* Dark Matter: results of the Baikal neutrino experiment

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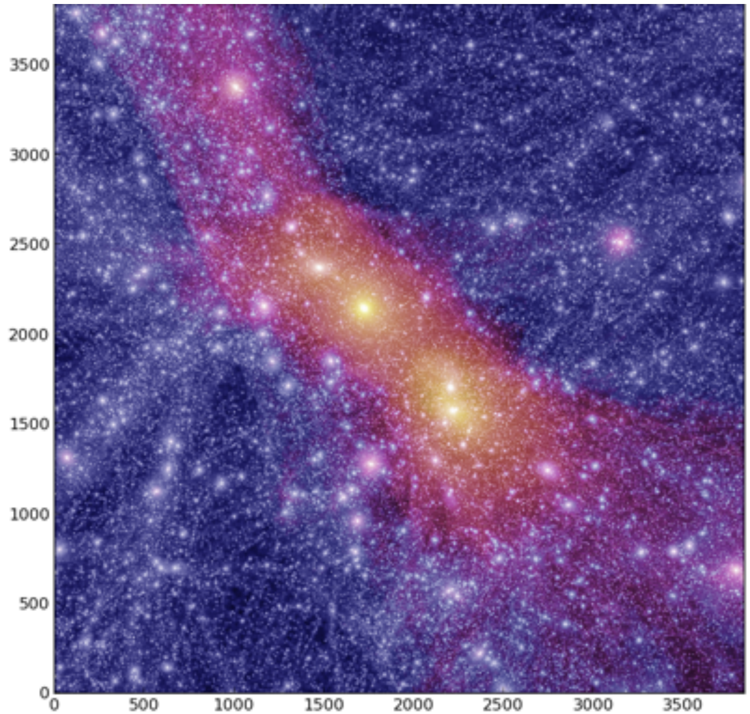
17–12–01547

WIMP and CDM: the link?

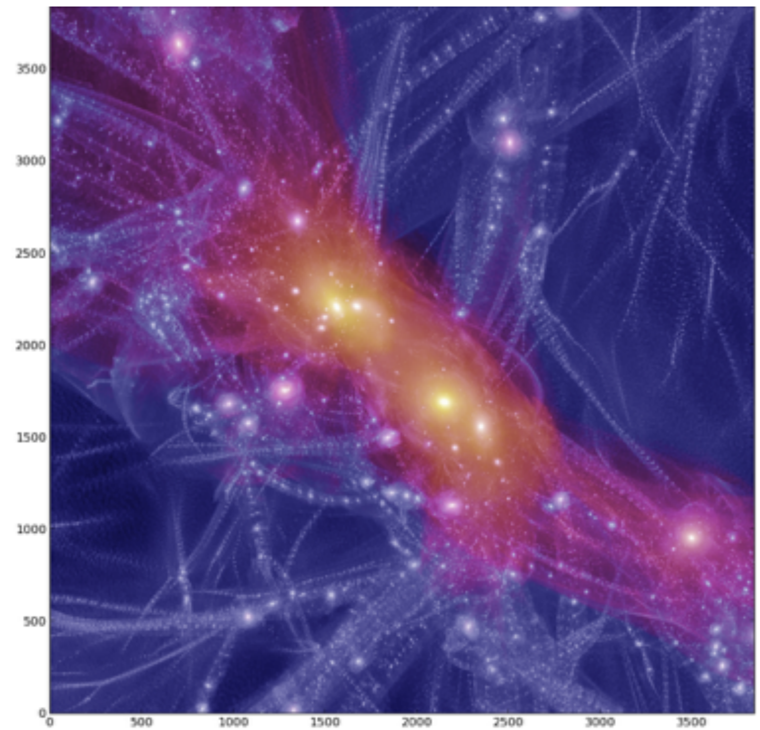
Instead of introduction

Simulation of what the Universe looks like



WIMP are CDM candidate

~ Simulation of what the Universe would look like without DM



CDM fit observations

Has been completed the analysis of Baikal NT200 data sample of 5 years in search for a dark matter signal from directions of the potential astrophysical sources: the Sun trajectory, the Galaxy Center, 22 dSphs mostly in the Southern hemisphere and the Large Magellanic Cloud known as the largest satellite galaxy of the Milky Way. The upper limits have been obtained at 90\% C.L.

Have been obtained preliminary estimates in combined analysis of the ANTARES data sample in 2016 year with the Baikal NT200 for upper limits on flux from the GC

State at the beginning of reasearch of the Baikal-GVD sensitivity to a dark matter signal: first estimate in the GC direction and selection of nearly vertical events in application to expected flux from the Earth's core.

Baikal published works on DM searches

Baikal Collaboration, A.D. Avrorin et al., "Search for neutrino emission from relic dark matter in the Sun with the Baikal **NT200** detector", **Astropart.Phys. 62 (2015) 12-20,** [arXiv:1405.3551]. — Sun

1st wsh Dark Ghosts

Baikal Collaboration, A.D. Avrorin et al., "Sensitivity of **Baikal-GVD** neutrino telescope to neutrino emission toward the center of Galactic dark matter halo", **JETP Lett. 101 (2015) no.5, 289-294,** [arXiv:1412.3672].

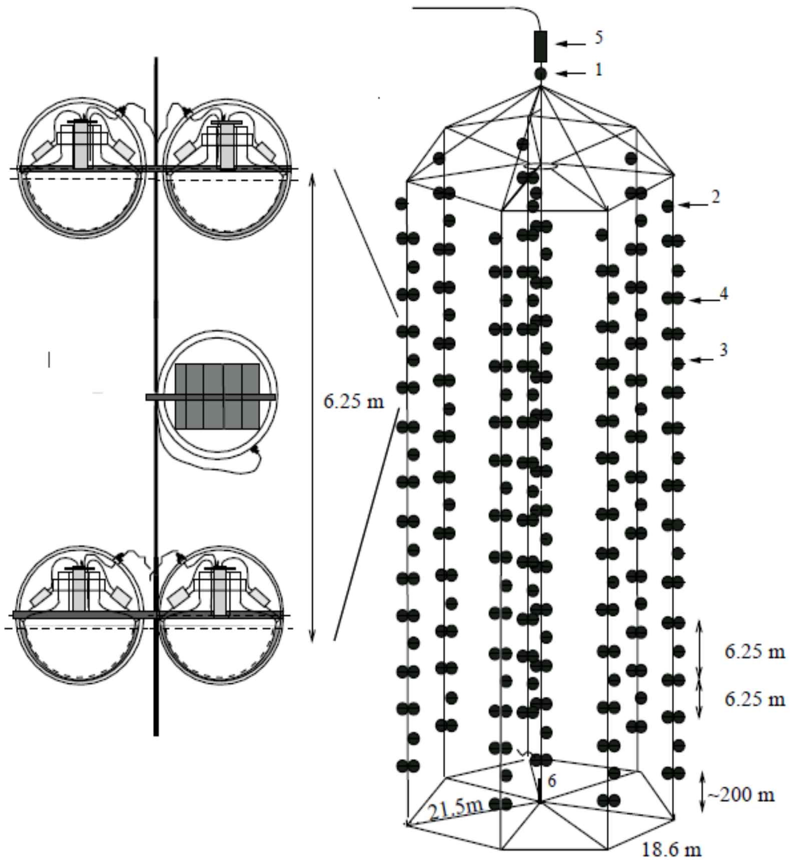
Baikal Collaboration, A.D. Avrorin et al., "A search for neutrino signal from dark matter annihilation in the center of the Milky Way with Baikal **NT200**", **Astropart.Phys. 81 (2016) 12-20**, [arXiv:1512.01198].

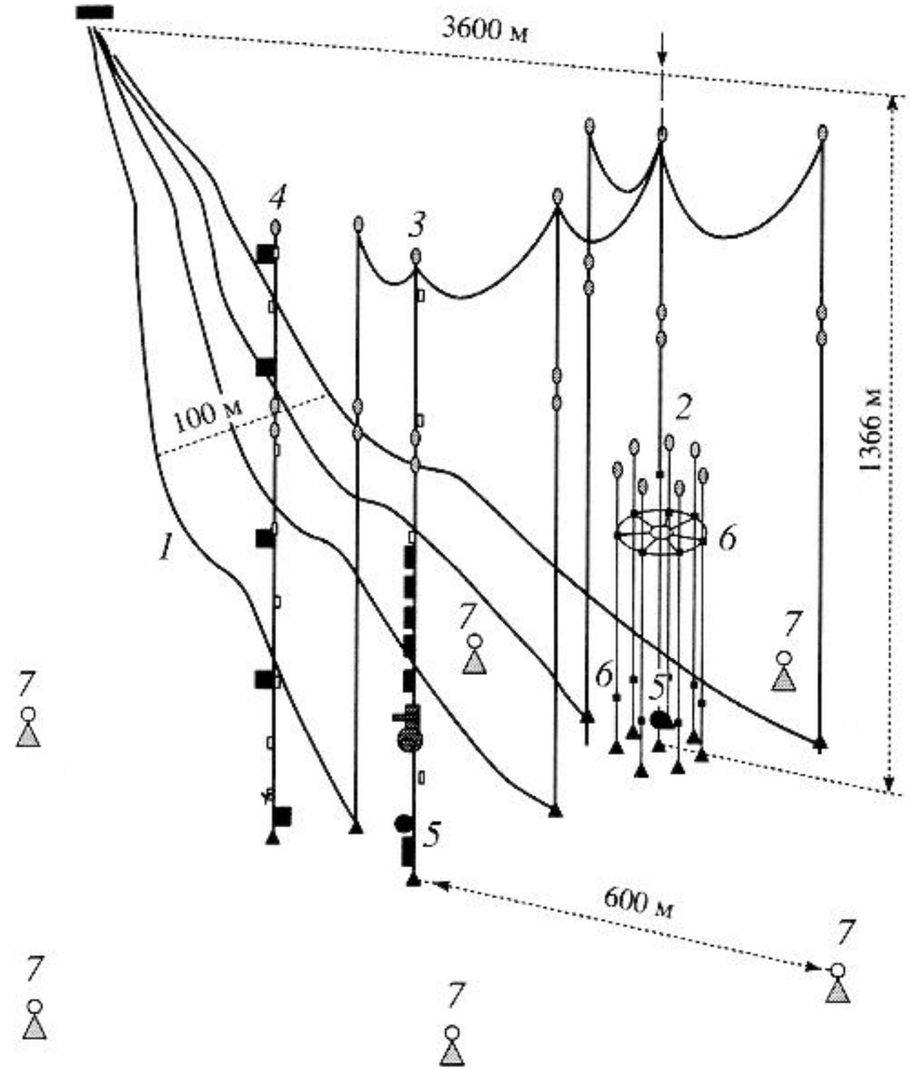
— Galactic Center

Baikal Collaboration, A.D. Avrorin et al., "Constraint in dark matter signal from a combined observation of dSphs and the LMC with the Baikal **NT200**", **J.Exp.Theor.Phys. 125 (2017) no.1, 80-90,** [arXiv:1612.03836]. — Galaxy Clusters, Dwarf SG

Previous **Baikal-NT200** results: 2005, diss. Zh.-Djilkibaev — Earth

Baikal NT200, Heptagon and Hydroacoustic system

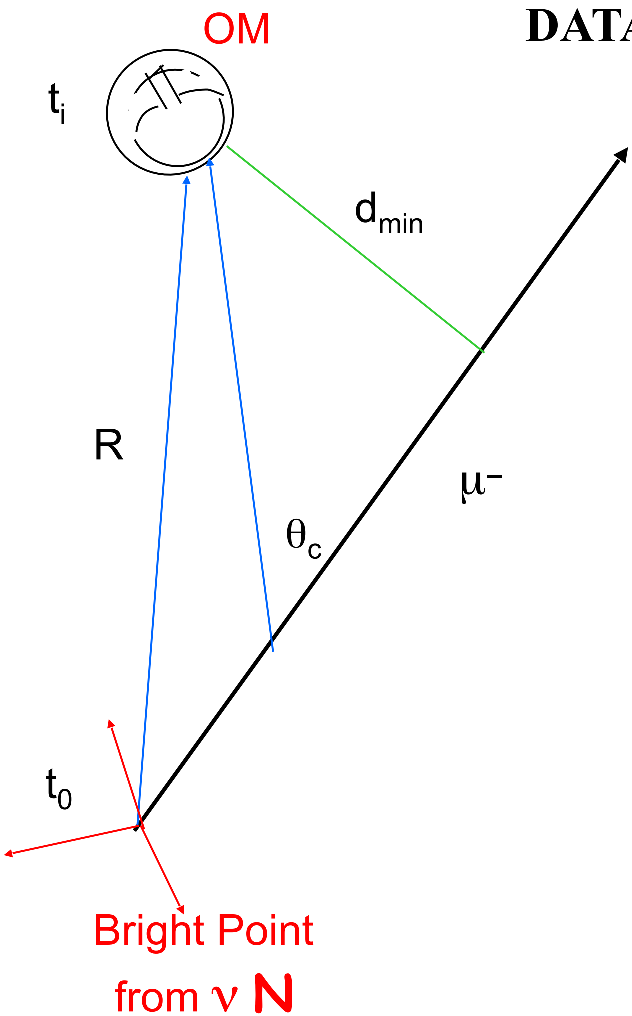




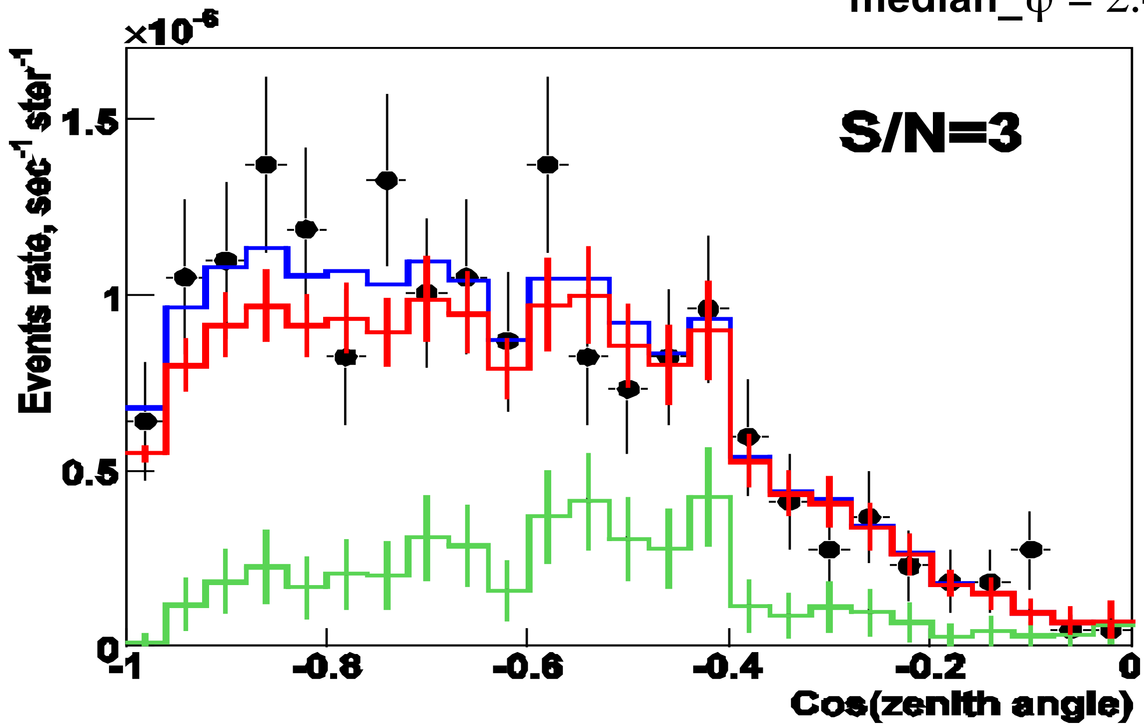
NT200 neutrino events

DATA ?= SIGNAL ν + ATM ν + ATM μ + KHz_noise

MC estimate



E_th ~ 10 GeV
median_ψ = 2.4°

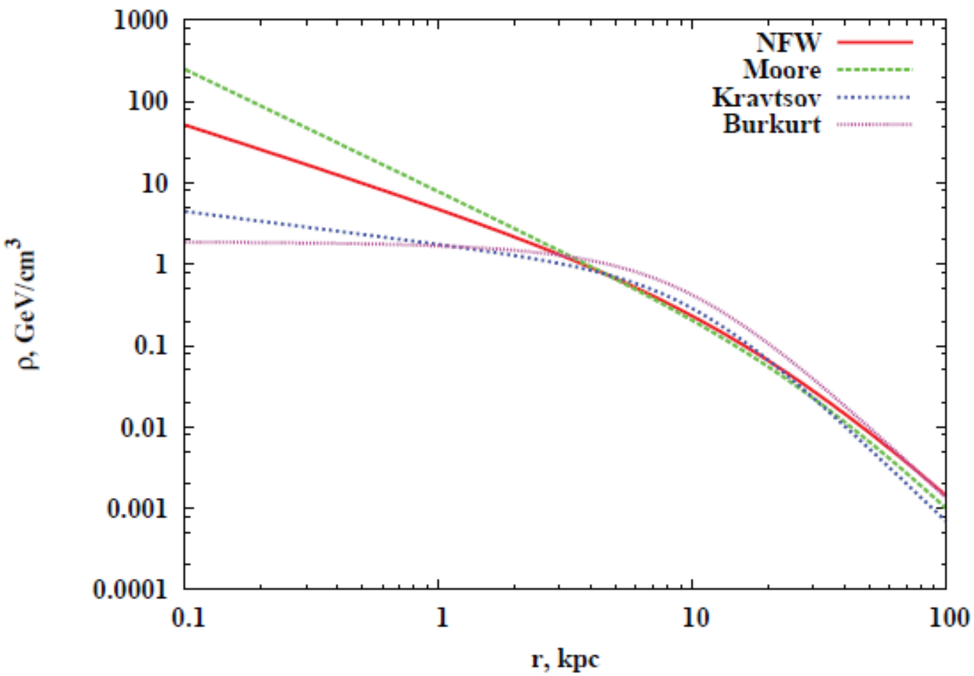


WIMPs from Galactic Center

WIMP signature in gamma-rays or neutrino fluxes

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

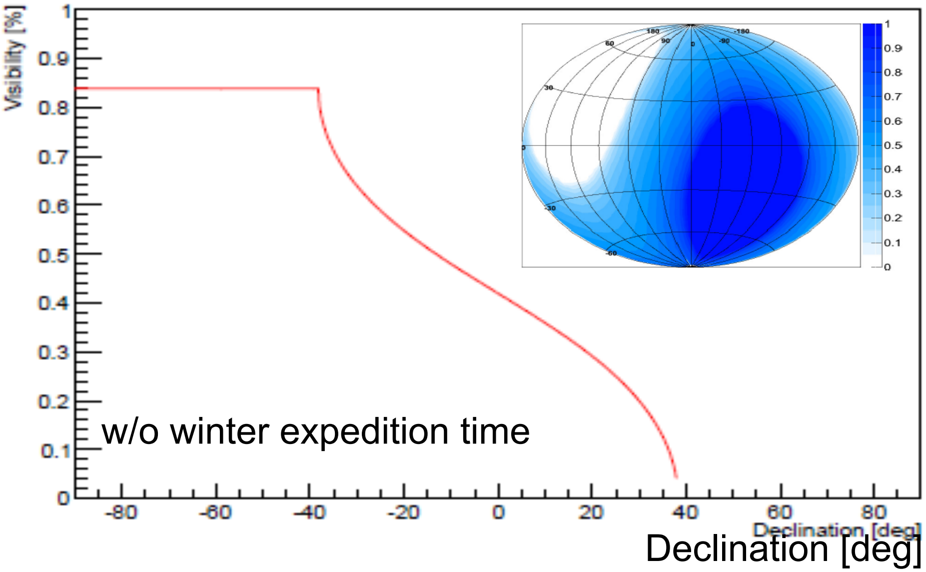
DM distribution (J-factor)



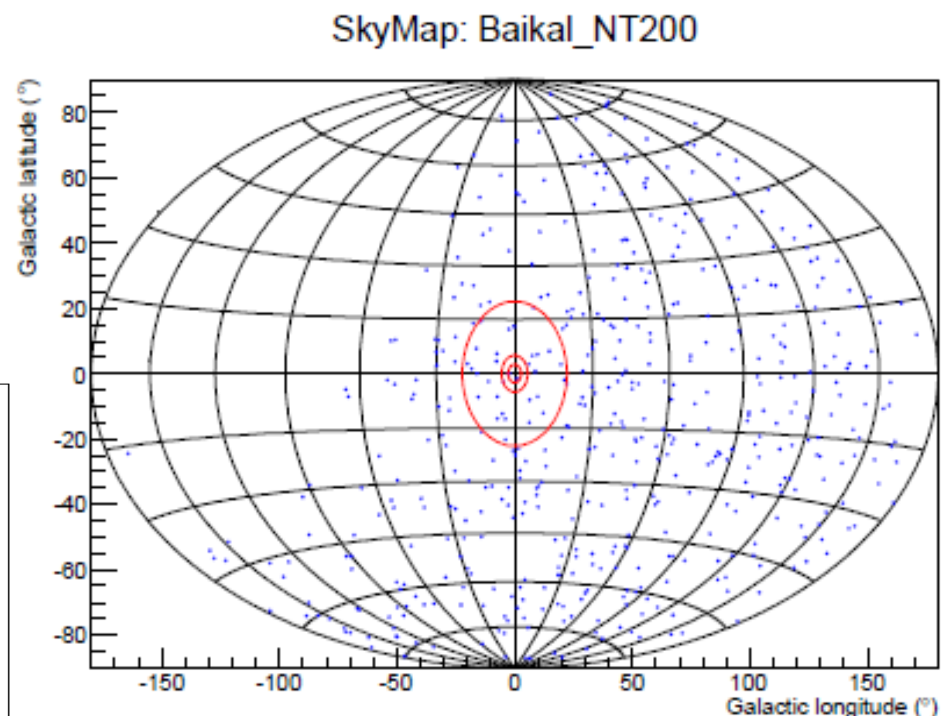
Model	α	β	γ	δ	r_*, kpc	ρ_*, GeV/cm^3
NFW	1	3	1	0	20	0.3
Burkert	2	3	1	1	9.26	1.88
Moore	1.5	3	1.5	0	28	0.27

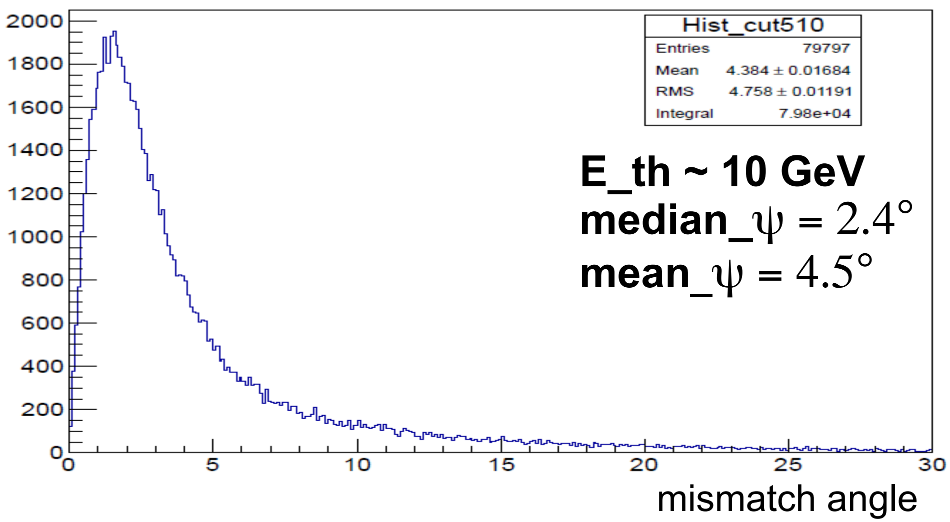
$$\rho(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}$$

Baikal NT200 visibility and angular resolution with selected evts

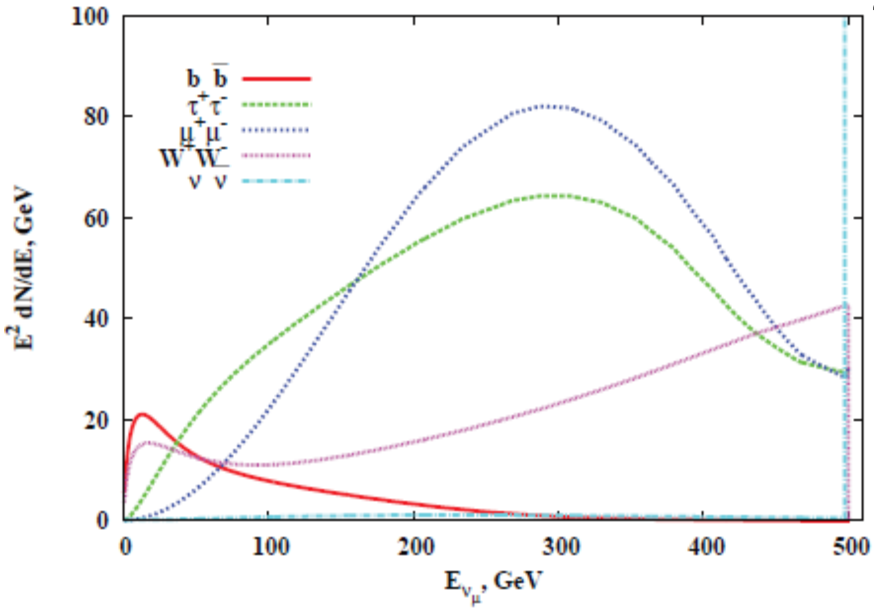


Events below horizon (zenith>100 deg.) and selection cuts

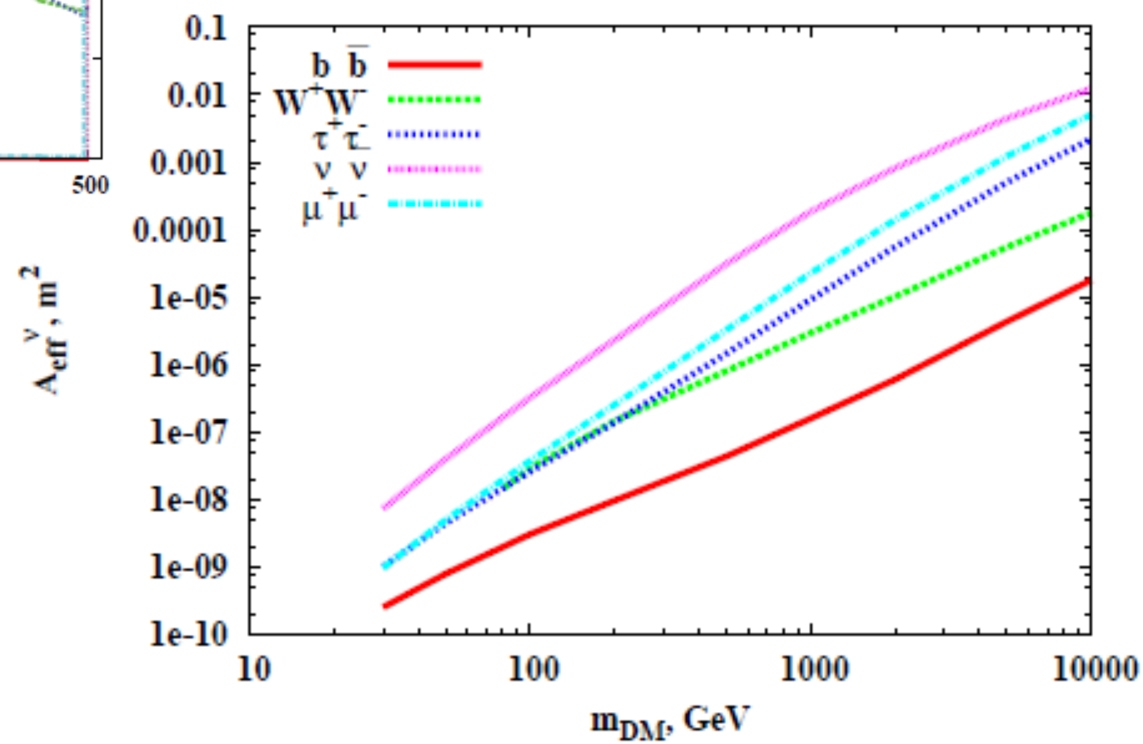




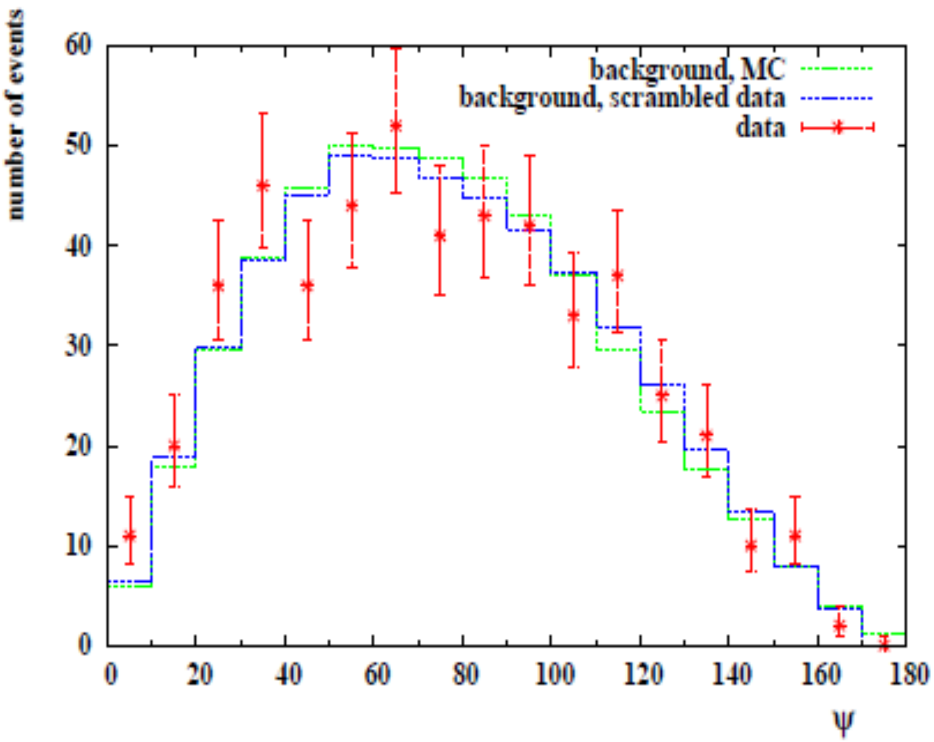
Neutrino spectra in WIMP annihilations and NT200 ν-Effective Areas

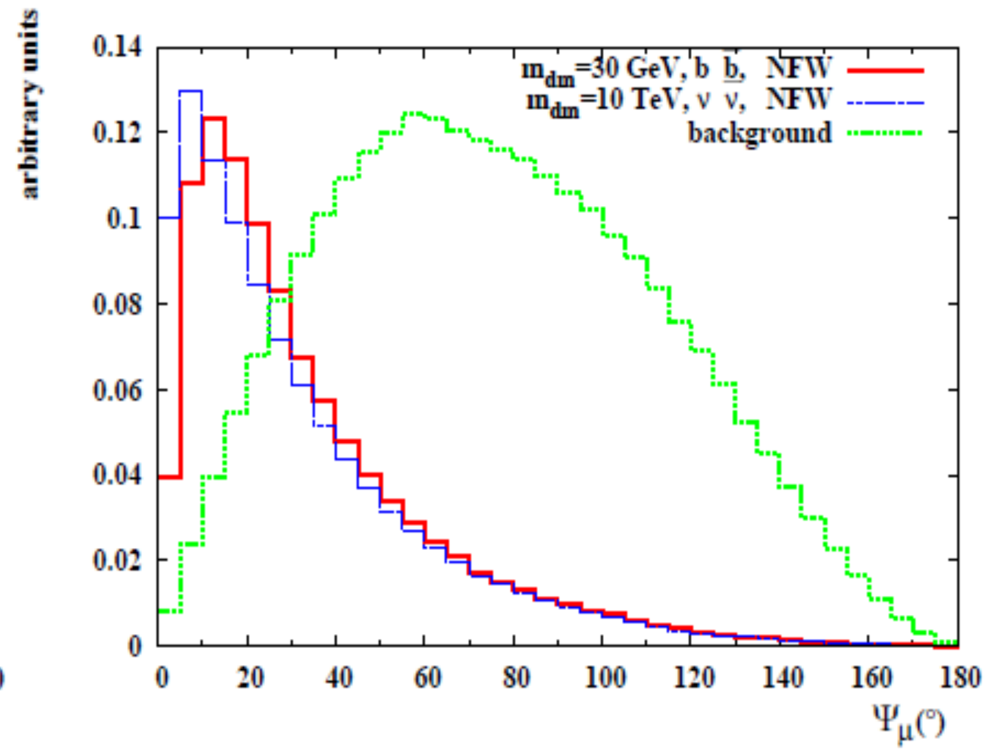


ν-generation in the GC and 3-flavors ν-propagation through the Earth



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





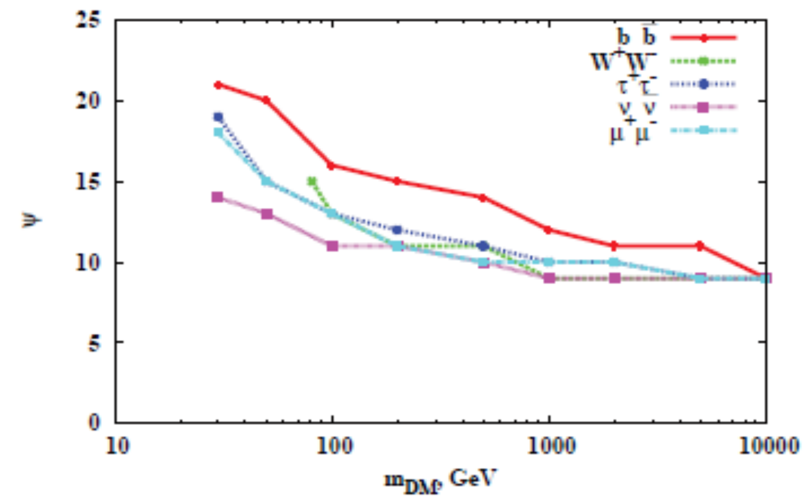
Cone	20°	5°	2.5°
N_obs	31	2	2
N_bkg	25.1	1.63	0.42

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:

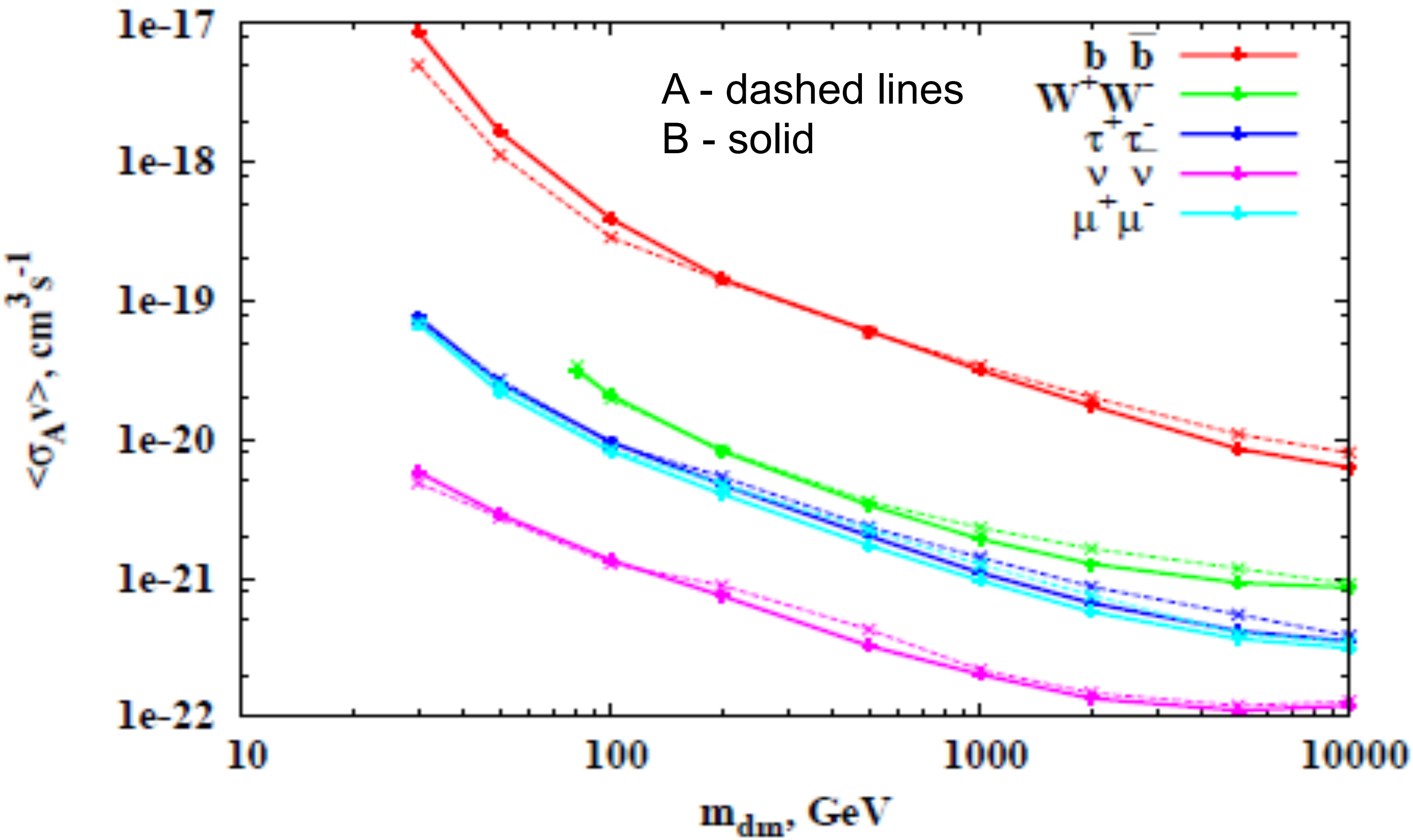
Angular distribution $f(\psi) = \frac{1}{N_S+N_B}\left(N_S f_S(\psi) + N_B f_B(\psi)\right)$

Likelihood function

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

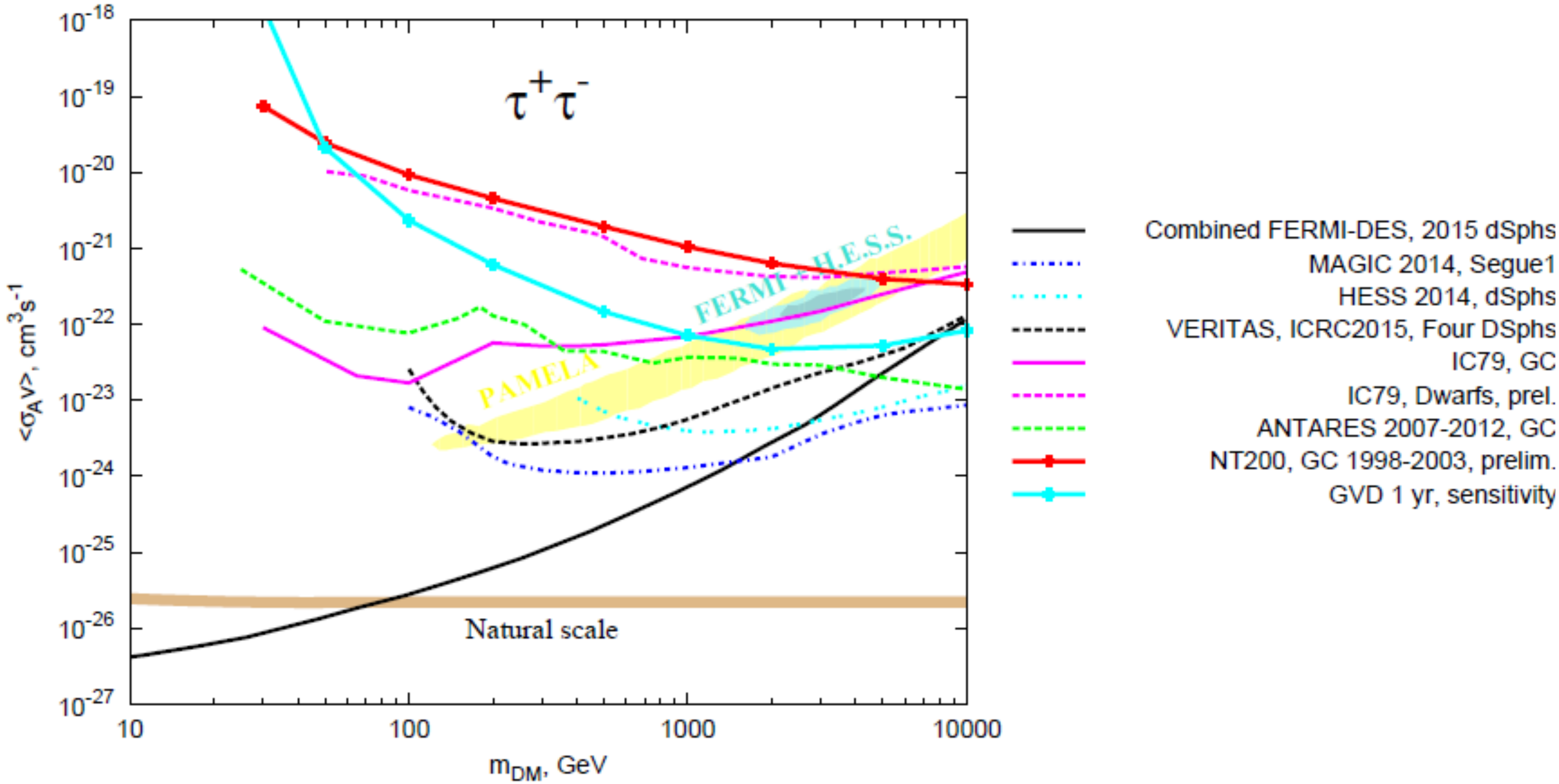
Systematic uncertainties: profile likelihood, $\lambda(N_S) = -2\ln\frac{\mathcal{L}(N_S,\hat{\hat{\theta}})}{\mathcal{L}(\hat{N}_S,\hat{\theta})}$

Baikal NT200 results: the upper limits at 90% CL



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

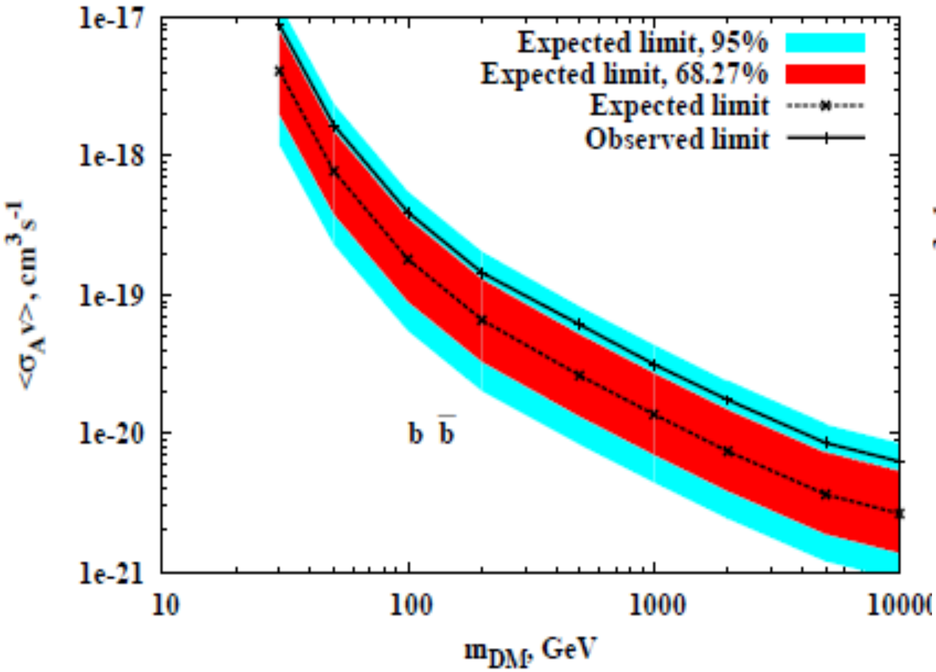
Baikal NT200 limits vs limits of NT and gammay-rays surveys

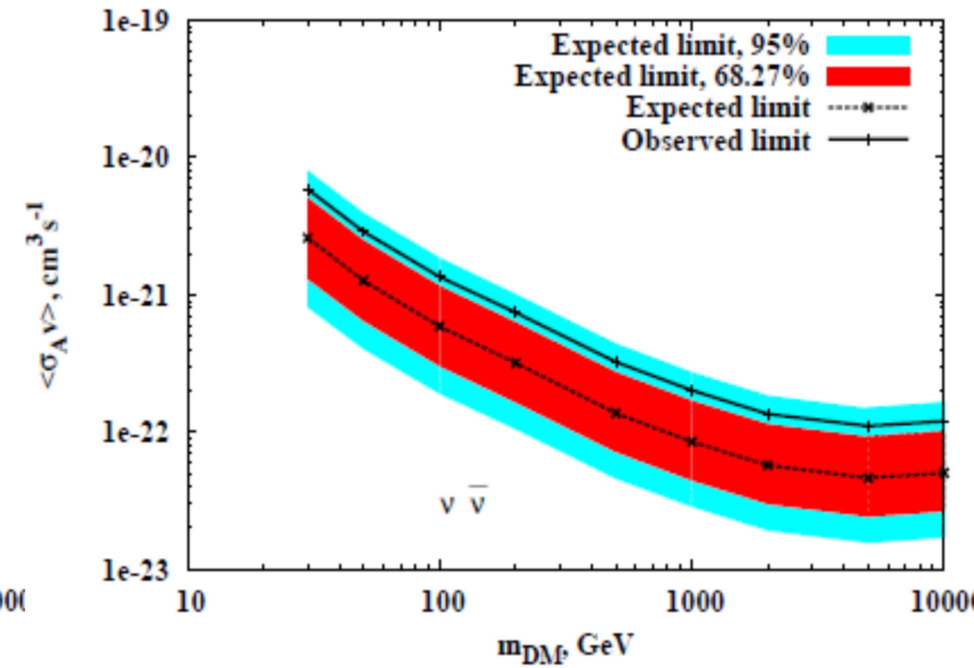


Baikal NT200: sensitivities to GC dm-signal from pseudo-experiments

Soft spectra: bb

Hard spectra: nu-nu

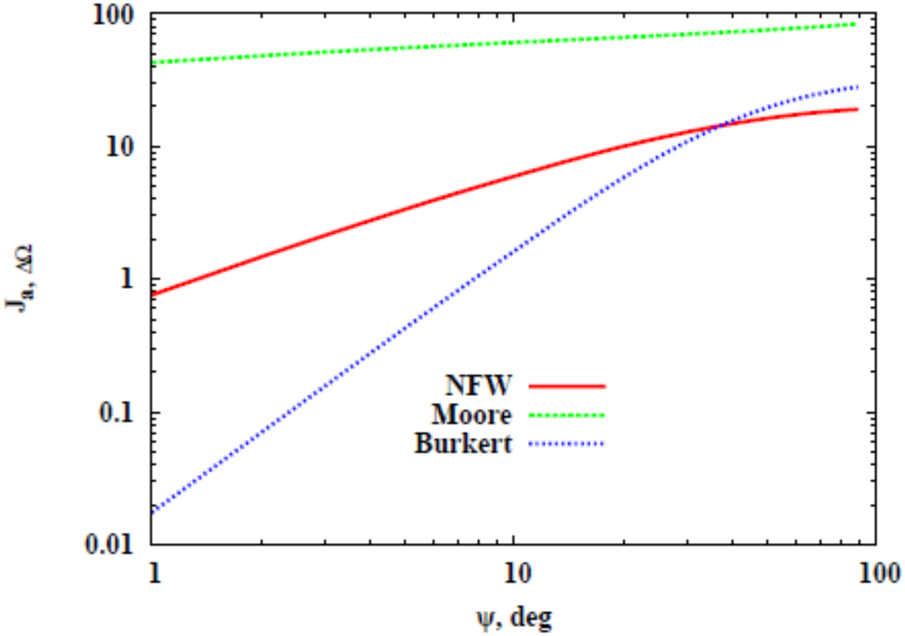




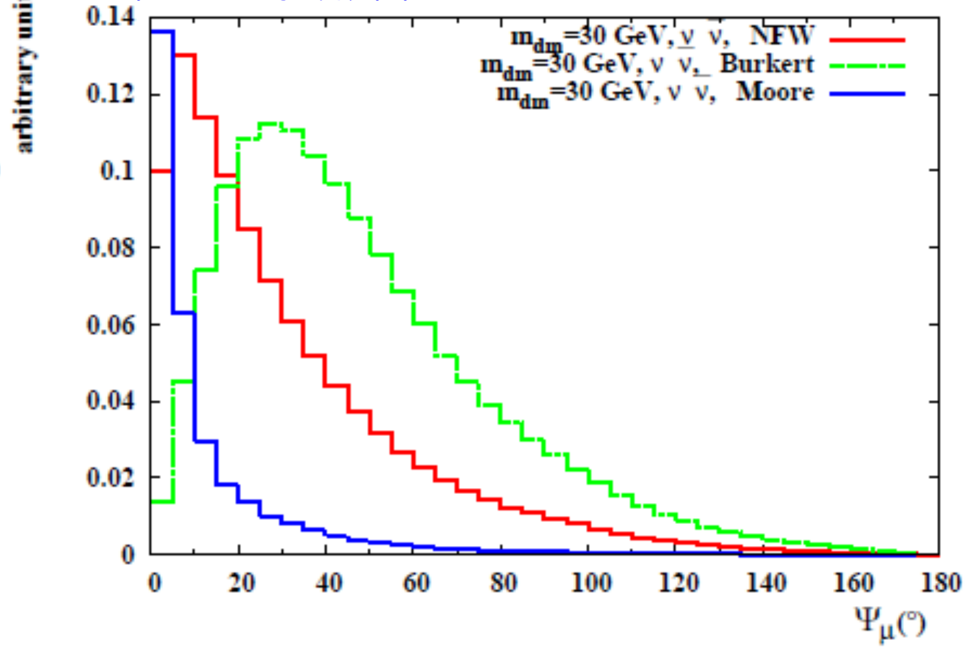
N_obs=113 @ psi<40deg

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

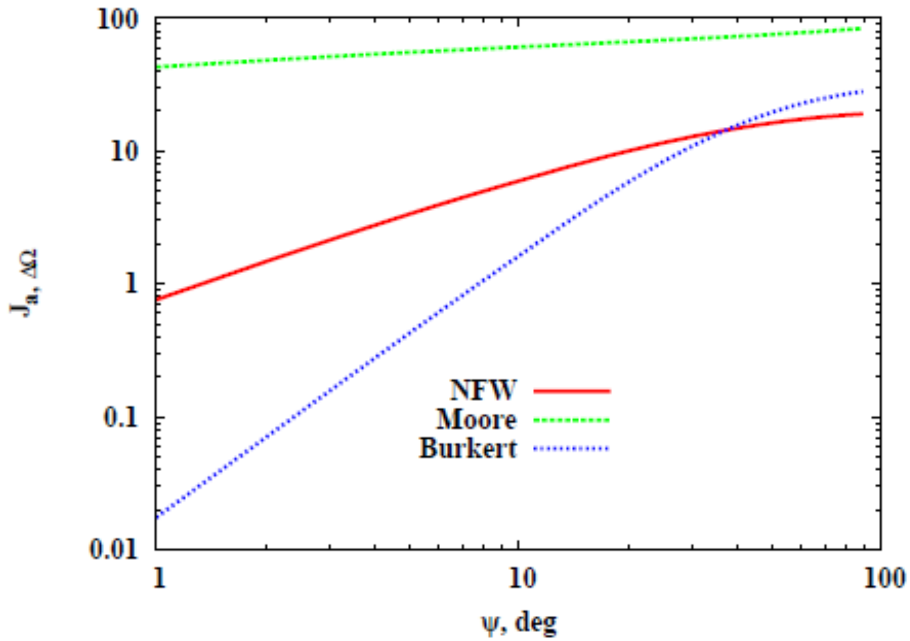
Astrophysical uncertainties in DM profiles



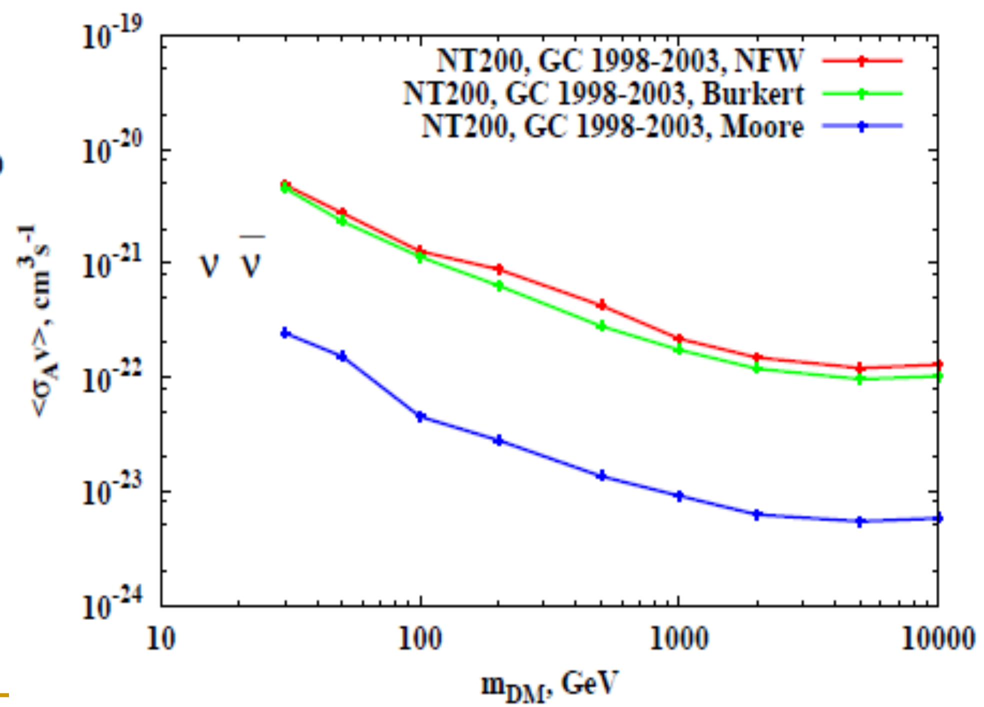
Angular mu-GC distr of a signal in ν–ν channel



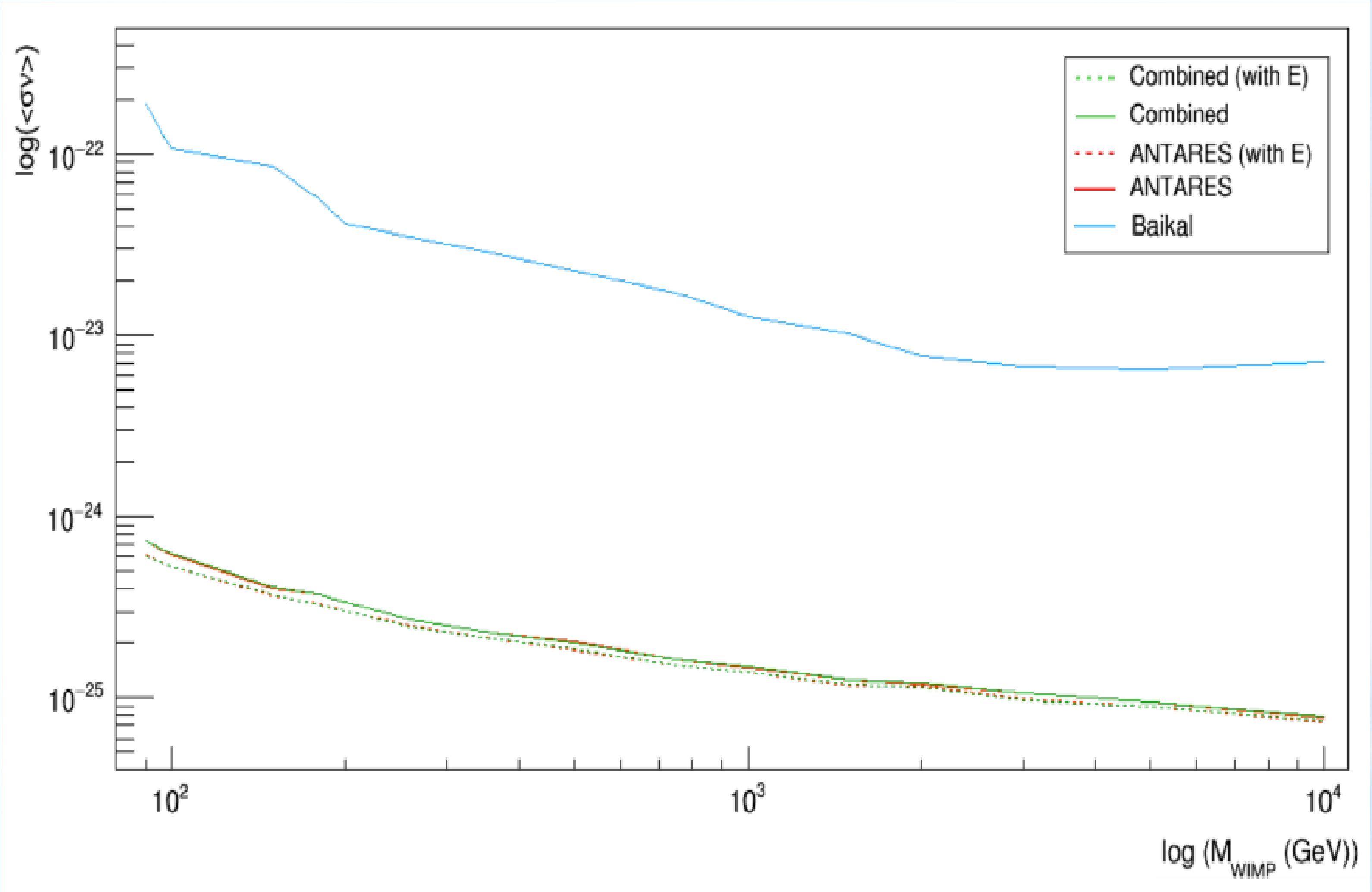
Astrophysical uncertainties in the Baikal NT200 upper limits on $\langle \sigma_{ann} v \rangle$



Direct ν–ν annihilation channel



The Galaxy Centre: preliminary combined analysis NT200/ANTARES (2101 l.days)



These sensitivities were calculated by Faye Havelock for the combined analysis with BAIKAL.

// **14 Classic DG** {"Carina","Fornax","Leo-I",
"Leo-II","Sculptor","Sextans","Bootes-I",
"Coma Berenices","Hercules ","Leo-IV","Leo-V",
"Leo-T","Segue-1","Segue-2"}

WIMPs from dwarfs

// **8 DES new** discovered DG in 2015
{ "Reticulum2","Eridanus2","Horologium1","Pictor",
"Phoenix2","Indus1","Eridanus3","Tucana2"}

DES: discovery of nine dwarfs

S.Koposov+ 2015

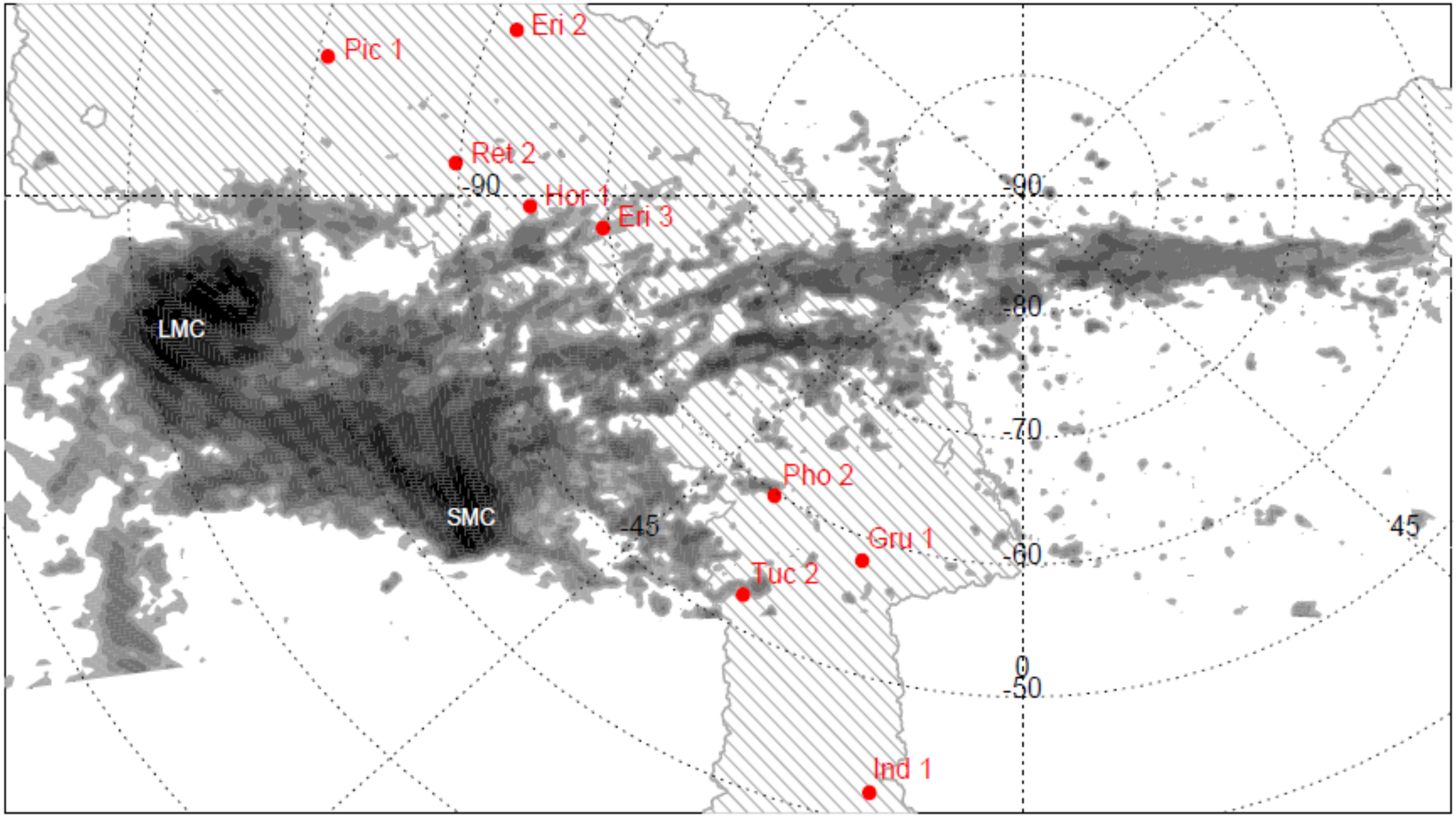


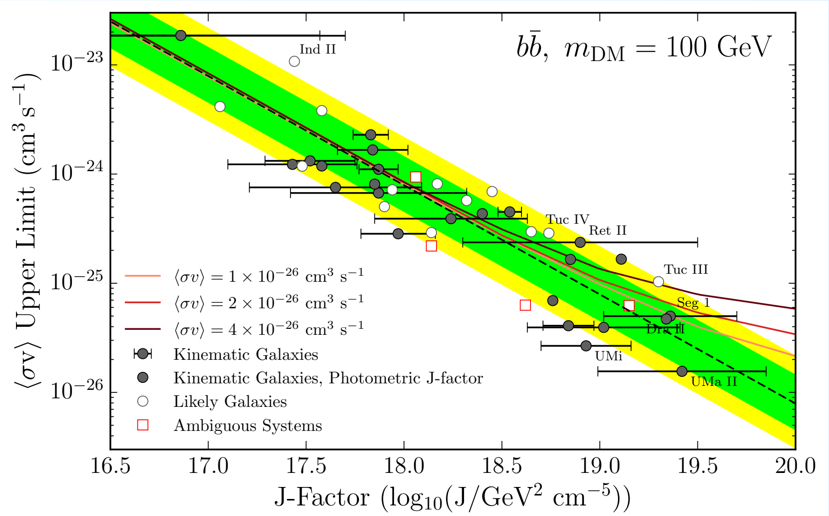
Figure 22. Positions of the DES satellites with respect to the Magellanic gaseous Stream near the Southern Galactic Pole. The Stream's HI column density from Putman et al. (2003) is shown as filled contours, with darker shades corresponding to higher densities. Hatched area contour shows the current DES footprint. The DES satellites appear to be avoiding regions with high HI column density.

SEARCHING FOR DARK MATTER ANNIHILATION IN RECENTLY DISCOVERED MILKY WAY SATELLITES WITH FERMI-LAT

arXiv:1611.03184

Table 1
Confirmed and Candidate Dwarf Galaxies

(1) Name	(2) l, b (deg, deg)	(3) Distance (kpc)	(4) $r_{1/2}$ (pc)	(5) M_V (mag)	(6) $\log_{10}(J_{\rm meas})$ $\log_{10}(\mathrm{GeV^2\,cm^{-5}})$	(7) $\log_{10}(J_{\rm pred})$ $\log_{10}(\mathrm{GeV^2\,cm^{-5}})$
			Kinematically Confirmed Galaxies			
Boötes I*	358.08, 69.62	66	189	-6.3	18.2 ± 0.4	18.5
Boötes II	353.69, 68.87	42	46	-2.7	...	18.9
Boötes III	35.41, 75.35	47	...	-5.8	...	18.8
Canes Venatici I	74.31, 79.82	218	441	-8.6	17.4 ± 0.3	17.4
Canes Venatici II*	113.58, 82.70	160	52	-4.9	17.6 ± 0.4	17.7
Carina*	260.11, -22.22	105	205	-9.1	17.9 ± 0.1	18.1
Coma Berenices*	241.89, 83.61	44	60	-4.1	19.0 ± 0.4	18.8
Draco*	86.37, 34.72	76	184	-8.8	18.8 ± 0.1	18.3
Draco II	98.29, 42.88	24	16	-2.9	...	19.3
Fornax*	237.10, -65.65	147	594	-13.4	17.8 ± 0.1	17.8
Hercules*	28.73, 36.87	132	187	-6.6	16.9 ± 0.7	17.9
Horologium I	271.38, -54.74	87	61	-3.5	...	18.2
Hydra II	295.62, 30.46	134	66	-4.8	...	17.8
Leo I	225.99, 49.11	254	223	-12.0	17.8 ± 0.2	17.3
Leo II*	220.17, 67.23	233	164	-9.8	18.0 ± 0.2	17.4
Leo IV*	265.44, 56.51	154	147	-5.8	16.3 ± 1.4	17.7
Leo V	261.86, 58.54	178	95	-5.2	16.4 ± 0.9	17.6
Pisces II	79.21, -47.11	182	45	-5.0	...	17.6
Reticulum II	266.30, -49.74	32	35	-3.6	18.9 ± 0.6	19.1
Sculptor*	287.53, -83.16	86	233	-11.1	18.5 ± 0.1	18.2
Segue 1*	220.48, 50.43	23	21	-1.5	19.4 ± 0.3	19.4
Sextans*	243.50, 42.27	86	561	-9.3	17.5 ± 0.2	18.2
Triangulum II	140.90, -23.82	30	30	-1.8	...	19.1
Tucana II	328.04, -52.35	58	120	-3.9	...	18.6
Ursa Major I	159.43, 54.41	97	143	-5.5	17.9 ± 0.5	18.1
Ursa Major II*	152.46, 37.44	32	91	-4.2	19.4 ± 0.4	19.1
Ursa Minor*	104.97, 44.80	76	120	-8.8	18.9 ± 0.2	18.3
Willman 1*	158.58, 56.78	38	19	-2.7	...	18.9
			Likely Galaxies			
Columba I	231.62, -28.88	182	101	-4.5	...	17.6
Eridanus II	249.78, -51.65	331	156	-7.4	...	17.1
Grus I	338.68, -58.25	120	60	-3.4	...	17.9
Grus II	351.14, -51.94	53	93	-3.9	...	18.7
Horologium II	262.48, -54.14	78	33	-2.6	...	18.3
Indus II	354.00, -37.40	214	181	-4.3	...	17.4
Pegasus III	69.85, -41.81	205	57	-4.1	...	17.5
Phoenix II	323.69, -59.74	96	33	-3.7	...	18.1
Pictor I	257.29, -40.64	126	44	-3.7	...	17.9
Reticulum III	273.88, -45.65	92	64	-3.3	...	18.2
Sagittarius II	18.94, -22.90	67	34	-5.2	...	18.4
Tucana III	315.38, -56.18	25	44	-2.4	...	19.3
Tucana IV	313.29, -55.29	48	128	-3.5	...	18.7
			Ambiguous Systems			
Cetus II	156.47, -78.53	30	17	0.0	...	19.1
Eridanus III	274.95, -59.60	96	12	-2.4	...	18.1
Kim 2	347.16, -42.07	105	12	-1.5	...	18.1
Tucana V	316.31, -51.89	55	16	-1.6	...	18.6



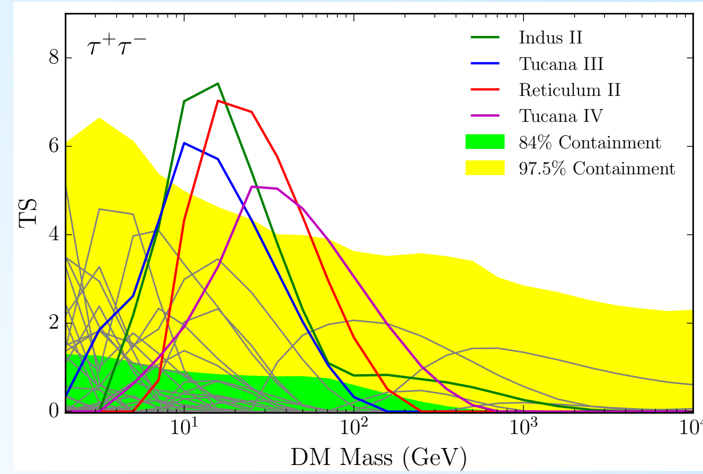
$$\frac{d\phi_\nu}{dE_\nu d\Omega} = J_a(\psi)\,\frac{\langle\sigma_a v\rangle}{8\pi m_{DM}^2}\,\frac{dN_\nu}{dE_\nu}.$$

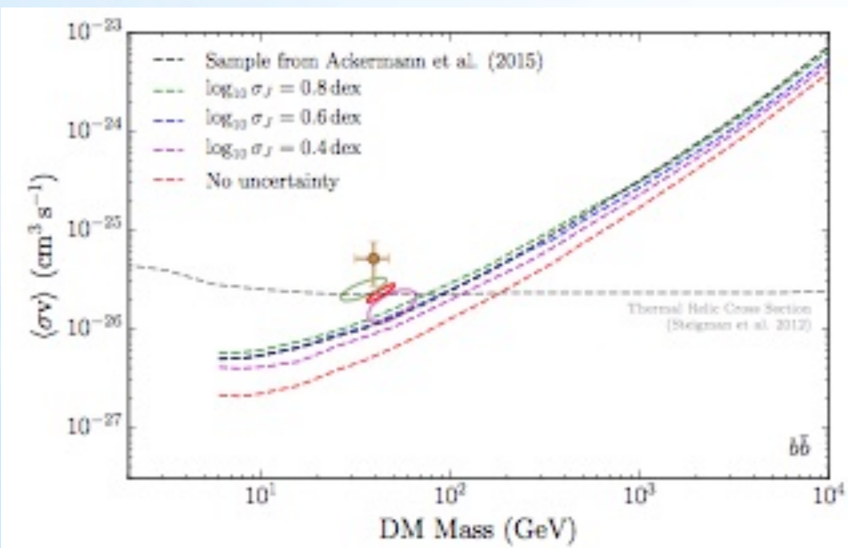
SEARCHING FOR DARK MATTER ANNIHILATION IN RECENTLY DISCOVERED MILKY WAY SATELLITES WITH FERMI-LAT

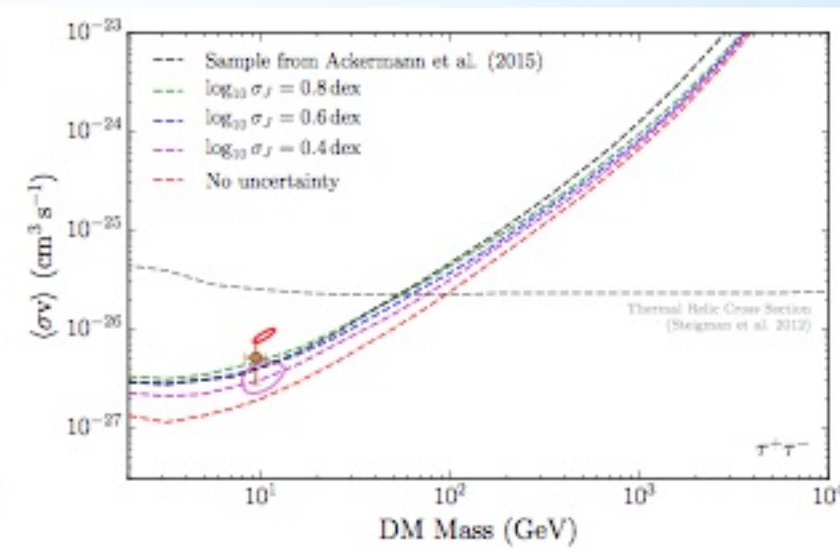
Table 2
Targets with the Largest Excesses above Background

(1) Name	(2) Channel	(3) Mass (GeV)	(4) TS	(5) $p_{\rm local}$	(6) $p_{\rm target}$	(7) $p_{\rm sample}$
Indus II	$\tau^+\tau^-$	15.8	7.4	0.01 (2.3σ)	0.04 (1.7σ)	0.84 (-1.0σ)
Reticulum II	$\tau^+\tau^-$	15.8	7.0	0.01 (2.3σ)	0.05 (1.7σ)	0.88 (-1.2σ)
Tucana III	$\tau^+\tau^-$	10.0	6.1	0.02 (2.1σ)	0.06 (1.5σ)	0.94 (-1.6σ)
Tucana IV	$\tau^+\tau^-$	25.0	5.1	0.02 (2.1σ)	0.09 (1.3σ)	0.98 (-2.1σ)

Note. — (1) Target name (2) best-fit DM annihilation channel (3) best-fit DM particle mass (4) highest TS value (5) local p-value calibrated from random blank regions (6) target p-value applying a trials factor from testing multiple DM annihilation spectra (7) sample p-value applying an additional trials factor from analyzing 45 targets. The Gaussian significance associated with each p-value is given in parentheses. More details can be found in Section 3.

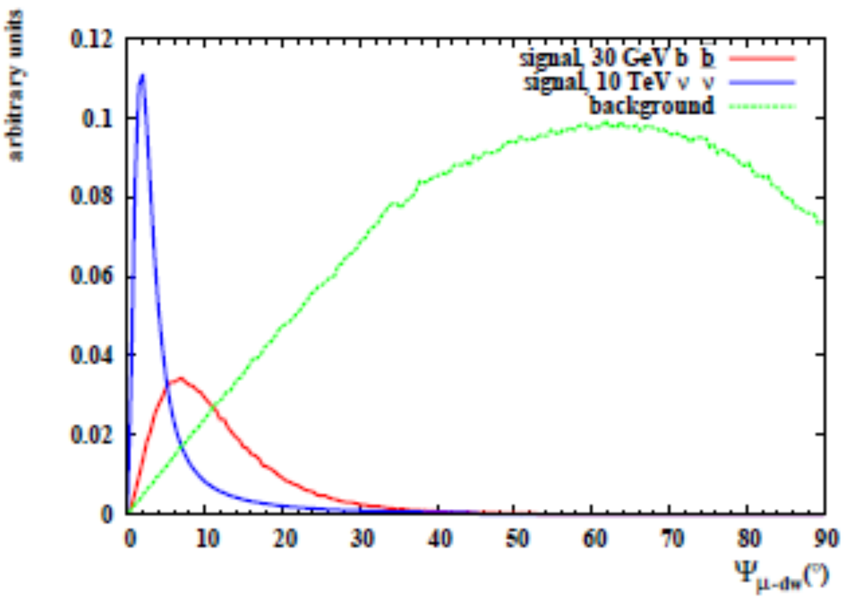


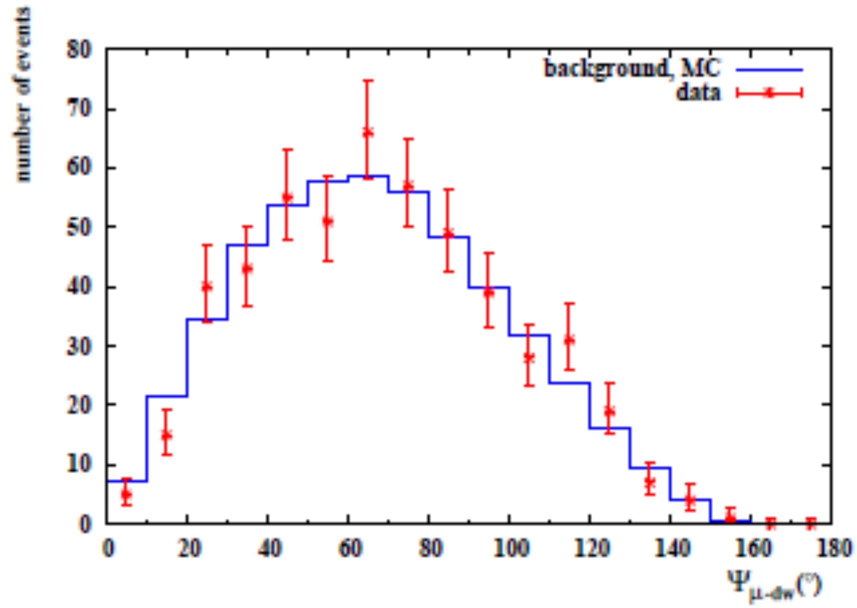




arXiv:1611.03184

Reticulum 2 : NT200 background and signal angular distributions





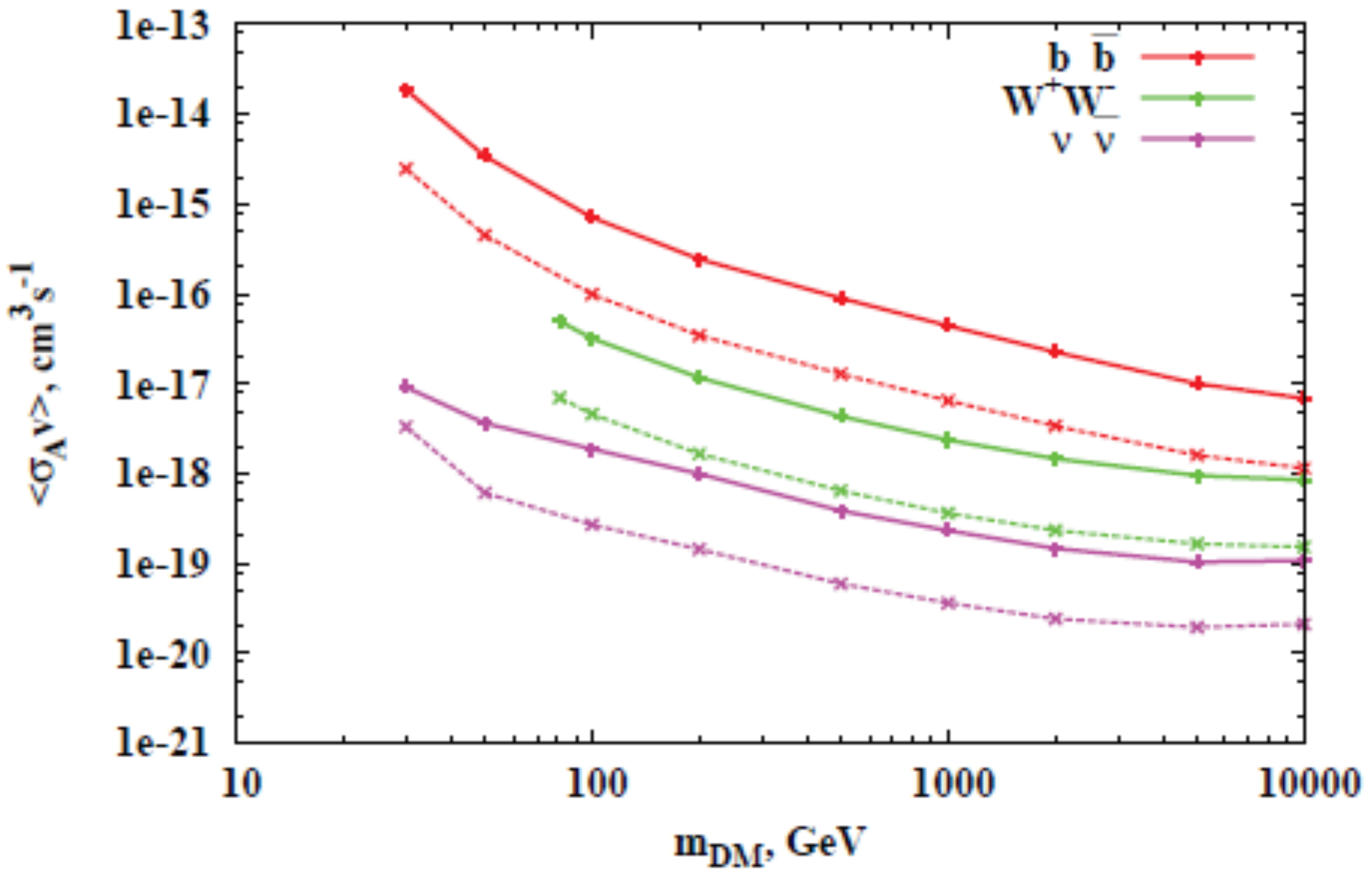
$$\mathcal{L}(N_S) = \frac{(N_B+N_S)^n}{n!} e^{-(N_B+N_S)} \mathcal{J}(J_2^{dw} | J_2^{dw,obs}, \sigma^{dw}) \prod_{i=1}^{n} f(\psi_i, N_B, N_S)$$

with $\mathcal{J}(J_2^{dw} | J_2^{dw,obs}, \sigma^{dw}) = \frac{1}{\ln(10) J_2^{dw,obs} \sqrt{2\pi}\sigma_{dw}} \times e^{-\left(\log_{10}(J_2^{dw}) - \log_{10}(J_2^{dw,obs})\right)/2\sigma_{dw}^2}$

σ_{dw} - uncertainty in J-factor

Baikal NT200 UpLim 90% with syst: Segue1 and Reticulum 2

(solid) (dashed)

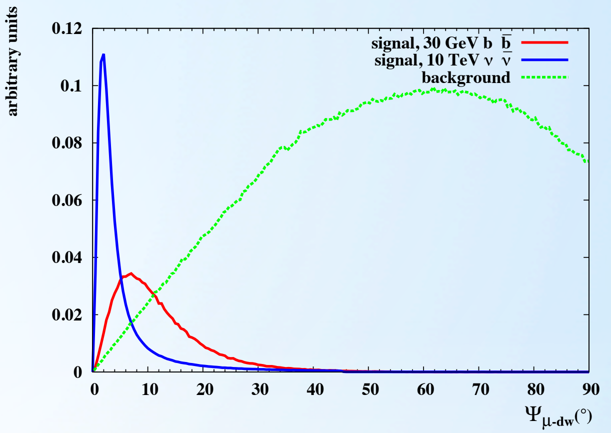


Name	δ	α	$\log_{10}(J_2^{dw,obs}/GeV^2cm^{-5})$	σ_{dw}
Segue 1	16.08	151.77	19.36	0.29
Reticulum 2	-54.05	53.92	19.8	0.4

Baikal sensitivity to DM annihilation: TS

dSphs	nu-nu 30 GeV	nu-nu 10 TeV	bb 30 GeV	bb 10 TeV
Sculptor	0.43342	0.249807	0.108297	0.404067
Coma Berenices	0.627259	0.204246	0.979732	0.300647
Seque-1	2.06363	1.18917	1.82143	1.38939
Reticulum-2	0.771784	1.39208	0.201986	1.30422
Tucana-2	4.452	2.79711	3.34184	3.24784

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

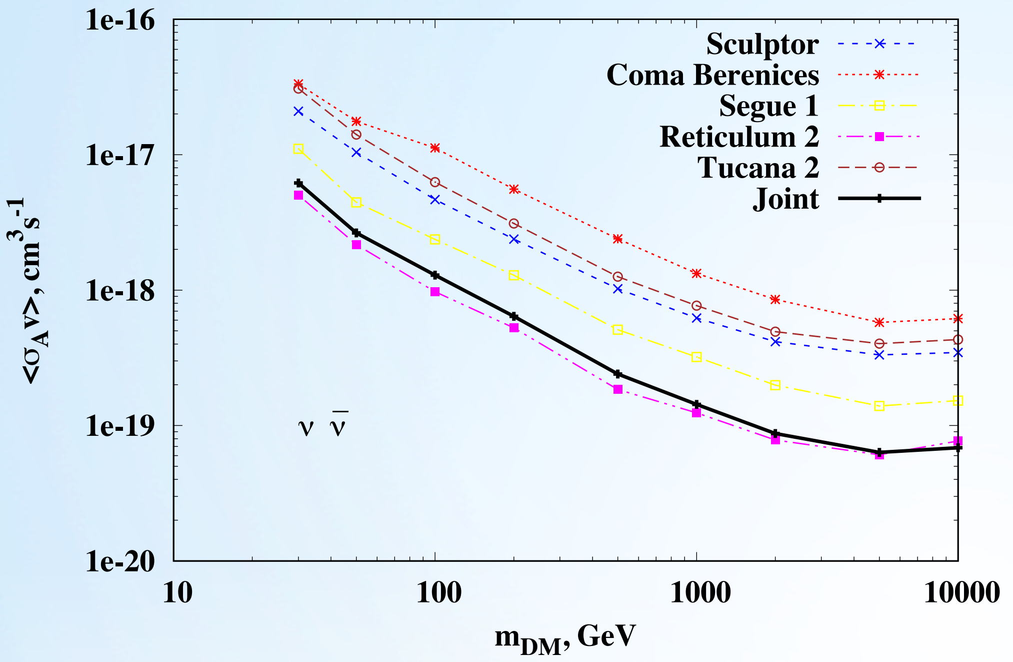


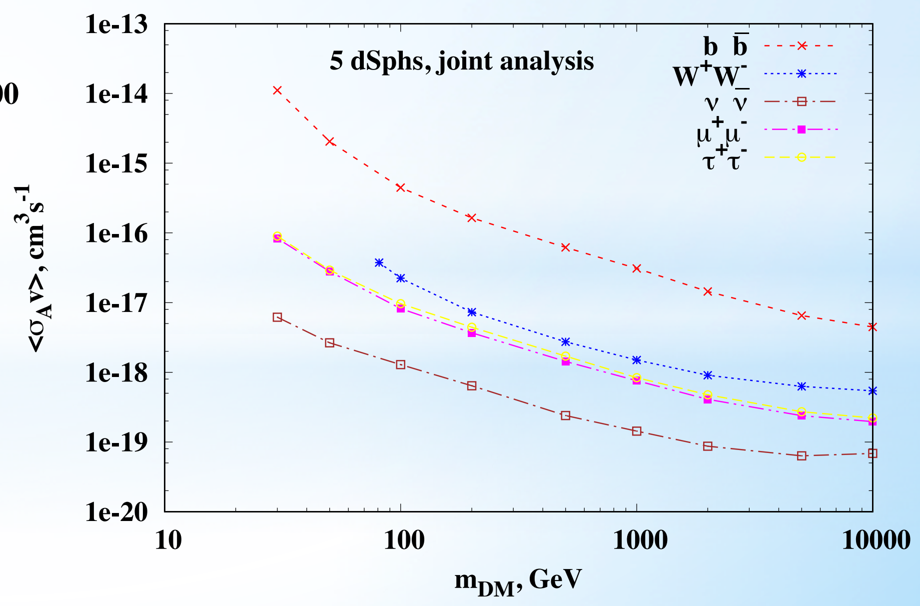
$$f(\psi, N_S, N_B) = \frac{1}{N_S+N_B}\left(N_S f_S(\psi) + N_B f_B(\psi)\right),$$

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

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

Baikal upper limits towards 5 dSphs and combined analysis





Direction towards the Large Magellanic Cloud

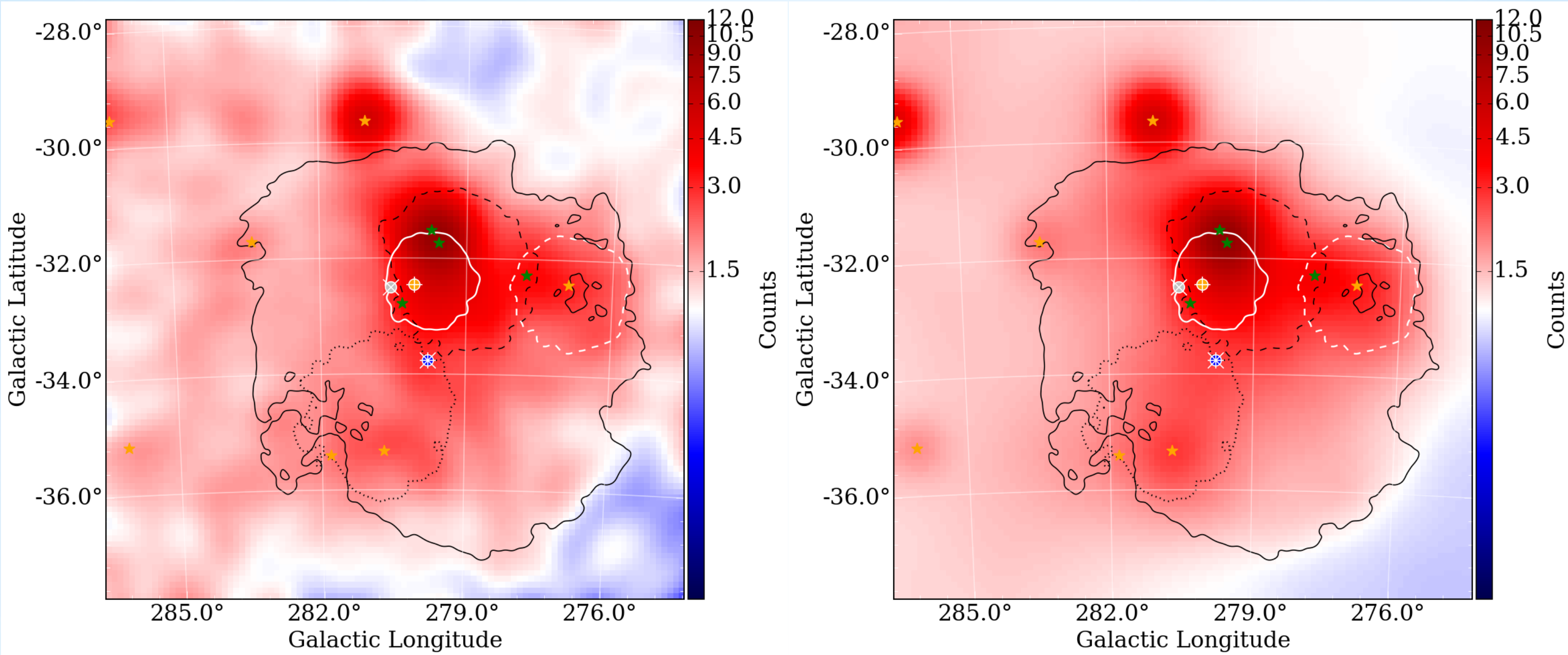


FIG. 6: Left: Counts map of the LMC region, in the energy range from 792 MeV to 12.6 GeV. Right: Model map of the same region and for the same energy range created from the emission model (see text for details). Both maps are binned in $0\overset{\circ}{.}1 \times 0\overset{\circ}{.}1$ pixels and smoothed with a $\sigma = 0\overset{\circ}{.}3$ Gaussian kernel. The possible locations of the LMC center (Tab. I) are shown: `stellar` (white circle with $\times$ cross), `outer` (orange circle with $+$ cross), and `HI` (blue circle with $\ast$ cross). Smoothed contours of extended components of the background emission model are also shown: `E0` (solid black lines), `E1` (dashed black), `E2` (white dashed), `E3` (white solid), and `E4` (black dotted); the contours are drawn at 2% of the peak level for each of the extended sources. Green stars mark the point-like objects PS1 to PS4 in our background emission model, orange stars are point sources in the 2^{nd} *Fermi*-LAT point source catalog. Recall that the extended emission sources are correlated with the gas column density, resulting in the irregular shapes. The effective angular resolution can be inferred from the distribution of counts around the point-like sources. Galactic diffuse emission is visible outside of the LMC region.

FERMI-LAT arXiv:1502.01020

The LMC rotation curve data

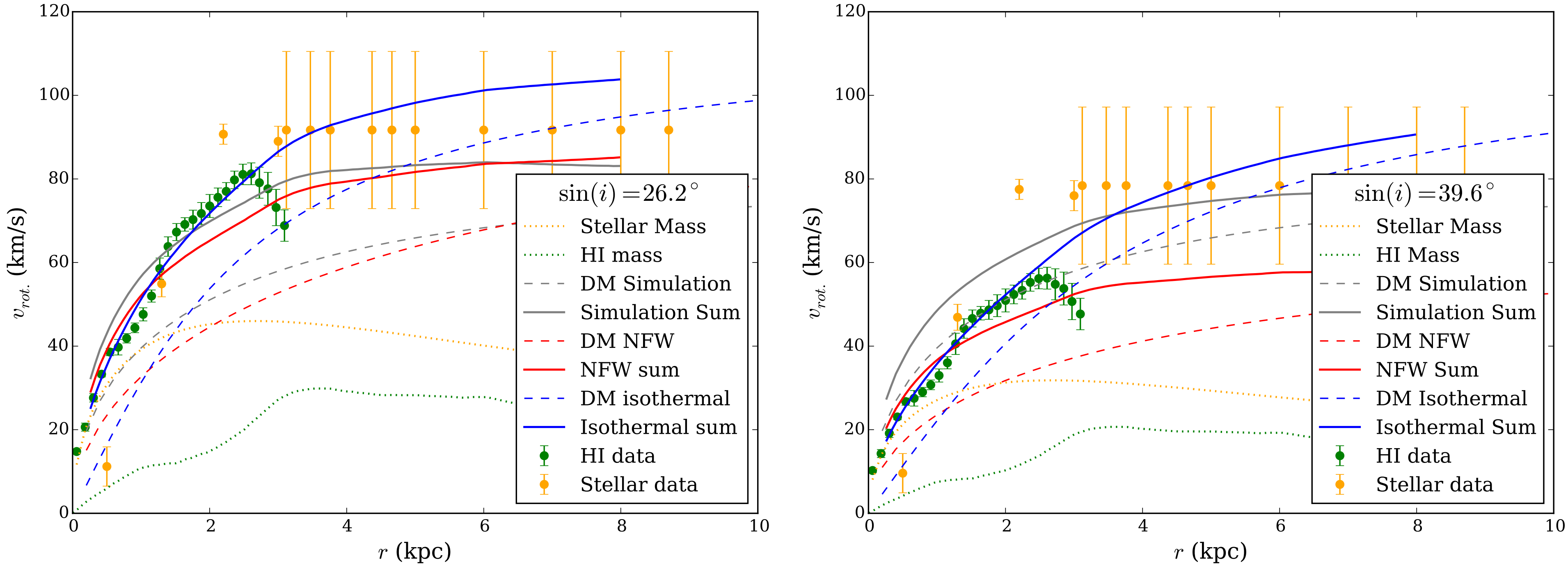
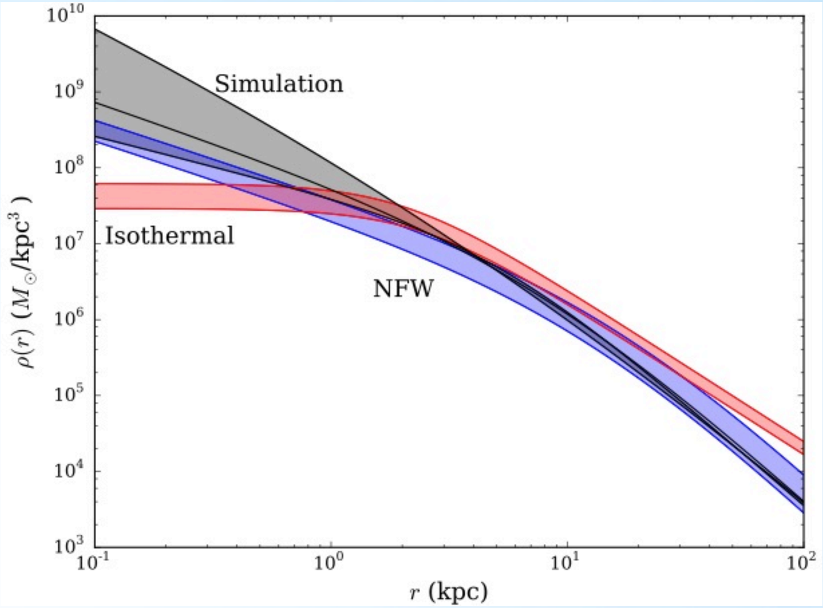


FIG. 1: LMC rotation curve data, assuming an inclination i that maximizes (left) and minimizes (right) the dark matter density. Stellar $v_{\rm rot}$ data are shown with orange points [80], and H I $v_{\rm rot}$ data [79] in green. The orange dotted line denotes the contribution to $v_{\rm rot}$ from the stellar mass, and the contribution from the H I+He gas is shown in dotted green [84]. The $v_{\rm rot}$ values predicted by NFW and isothermal profiles fit to data are shown by red and blue dashed lines, respectively. Solid lines show $v_{\rm rot}$ of the dark matter profiles plus contribution from the stars and gas, with the maximum values in the left plot and the minimum on the right. Grey lines show the mean profile of dark matter fit from simulations of LMC-like galaxies (dashed is dark matter-only, solid is dark matter plus stars and gas), and are not fit to the stellar and H I data points. The simulated dark matter rotation curve is independent of inclination angle, and the flat rotation curve beyond 3 kpc is based on the results of Ref. [80].

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.

$$J_{\Delta\Omega} = \int d(\cos\psi)d\phi J(\psi)$$

Baikal limits on DM annihilations in the LMC

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

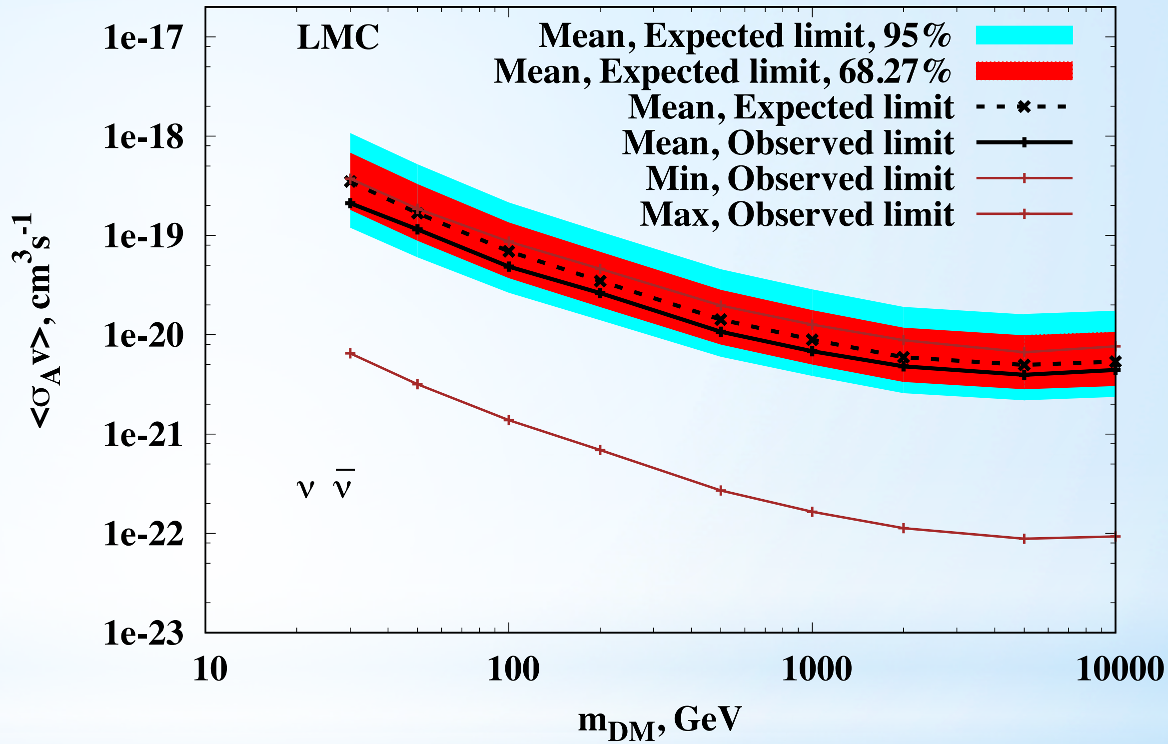
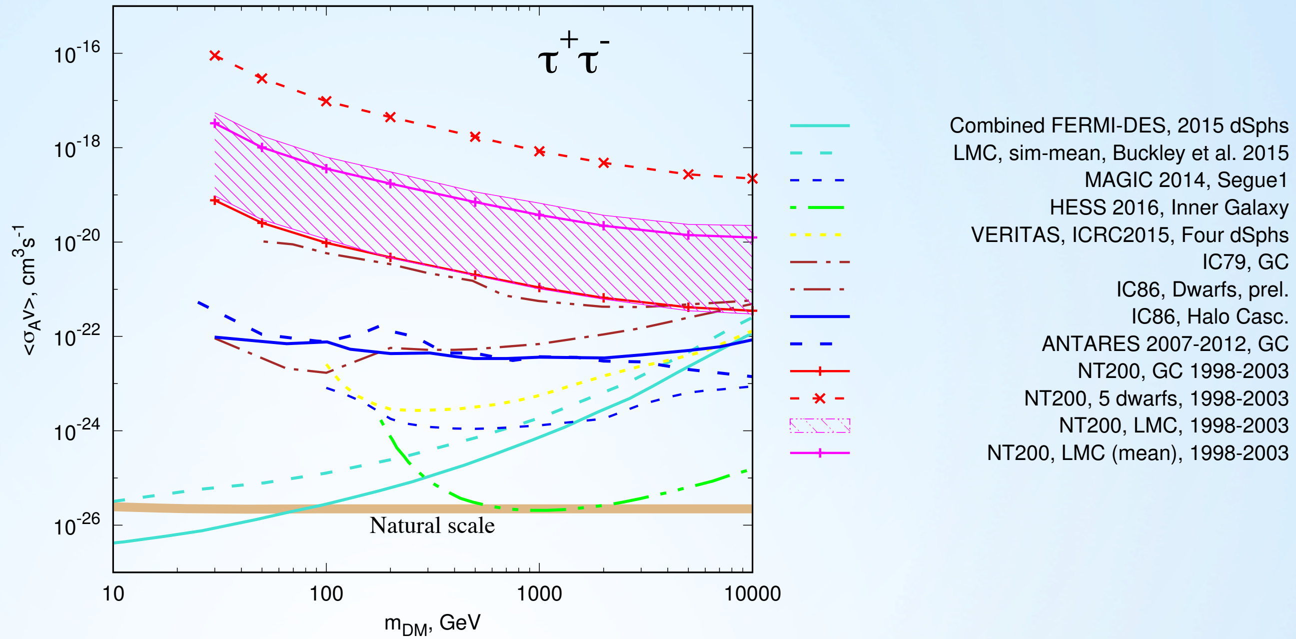
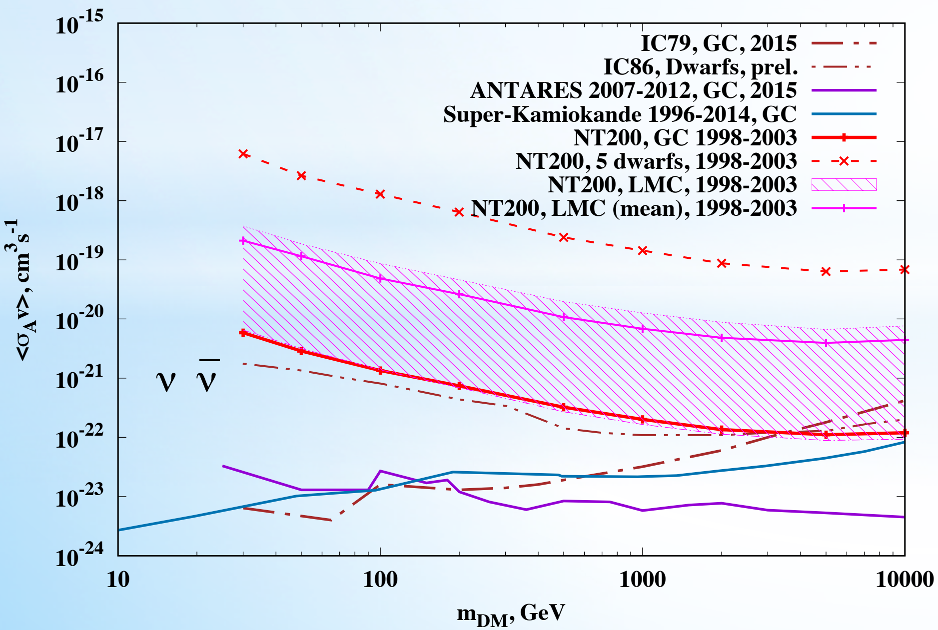
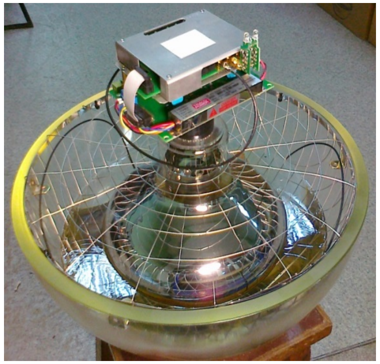


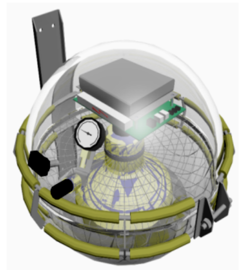
Fig. 8. 90% CL upper limits from the NT200 data assuming different dark matter density profiles for LMC (solid lines) and sensitivity (dashed line) on dark matter annihilation cross section assuming annihilation to $\nu\bar{\nu}$. Colored bands represent 68% (red) and 95% (blue) quantiles.

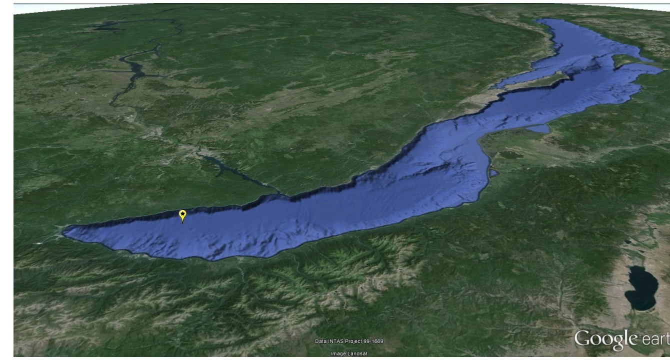
Towards the LMC: upper limits of γamma- and ν- telescopes





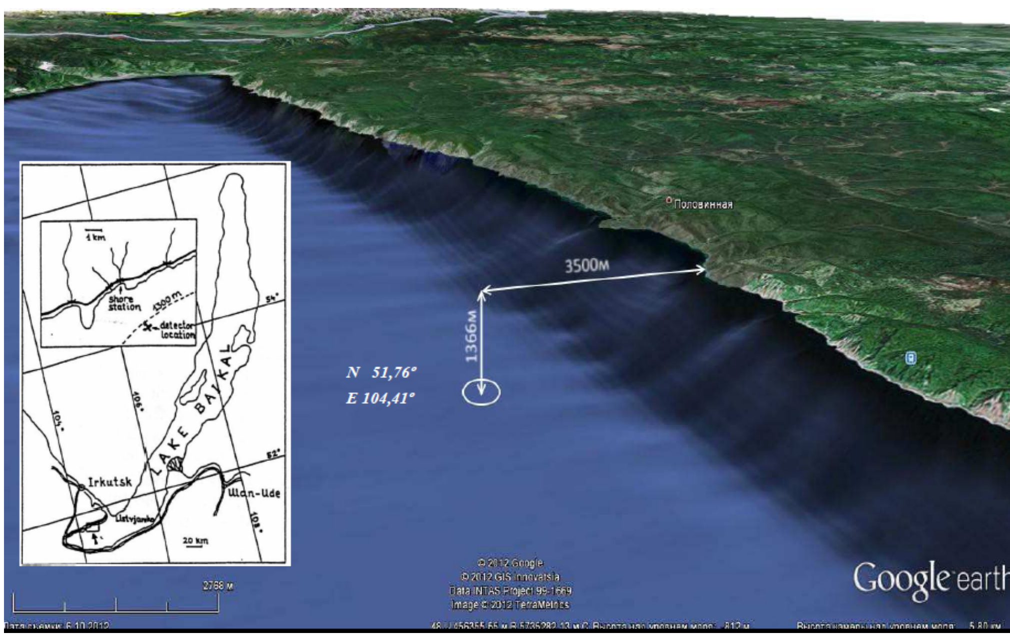


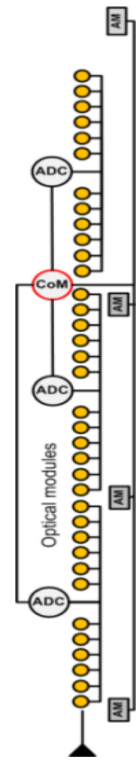




Optical module
PMT: R7081-100

Baikal-GVD

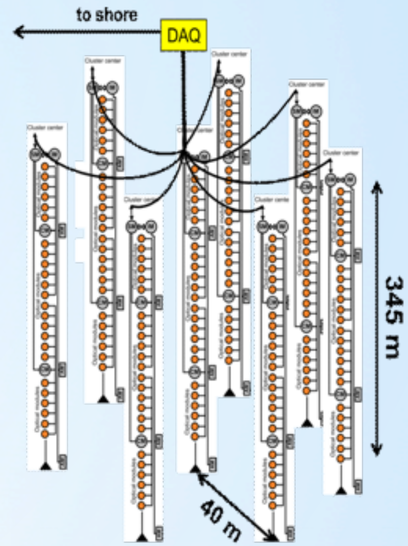




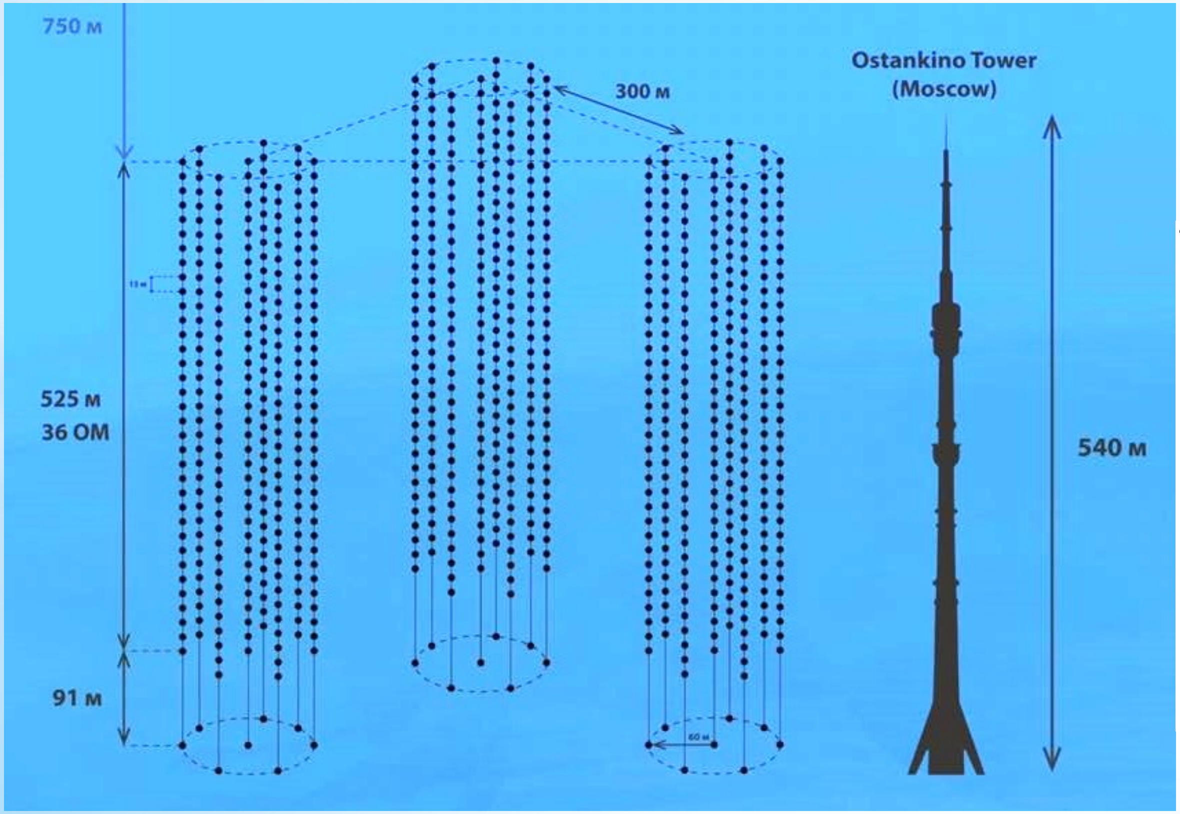
Data taken with three Baikal-GVD clusters

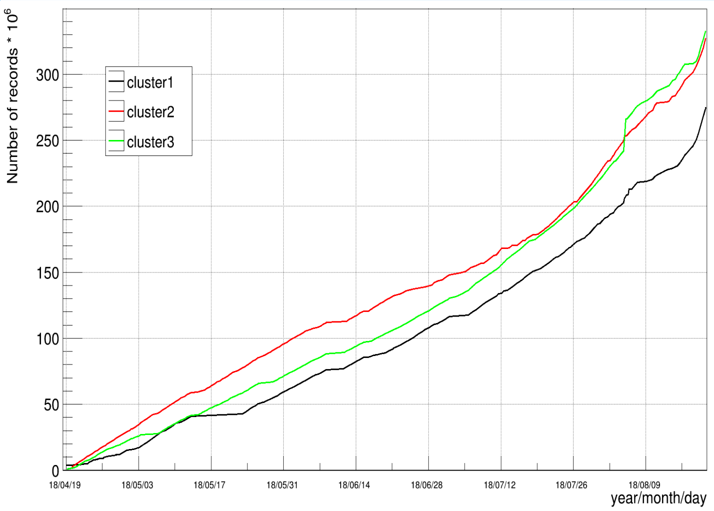
Configuration	2015	2016	2017	2018
The number of OMs	192	288	576	864
Geometric sizes, m	∅80×345	∅120×525	2×∅120×525	3×∅120×525
Eff. Vol	0.03 km³	0.05 km³	0.1 km³	0.15 km³

2015: «Dubna»
8 strings (192 OMs)



2018: 24 strings (864 OMs)



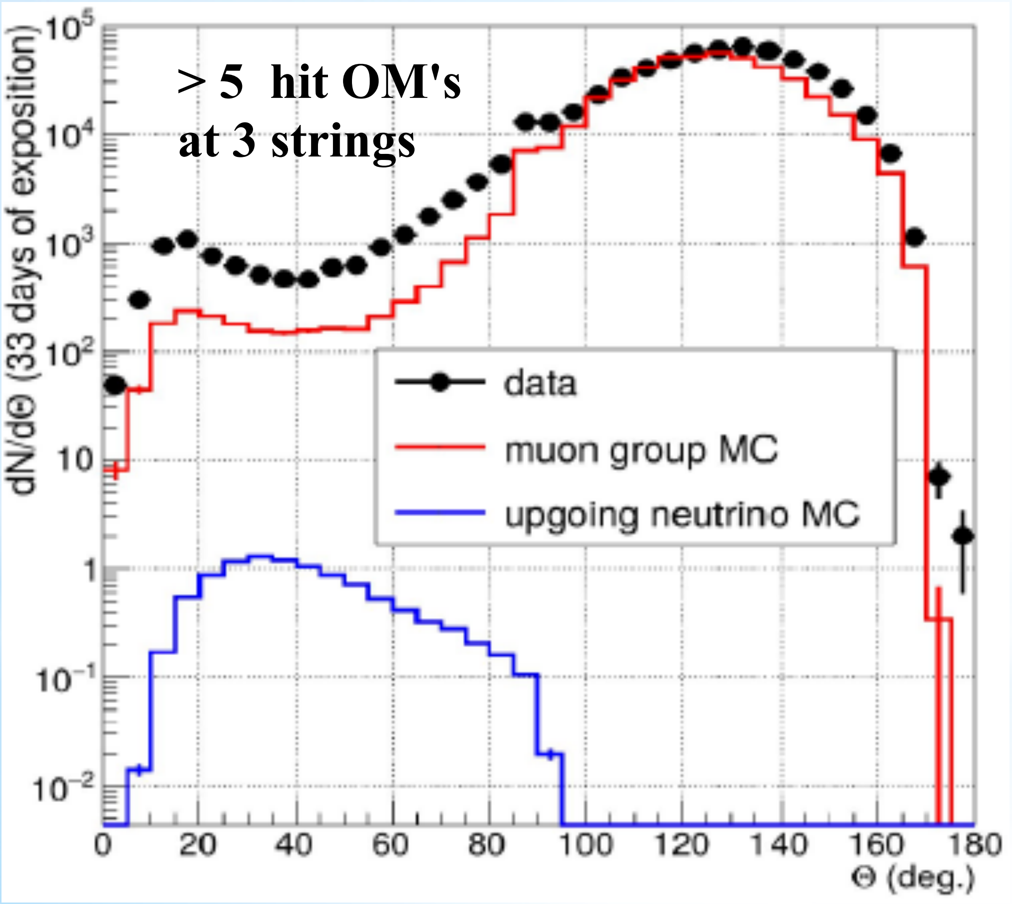


Search for muon neutrinos

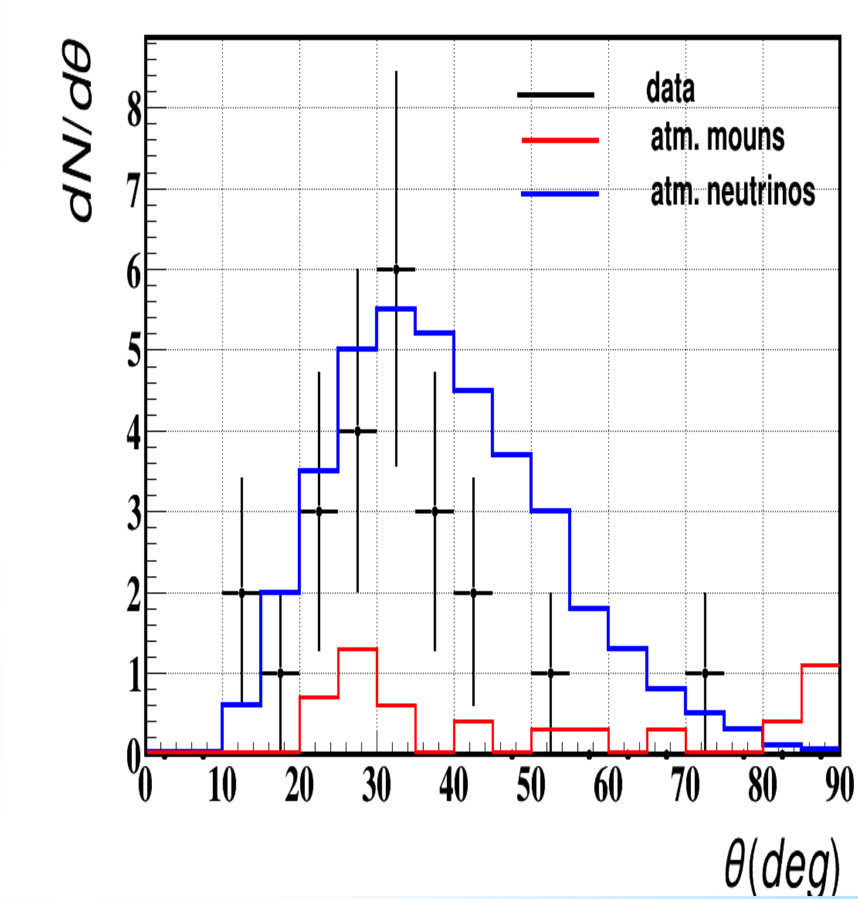
analysis of 2016 data sample – 182 l.days, 6.86×10^8 accumulated events

Muon neutrinos are detected as a muon tracks from bottom hemisphere

After reconstruction: 1 cluster, 33 live days

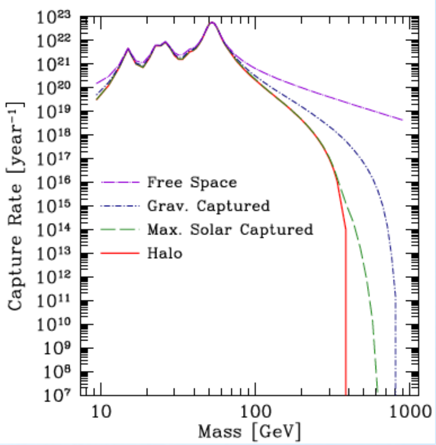


After BDT cut: 23 events were selected in the signal region



Zenith angle distributions of muons

Nearly vertical events: start searches for DM from the Earth core



Experimental data sample: 1st GVD-cluster 2016, 182 l.days, total number of events 6.86×10^8

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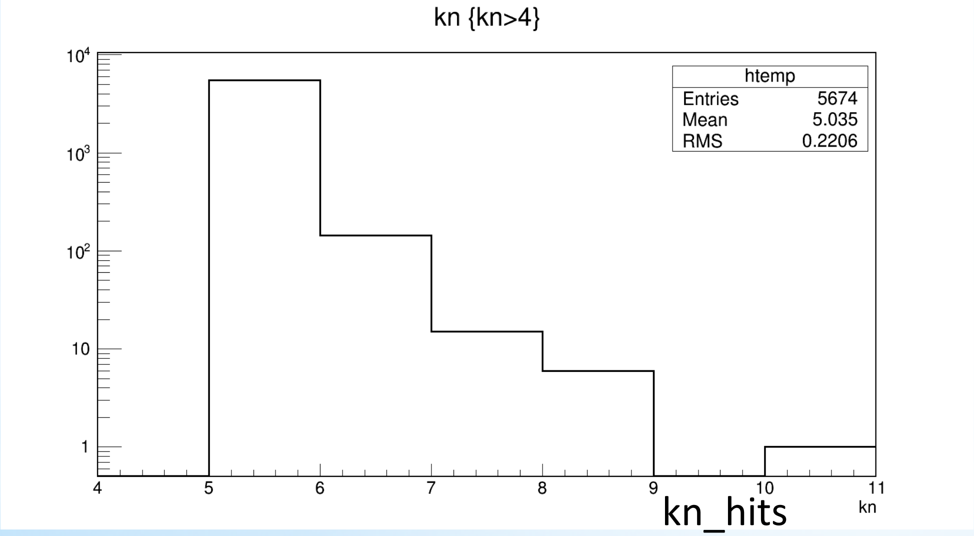
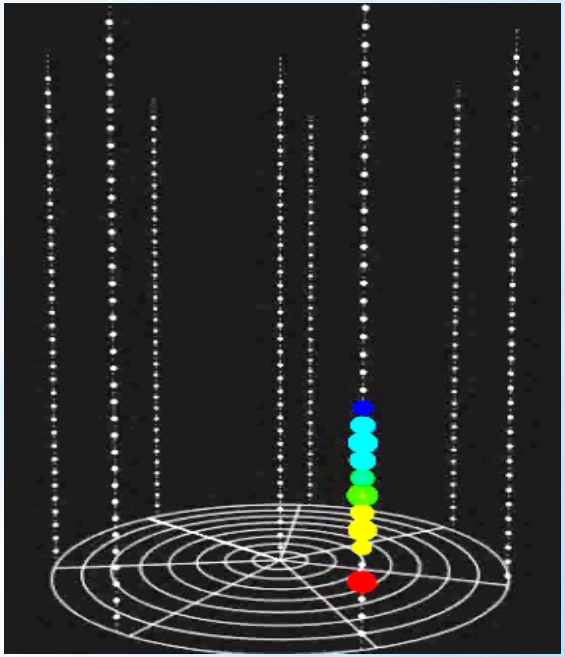
Selection criteria:
Causality cuts;
Presence at one string the chain of 5 hits or more with velocities of speed of signal between OM pairs within physical window 0.2—0.4 m/ns, while their amplitudes per OM should be higher 3p.e.
Also preferable is a single pulse per hit.

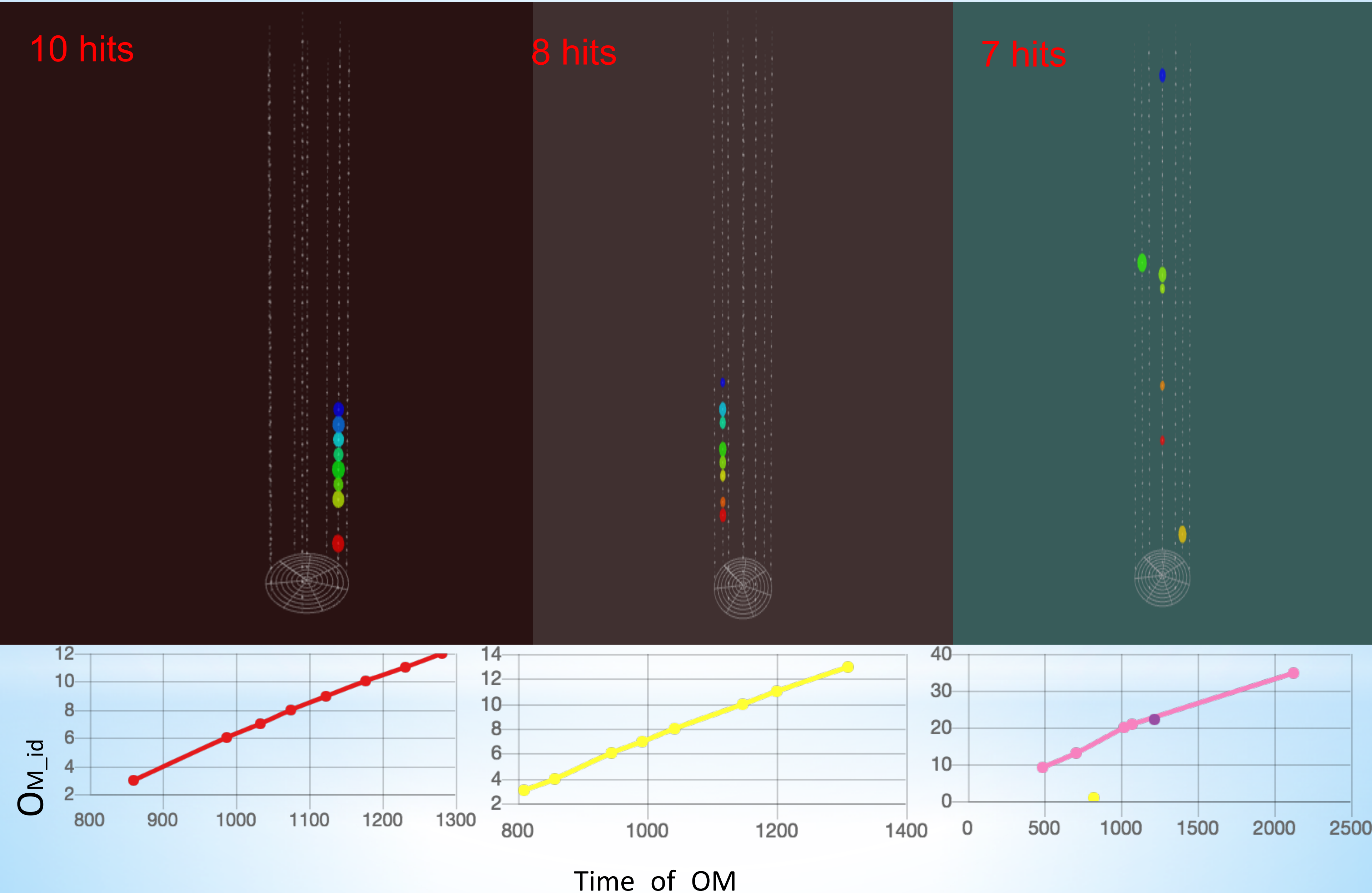


2016, 1st cluster, Run 404, event with 10 hits: no gap in 9



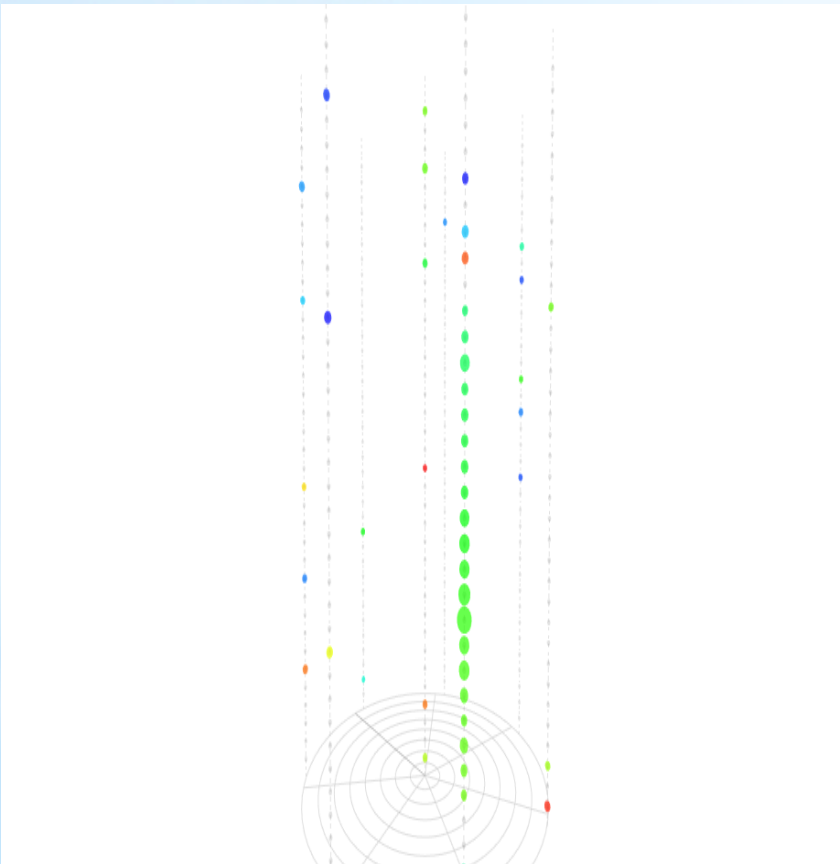
5674 selected candidates to look for neutrinos: 144 events with 6 hits, 15 events with 7 hits, 6 events - 8 hits and only one of them has 10 hits.

Nearly vertical events: neutrino candidates

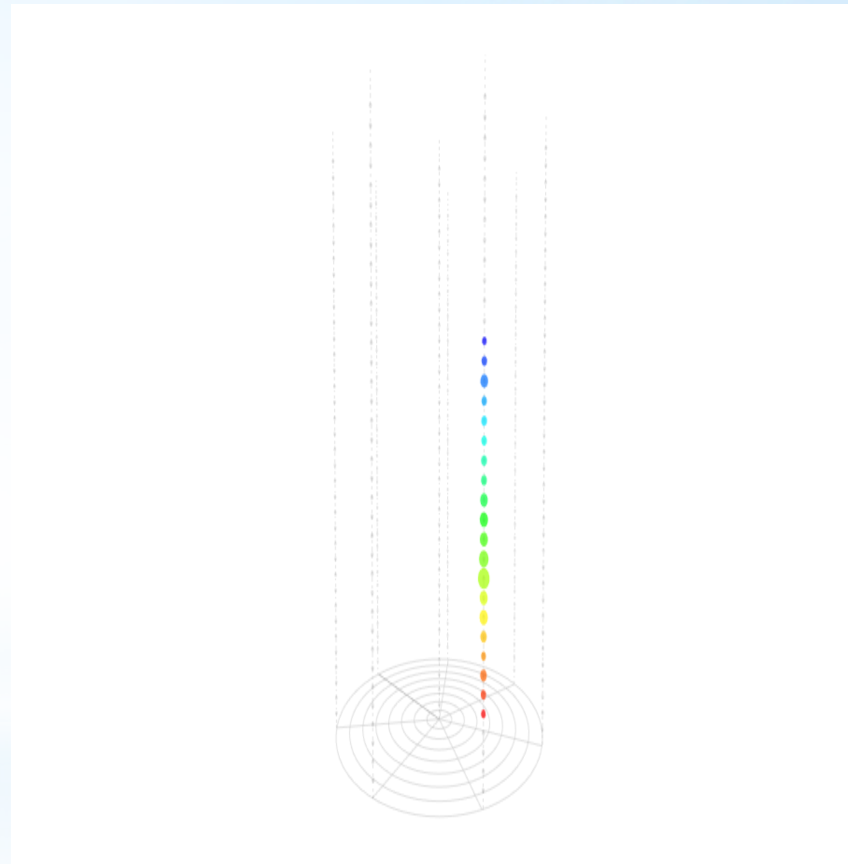


Reco with BARS: MC event example

MC original



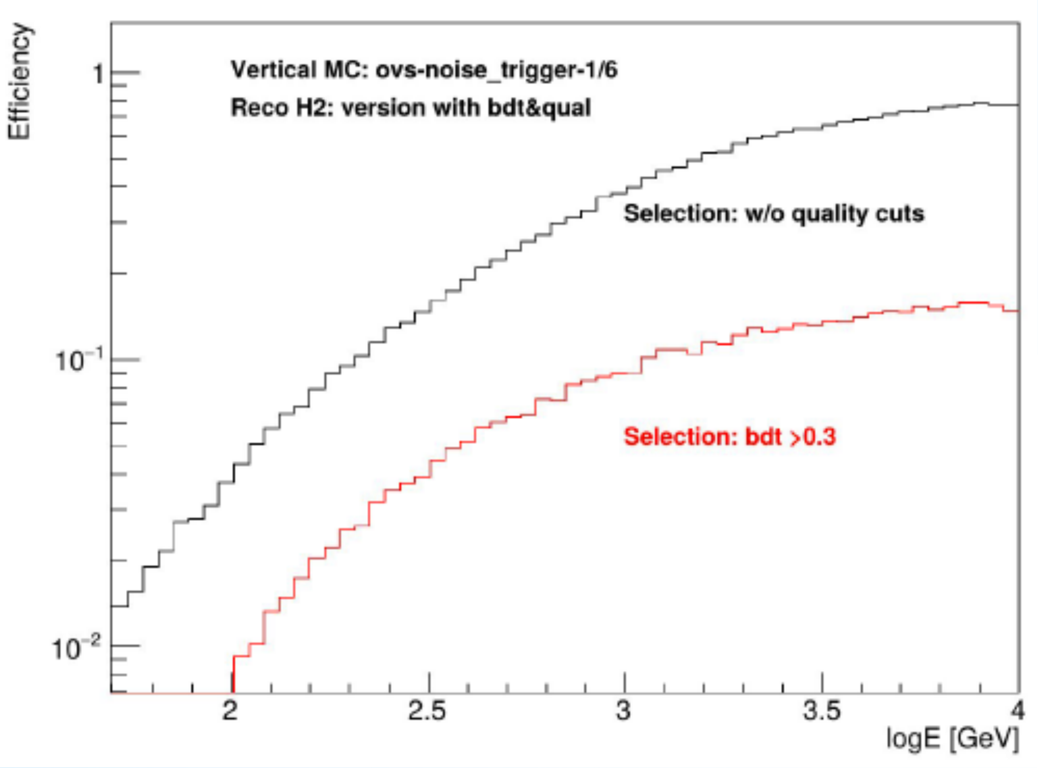
reconstructed (20 hits)



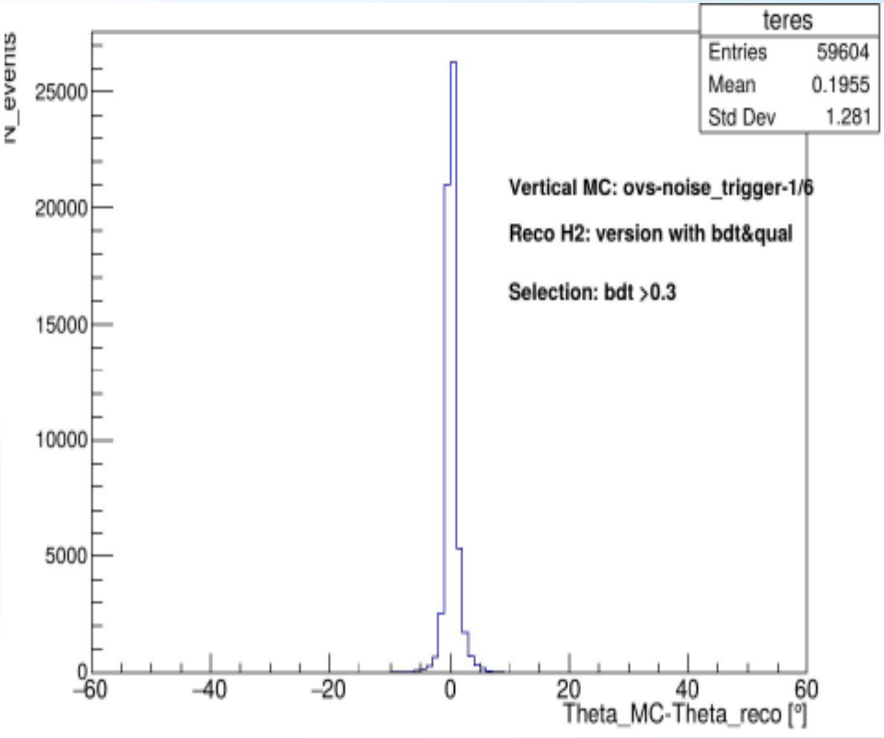
Example: nuEnergy=1.6 TeV; Theta_MC= 4.60°; Theta_rec=3.99°

Vertical upgoing MC sample: working points

Reconstruction efficiency:

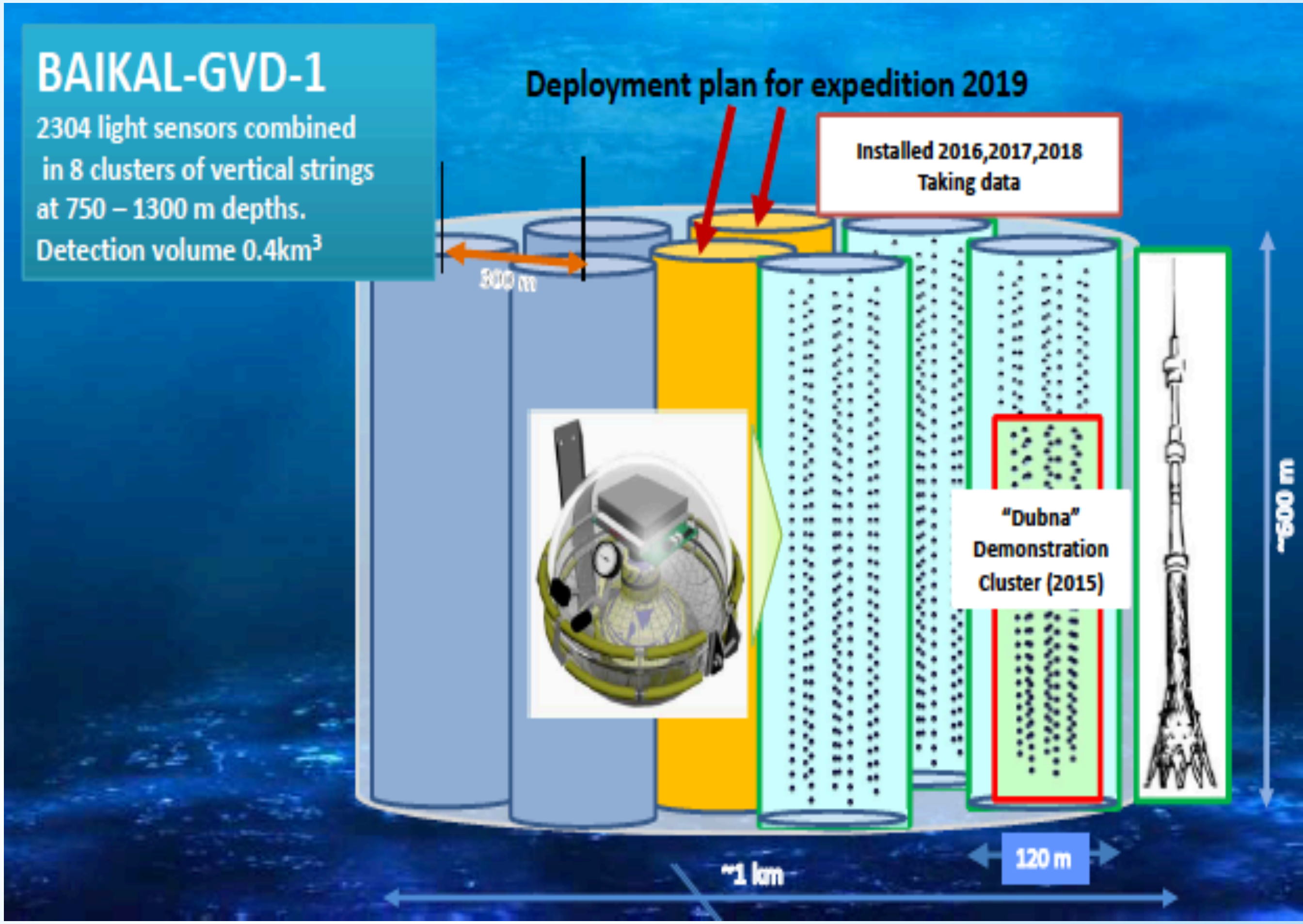


Reconstruction of zenith angle



*Outlook

We expect to improve the Baikal results with incoming data of the Gigaton Volume Detector in search for neutrino signal from expected annihilations of Dark Matter particles inside the astrophysical sources



Instead of SUMMARY

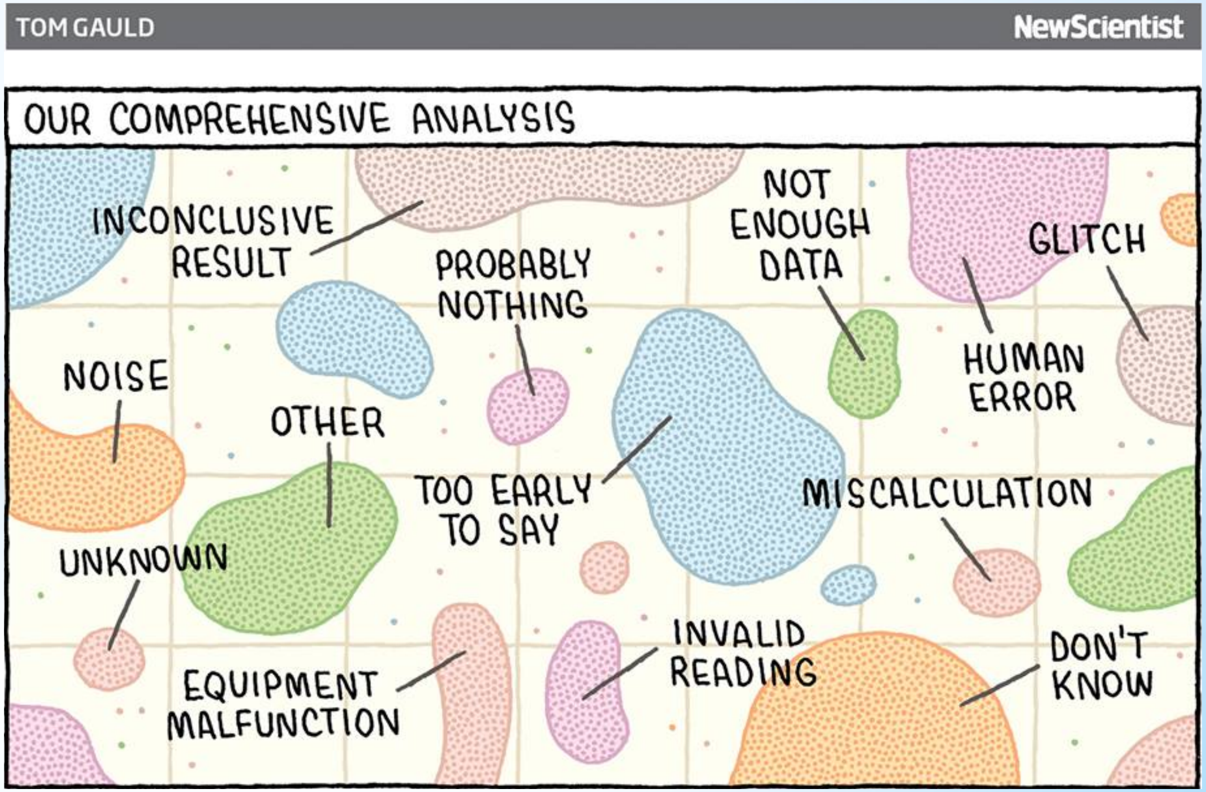
Some problems within LCDM

No DM particle was found so far

Milky Way satellites (galaxies in subhalo): we don't detect as many as predicted by CDM

DM halo profile of dwarfs galaxies: observed profiles are not NFW, unlike CDM predicts

Yet not found in surveys big galaxies to form stars predicted by CDM



Thank you for your attention!

Olga Suvorova
INR RAS
13 November 2018, Brussels-Moscow