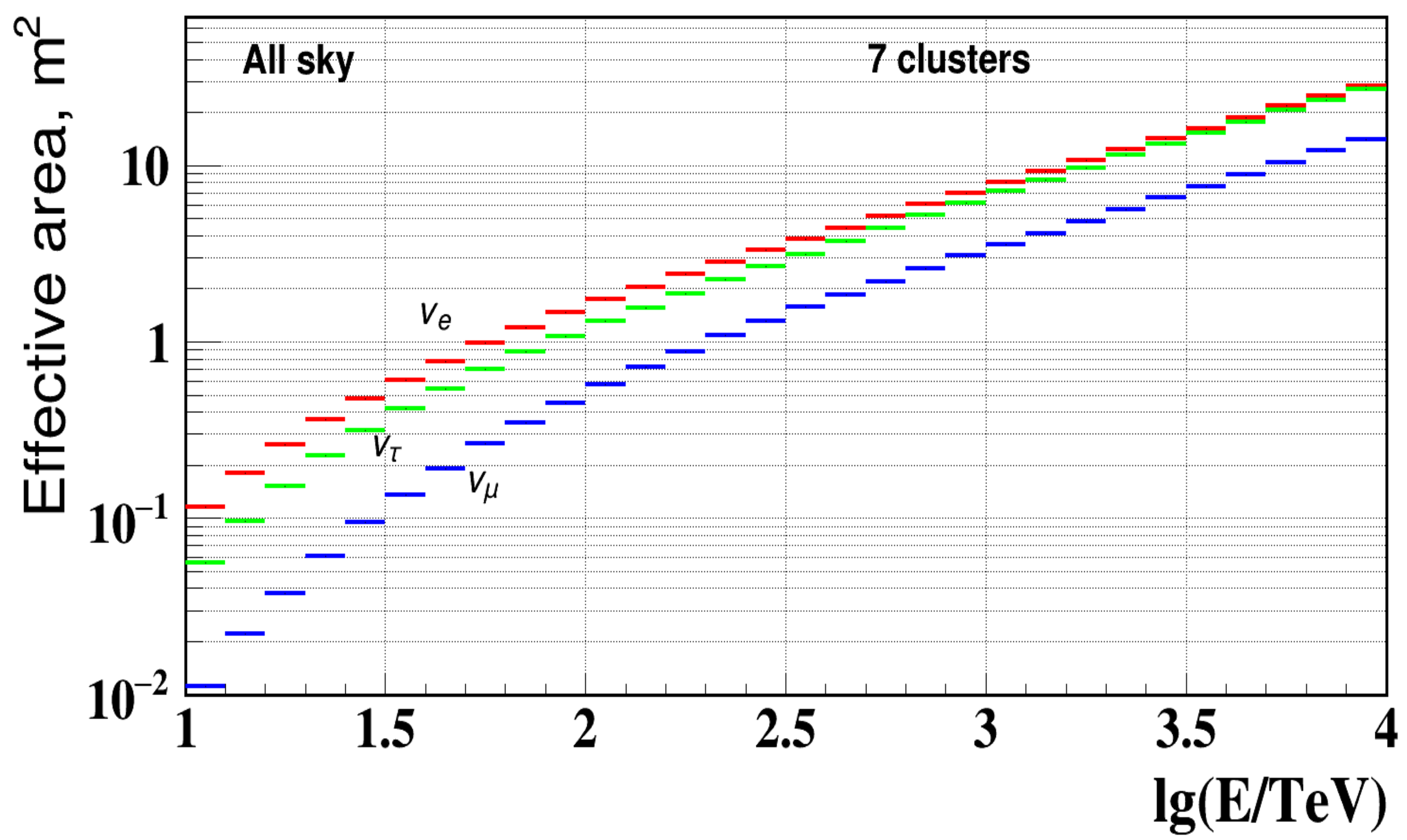
Energy resolution: δE/E ~ 30% averaged by E^{-2} ν_e spectrum



ν_e effective area (m^2) for single GVD cluster after all cuts: vs (Direction and Energy)

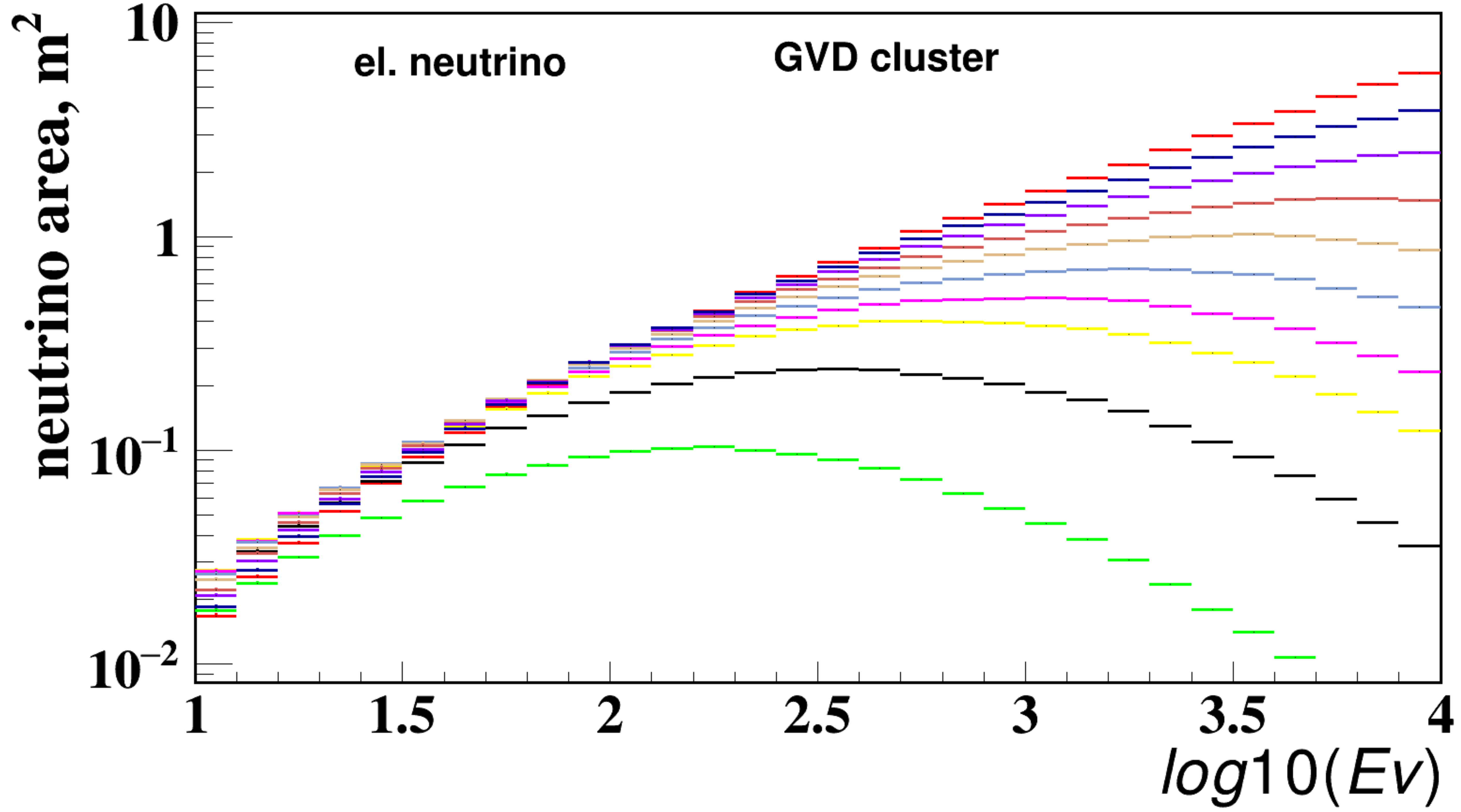


Neutrino effective area for 7 GVD clusters after all cuts

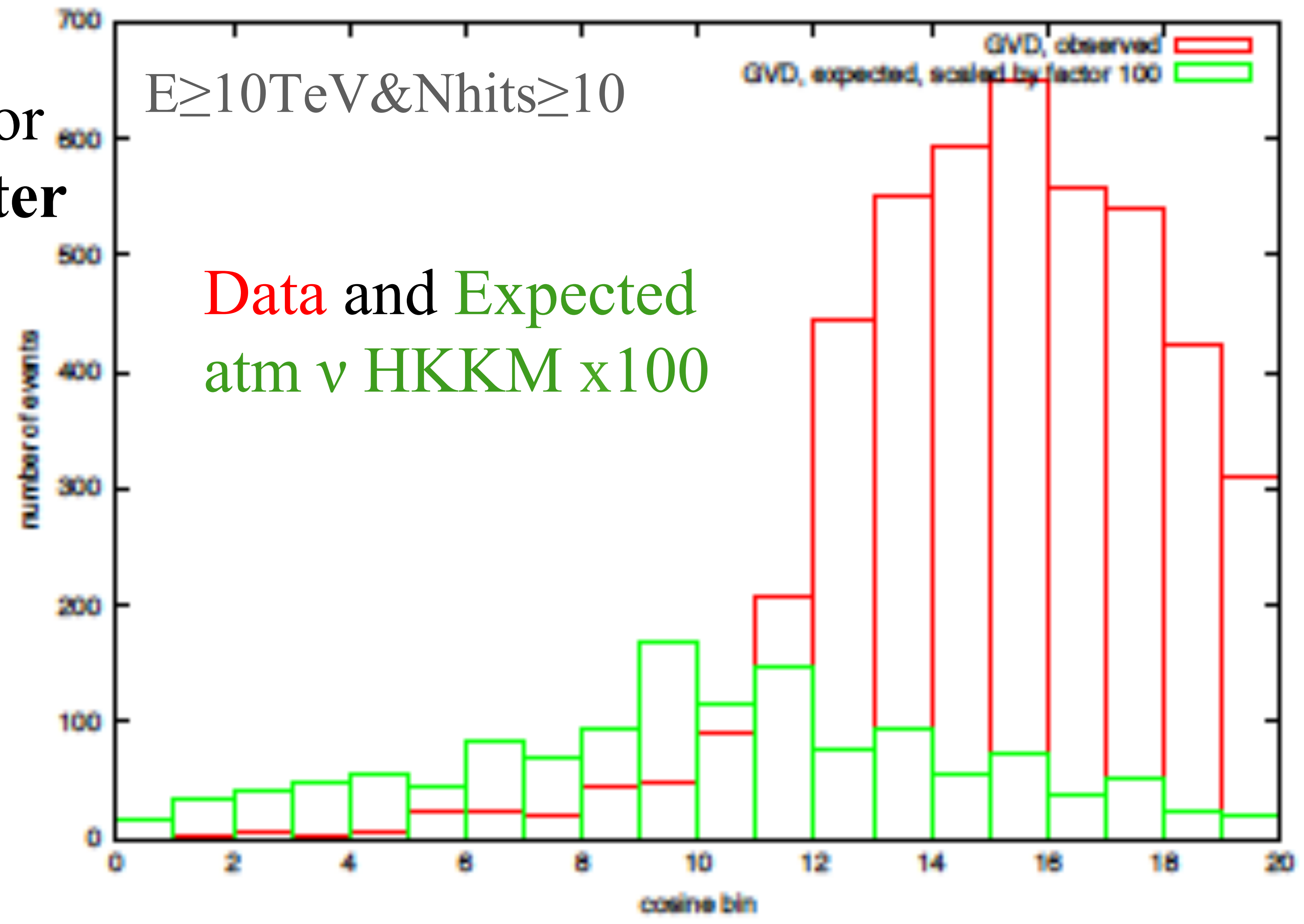


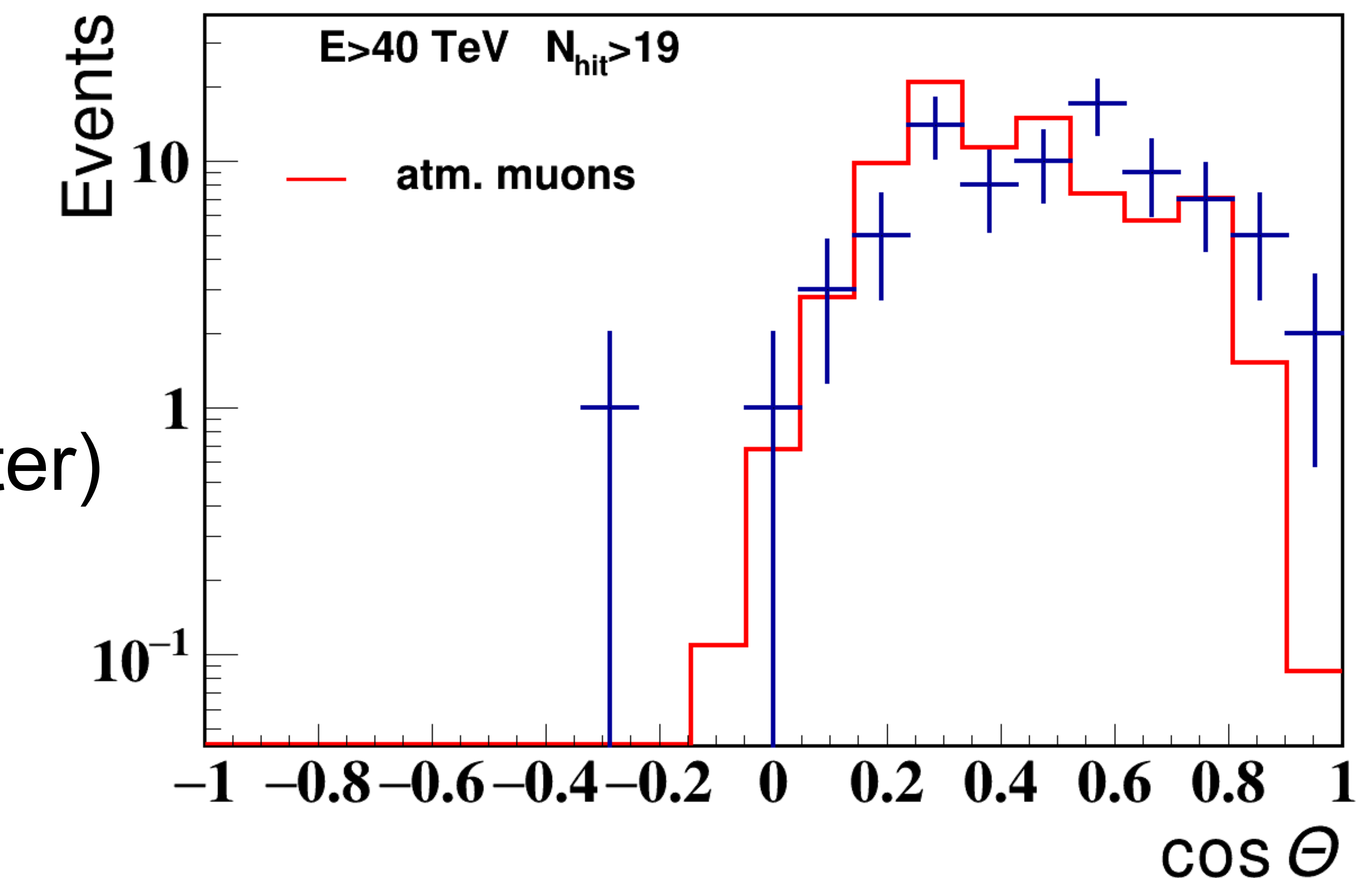
Baikal Gigaton Volume Detector (GVD-I)

is designed to measure neutrino fluxes in TeV-to-PeV energies.



HE cascades for **690 days/cluster**





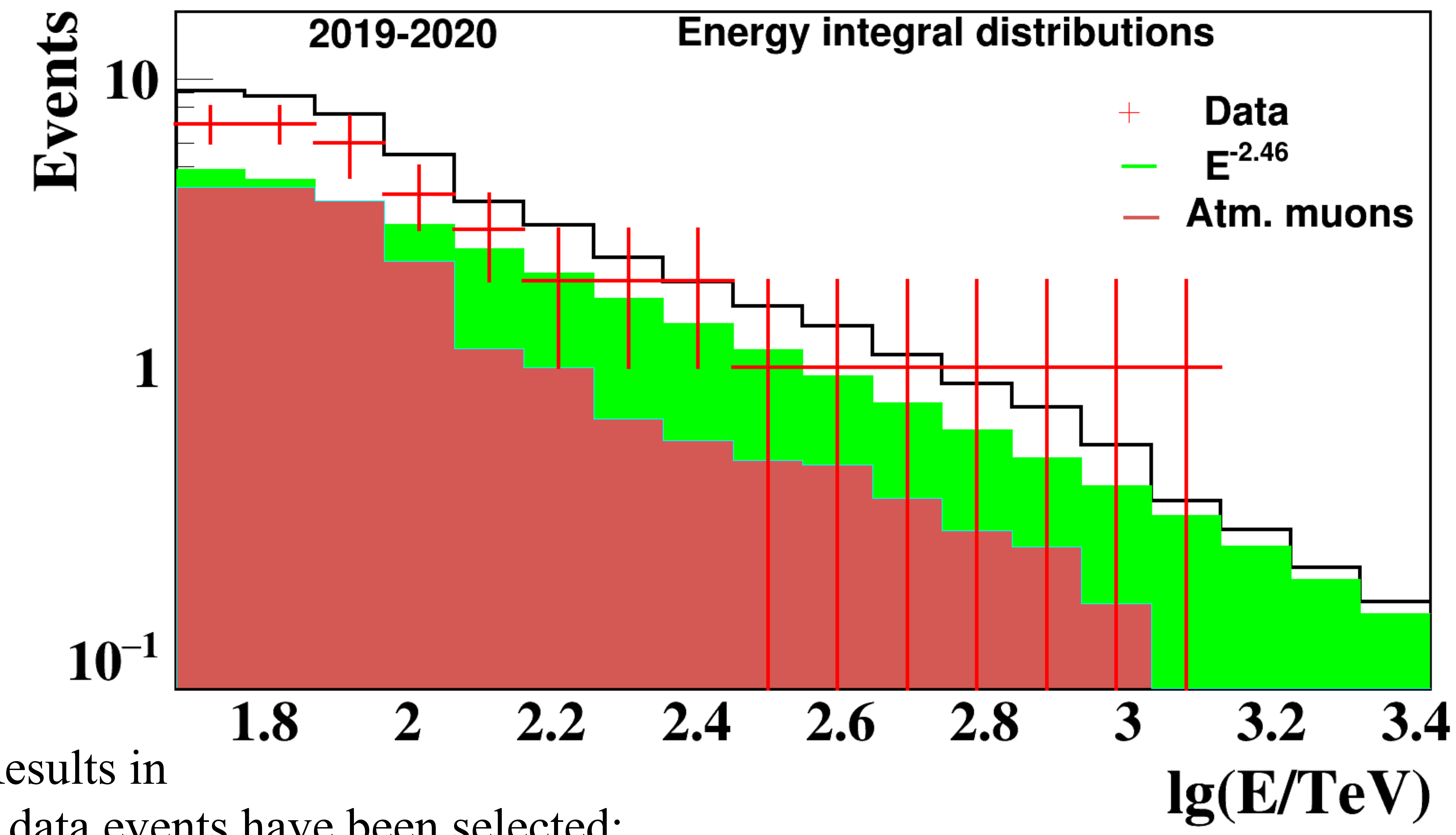
For **livetime *2915* days** (in terms of one cluster) HE cascades were selected: 72 events with $E > 40$ TeV and $N_{hit} > 19$

JETP, 2022, 161-4, A.D.Avrorin et al (Baikal-GVD Coll.)

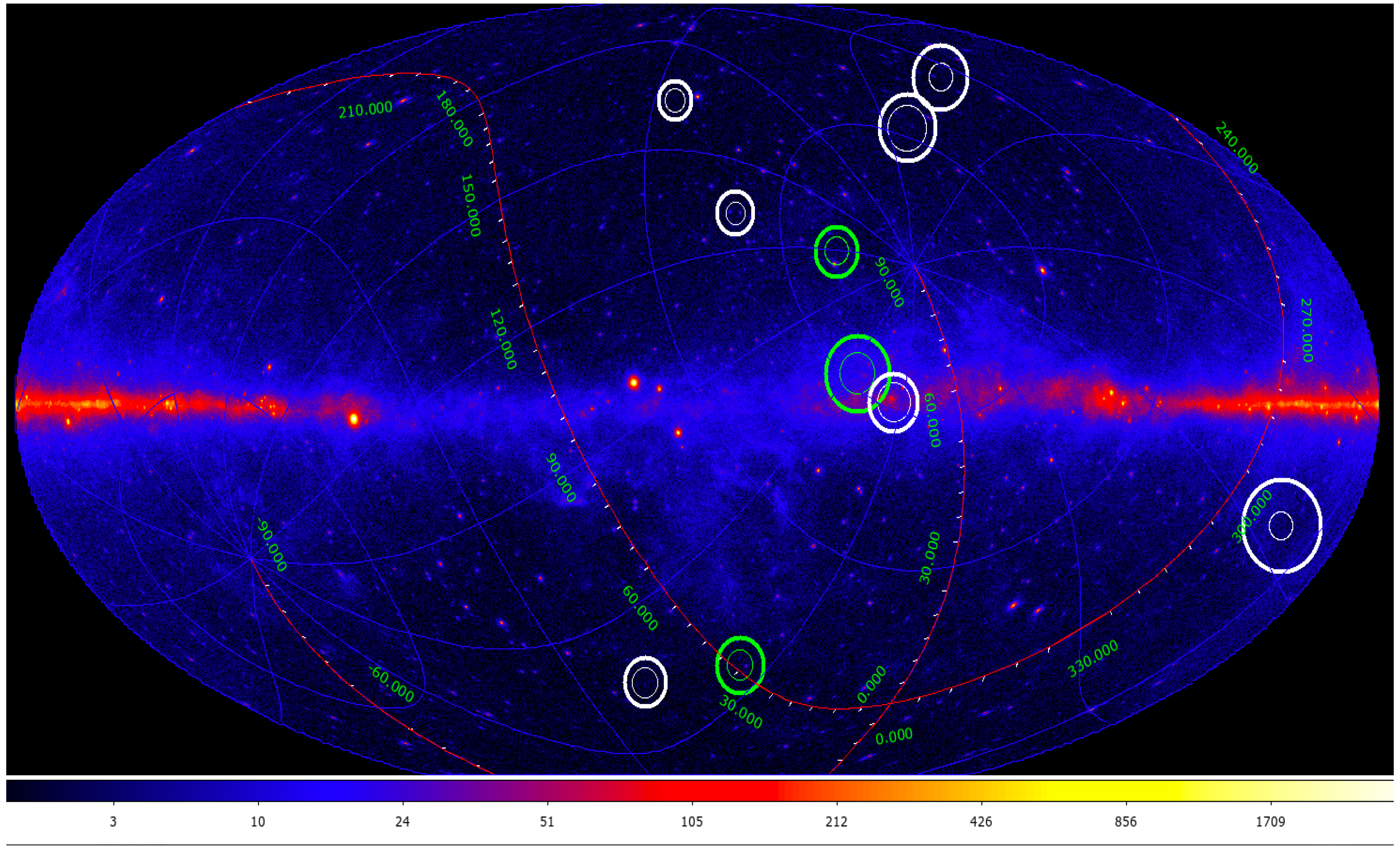
Baikal Gigaton Volume Detector (GVD-I)

is designed to measure neutrino fluxes in TeV-to-PeV energies

For **livetime *2915* days** (in terms of one cluster) HE cascades were selected: 72 events with E > 40 TeV and N_{hit} > 19, 10 events with E > 100 TeV and N_{hit} > 19. Additional requirements to reject atm muon bundles: analysis of hits vs time (N_{Type_2} = 0, $E_{rec} \geq$ 60 TeV) or (N_{Type_2} = 1, $E_{rec} \geq$ 100 TeV)



Results in
7 data events have been selected;
4 events are expected from atm.muons;
5 events are expected from $E^{-2.46}$ astrophysical flux with IceCube normalization $4.1 \cdot 10^{-6}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}



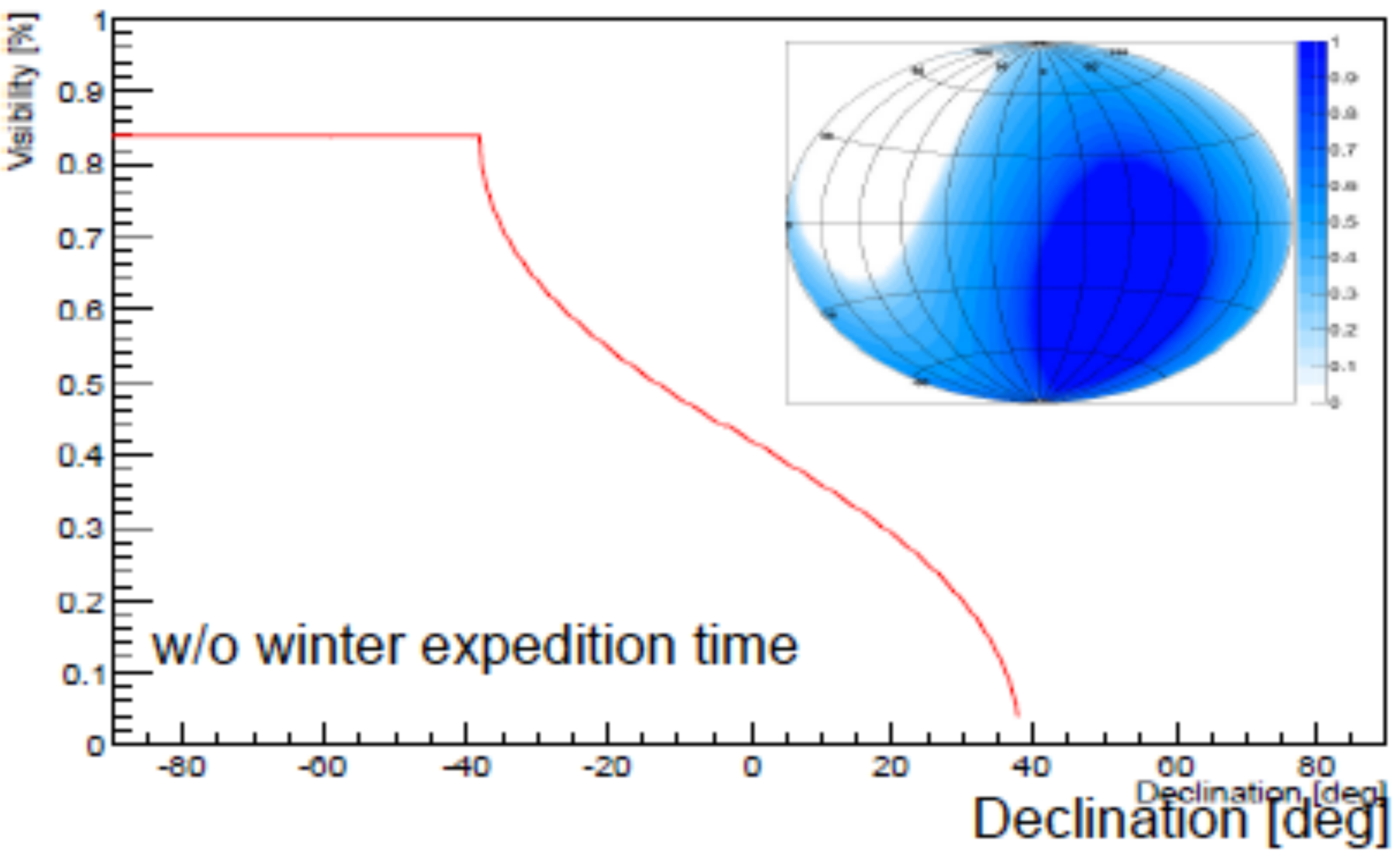
Containment circles 95%(68%):
Green – 2018 data samlpe of 3 selected events for 690 live days;
White – 2019 data samlple of 7 selected events for 2915 live days.

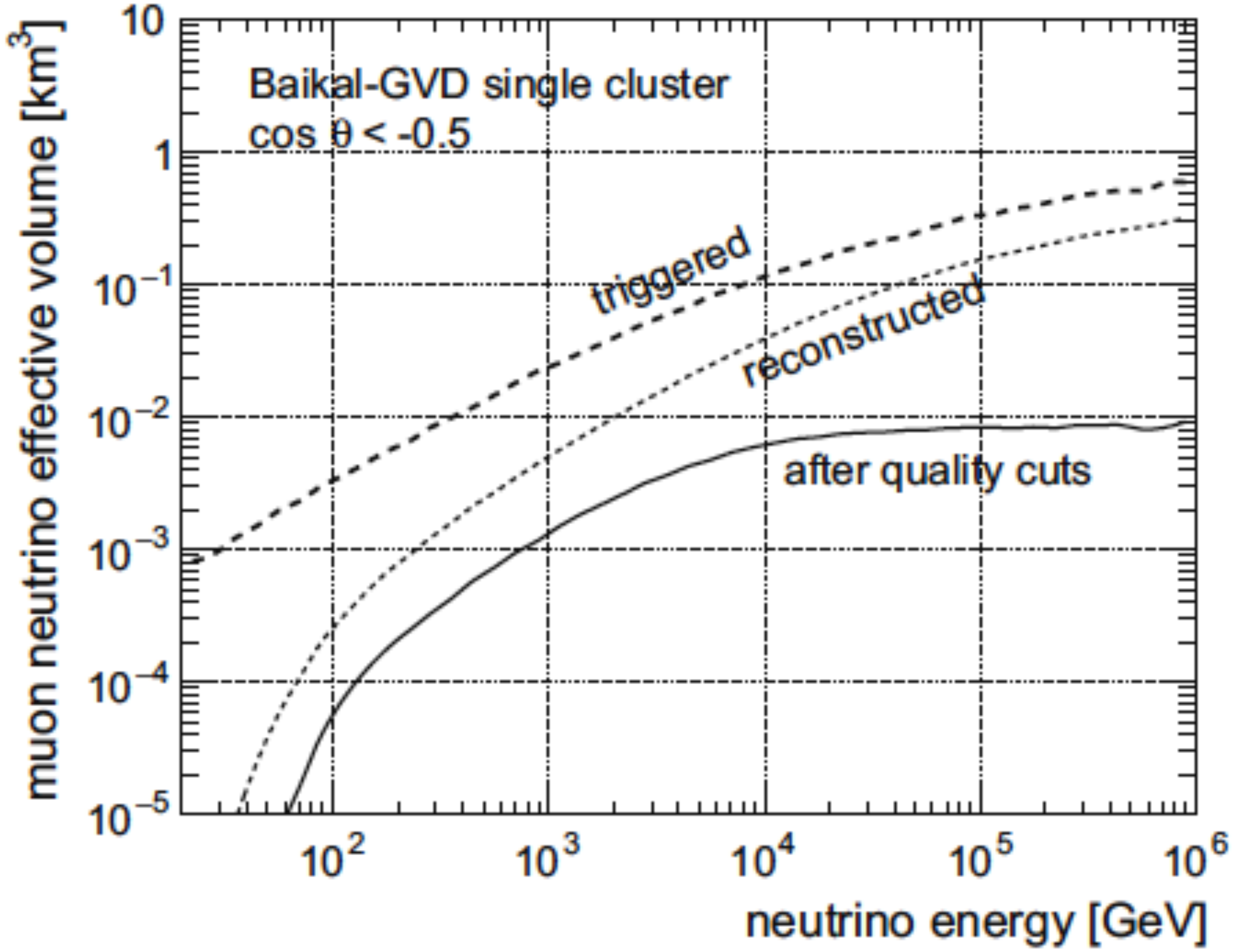
ICRC2021, Zh.Dzhilkibaev, VLVnT2021, M.Shelepov

JETP, 2022, 161-4, A.D.Avrorin et al (Baikal-GVD Coll.)

Baikal-GVD effective volume for upward-going muon neutrinos

The current DM aboundance emerges naturally assuming typical weak interaction cross sections and WIMPs in mass range of GeV to TeV





Note: Baikal-GVD's FoV is upto +40° on declination for upgoing muons and 4π view in cascade search mode.

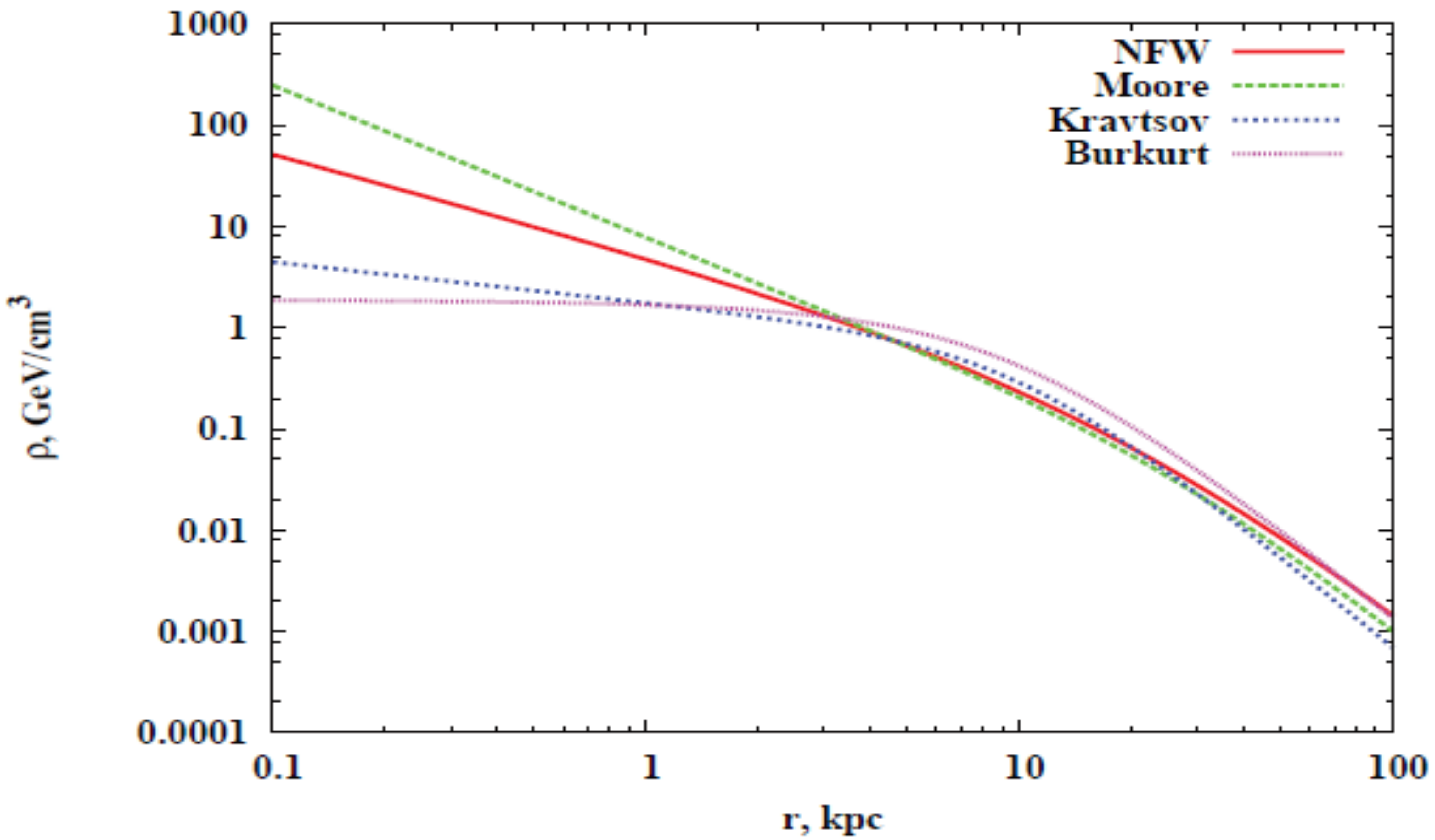
Fig. 5 Effective volume of a standard Baikal-GVD cluster for muon neutrino CC interactions at trigger level (thick dashed line), at reconstruction level using the χ^2-based reconstruction (thin dashed line), and after the event selection cuts optimized for the atmospheric neutrino spectrum (solid line). Shown are the average curves over the zenith angle range $\theta > 120°$ (upward-going)

Eur.Phys.J.C (2021)81:1025
V.Allakhverdyan et al (Baikal-GVD Coll.)

WIMP signature in gamma-rays or neutrino fluxes

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

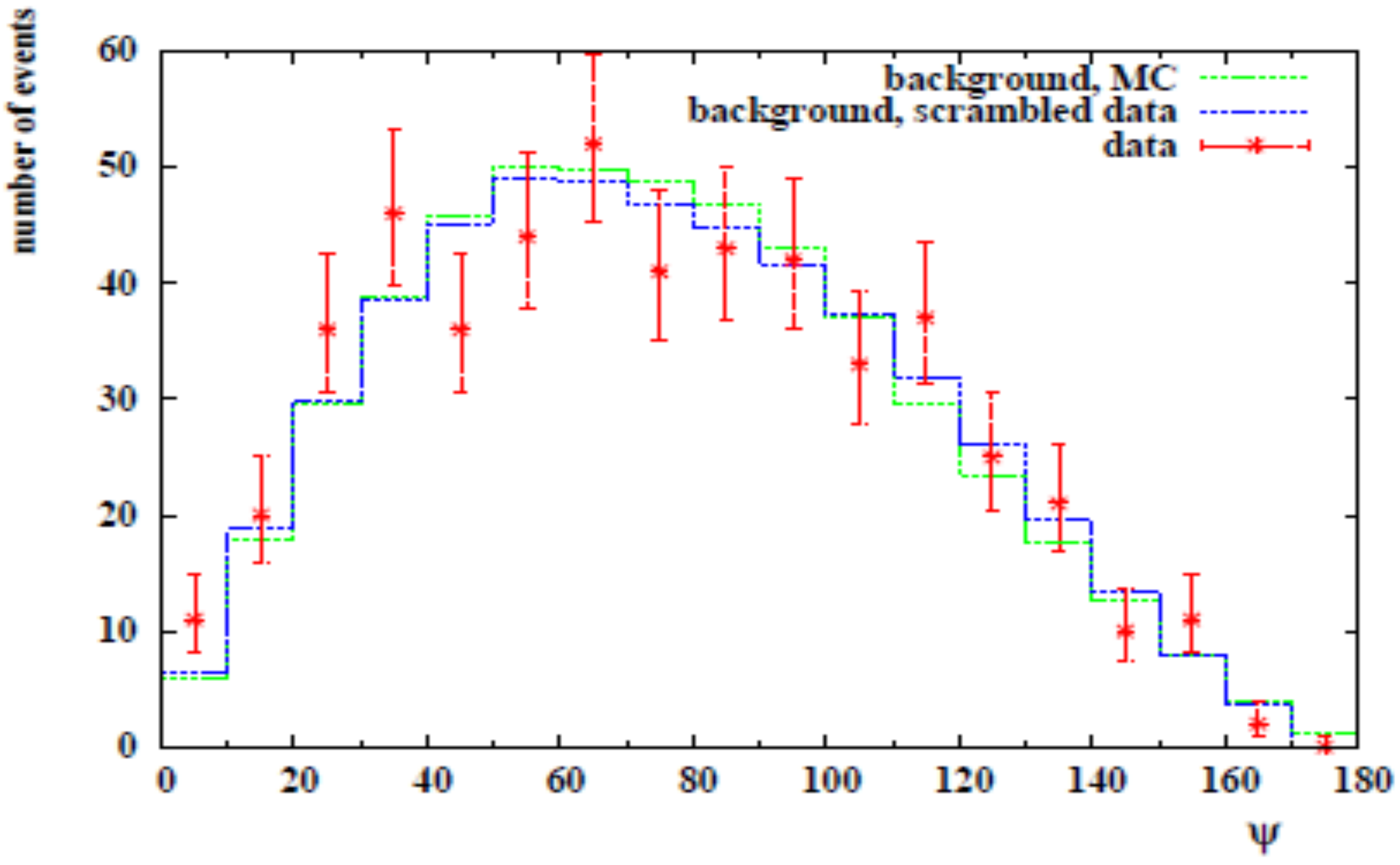
DM distribution (J-factor)

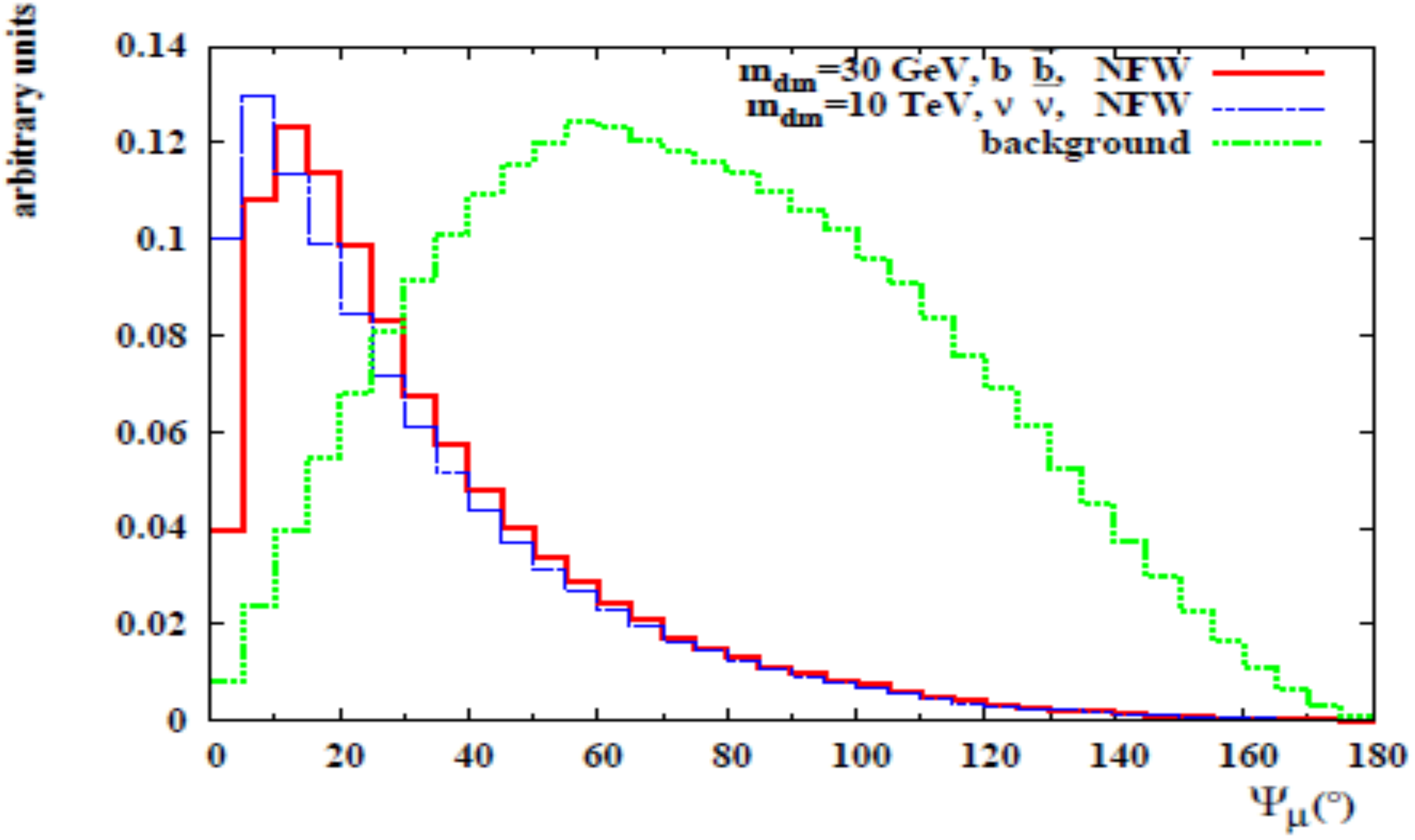


Model	α	β	γ	δ	r_*, kpc	ρ_*, GeV/cm^3
NFW	1	3	1	0	20	0.3
Burkert	2	3	1	1	9.26	1.88
Moore	1.5	3	1.5	0	28	0.27

$$\rho(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}$$

Angular mu-GC distributions: real data, mix-bckg and expected signal

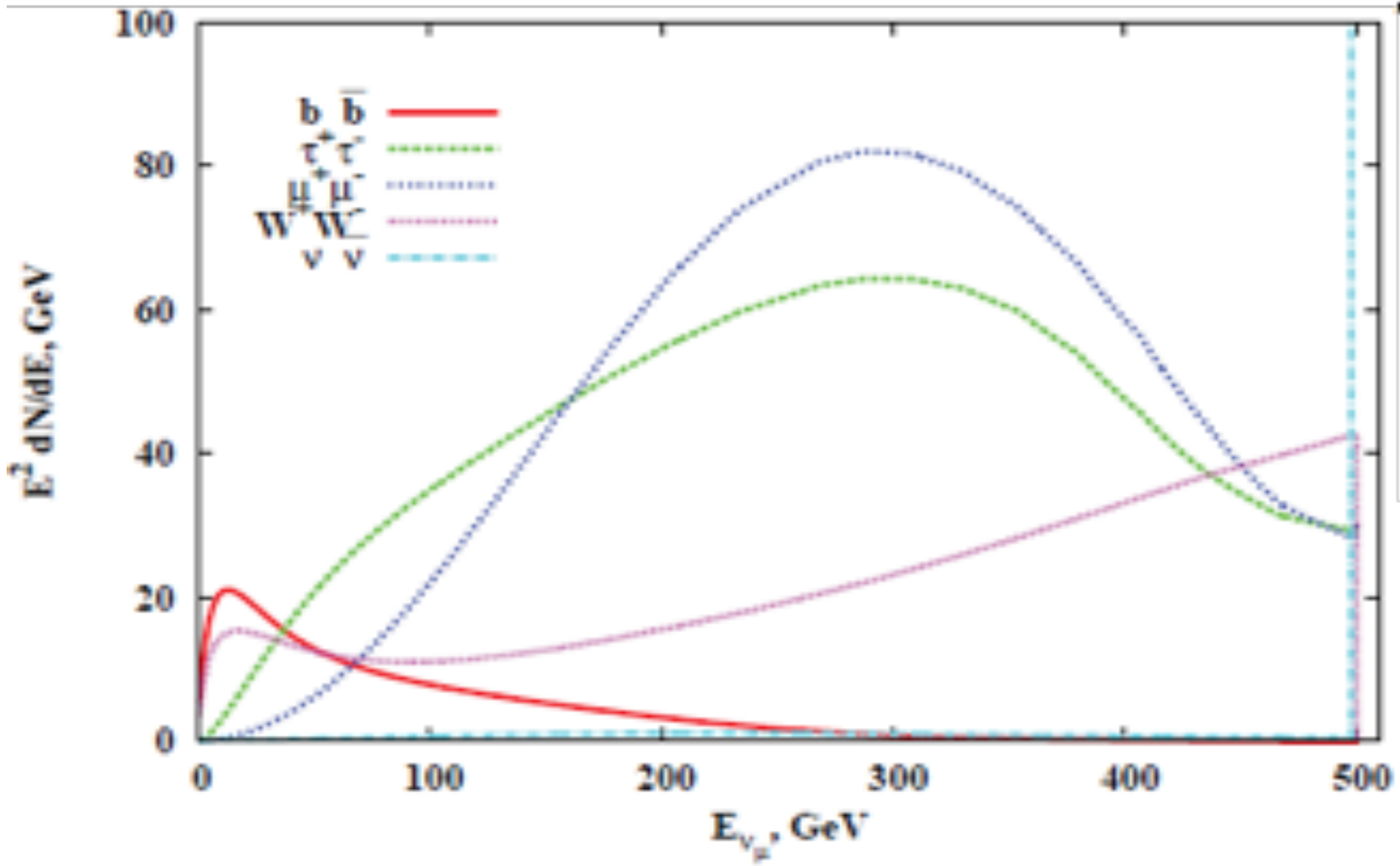




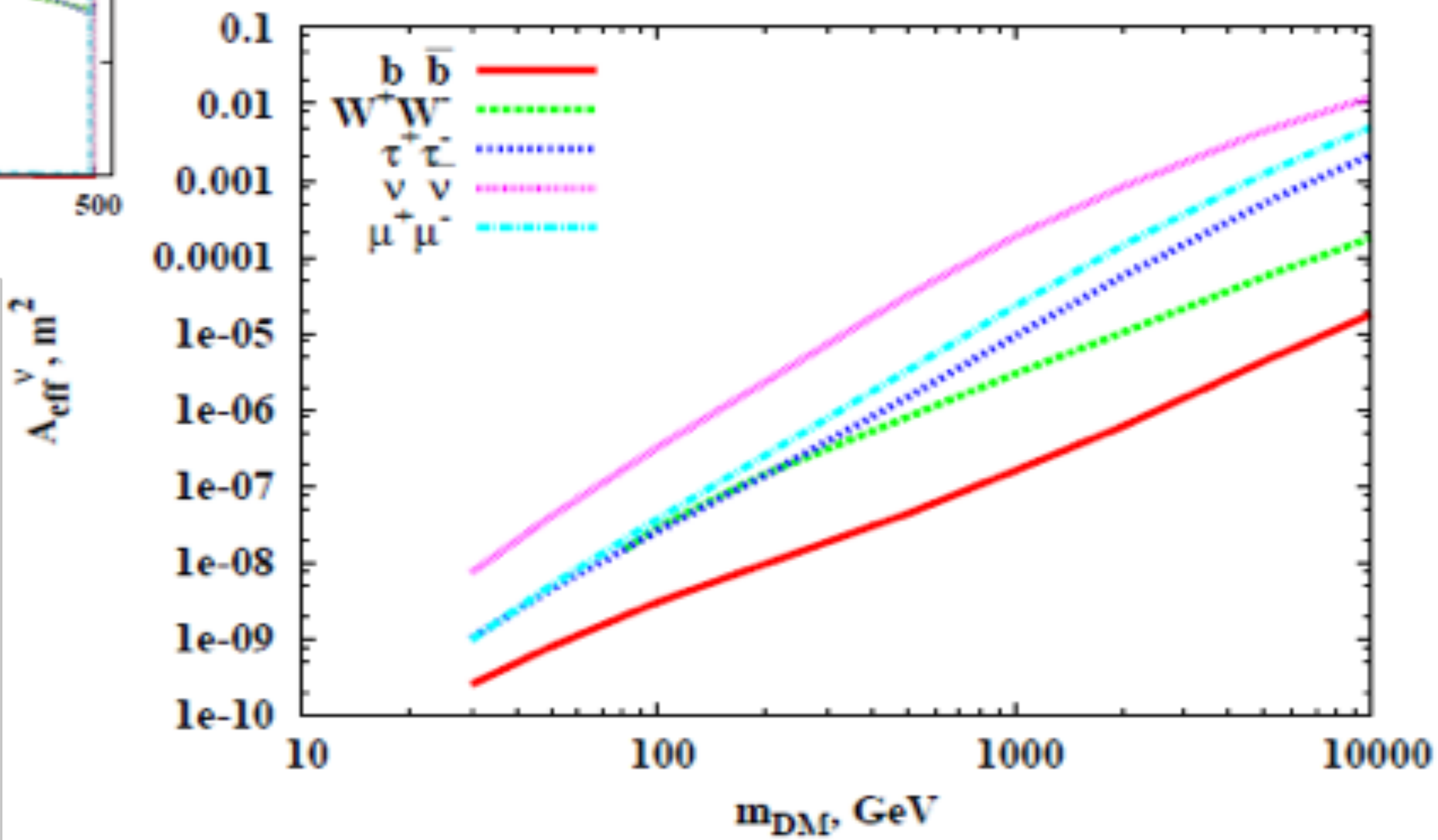
Cone	20°	5°	2.5°
N_obs	31	2	2
N_bkg	25.1	1.63	0.42

V.Avrorin et al (Baikal-GVD Coll.),
Astropart.Phys. 81 (2016) 12

Neutrino spectra in WIMP annihilations and NT200 ν-Effective Areas



ν-generation in the GC and 3-flavors ν-propagation through the Earth



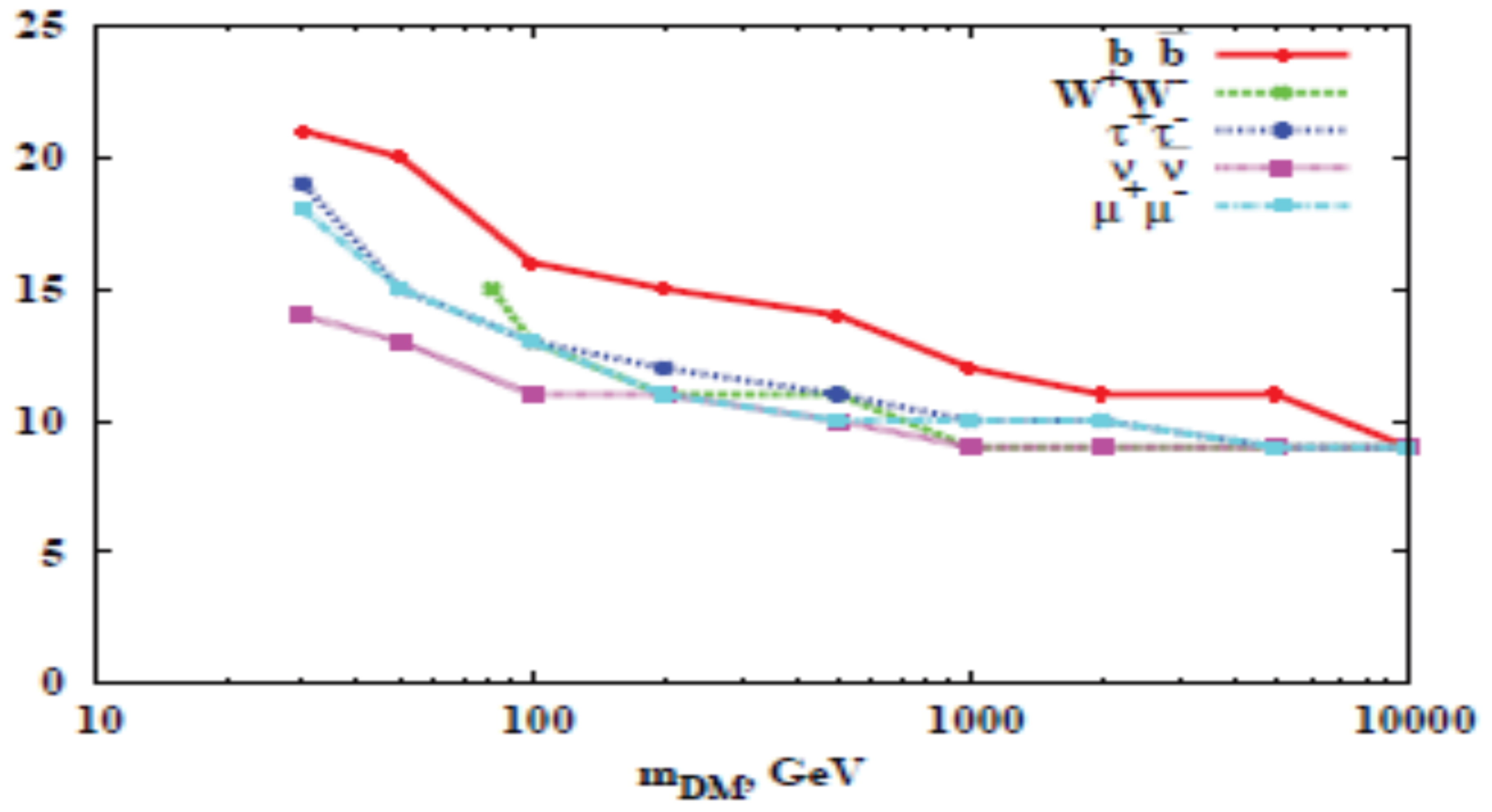
V.Avrorin et al (Baikal-GVD Coll.), *Astropart.Phys.* 81 (2016) 12

Galactic Center: Baikal NT200 search for WIMPs

Analysis I:

Choose cone half-angle ψ

maximize S/N ratio $\frac{\bar{N}^{90}}{\sqrt{N_B}}(\psi)$ ➢



Analysis II:

Angular distribution $f(\psi) = \frac{1}{N_S+N_B}(N_S f_S(\psi) + N_B f_B(\psi))$

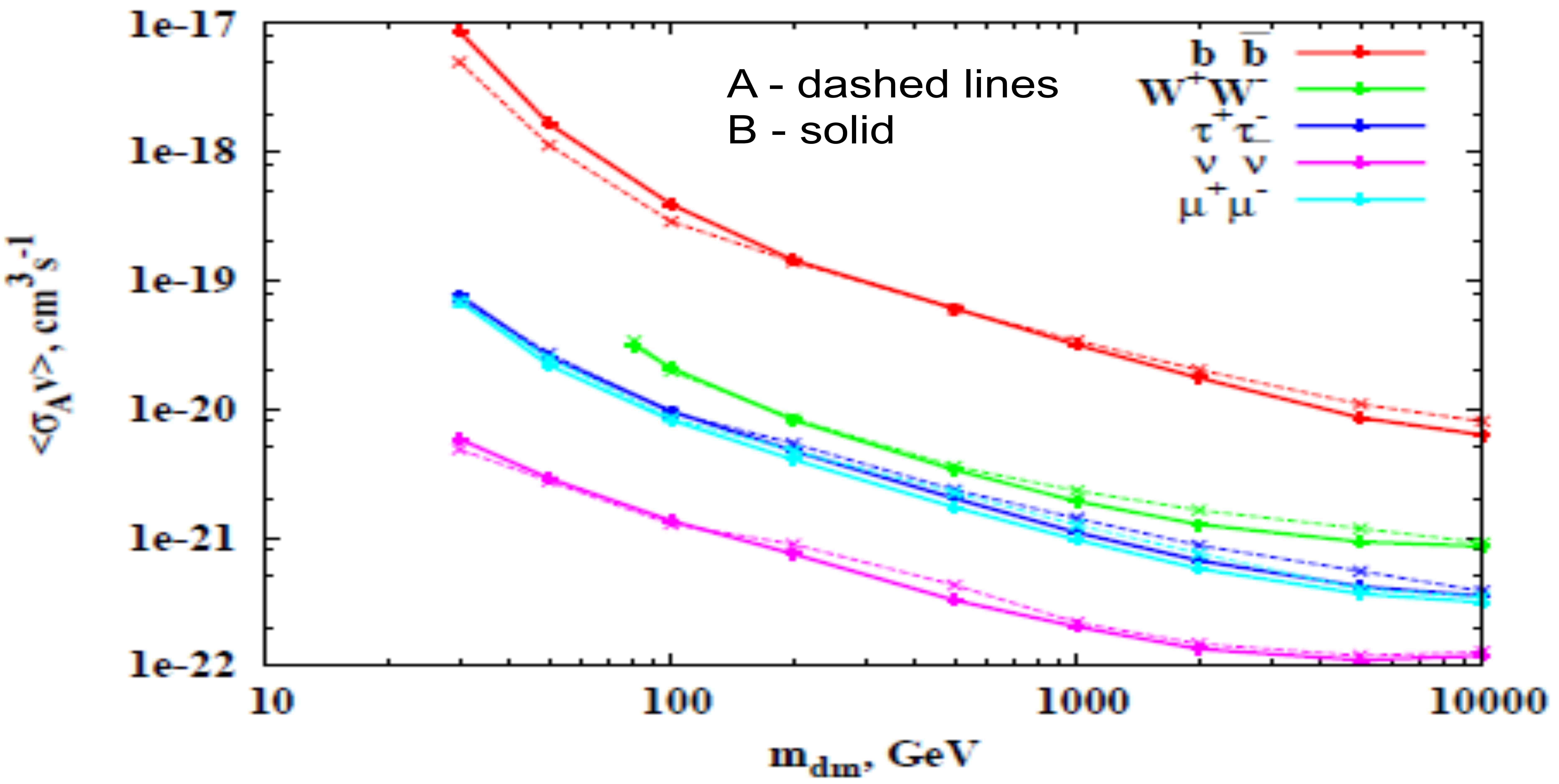
Likelihood function

$$\mathcal{L}(N_S) = \frac{(N_B + N_S)^n}{n!} e^{-(N_B+N_S)} \prod_{i=1}^{n} f(\psi_i, N_B, N_S)$$

Systematic uncertainties: profile likelihood, $\lambda(N_S) = -2\ln\frac{\mathcal{L}(N_S,\hat{\hat{\theta}})}{\mathcal{L}(\hat{N}_S,\hat{\theta})}$

V.Avrorin et al (Baikal-GVD Coll.),
Astropart.Phys. 81 (2016) 12

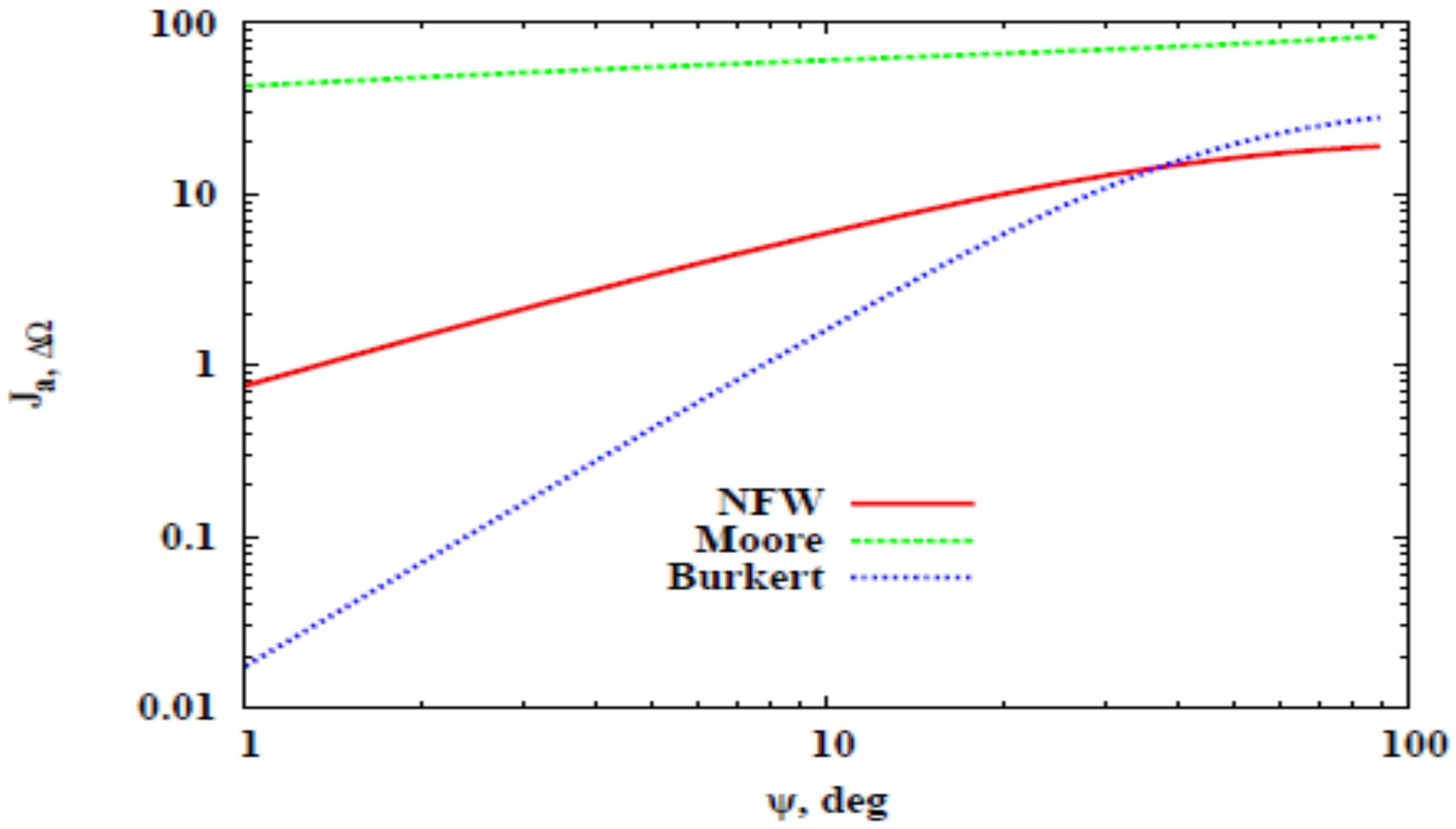
Baikal NT200 results: the upper limits at 90% CL



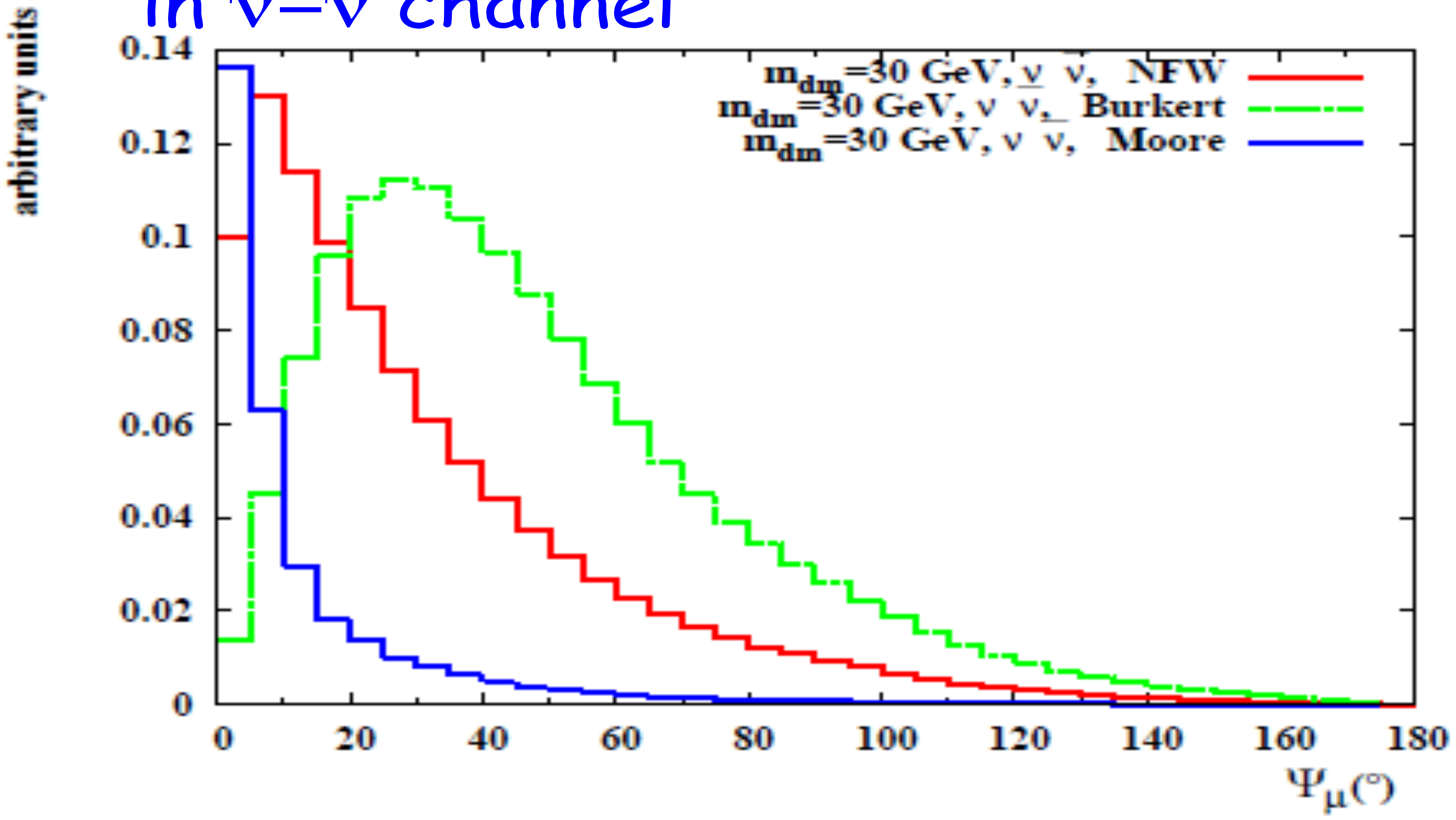
Systematics: experiment (about 30%) and theory (upto 15%) without astrophysical uncertainties

V.Avrorin et al (Baikal-GVD Coll.), *Astropart.Phys.* 81 (2016) 12

Astrophysical uncertainties in DM profiles



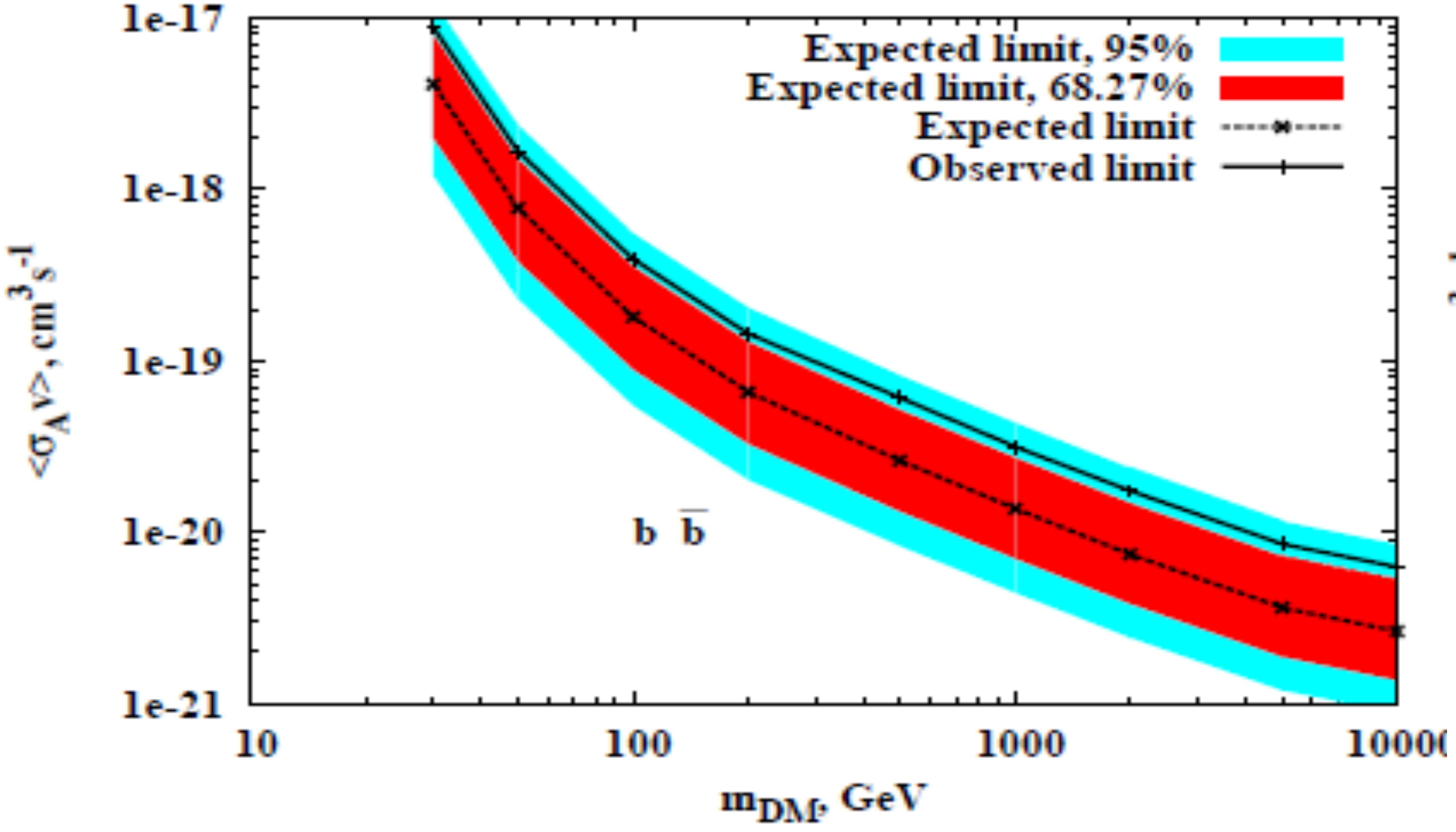
Angular mu-GC distr of a signal in ν–ν channel



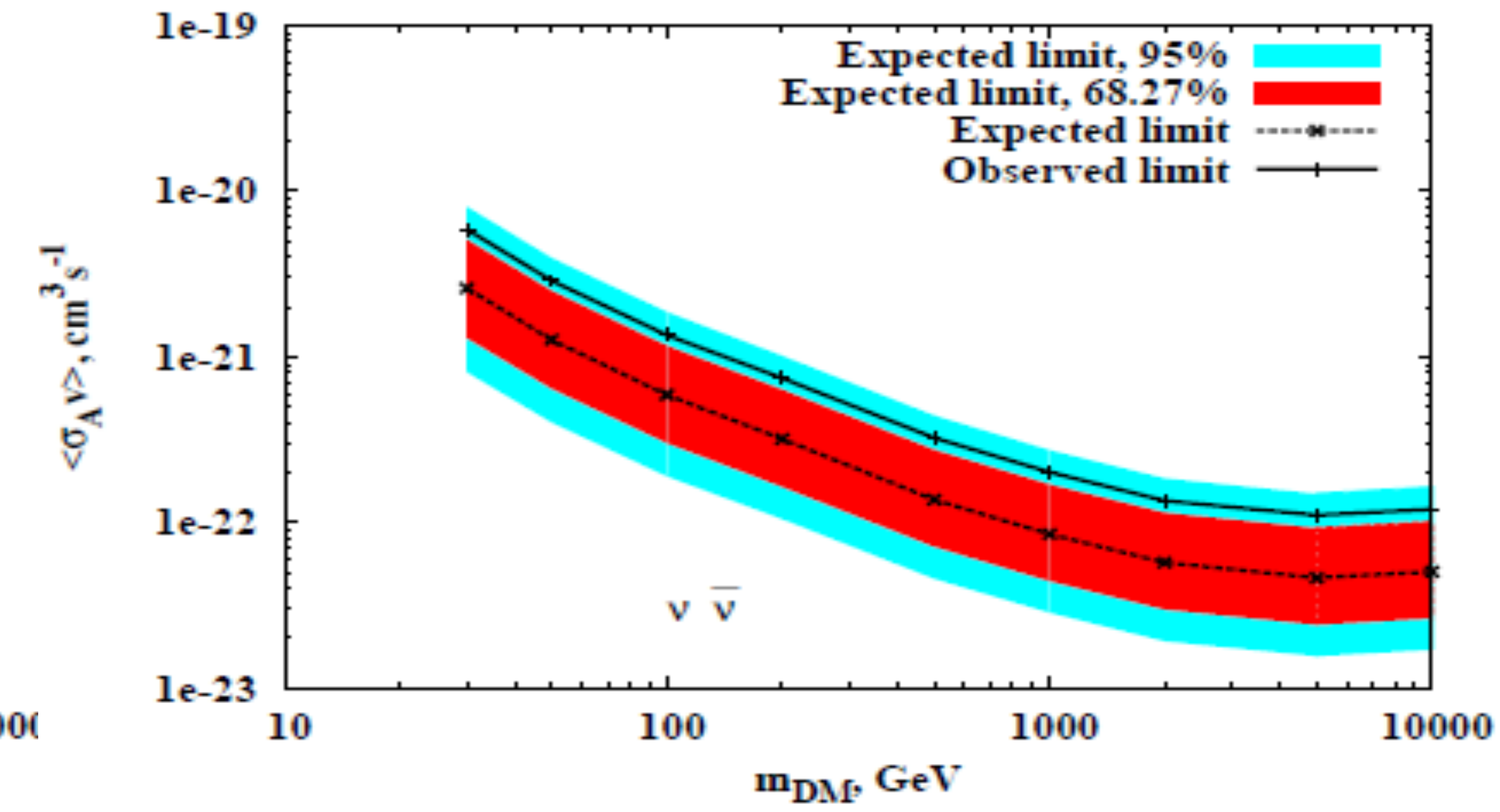
V.Avrorin et al (Baikal-GVD Coll.), *Astropart.Phys.* 81 (2016) 12

Baikal NT200: sensitivities to GC dm-signal from pseudo-experiments

Soft spectra: bb



Hard spectra: nu-nu



N_obs=113 @ psi<40deg

TS= 5.8 - 6.6 (no syst) and TS= 1.4 - 1.6 with syst.

V.Avrorin et al (Baikal-GVD Coll.), *Astropart.Phys.* 81 (2016) 12

Baikal-GVD 1year GC-sensitivity for 12 clusters (2304 OM, 345m), first estimates

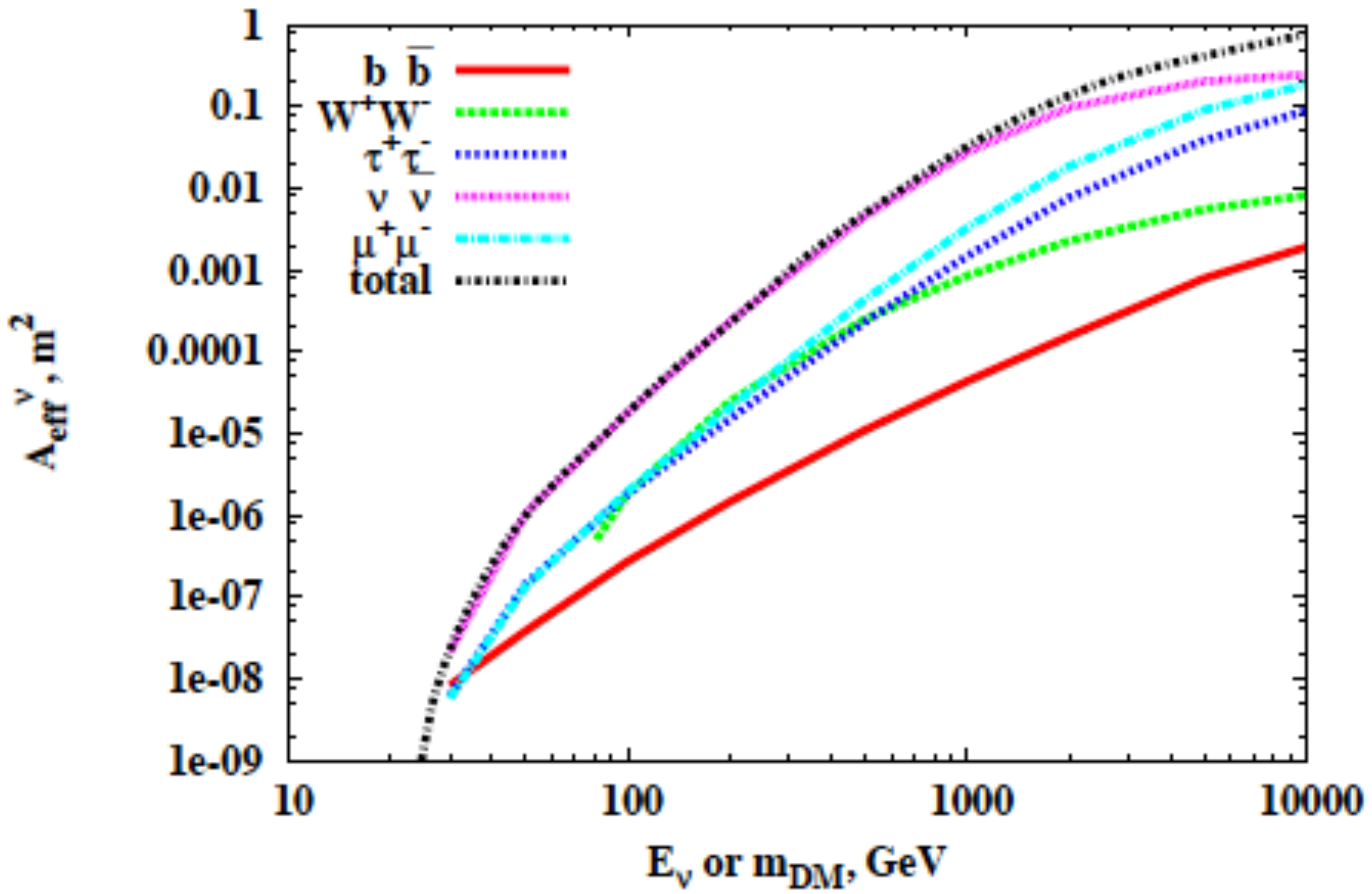


Figure 2: Neutrino effective area of single Baikal-GVD cluster (black) and averaged over neutrino spectra effective areas for different annihilation channels (color).

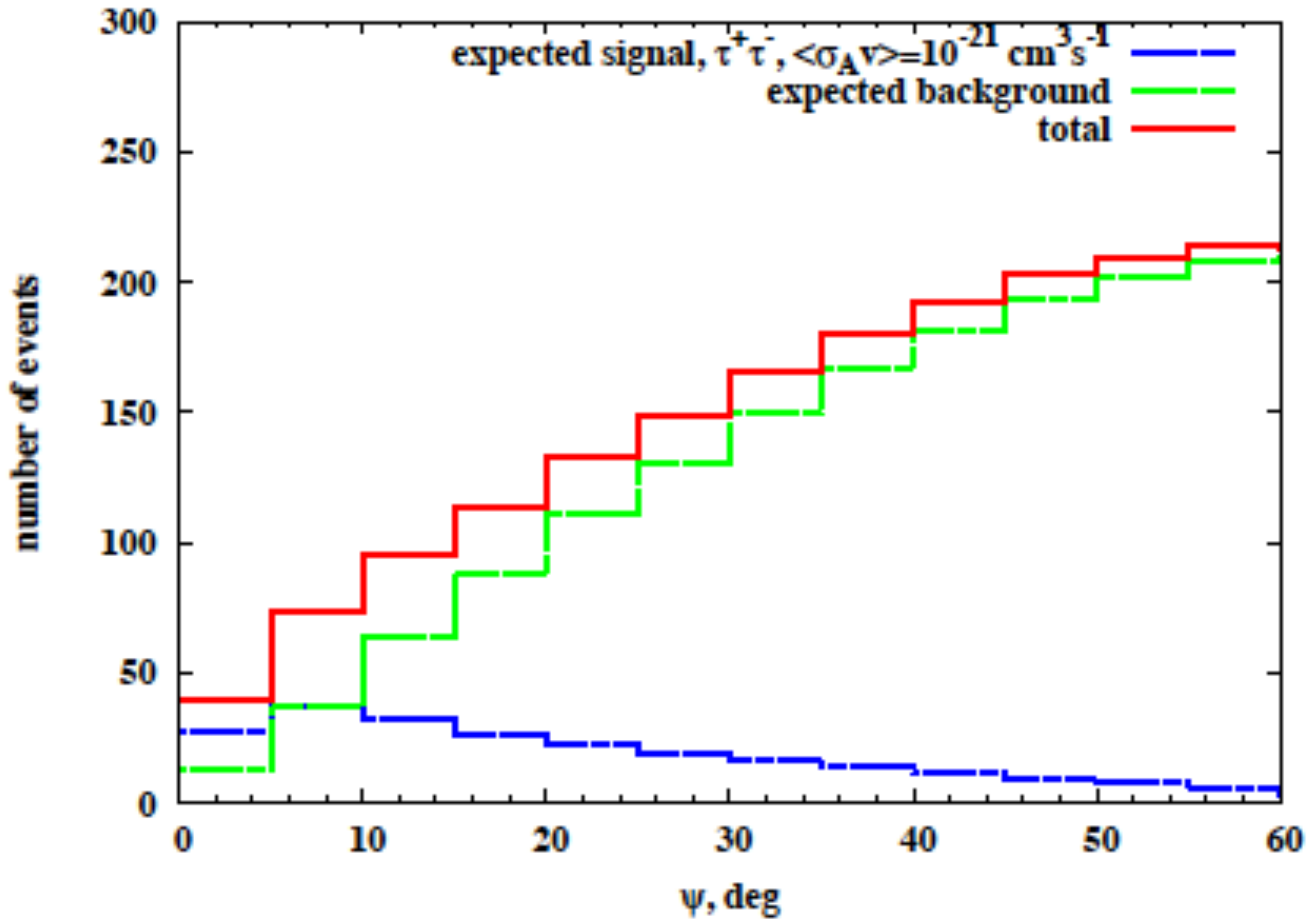


Figure 4: Distribution of background and signal events in angular distance from GC.

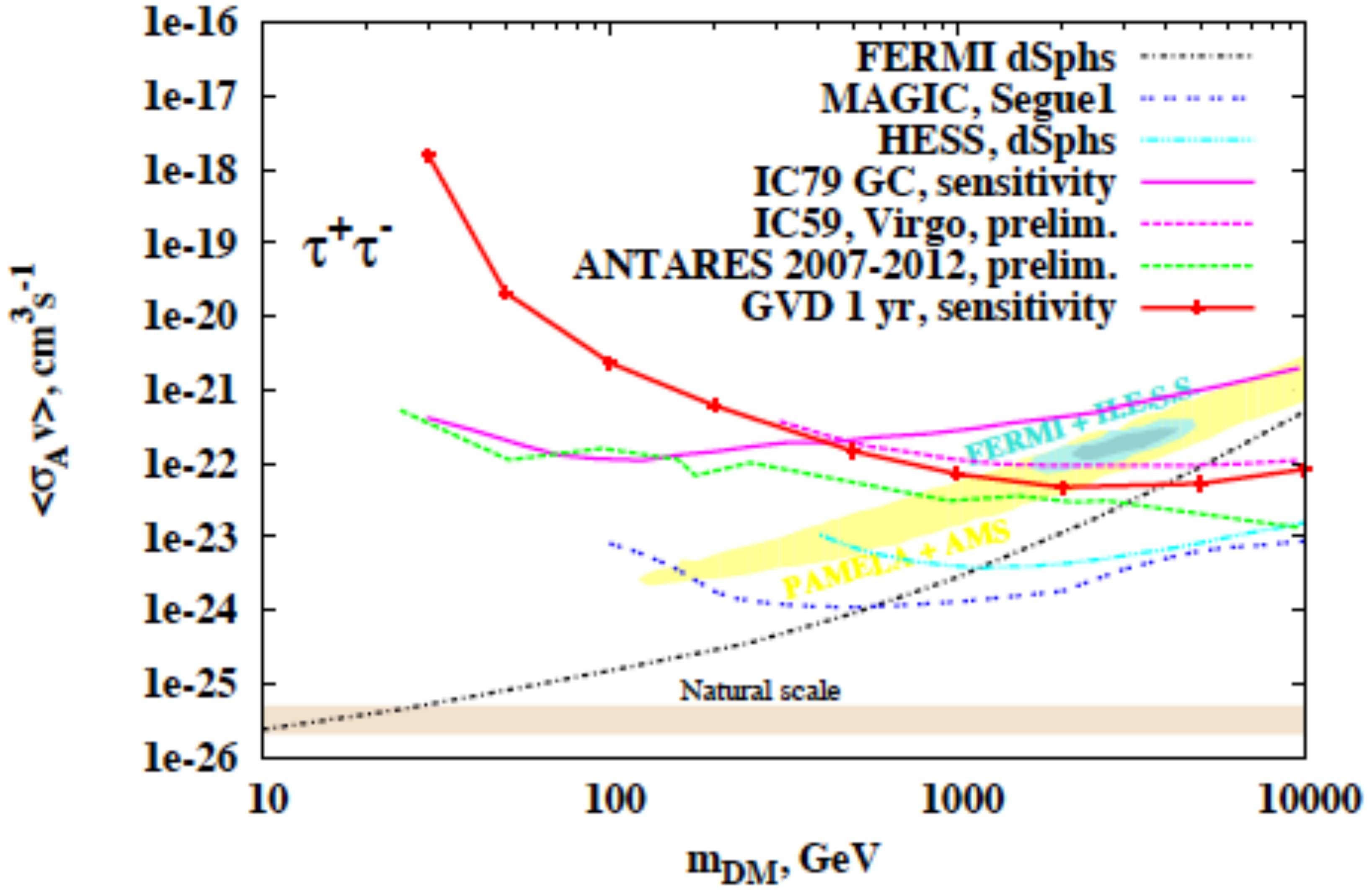


Figure 6: Sensitivity of GVD to $\langle \sigma v \rangle$ in comparison with other experiments.

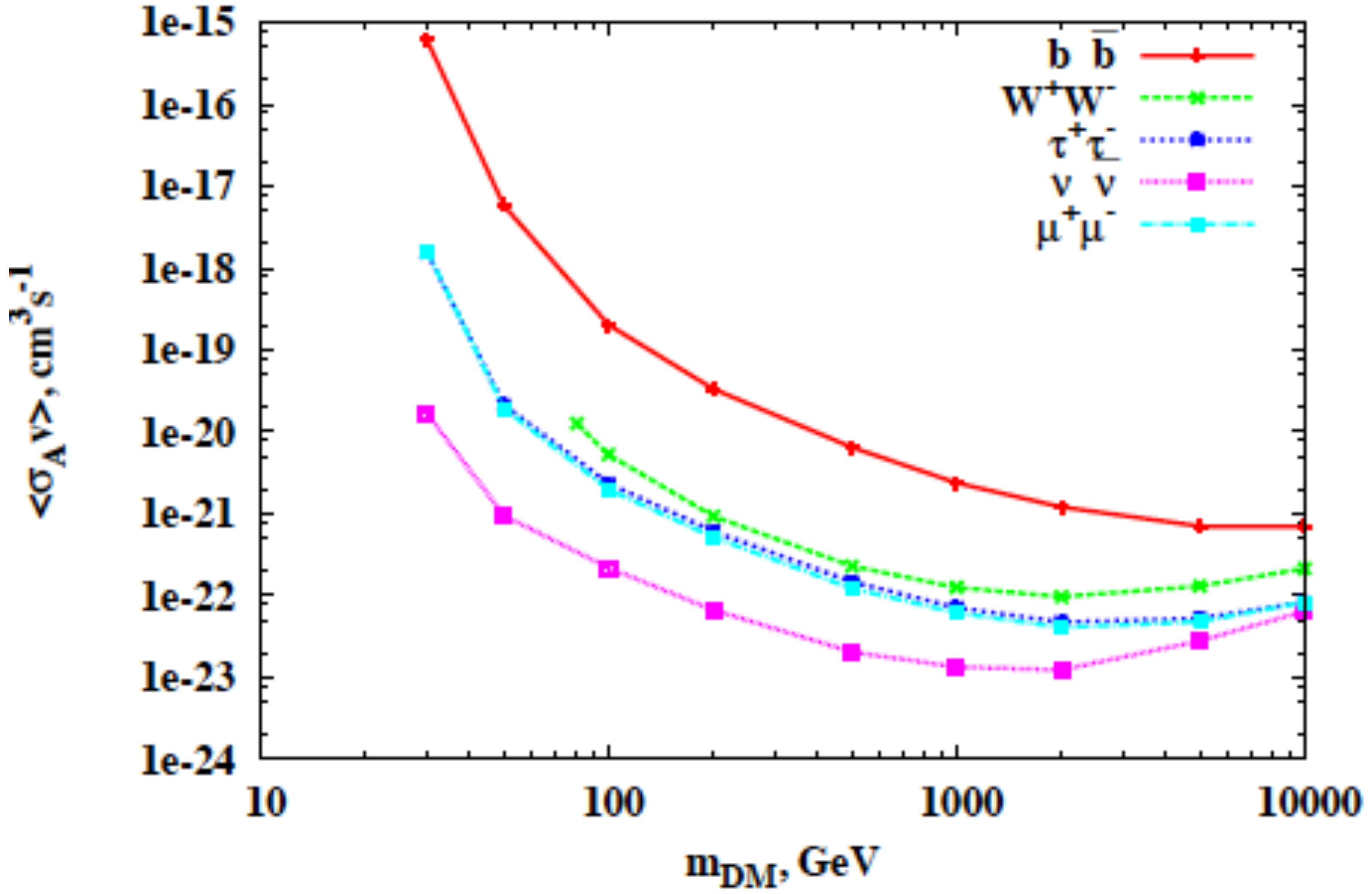


Figure 5: Sensitivity of GVD to $\langle \sigma v \rangle$ for one year for different annihilation channels.

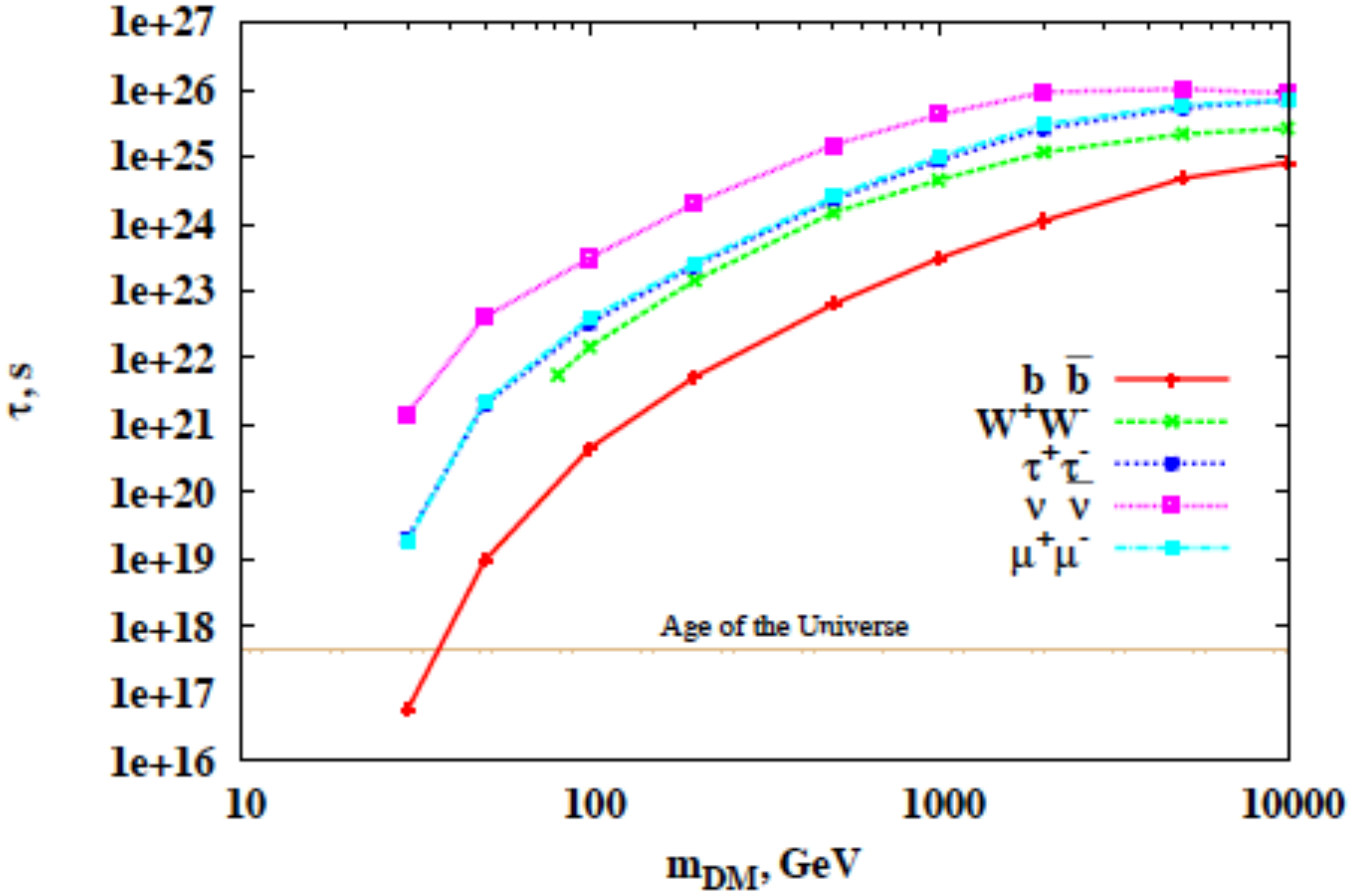


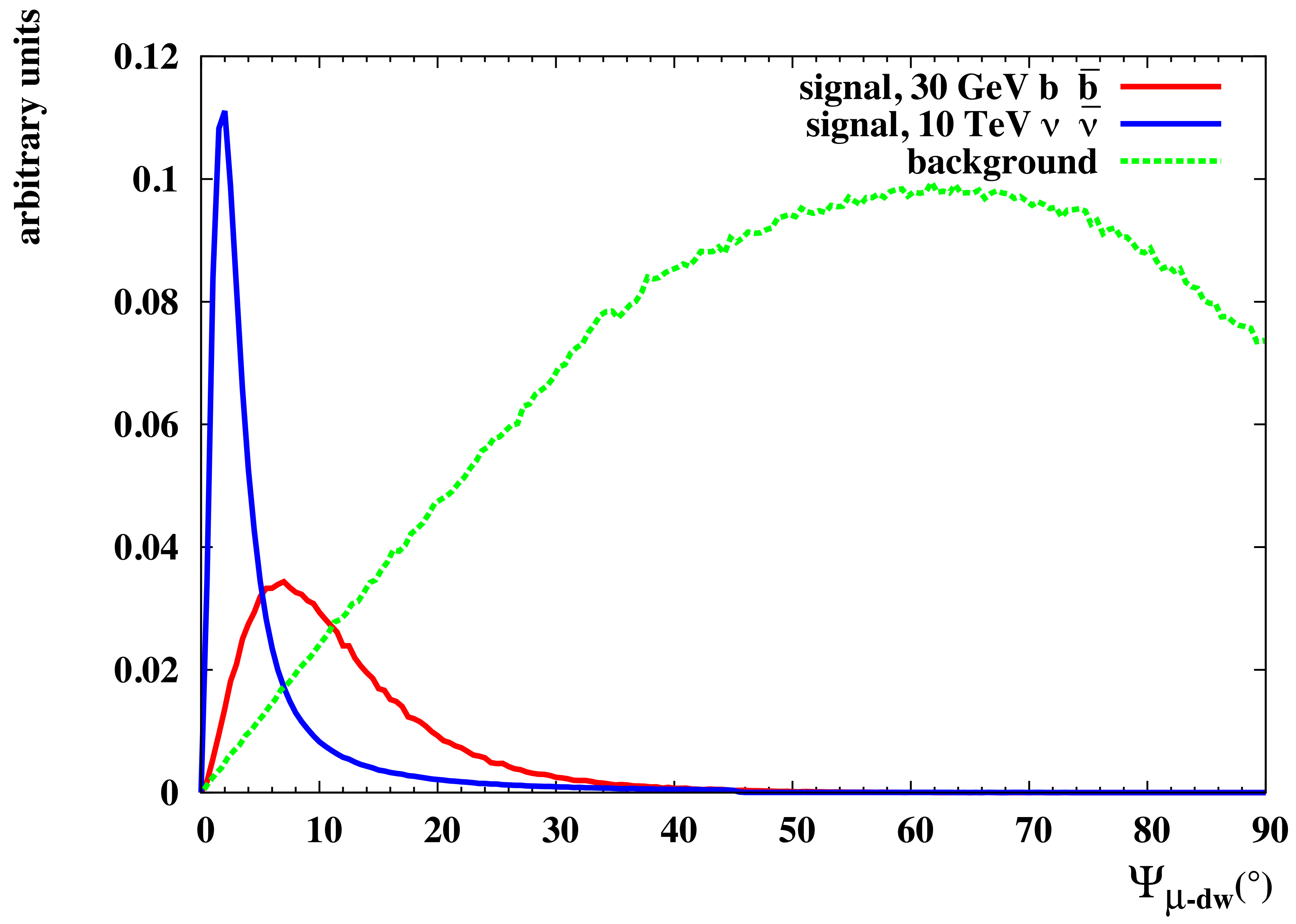
Figure 7: GVD-Baikal sensitivity to τ_{DM} for $T = 1$ yr.

JTEP Lett. 101 (2015) 5, 269
V.Avrorin et al (Baikal-GVD Coll.)

DM constrains from observation of 22 dSphs by Baikal-NT200

Name	Dec	RA	$\overline{\log_{10} J}$	N_S	N_B	TS, $b\bar{b}$ 30 GeV	TS, $\nu\bar{\nu}$ 10 TeV
Carina	-50.97	100.40	18.1 ± 0.23^a	30	29.3	0.10	1.11
Fornax	-34.45	40.0	18.2 ± 0.21^a	25	26.0	0.02	0
Leo-I	12.31	152.12	17.7 ± 0.18^a	14	11.6	1.15	0.05
Leo-II	22.15	168.37	17.6 ± 0.18^a	11	6.81	2.19	0
Sculptor	-33.71	15.04	18.6 ± 0.18^a	29	24.5	0	0.25
Sextans	-1.61	18.26	18.4 ± 0.27^a	23	17.6	2.50	0
Bootes-I	14.50	210.03	18.8 ± 0.22^a	12	10.7	0.05	0.95
Coma Berenices	23.90	186.75	19.0 ± 0.25^a	10	6.12	0.76	0.12
Hercules	12.79	247.76	18.1 ± 0.25^a	9	11.3	0	0
Leo-IV	-0.53	173.24	17.9 ± 0.28^a	18	16.8	0.0	0.48
Leo-V	2.22	172.79	16.37 ± 0.9^b	18	15.4	0.0	0
Leo-T	17.05	143.72	17.11 ± 0.4^b	14	9.34	0	0
Segue-1	16.08	151.77	19.5 ± 0.29^a	13	9.76	1.28	0.78
Segue-2	20.18	34.82	16.21 ± 1.0^b	8	7.83	0.03	0.99
Reticulum-2	-54.05	53.92	19.8 ± 0.9^c	20	28.7	0.01	0.76
Eridanus-2	-43.53	56.09	17.3 ± 0.4^d	25	27.5	0	0
Horologium-1	-54.11	43.87	18.4 ± 0.4^d	22	28.8	1.02	0
Pictor-1	-50.28	70.95	18.1 ± 0.4^d	19	28.6	0	0
Phoenix-2	-54.41	354.99	18.4 ± 0.4^d	35	28.2	2.34	0
Indus-1	-51.16	317.20	18.3 ± 0.4^d	28	27.3	0	0
Eridanus-3	-52.28	35.69	18.3 ± 0.4^d	29	28.7	0.63	4.96
Tucana-2	-58.57	343.06	18.8 ± 0.4^d	31	27.4	2.38	1.98

$$\frac{d\phi_\nu}{dE_\nu d\Omega} = J_a(\psi)\,\frac{\langle\sigma_a v\rangle}{8\pi m_{DM}^2}\,\frac{dN_\nu}{dE_\nu}.$$



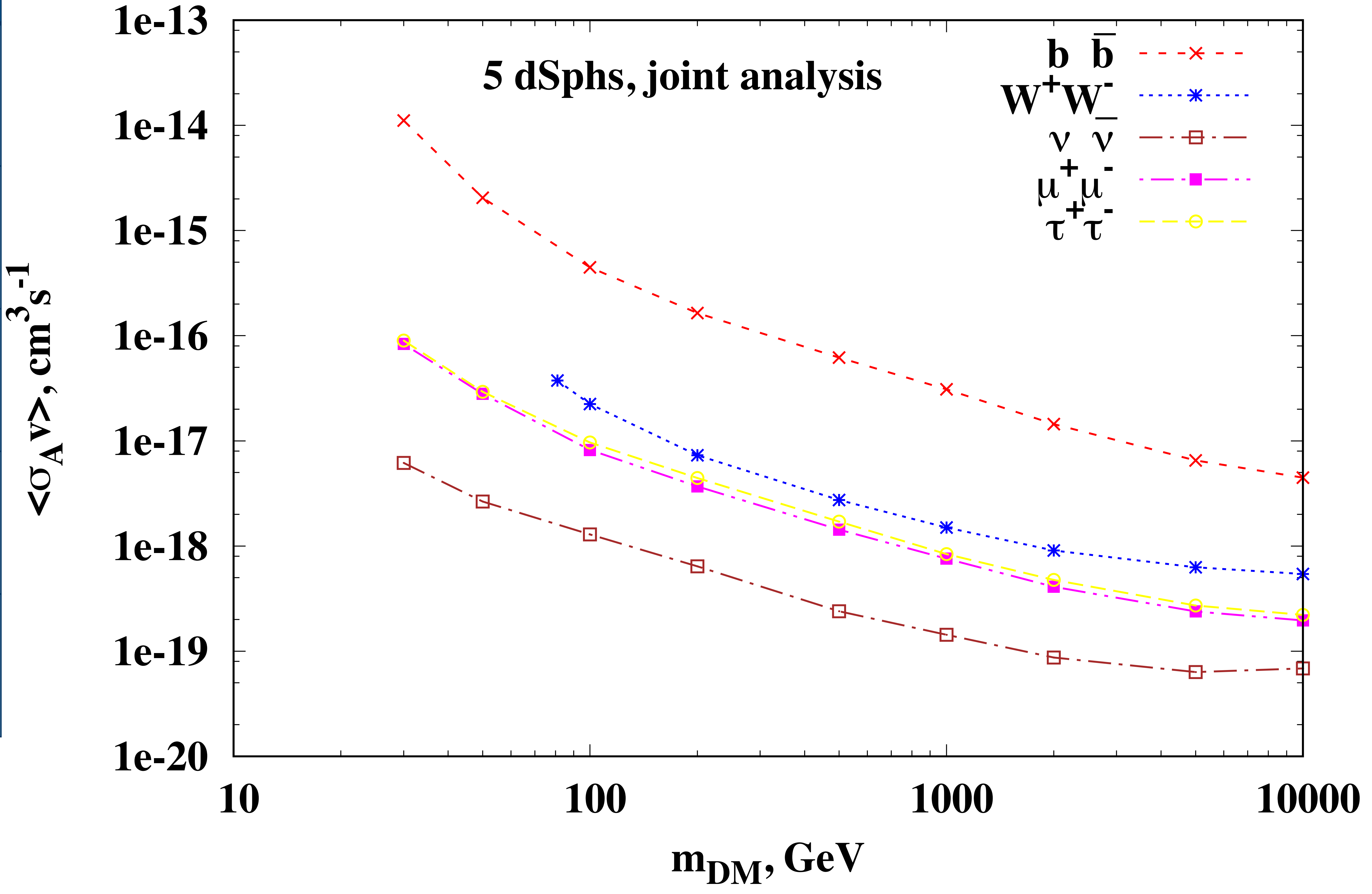
JTEP, 125 (2017) 80, V.Avrorin et al (Baikal-GVD Coll.)

Baikal sensitivity to DM annihilation: TS, UL in combined analisys

JTEP, 125 (2017) 80, V.Avrorin et al (Baikal-GVD Coll.)

$$\lambda(N_S) = -2\ln\frac{\mathcal{L}(N_S, \hat{\hat{\theta}}(N_S))}{\mathcal{L}(\hat{N}_S, \hat{\theta})}$$

dSphs	nu-nu 30 GeV	nu-nu 10 TeV	bb 30 GeV	bb 10 TeV
Sculptor	0.43	0.25	0.11	0.40
Coma Berenices	0.63	0.20	0.98	0.30
Seque-1	2.06	1.19	1.82	1.39
Reticulum-2	0.77	1.39	0.21	1.30
Tucana-2	4.45	2.80	3.34	3.25



$$f(\psi, N_S, N_B) = \frac{1}{N_S + N_B}\left(N_S f_S(\psi) + N_B f_B(\psi)\right),$$

$$\mathcal{L}(\langle\sigma_a v\rangle) = \frac{(N_B + N_S)^n}{n} e^{-(N_B+N_S)} \times \prod_{i=1}^{n} f(\psi_i, N_B, N_S)$$

$$\mathcal{L}(\langle\sigma_a v\rangle, \theta) = \mathcal{N}\frac{(\epsilon_B N_B + \epsilon_S N_S)^n}{n} e^{-(\epsilon_B N_B + \epsilon_S N_S) - \frac{(\epsilon_S - 1)^2}{2\sigma_S^2} - \frac{(\epsilon_B - 1)^2}{2\sigma_B^2} - \frac{(\log_{10}(J) - \overline{\log_{10}(J)})^2}{2\sigma_J^2}} \prod_{i=1}^{n} f(\psi_i, \epsilon_B N_B, \epsilon_S N_S)$$

Baikal limits on DM annihilations in the LMC

$$N_S = T \frac{\langle \sigma_a v \rangle}{8\pi m_{DM}} J_{\Delta\Omega} \int_{E_{th}}^{m_{DM}} dE_\nu \frac{dN_\nu}{dE_\nu} S_\nu(E_\nu)$$

Applied DM profiles:

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_S}\right)^\gamma \left[1 + \left(\frac{r}{r_S}\right)^\alpha\right]^{\frac{\beta-\gamma}{\alpha}}} \theta(r_{max} - r)$$

Profile	α	β	γ	r_S, kpc	ρ_0, GeV/cm^3	$\log_{10} J$
sim-max	0.35	3.0	1.3	5.4	4.19	21.94
sim-mean	0.96	2.85	1.05	7.2	0.32	20.38
sim-min	1.56	2.69	0.79	4.9	0.46	20.25

Table 2. Parameters of dark matter halo profiles for Large Magellanic Cloud.

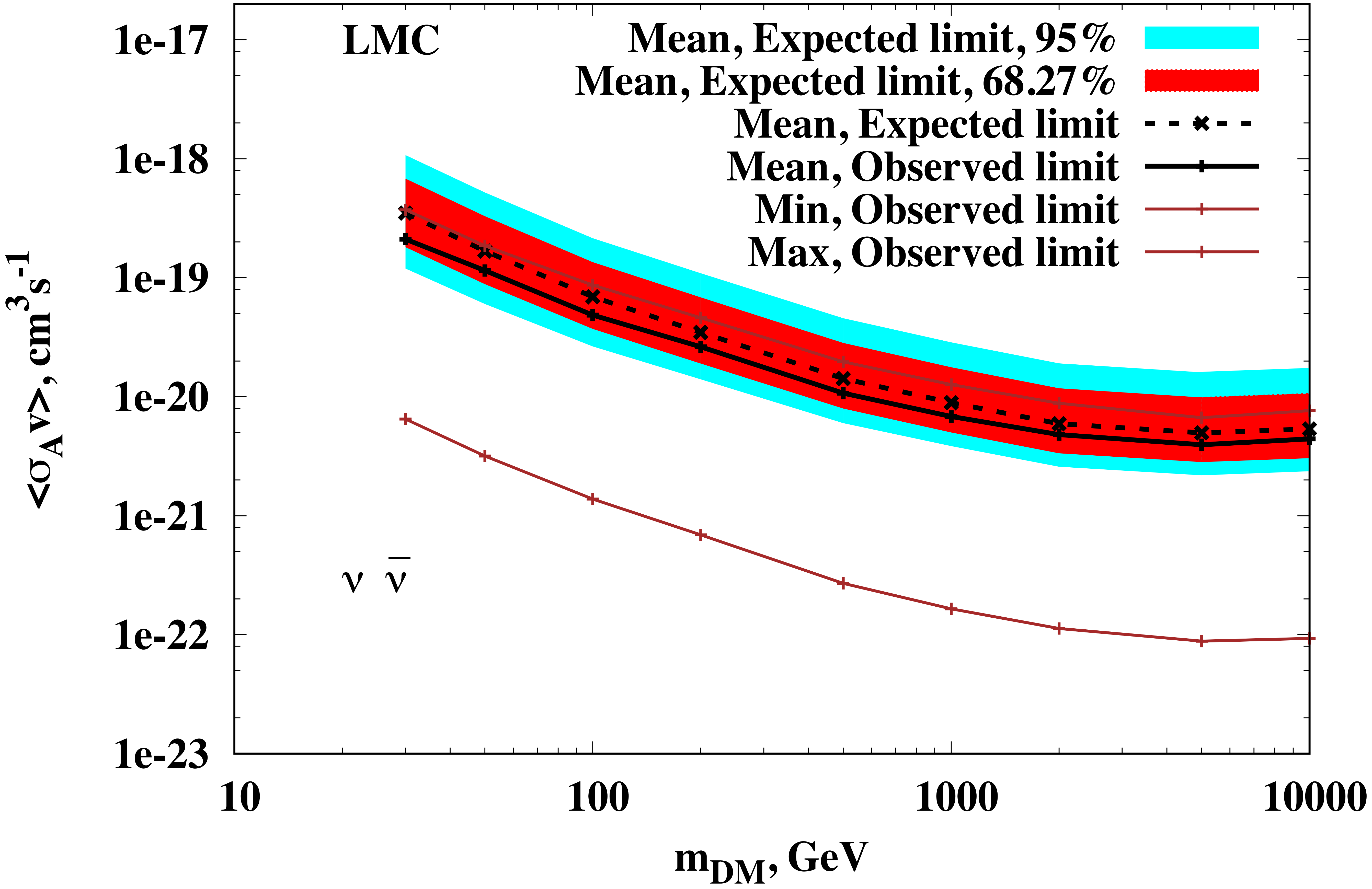
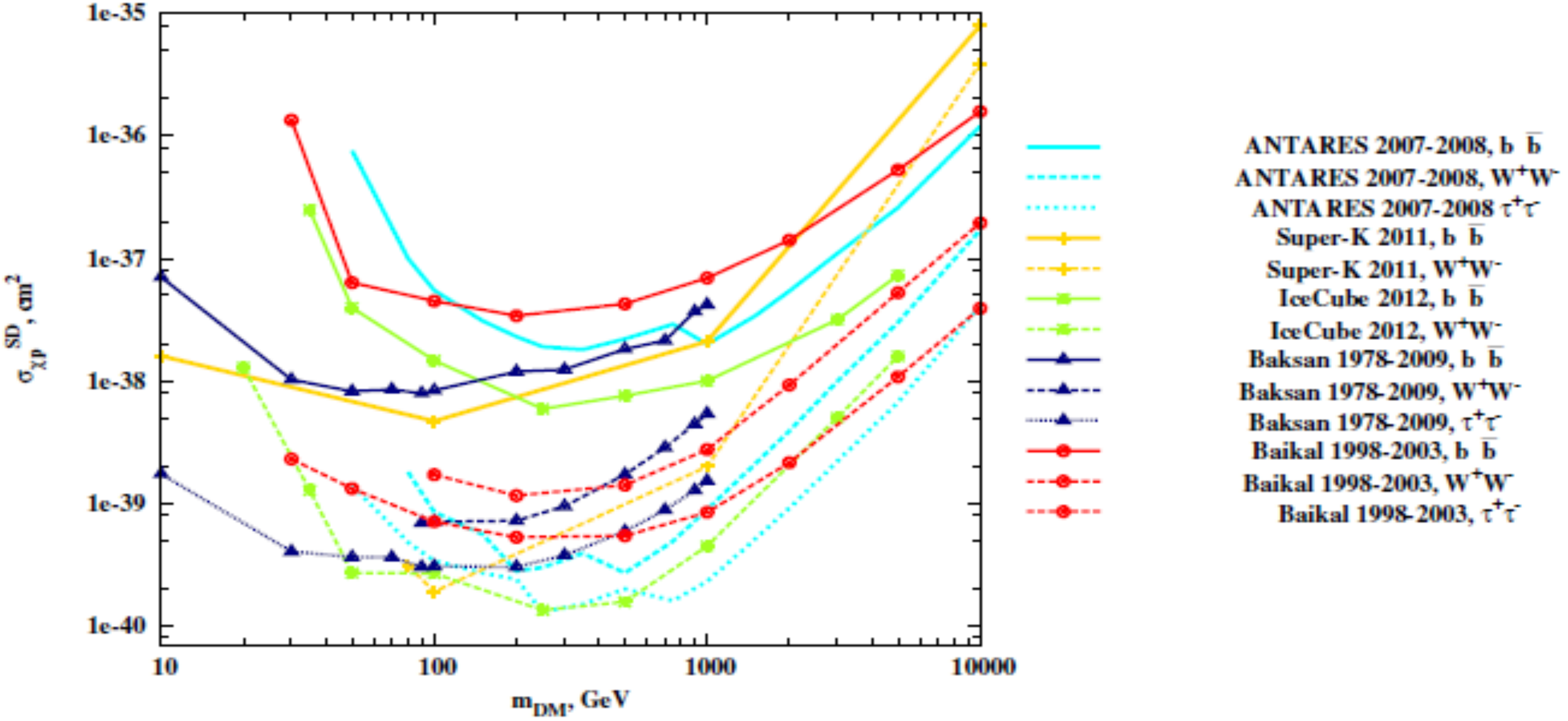


Fig. 8. 90% CL upper limits from the NT200 data assuming different dark matter density profiles for LMC (solid lines) and sensitivity (dashed line) on dark matter annihilation cross section assuming annihilation to $\nu\bar{\nu}$. Colored bands represent 68% (red) and 95% (blue) quantiles.

JTEP, 125 (2017) 80, V.Avrorin et al (Baikal-GVD Coll.)

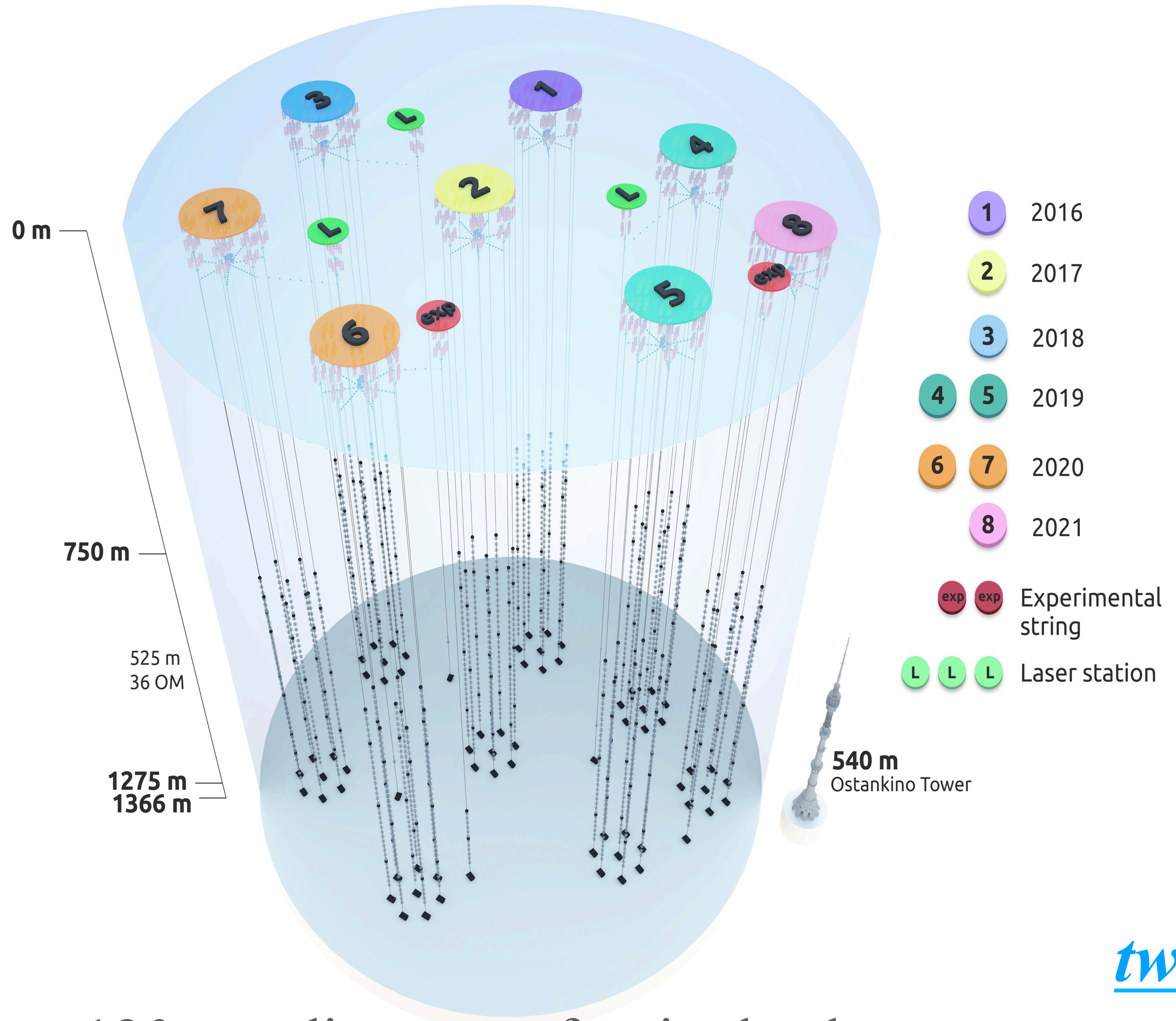
Solar DM: UL on spin-dependent (SD) cross section DM-p
Baikal NT200, Baksan, ANTARES, SK, IceCube (2014)

$$\frac{\sigma_p^{SD}}{\Gamma_A^{SD}} \cdot \Gamma_A^{Upp.Lim.} = \sigma_p^{SD,Upp.Lim.}, \qquad \frac{\sigma_p^{SI}}{\Gamma_A^{SI}} \cdot \Gamma_A^{Upp.Lim.} = \sigma_p^{SI,Upp.Lim.}$$



V.Avrorin et al (Baikal-GVD Coll.), *Astropart.Phys.* 62 (2015) 12

Baikal-GVD of 2021yr: 2304 OMs/ 64 strings/ 8 clusters



120 m - diameter of a single cluster,
300 m - distance between clusters

0.4 km^3 for cascades of E>>100 TeV

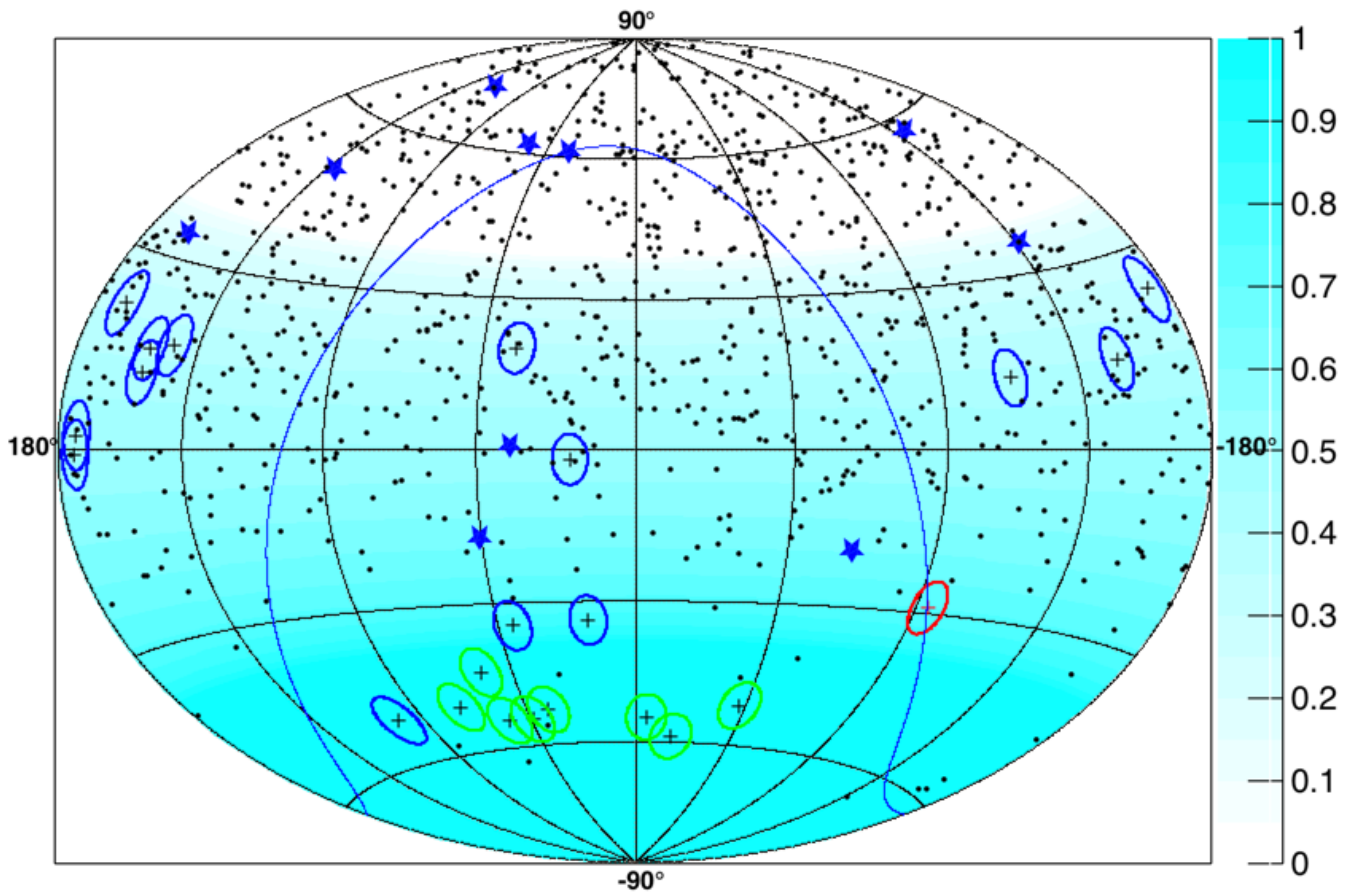
Apr 2022: two new clusters

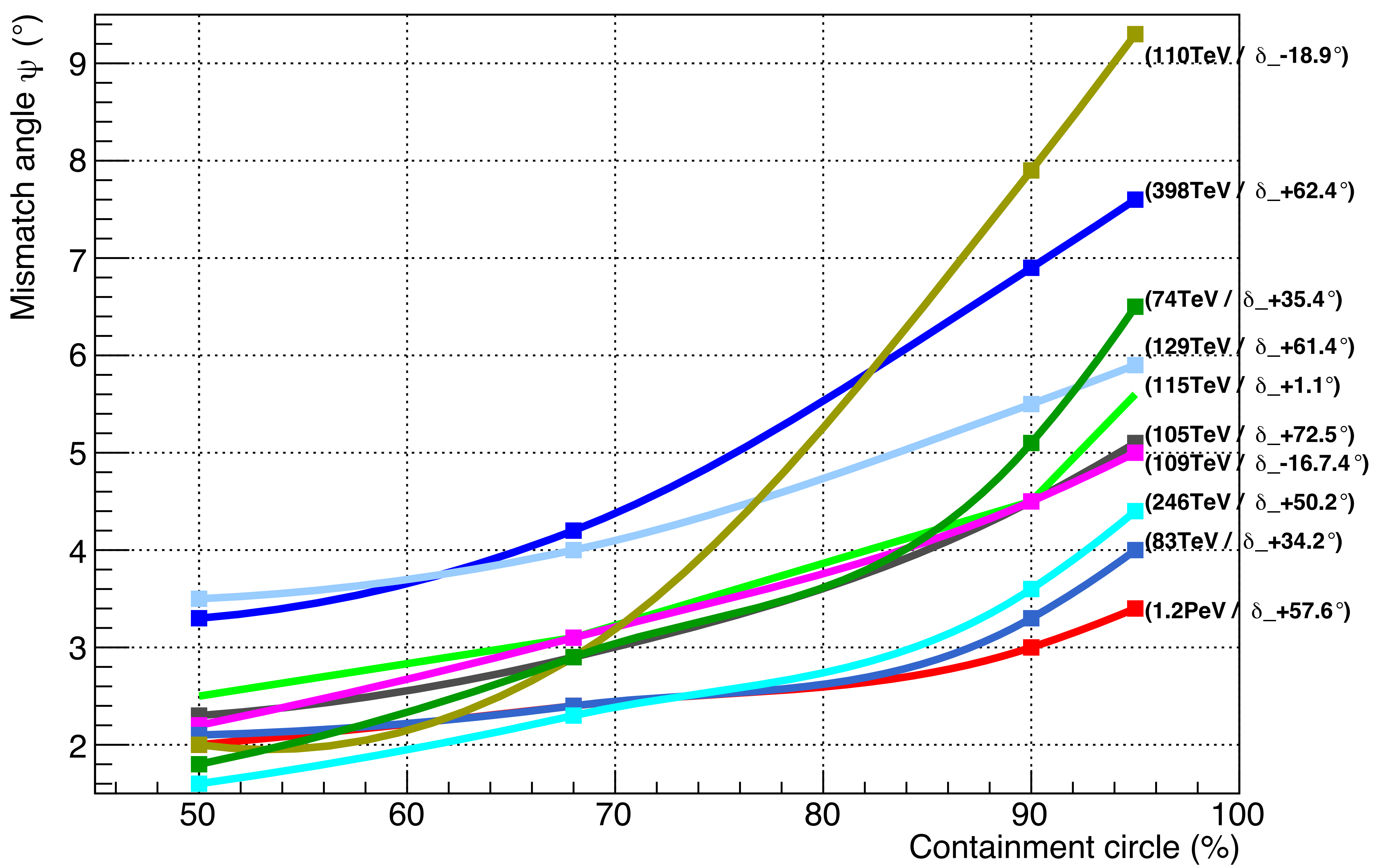
Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

ICRC2021, *Zh.-A.M. Dzhilkibaev and I.A.Belolaptikov;*
VLVnT2021, *V.M.Aynutdinov*

22-dSphs, GVD sample with E>40TeV and 10 Baikal-GVD alerts



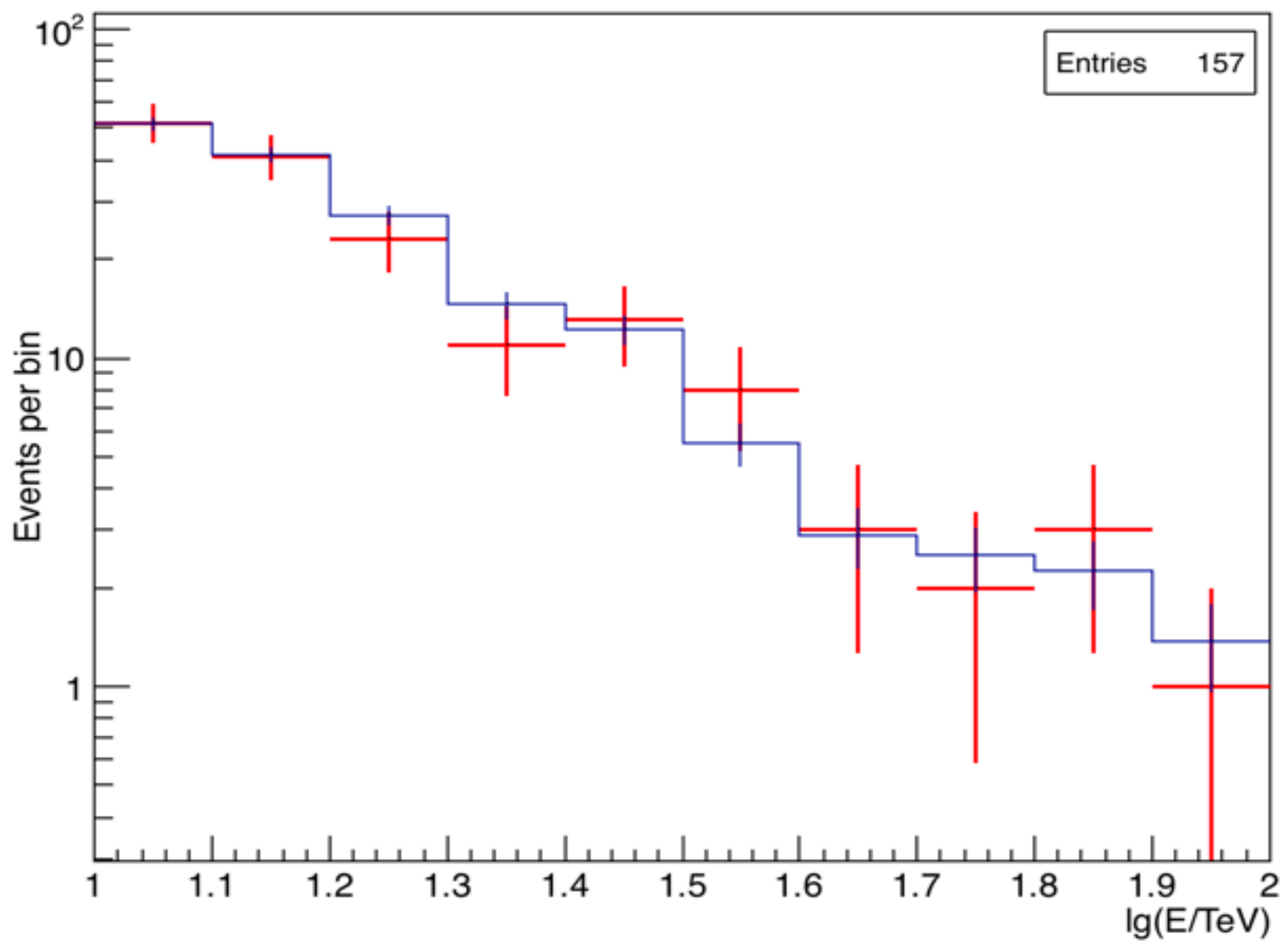


★Baikal-GVD, Esh>60 TeV, Nhit≥20
• Baikal-GVD, Esh>40 TeV, Nhit ≥10
• Galaxy Center
+ Dwarfs

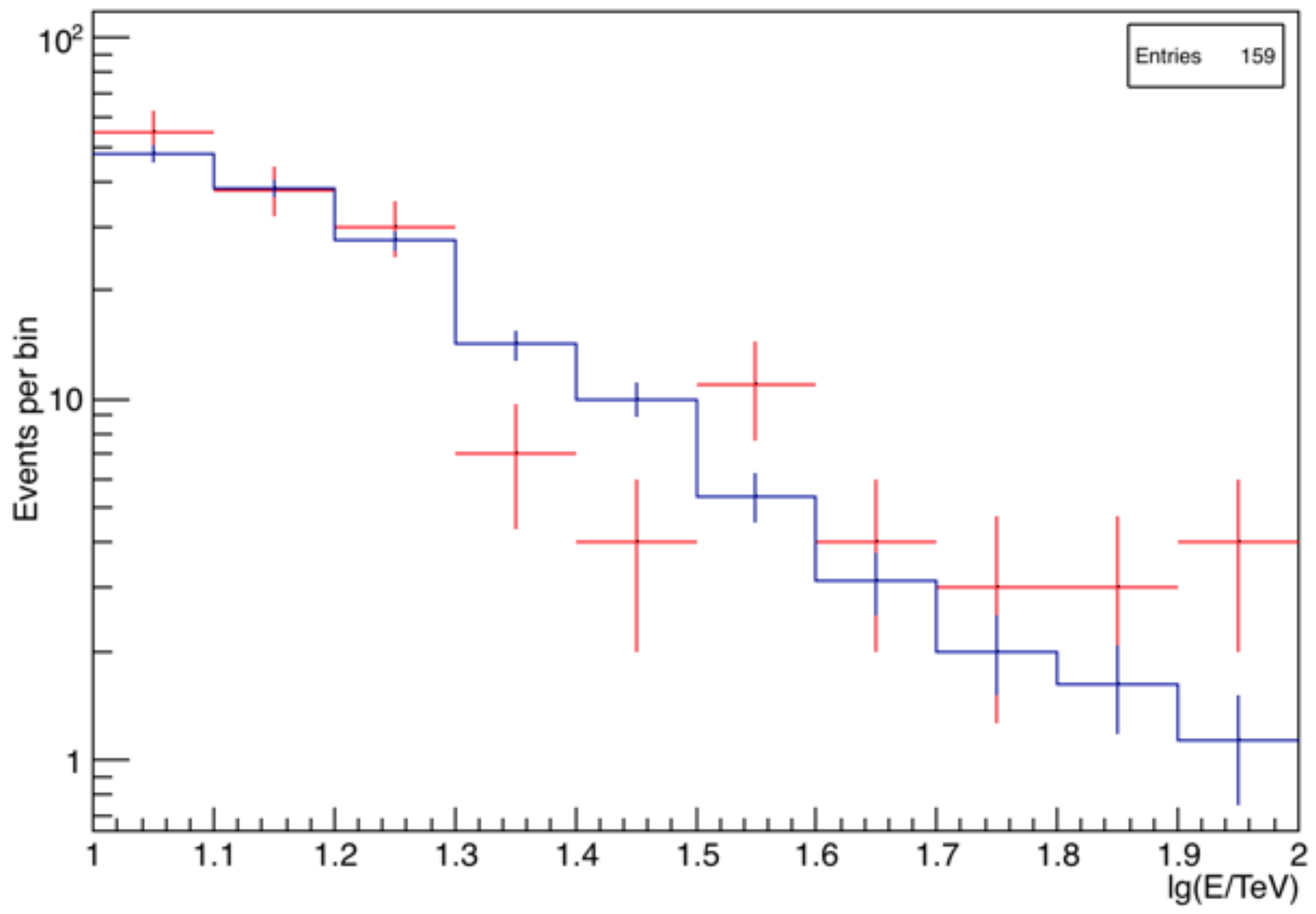
Half-open cone of event containments
at 50%, 68%, 90% and 95% levels

GVD cascades twd dwarfs Seg-2, Bootes-I, Leo-V/ Esh_cone_10

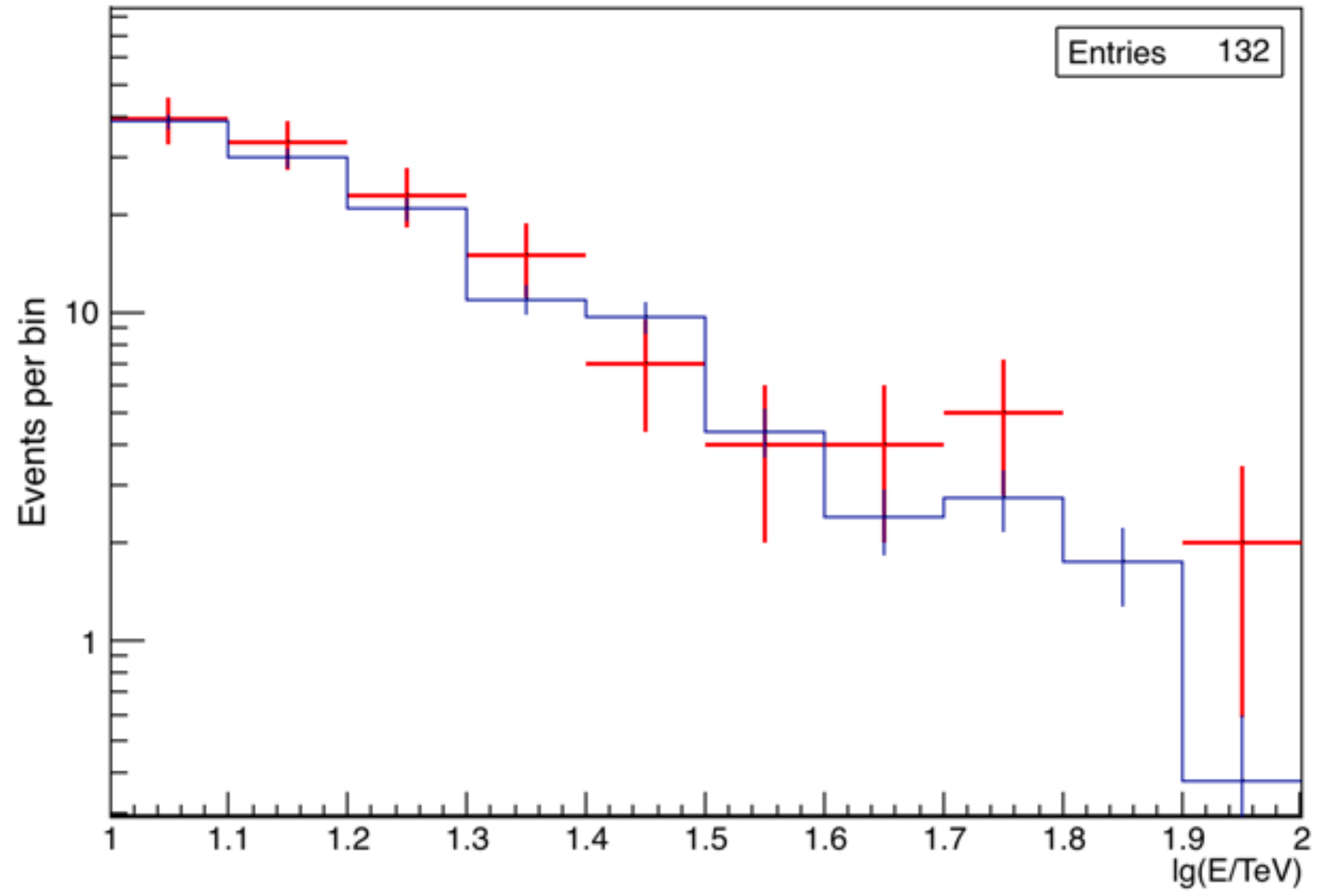
Segue-2, (ra_34.82/dec_20.18)



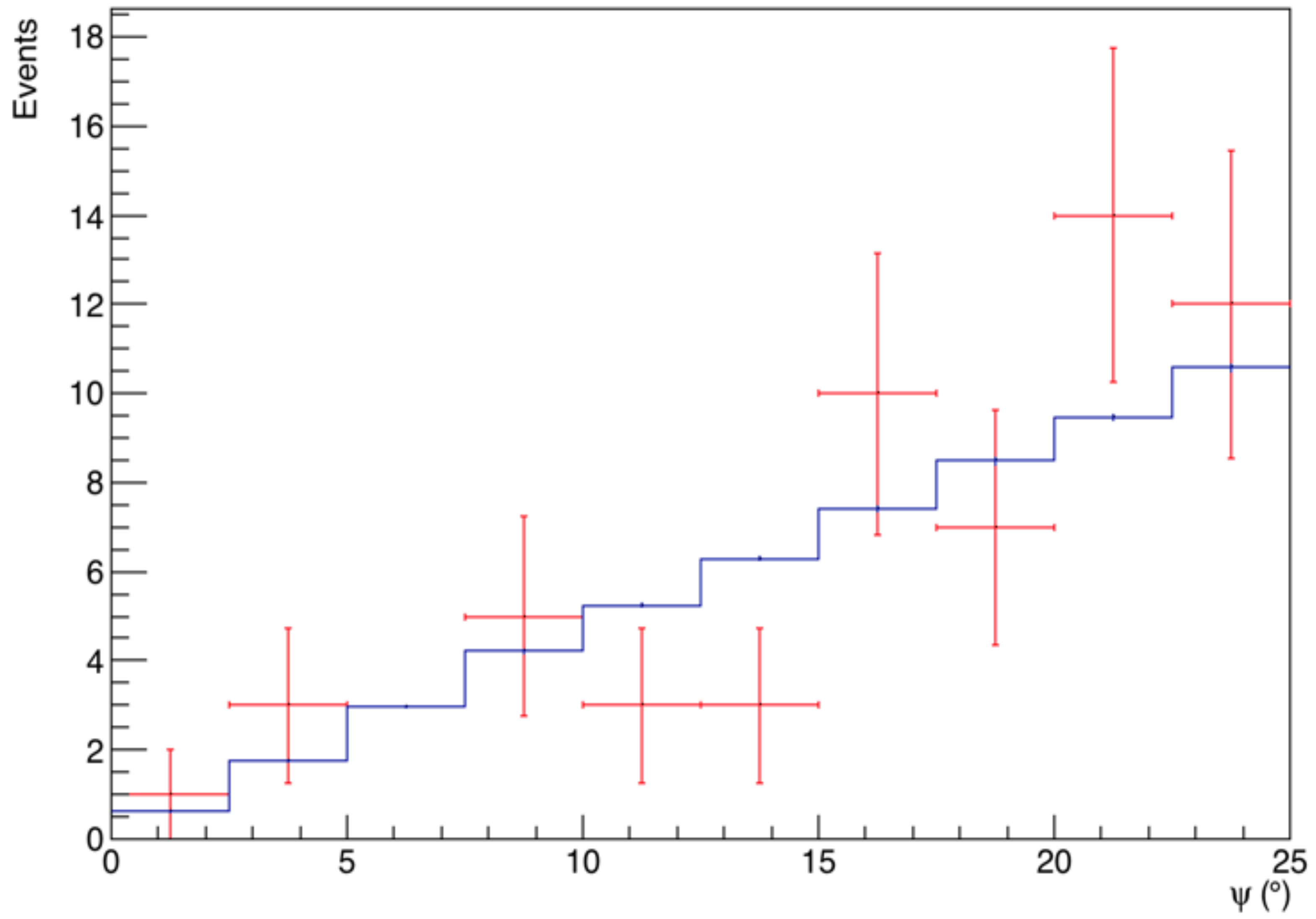
Bootes-I, (210.0/14.5)



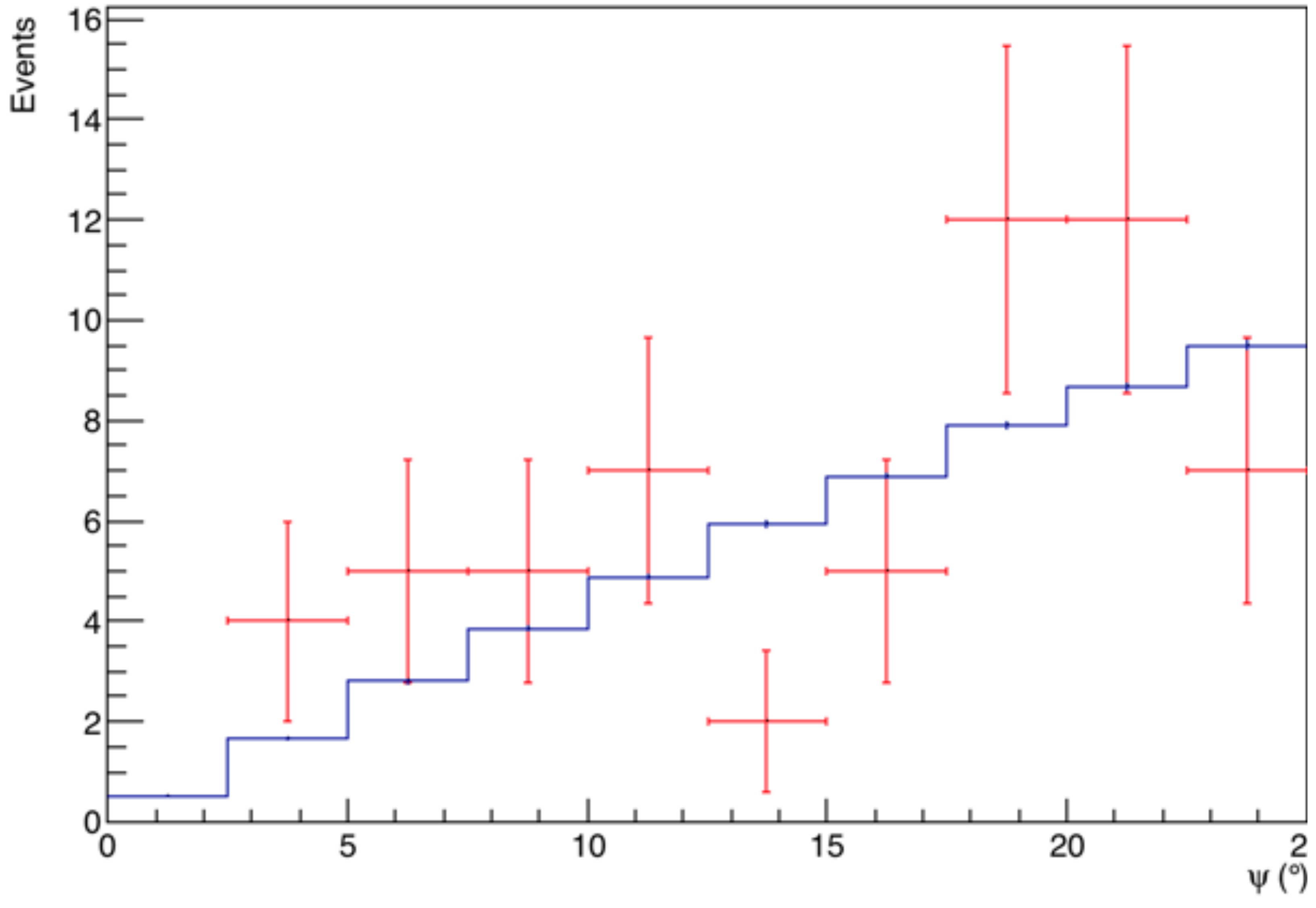
Leo-V, (ra_172.79/dec_2.22)



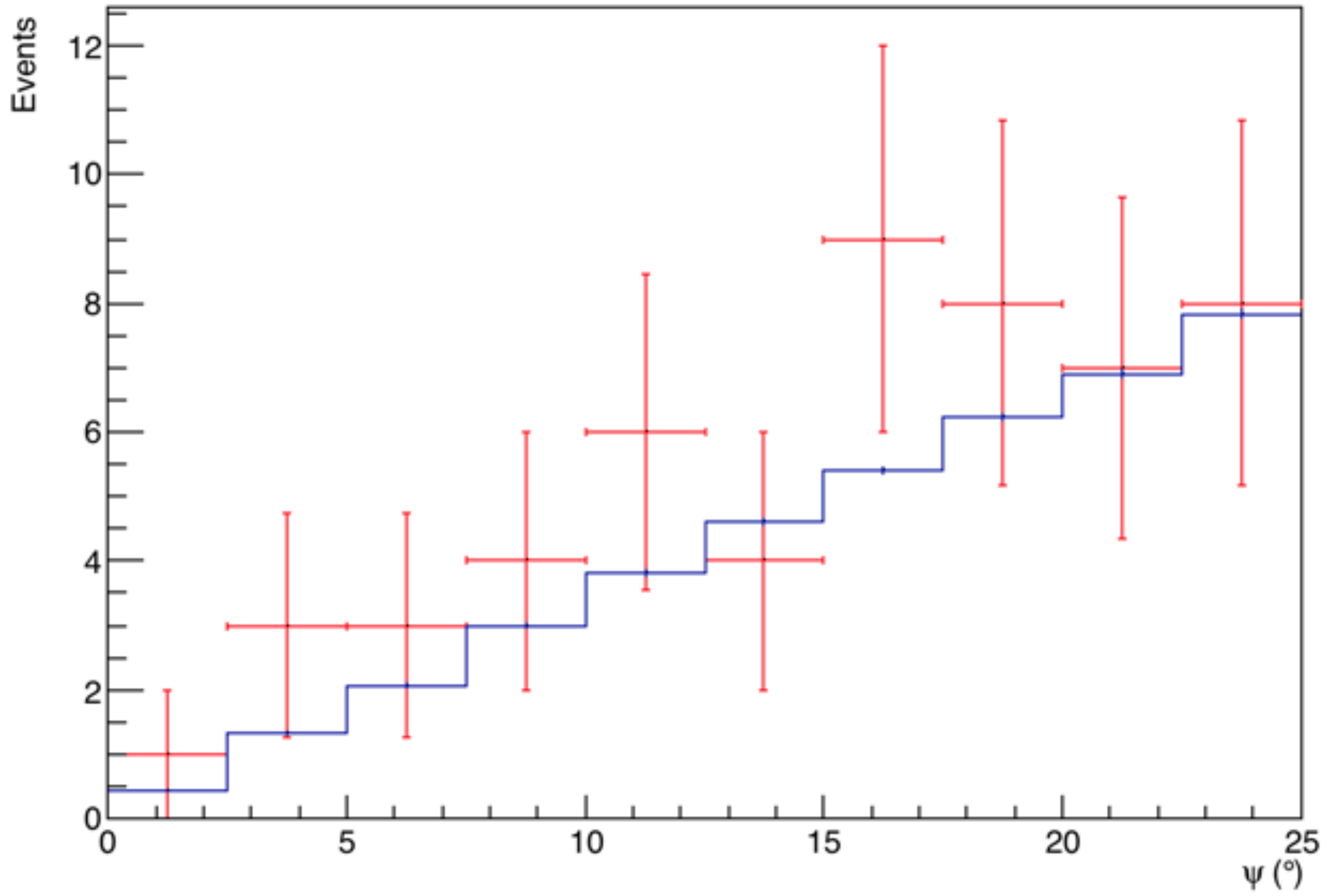
sample_cascades2018-2021: Seque-2



sample_cascades2018-2021: Bootes-I



sample_cascades2018-2021: Leo-V



GVD cascades twd dwarfs Sextans, Leo-T, Seg-1 / Esh_cone_10

* SUMMURY & OUTLOOK

✔ Baikal-GVD aims on detection of neutrinos in TeV-PeV range. First 10 GVD alerts (E>60 TeV) have been selected in 2018-2020 yrs. There is no their association with hidden sources of DM.

✔ Data sample of HE GVD cascades is currently under investigation towards dSphs on base of earlier studies and new advanteges of energy binning.

✔ Further progress in track reconstruction lies in the potential of multicluster events (HE) as well as parameter optimization in single-cluster events with low E-threshold (LE).

Thank you for your attention!