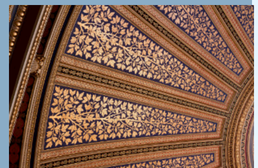
4th Uppsala workshop on Particle Physics with Neutrino Telescopes (PPNT19)



BSM searches with Baikal

Olga Suvorova, Sergey Demidov
INR RAS, Moscow

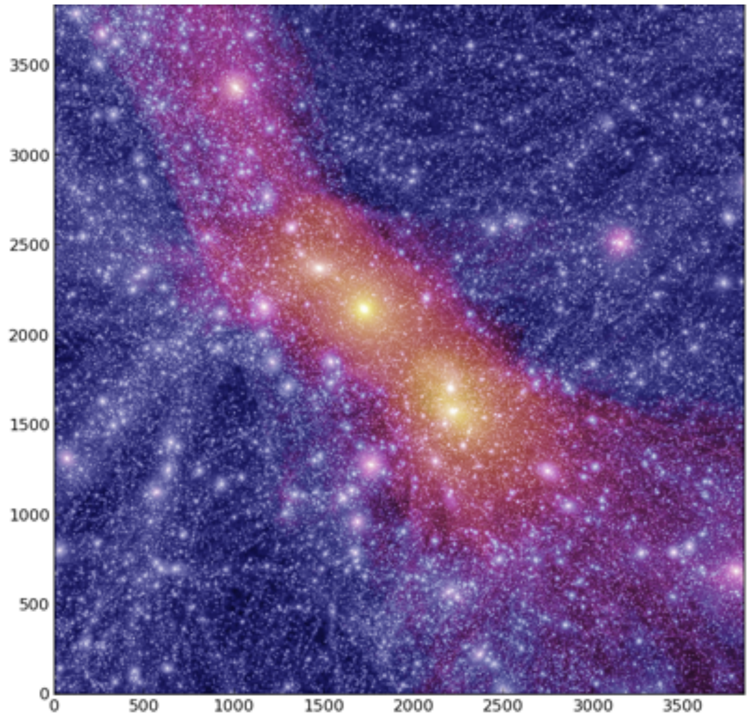
on behalf of the Baikal collaboration

7 October 2019, Uppsala University

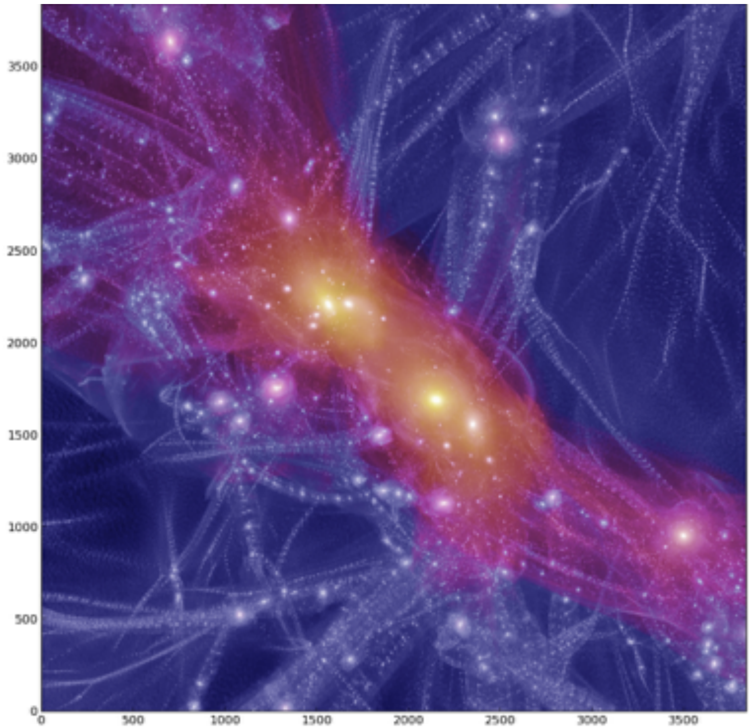
WIMP are CDM candidate

Instead of Introduction

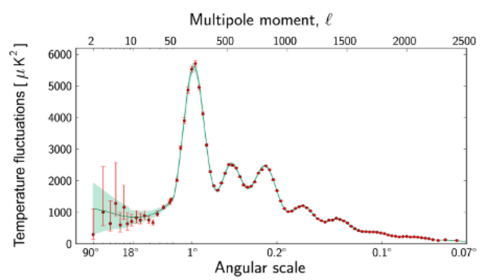
Simulation of what the Universe looks like



~ Simulation of what the Universe would look like without DM

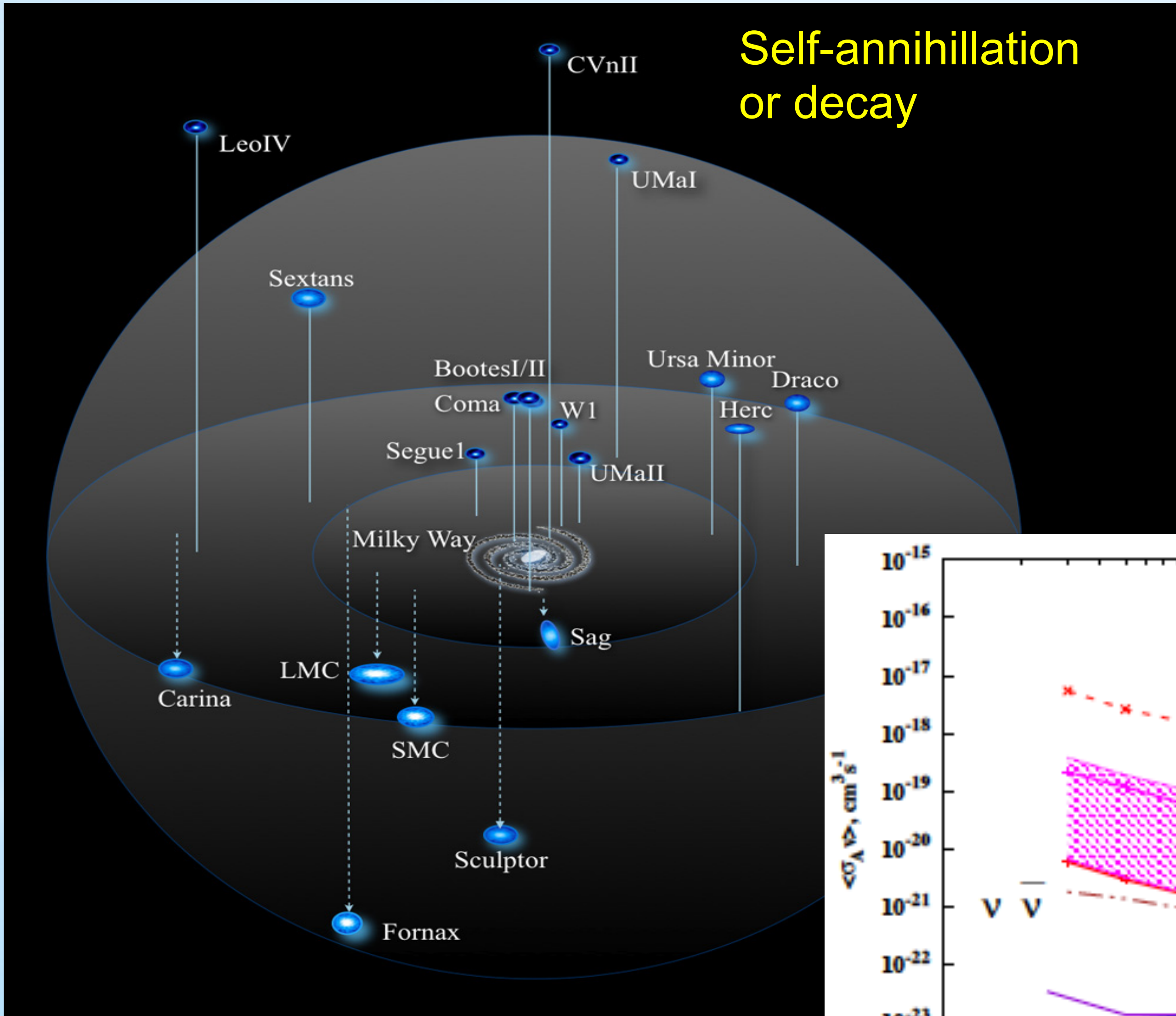


CDM fit observations

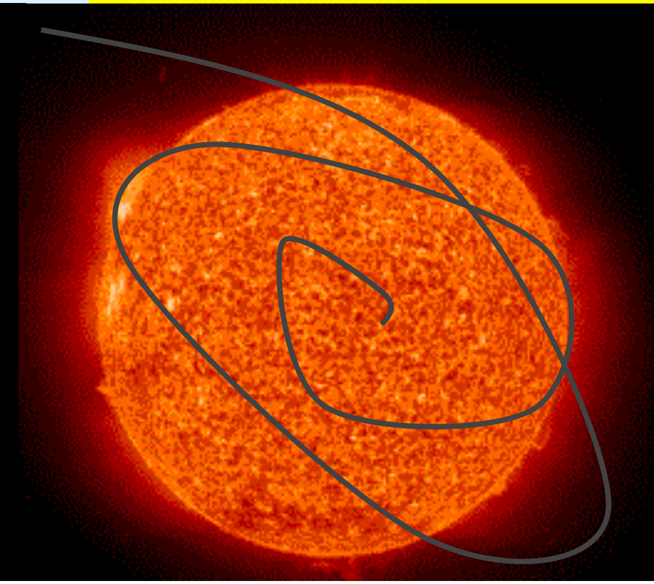


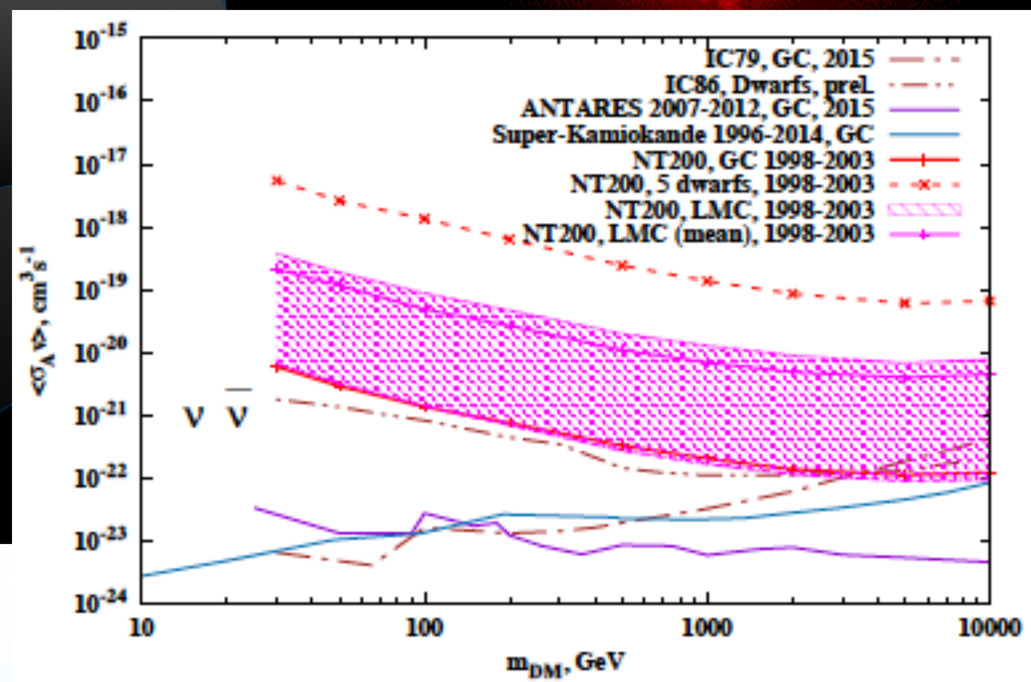
Status of our published works in search for DM: Upper Lim with NT-200 and GVD sensitivity

Baikal DM searches



Capture and scattering





Baikal site

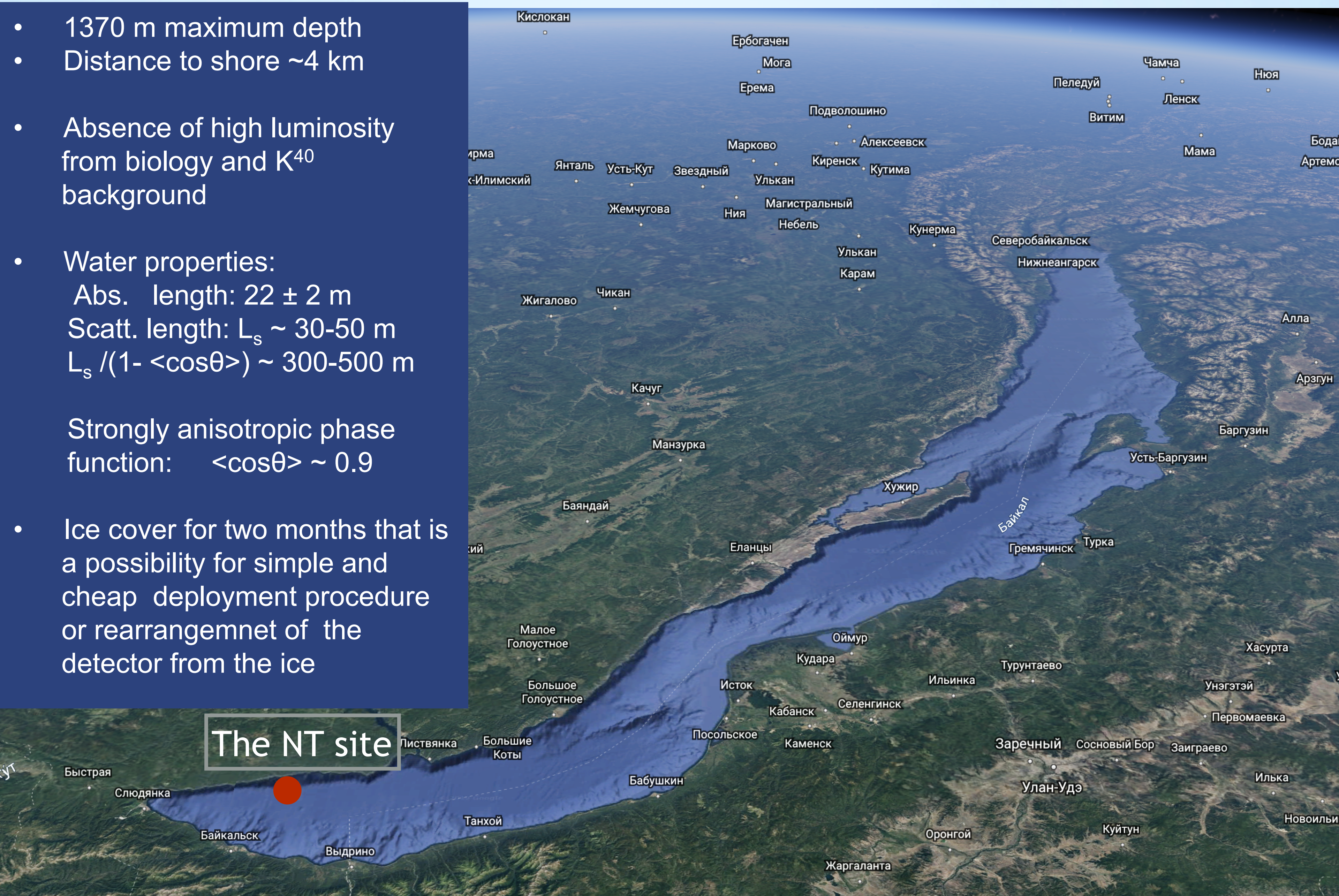
- 1370 m maximum depth
- Distance to shore ~4 km

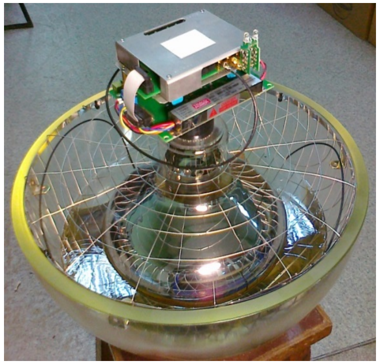
- Absence of high luminosity from biology and K^{40} background

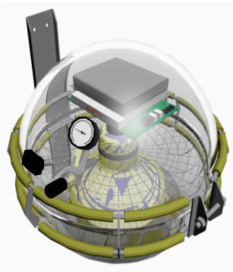
- Water properties:
  Abs. length: 22 ± 2 m
  Scatt. length: L_s ~ 30-50 m
  L_s /(1- <cosθ>) ~ 300-500 m

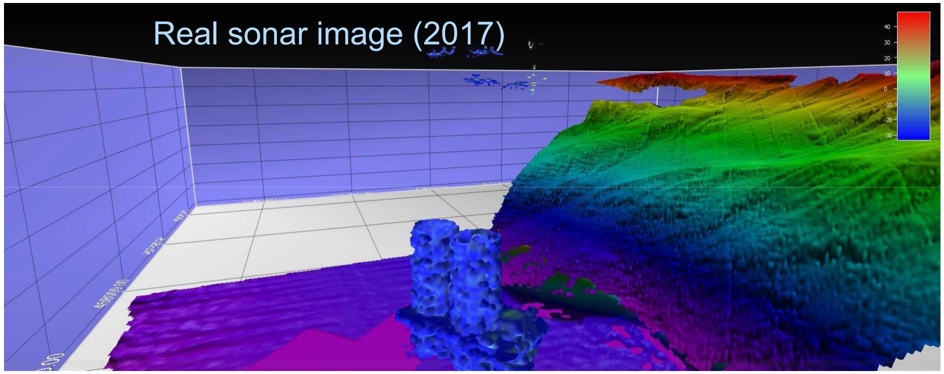
  Strongly anisotropic phase function: <cosθ> ~ 0.9

- Ice cover for two months that is a possibility for simple and cheap deployment procedure or rearrangemnet of the detector from the ice



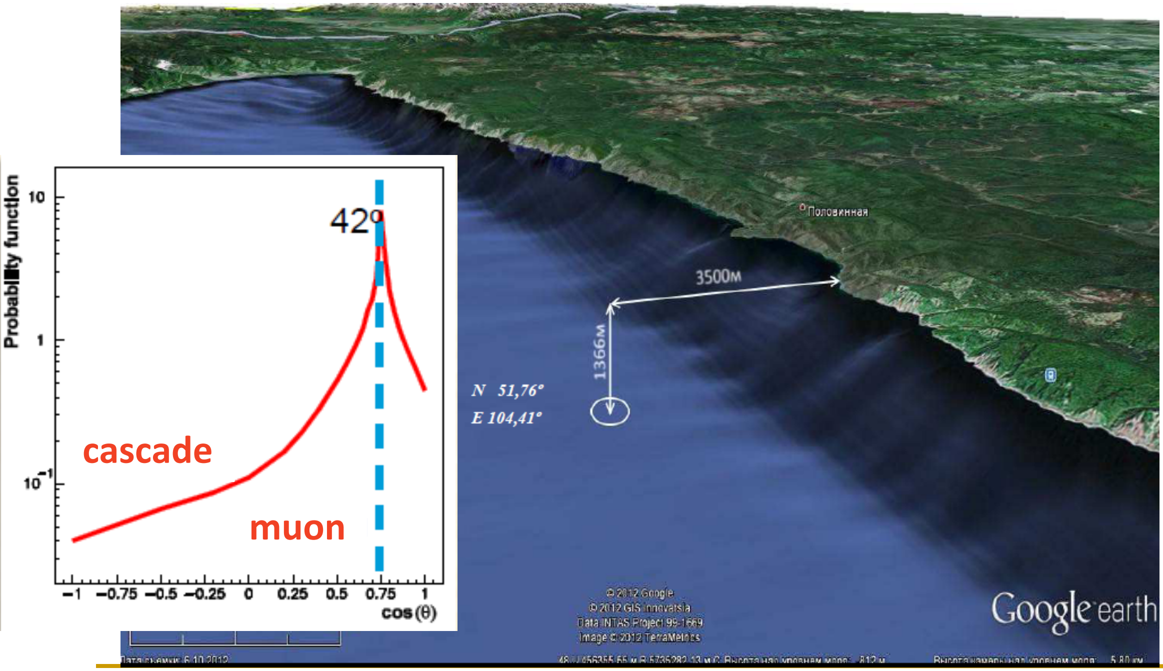


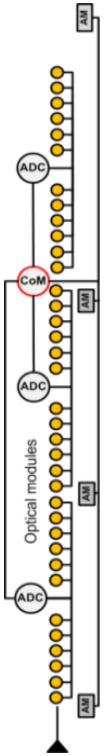




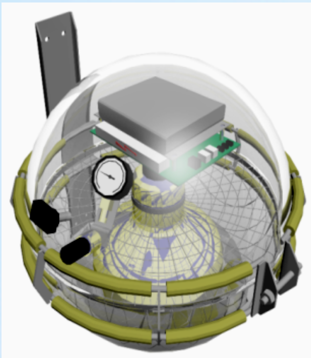
Optical module
PMT: R7081-100

Baikal-GVD

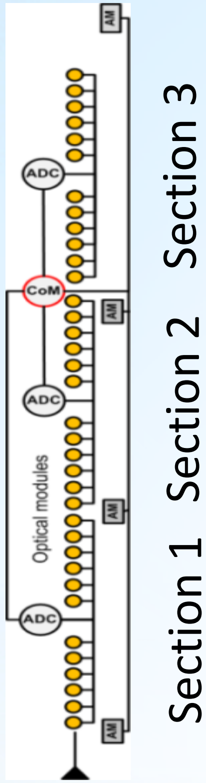


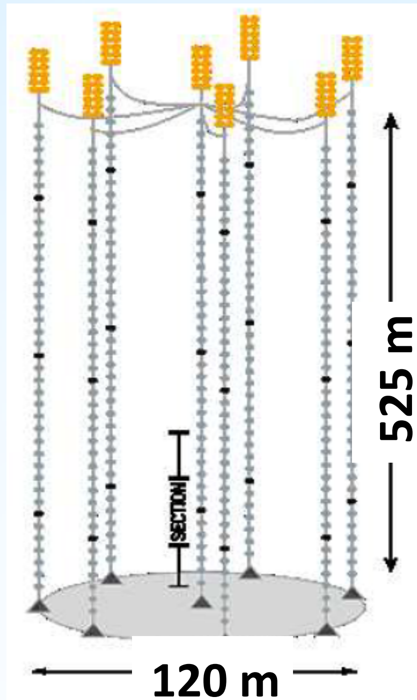


Baikal-GVD: phase I (2020-2021)

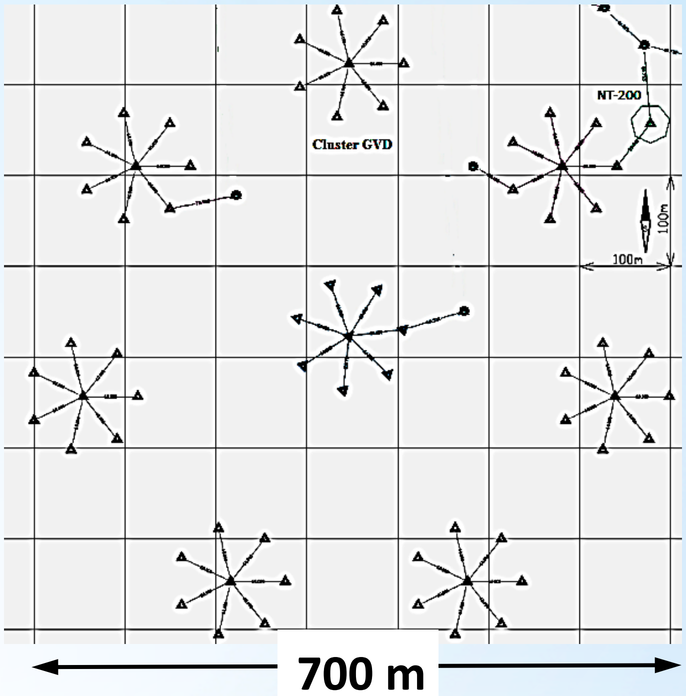


Optical module
PMT: R7081-100





Cluster: 8 strings



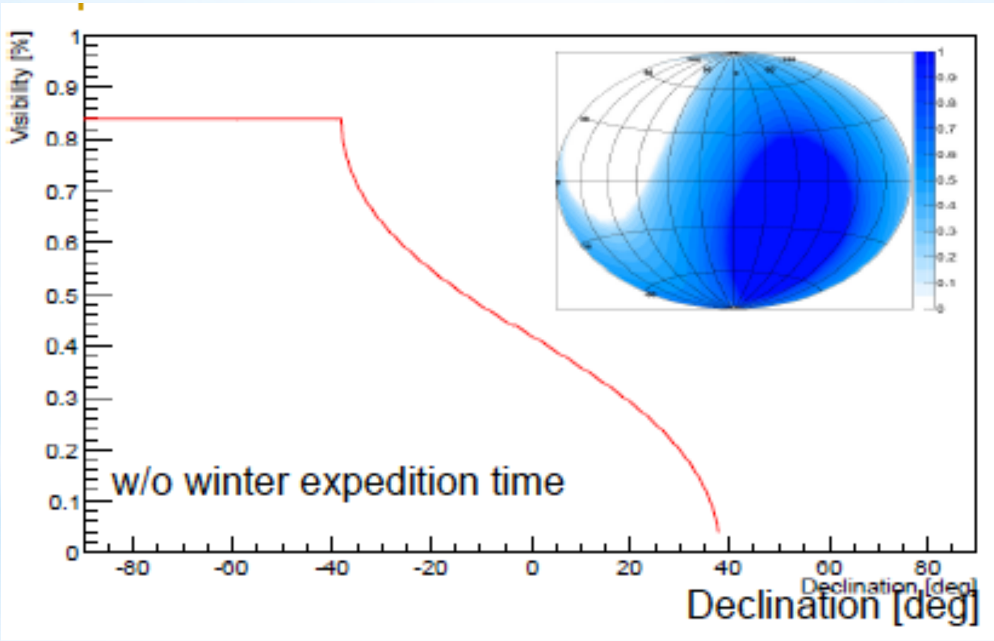
GVD-1: 8 clusters

GVD-1	
OMs	2304
Clusters (8 Strings)	8
Depths, m	750 – 1275
Eff. Volume	0.4 km^3

Directional resolution	Energy resolution
Cascades: 3.5° – 5.5°	δ(E/Esh) ~ 0.15
Muons: 0.25° - 0.5°	δ(lgE) ~ 0.4

Baikal Gigaton Volume Detector (GVD)

is targeting on VHE neutrinos from visible astrophysical sources in electromagnetics or gravitational waves either in DM phenomena through a gravitational field



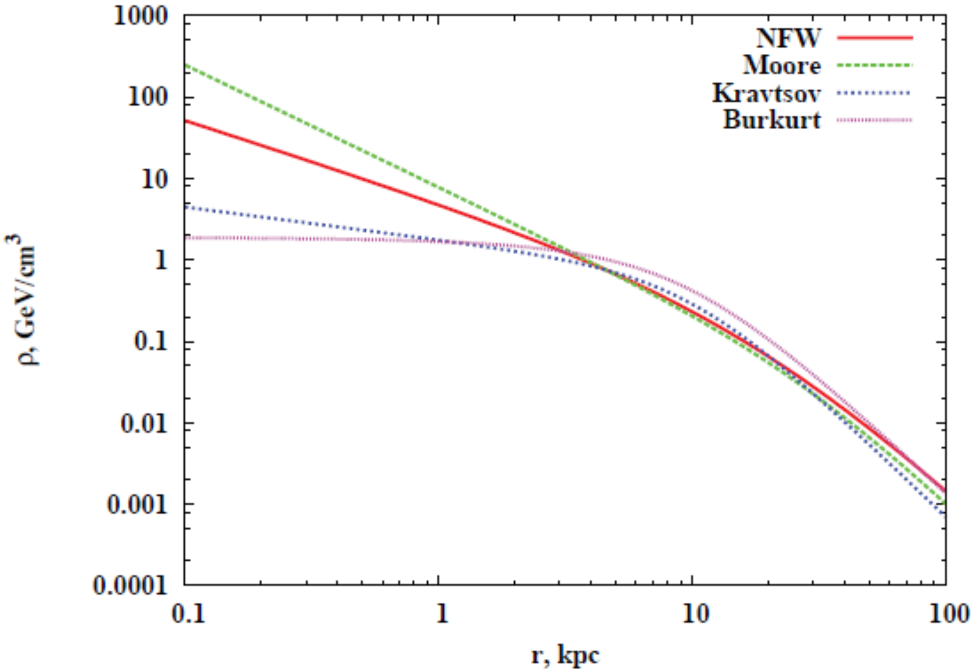
Note: Baikal-GVD's FoV is about +40° on declination for upgoing muons and 4π view in cascade search mode.

WIMPs from Galactic Center

WIMP signature in gamma-rays or neutrino fluxes

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

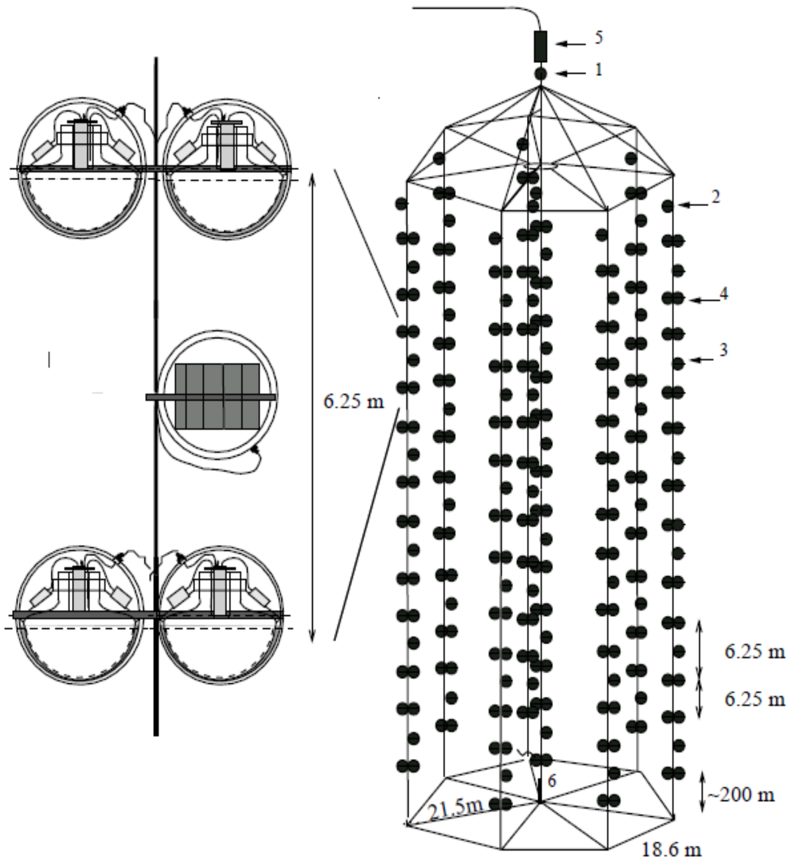
DM distribution (J-factor)

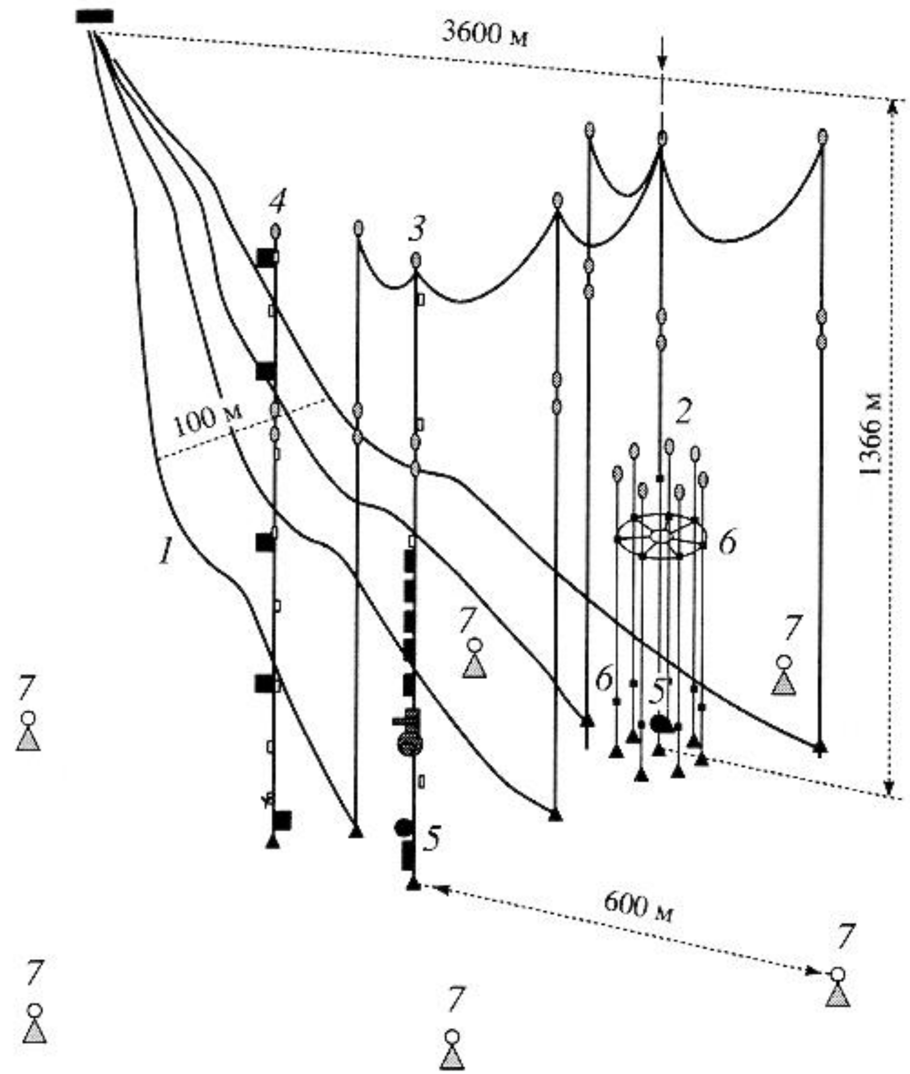


Model	α	β	γ	δ	r_*, kpc	ρ_*, GeV/cm^3
NFW	1	3	1	0	20	0.3
Burkert	2	3	1	1	9.26	1.88
Moore	1.5	3	1.5	0	28	0.27

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

Baikal NT200, Heptagon and Hydroacoustic system

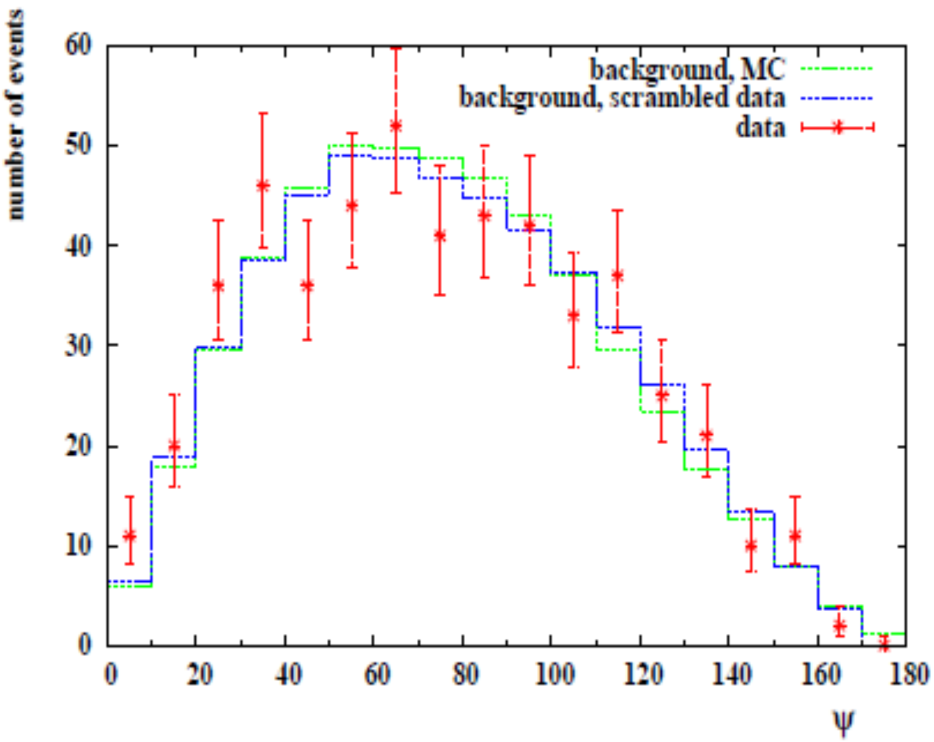


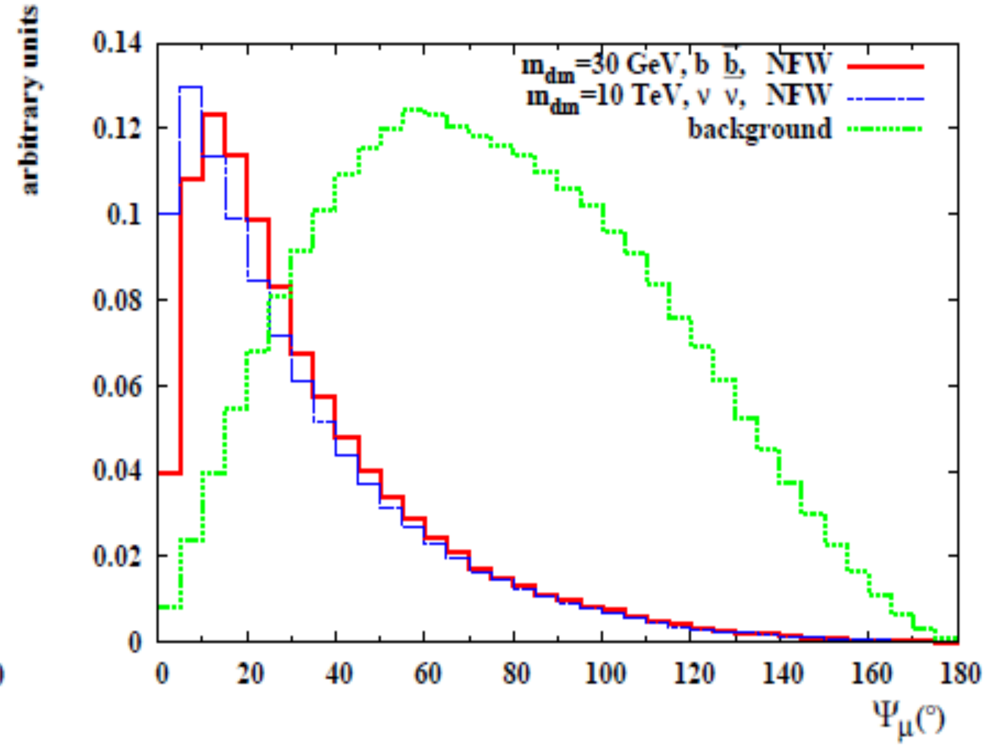


Upgoing muons
Eth=10 GeV;
ψ=2.5deg

Astropart J: A search for neutrino signal from dark matter annihilation in the center of the Milky Way with Baikal NT200

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

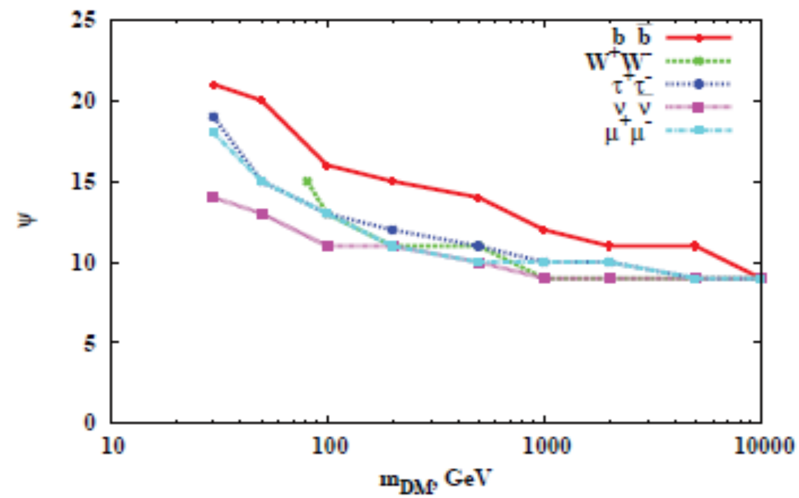




Cone	20°	5°	2.5°
N_obs	31	2	2
N_bkg	25.1	1.63	0.42

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:

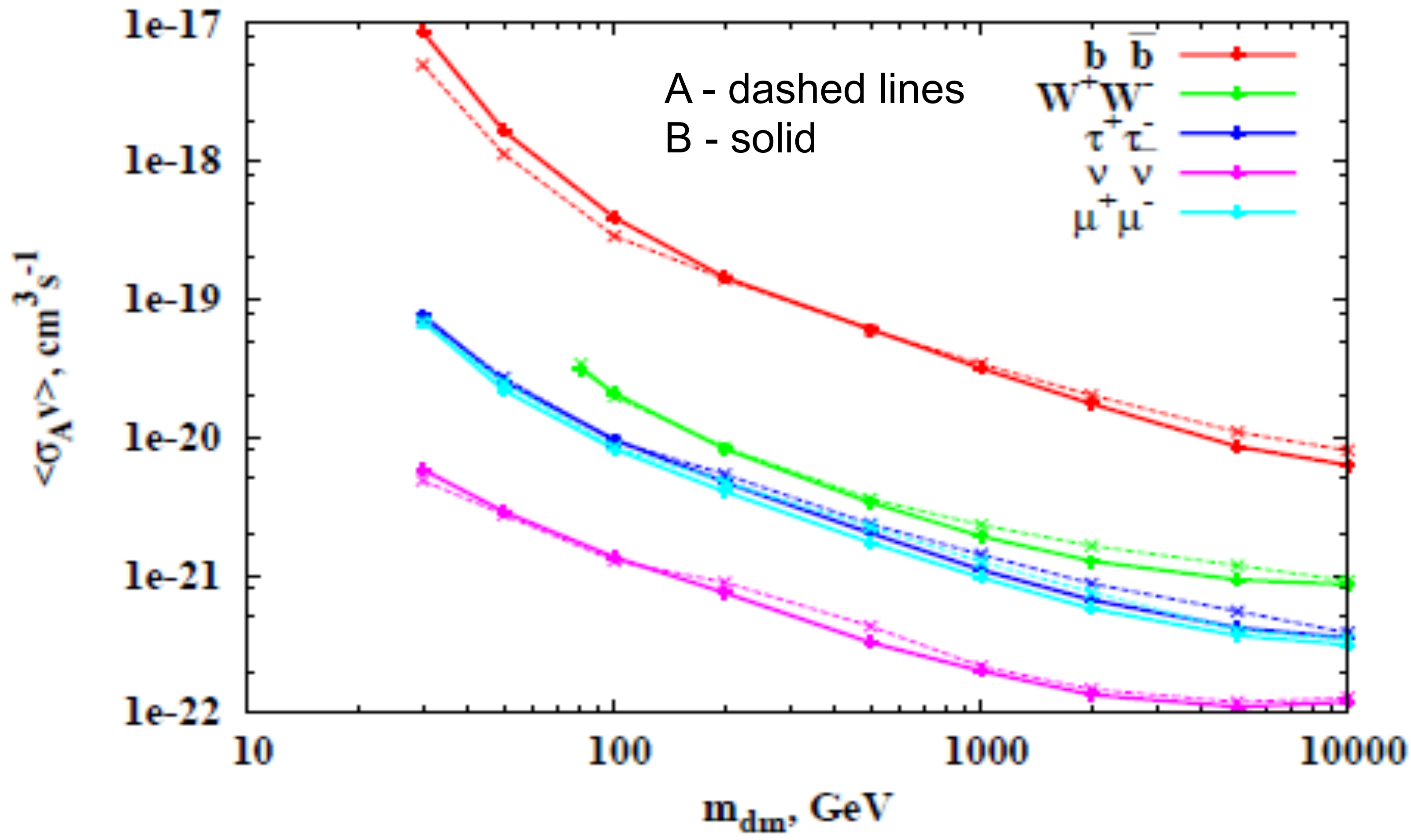
Angular distribution $f(\psi) = \frac{1}{N_S+N_B}\left(N_S f_S(\psi) + N_B f_B(\psi)\right)$

Likelihood function

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

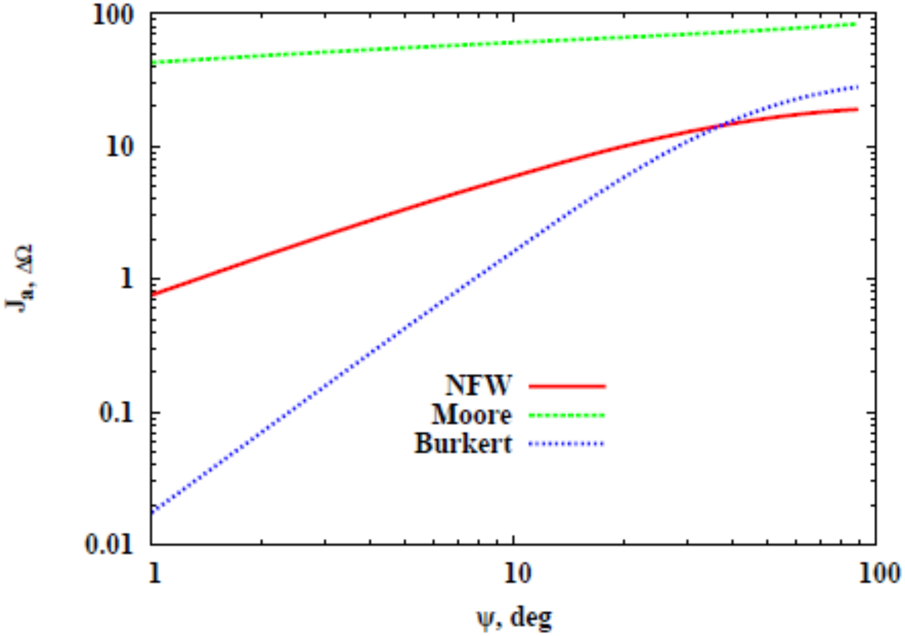
Systematic uncertainties: profile likelihood, $\lambda(N_S) = -2\ln\frac{\mathcal{L}(N_S,\hat{\hat{\theta}})}{\mathcal{L}(\hat{N}_S,\hat{\theta})}$

Baikal NT200 results: the upper limits at 90% CL

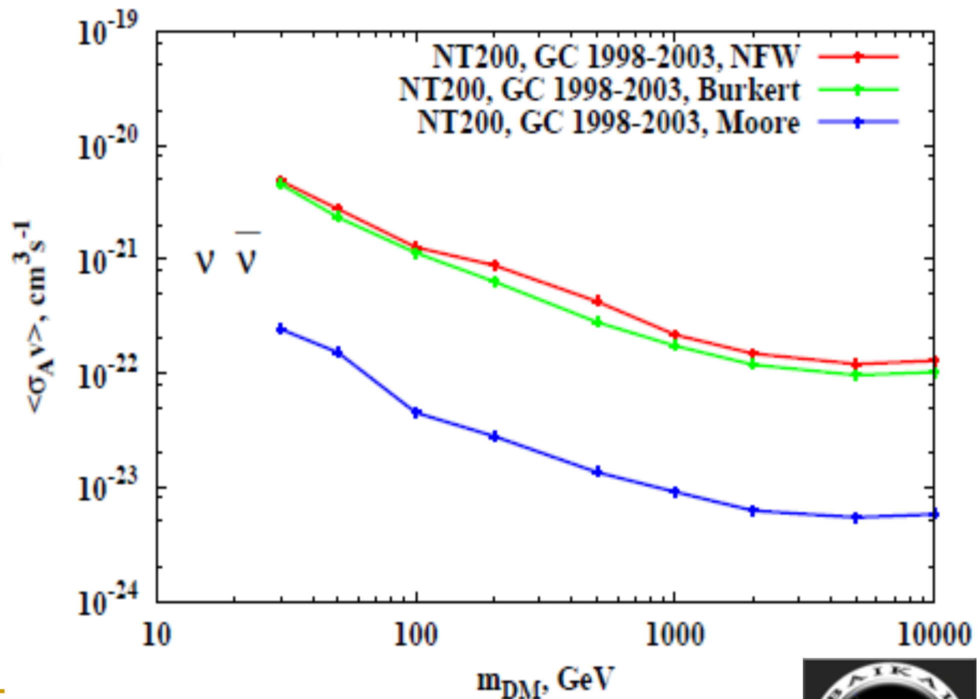


Systematics: experiment (about 30%) and theory (upto 15%) without astrophysical uncertainties

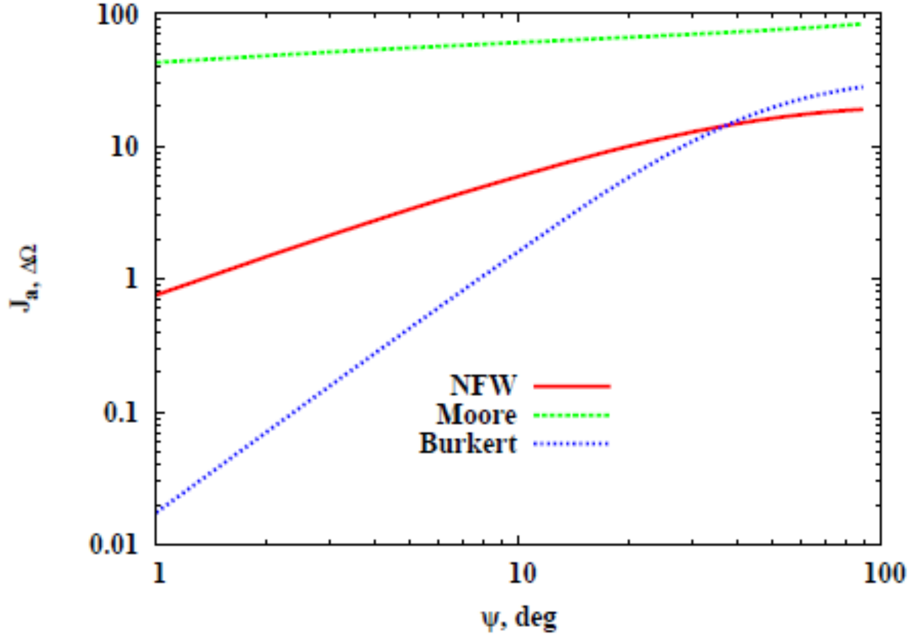
Astrophysical uncertainties in the Baikal NT200 upper limits on $\langle\sigma_{ann}v\rangle$



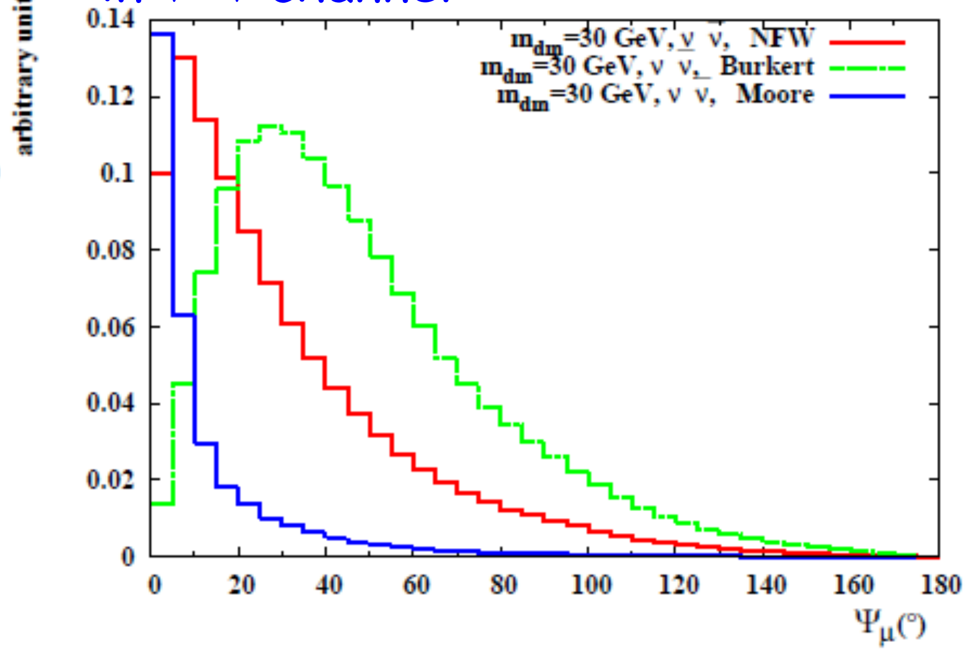
Direct ν–ν annihilation channel



Astrophysical uncertainties in DM profiles

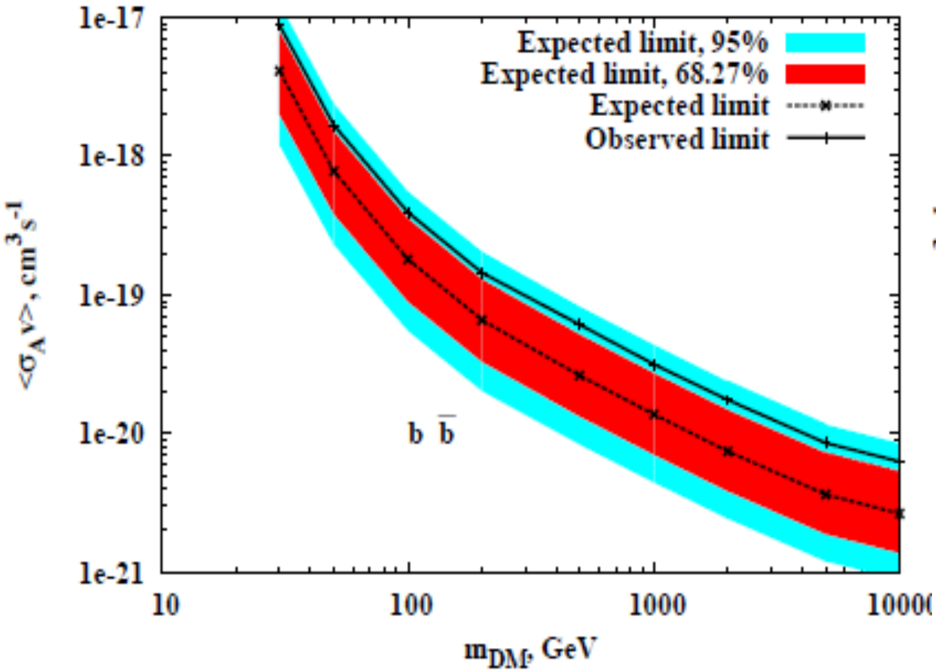


Angular mu-GC distr of a signal in ν−ν channel

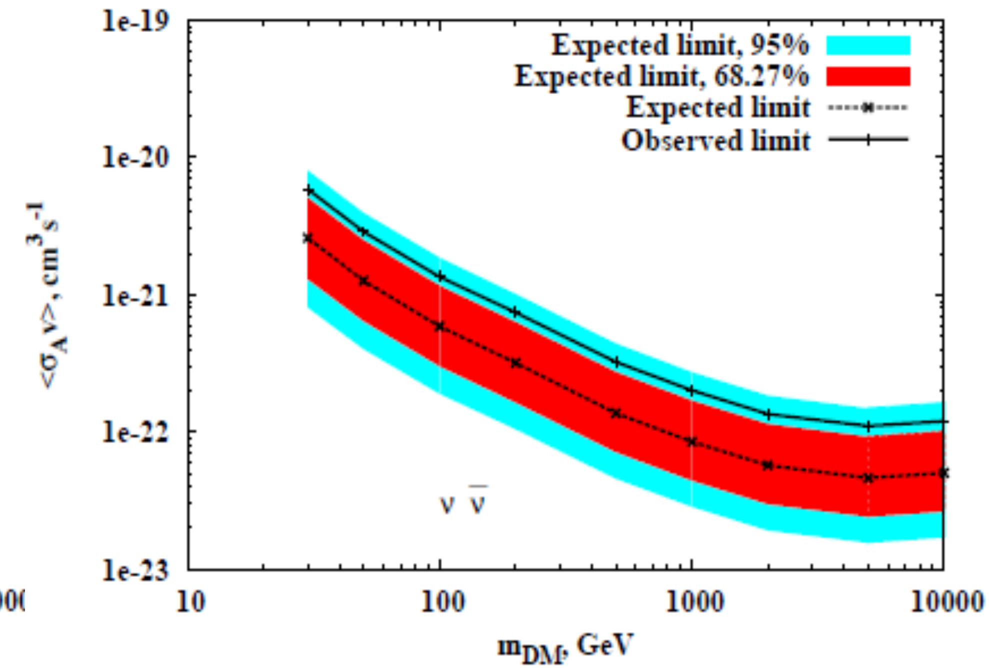


Baikal NT200: sensitivities to GC dm-signal from pseudo-experiments

Soft spectra: bb



Hard spectra: nu-nu



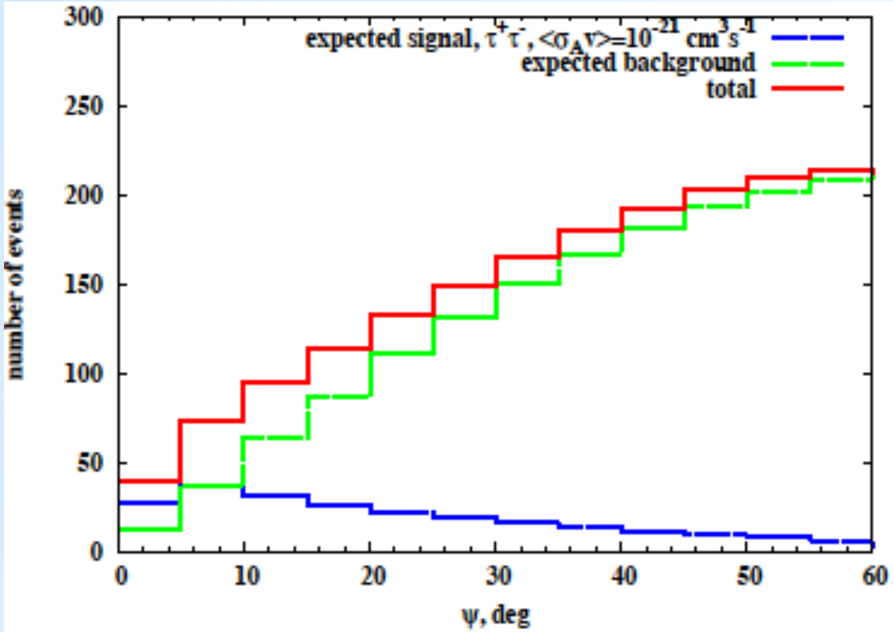
N_obs=113 @ psi<40deg

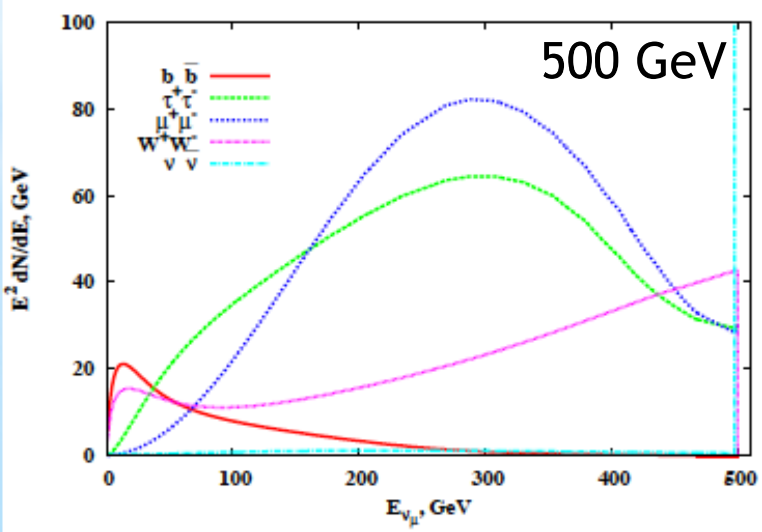
TS= 5.8 - 6.6 (no syst) and TS= 1.4 - 1.6 with syst.

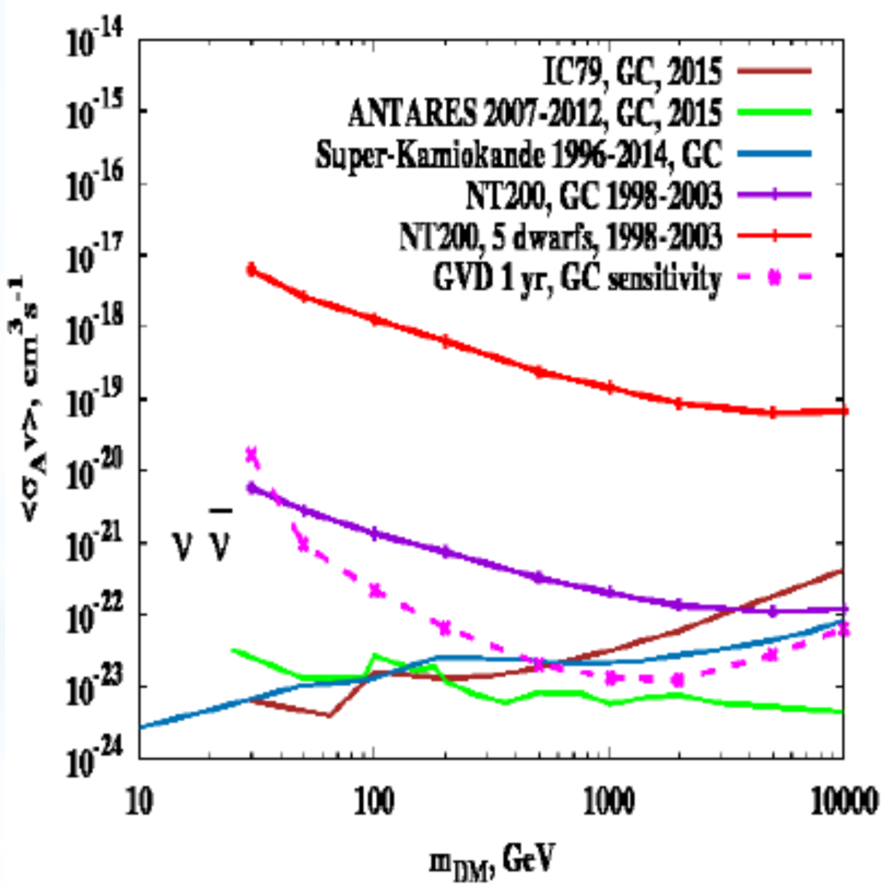
Baikal-GVD 1 year -sensitivity to DM annihilations in the GC

12 clusters, 2304 OMs (∅120×345)

Expexted number of upgoing muons 4300 for 1 year. Signal is simulated with NFW density profile. Sytematic uncertainties about 50% is included



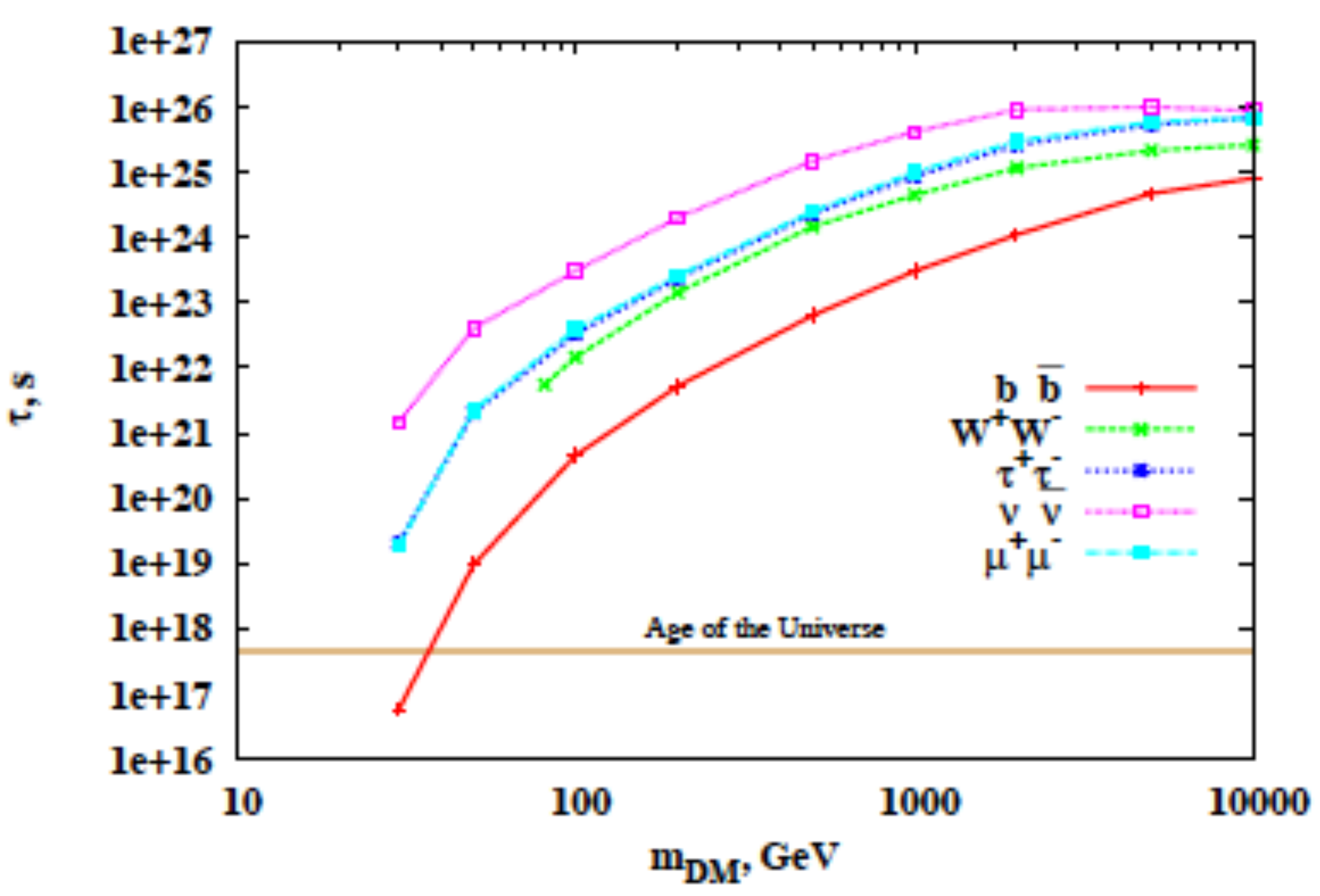




Baikal-GVD 1 year -sensitivity to DM decays in the GC

$$\frac{d\phi_\nu}{dE} = \frac{1}{\tau_{DM}} J_1(\psi) \frac{R_0 \rho_{local}}{4\pi m_{DM}} \frac{dN_\nu}{dE}$$

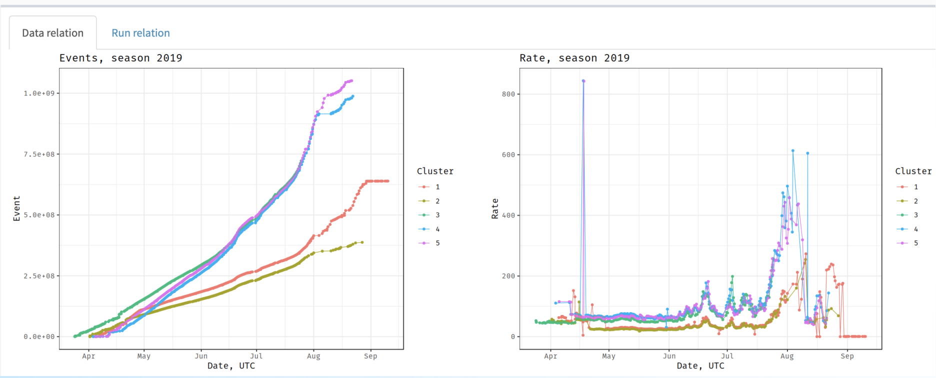
$$J_1(\psi) = \int_0^{l_{max}} \frac{dl}{R_0} \frac{\rho\left(\sqrt{R_0^2 - 2rR_0\cos\psi + r^2}\right)}{\rho_{local}}$$



Baikal-GVD status 2019:   5 clusters

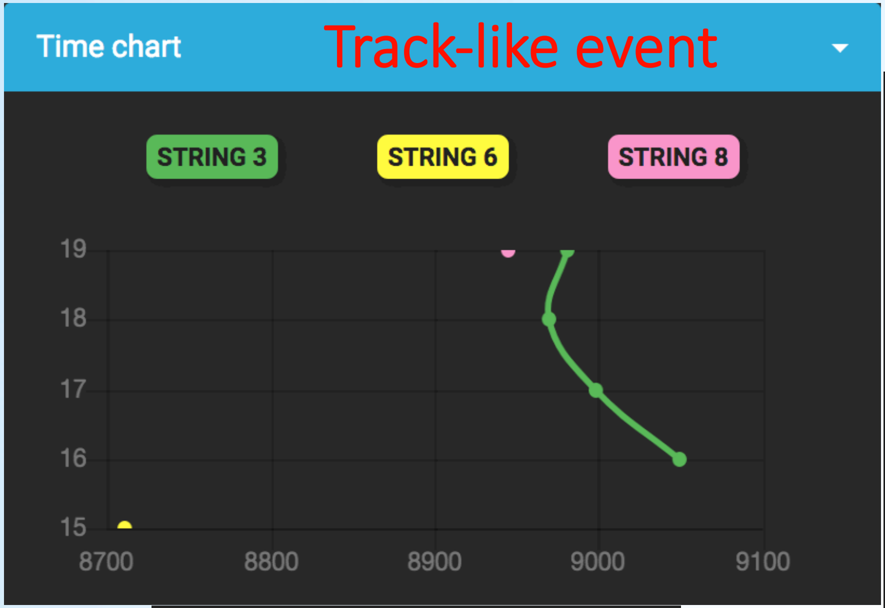
Configuration	2015	2016	2017	2018	2019
The number of OMs	192	288	576	864	1440
Geometric sizes, m	**∅80×345**	**∅120×525**	**2×∅120×525**	**3×∅120×525**	**5×∅120×525**
Eff. Volume	**0.03 km³**	**0.05 km³**	**0.1 km³**	**0.15 km³**	**0.25 km³**

Runs overview **Rates per clusters**

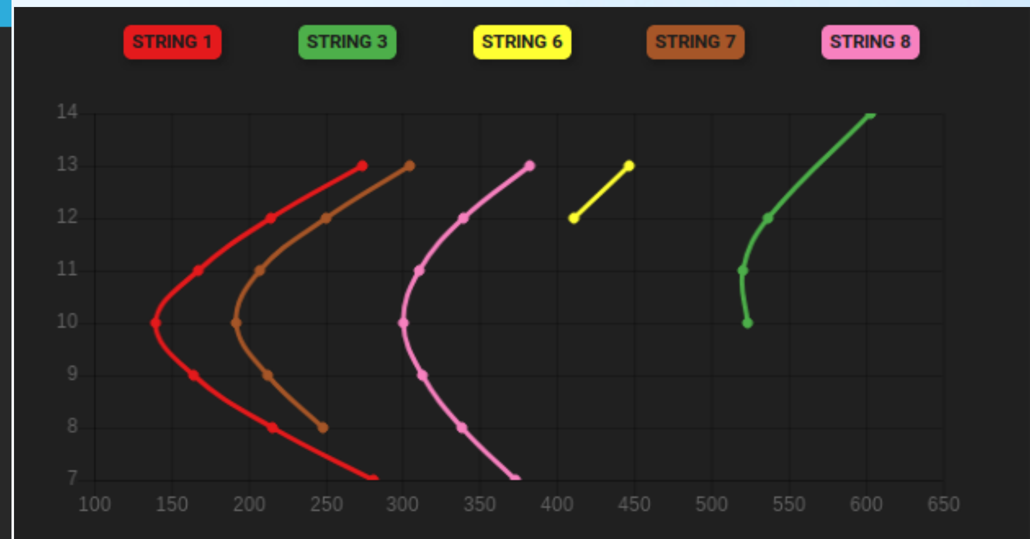


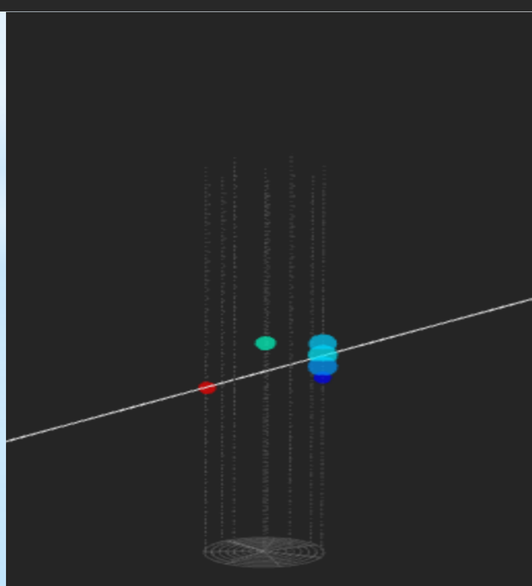
Total: 5 Clusters → 40 Strings → 120 Sections → 1440 OMs

Two modes in reconstruction of events: view in plane OM_z versus time

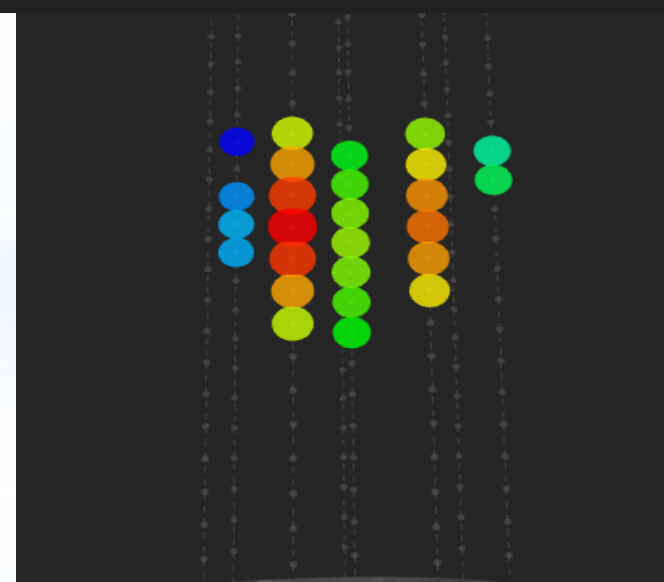


Cascade-like event



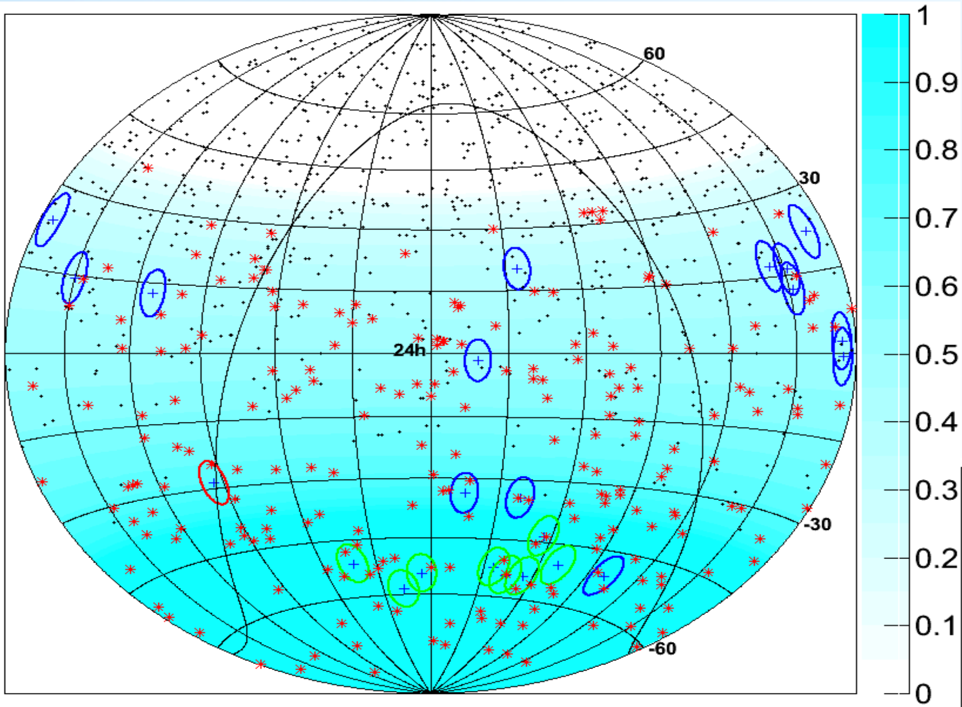


- T_first
- T_last

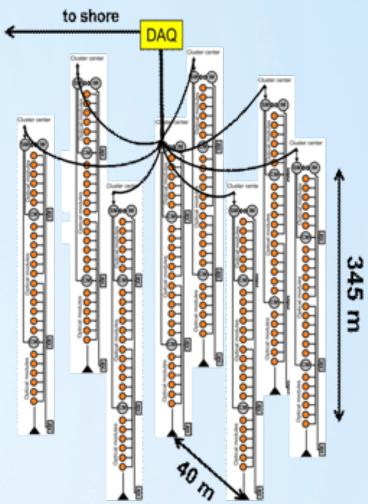


Baikal-GVD in search for TeVes neutrino, first step in 2015 results in: the only 1 cascade as non-atm candidate with Esh> 100 TeV

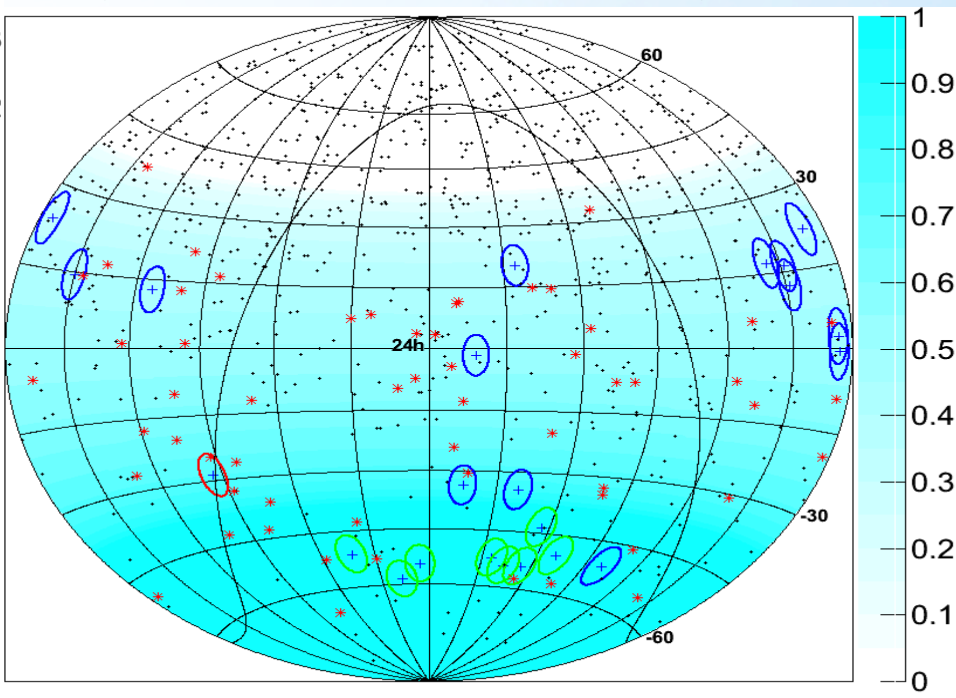
$E_{sh} \geq 1$ TeV, no cut on N_{hit}



«Dubna» 8 strings (192 OMs)

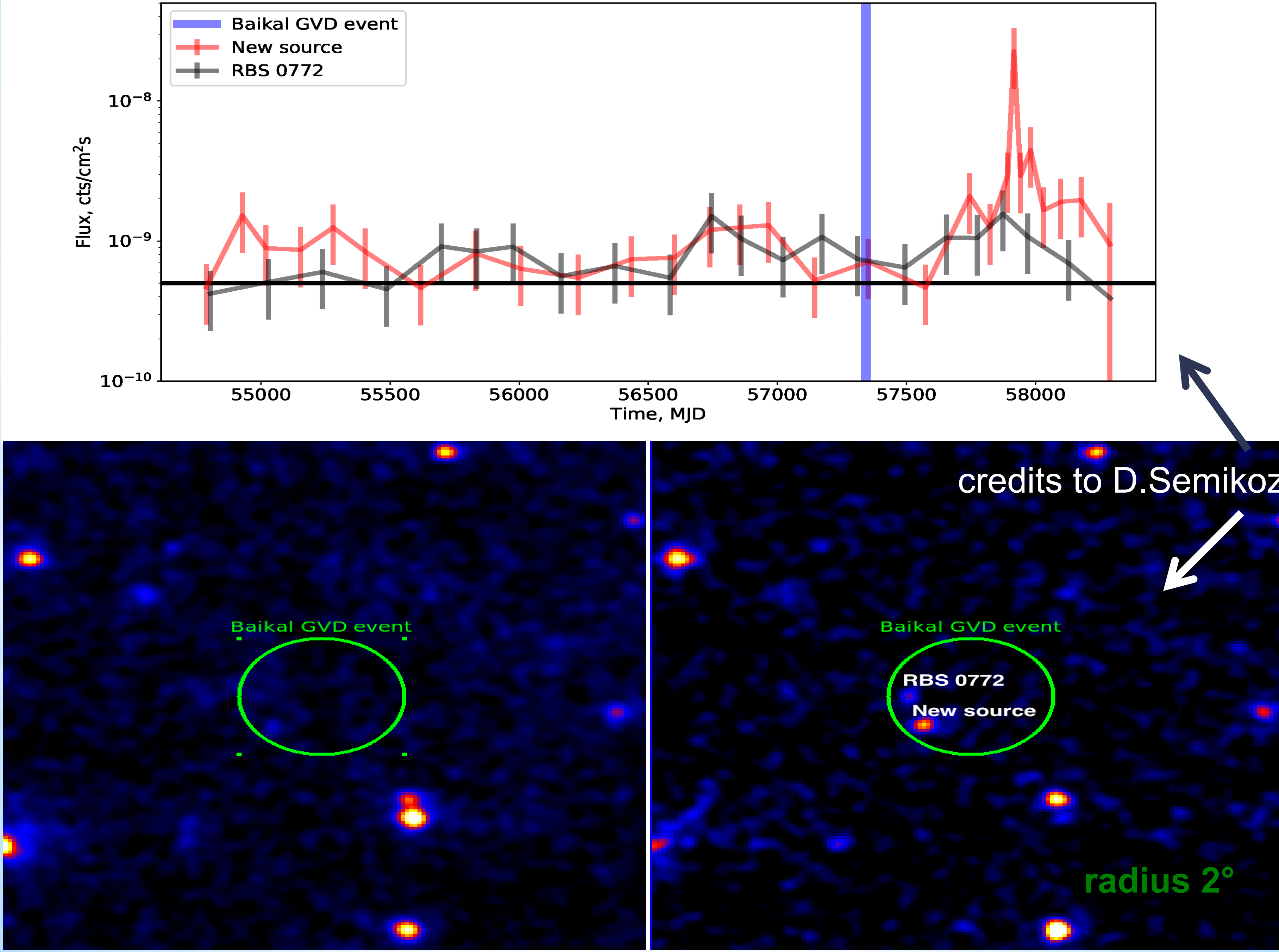


$E_{sh} \geq 100$ TeV, no cut on N_{hit}



- Galactic Center
- dSphs galaxies
- All cascade candidates
- Cascade candidates from bottom

Follow-up 1st GVD_cascade MJD 57342 {RA 139.7°; Dec 5.56°}

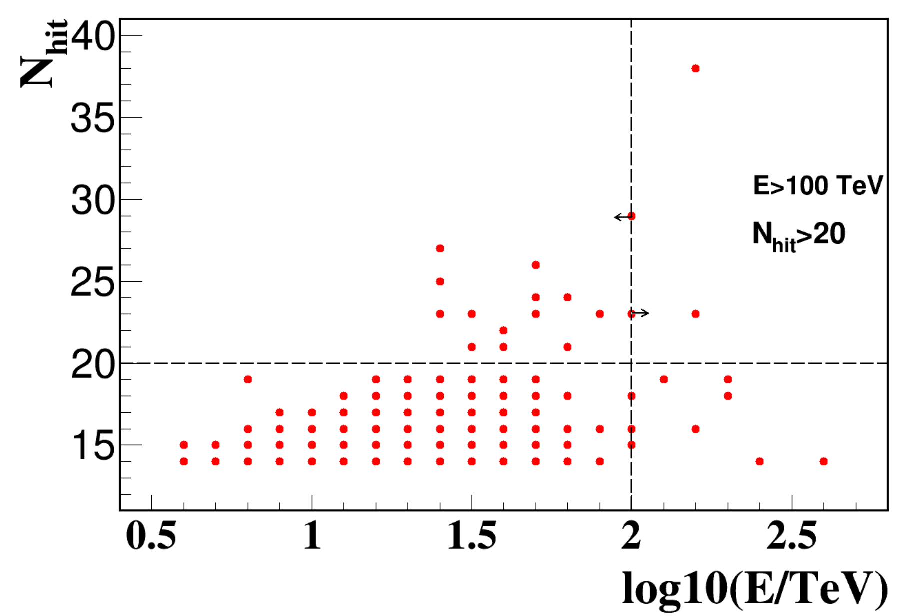


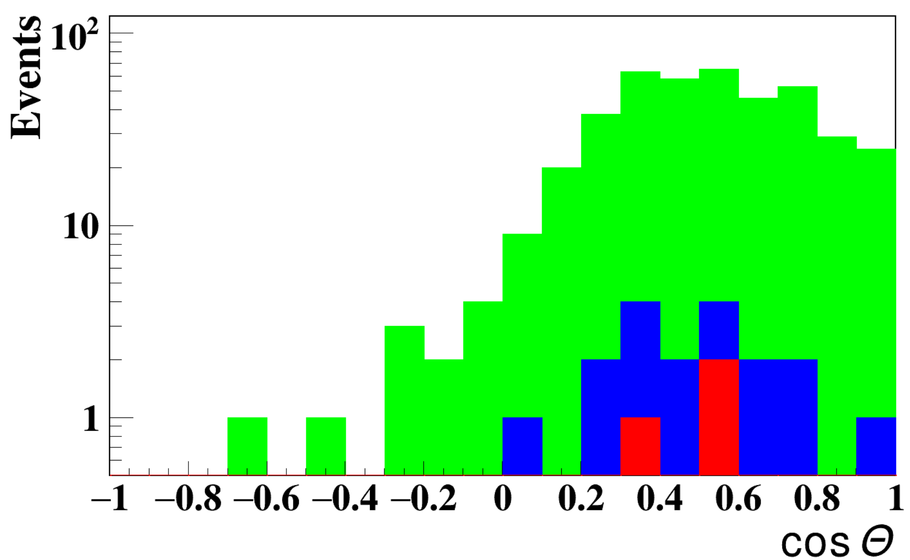
A search for cascades induced in GVD: 2016, 2018

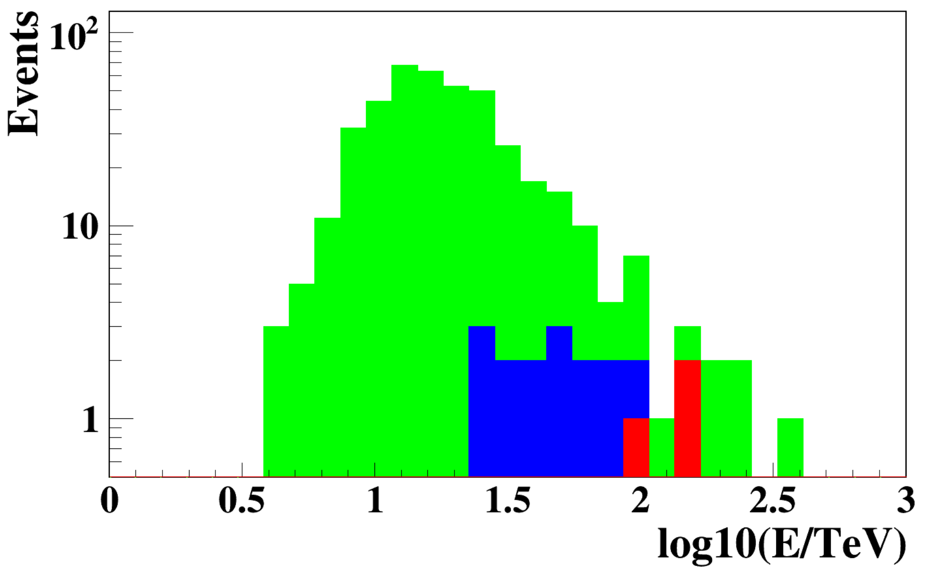
In 2016, 2018 data (2.4 year×cluster) selected number of cascade events :

(N_{hit} > 13 & E > 1 TeV) – 417 events
(N_{hit} > 20 & E > 1 TeV) – 18 events
(N_{hit} > 20 & E > 100 TeV) – 3+1 events

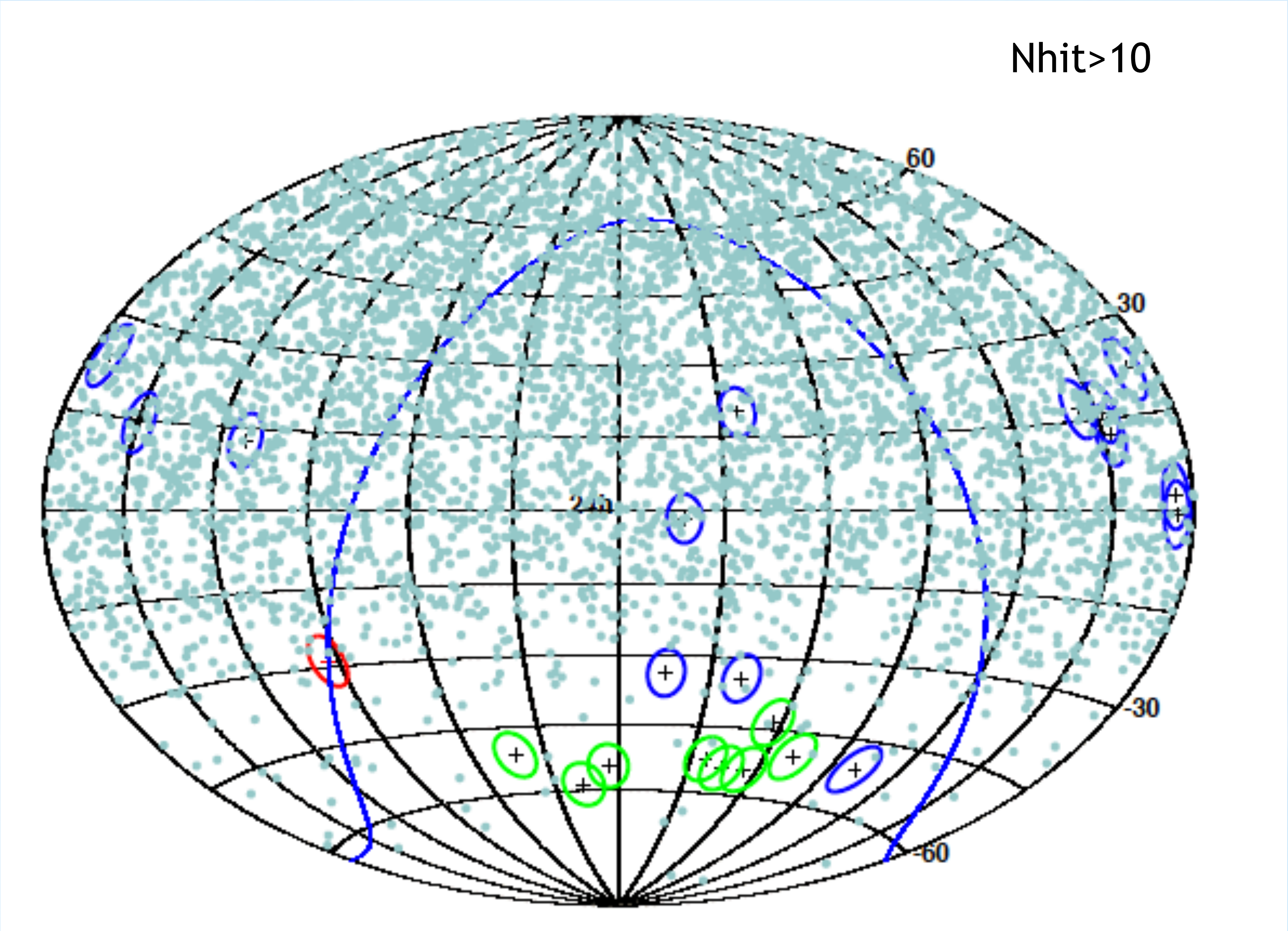
About 1.4 events are expected for 872 life days from astrophys. flux.
Three events have been selected for N_{hit} >20 and E > 100 TeV



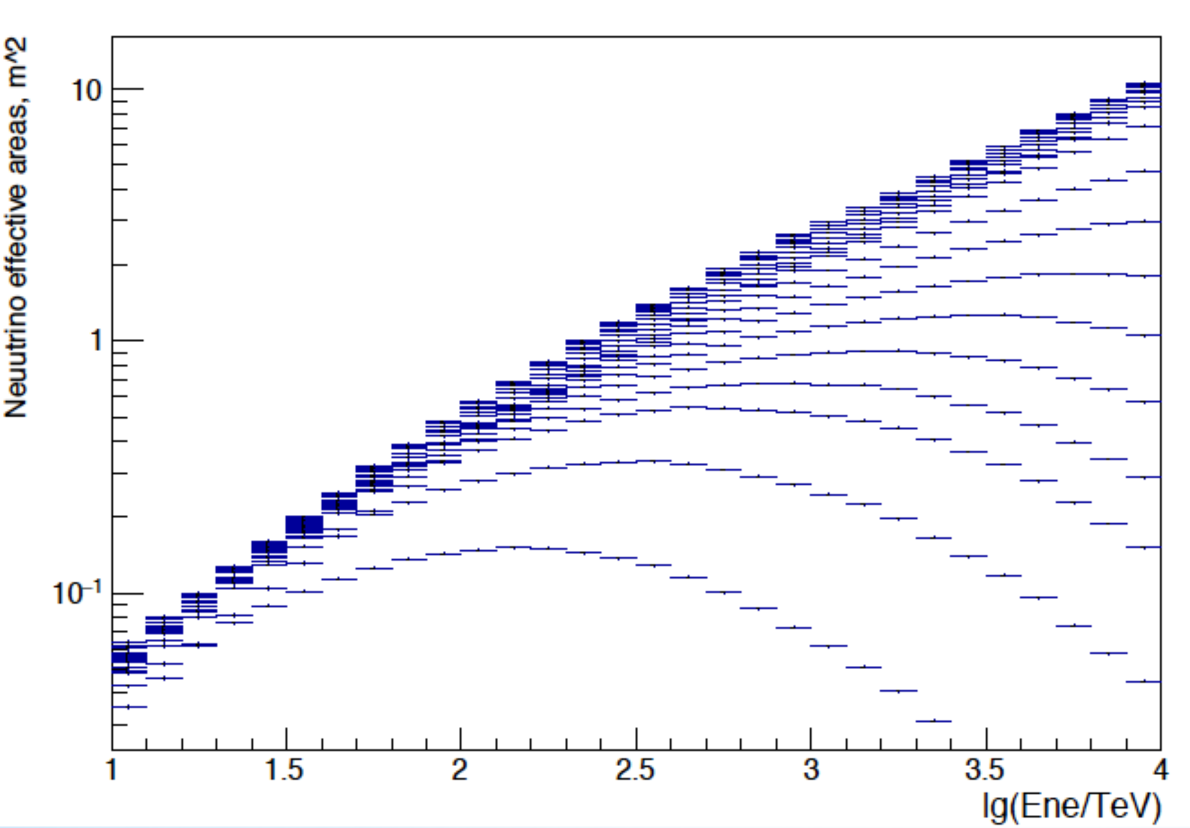


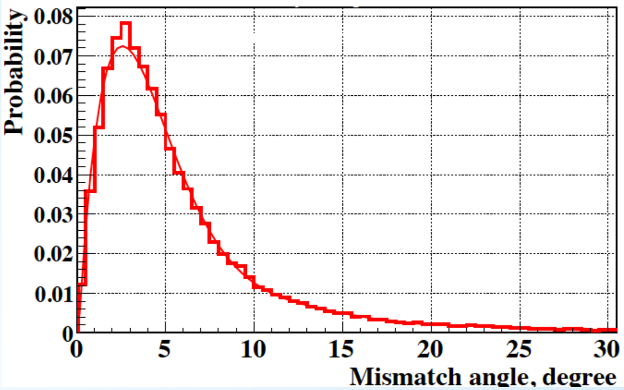


Sample of cascades induced in GVD: 2016, 2018



GVD areas, angular resolution, pdf with energy dependence





median ψ ~4.5deg

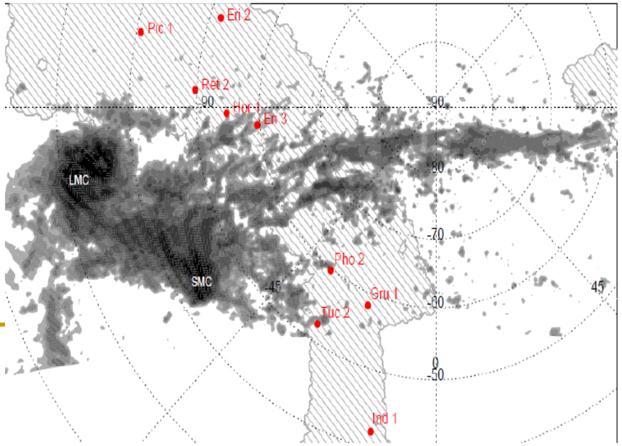
$$\mathcal{L}_{\mathrm{dSphs}} = \prod_{j=1}^{46} \left\{ \int \frac{dJ_j}{\log(10)\bar{J}_j\sqrt{2\pi}\sigma_j} \exp\left[-\frac{(\log_{10} J_j - \log_{10} \bar{J}_j)^2}{2\sigma_j^2} \right] \times \right.$$
$$\left. \times \prod_{i=1}^{N_{\mathrm{Fermi}}} \frac{1}{\sqrt{2\pi}\overline{\sigma}_{ij}} \exp\left[-\frac{\left(\frac{d\Phi_j}{dE_i} - \frac{d\bar{\Phi}_j}{dE_i}\right)^2}{2\overline{\sigma}_{ij}^2} \right] \right\}$$

in progress

// **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"}

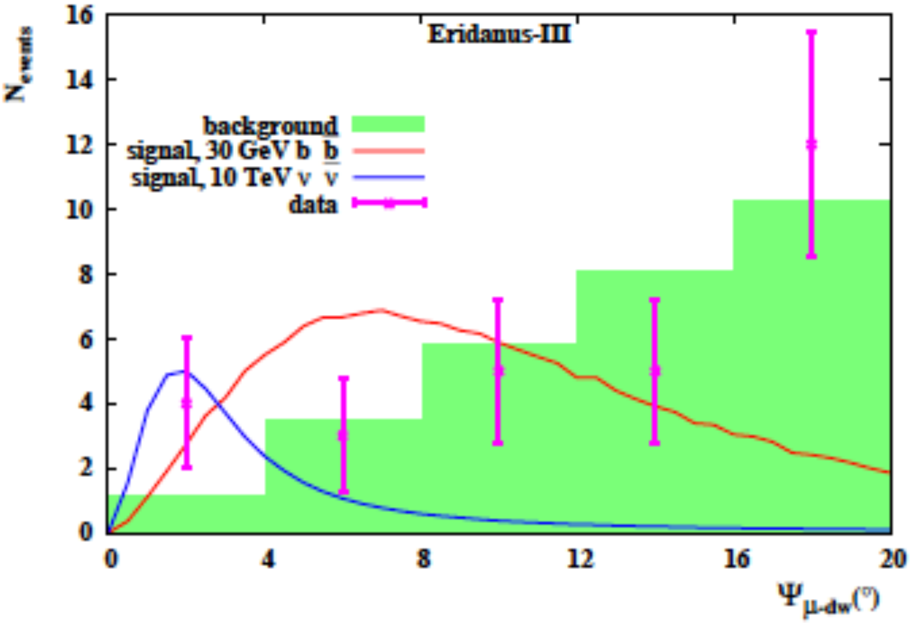


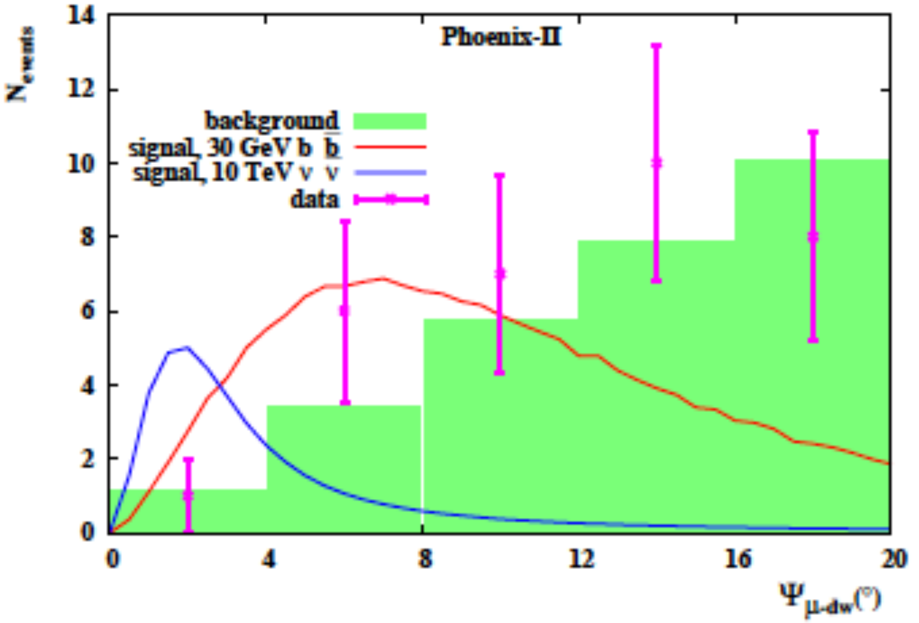
DM constrains from observation of 22 dSphs

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

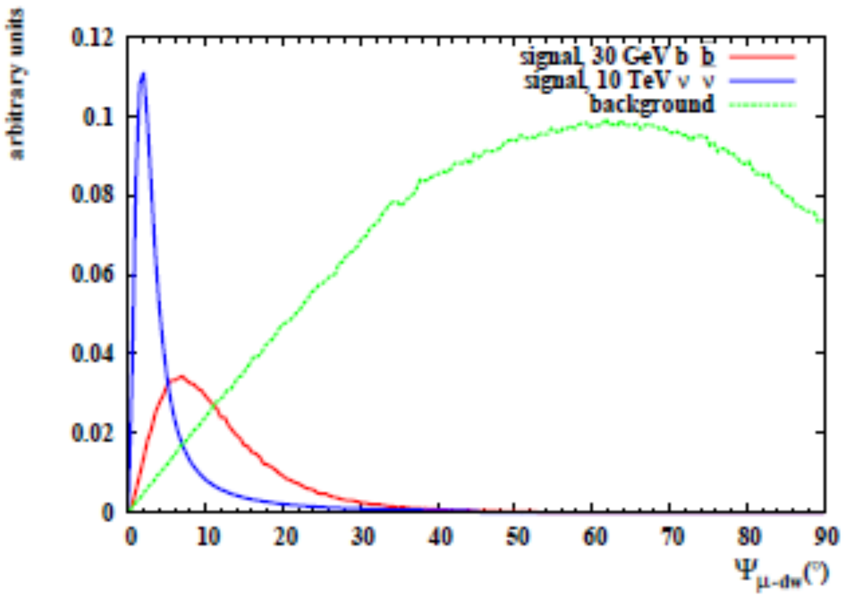
$$\frac{d\phi_\nu}{dE_\nu d\Omega} = J_a(\psi)\,\frac{\langle\sigma_a v\rangle}{8\pi m_{DM}^2}\,\frac{dN_\nu}{dE_\nu}$$

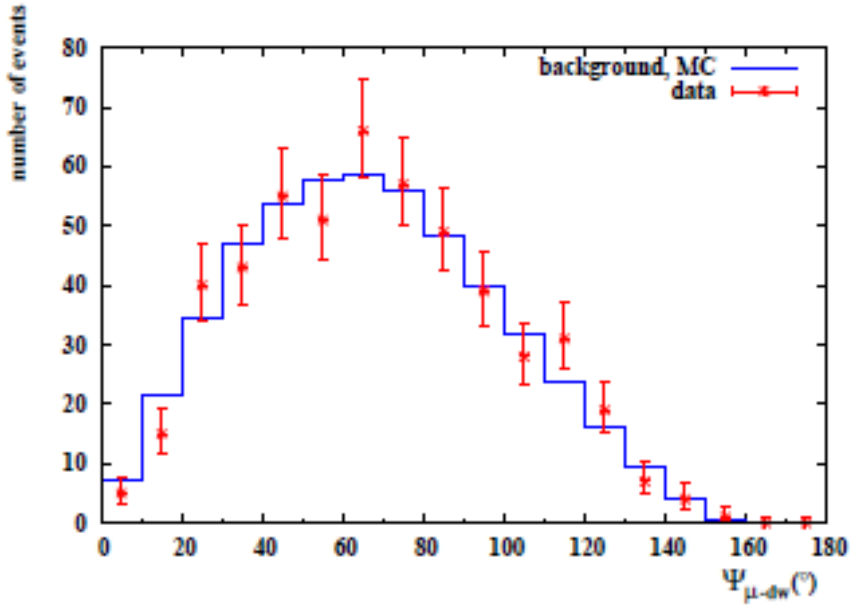
Angular distributions of signal and background for each dwarf





Reticulum 2 : NT200 background and signal angular distributions





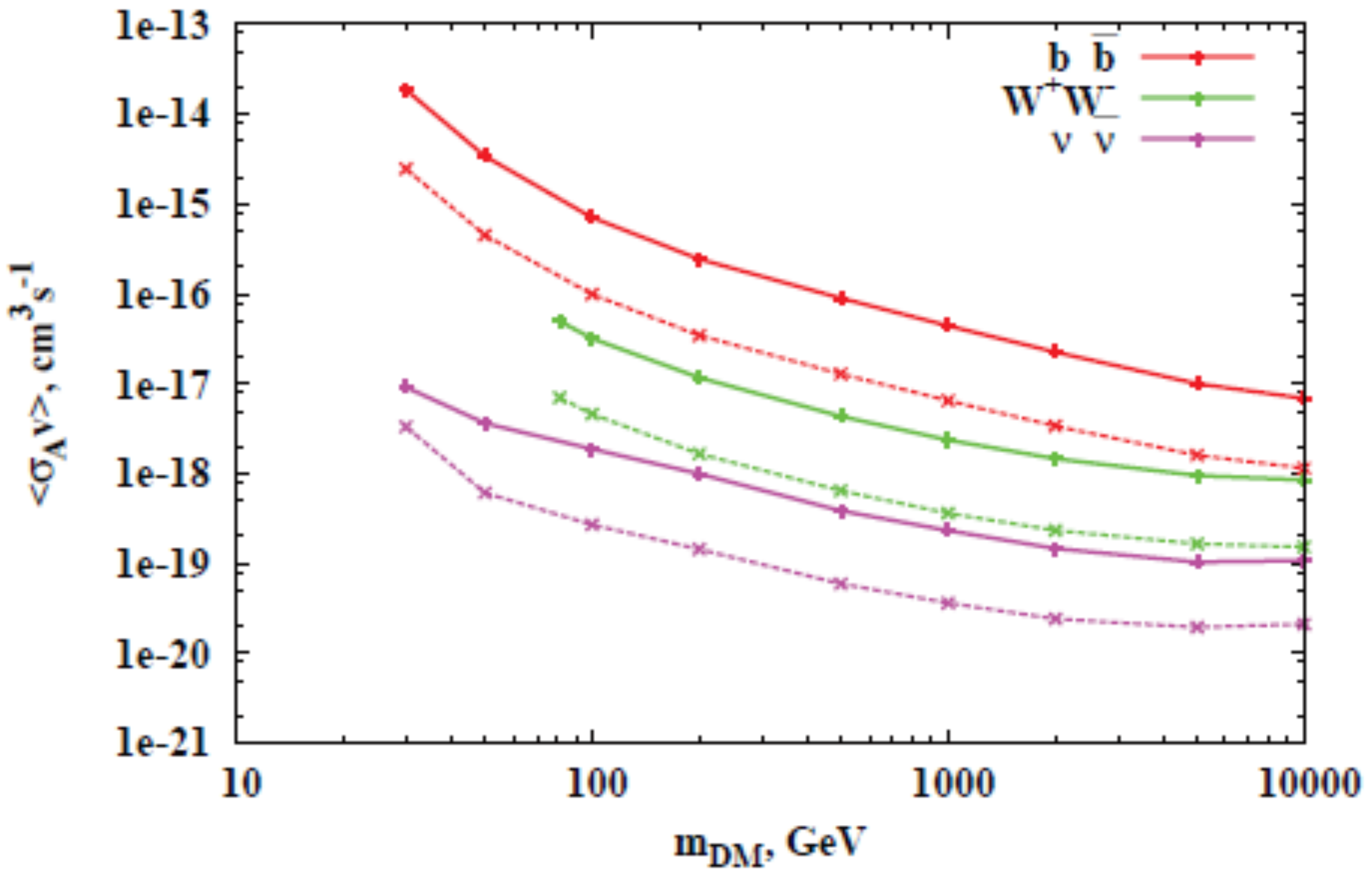
$$\mathcal{L}(N_S) = \frac{(N_B+N_S)^n}{n!} e^{-(N_B+N_S)} \mathcal{J}(J_2^{dw}|J_2^{dw,obs}, \sigma^{dw}) \prod_{i=1}^{n} f(\psi_i, N_B, N_S)$$

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)

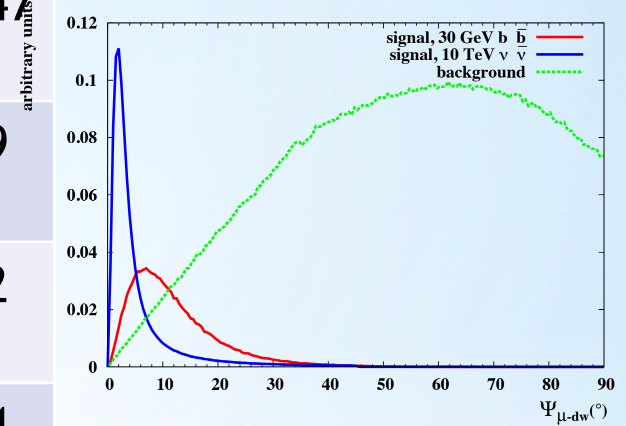


Name	δ	α	$\log_{10}(J_2^{dw,obs}/GeV^2cm^{-5})$	σ_{dw}
Segue 1	16.08	151.77	19.36	0.29
Reticulum 2	-54.05	53.92	19.8	0.4

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

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

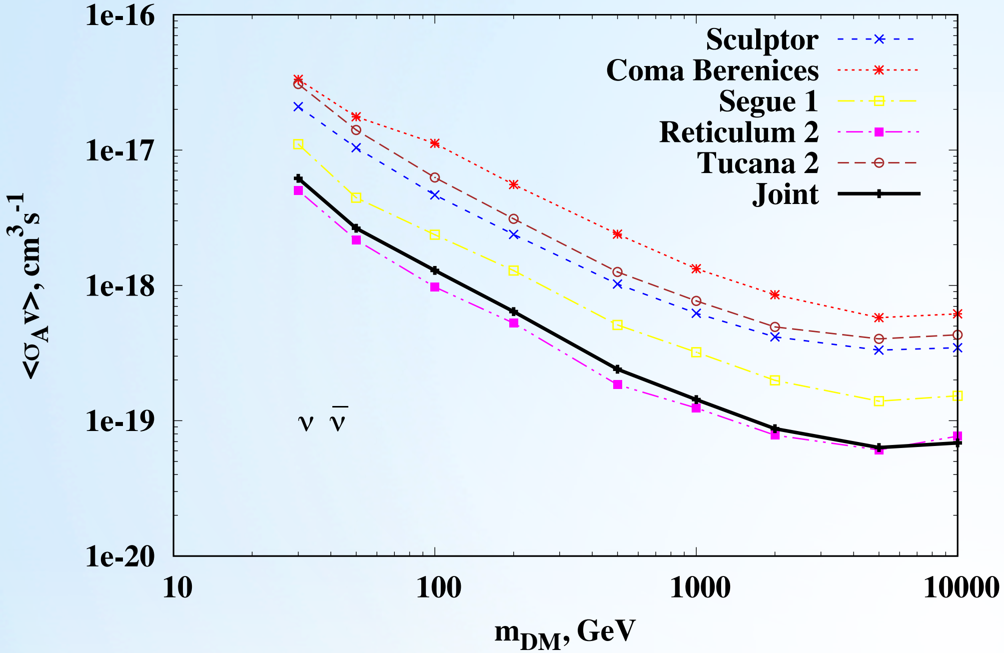


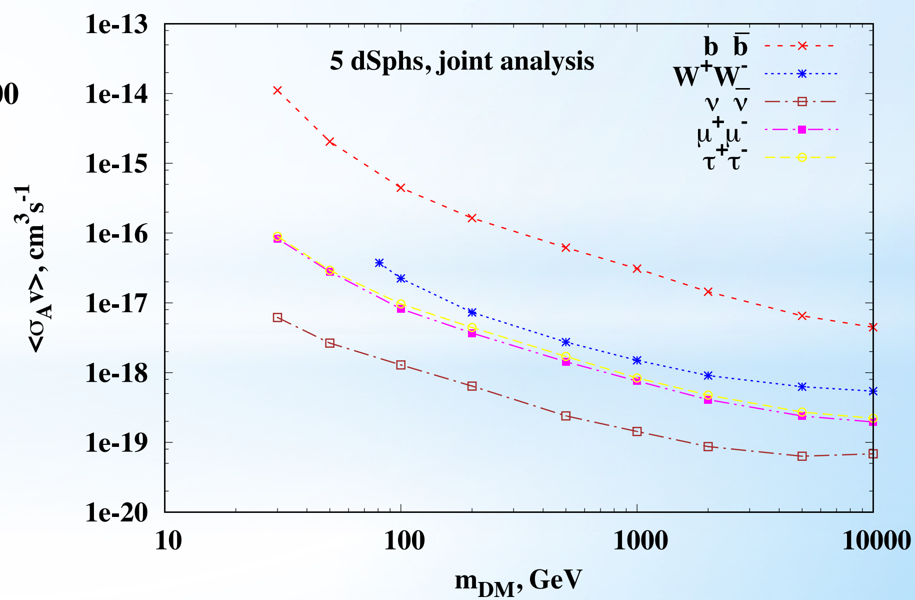
$$f(\psi, N_S, N_B) = \frac{1}{N_S + N_B}\left(N_S f_S(\psi) + N_B f_B(\psi)\right),$$

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

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

Baikal upper limits towards 5 dSphs and combined analysis





Direction towards the Large Magellanic Cloud

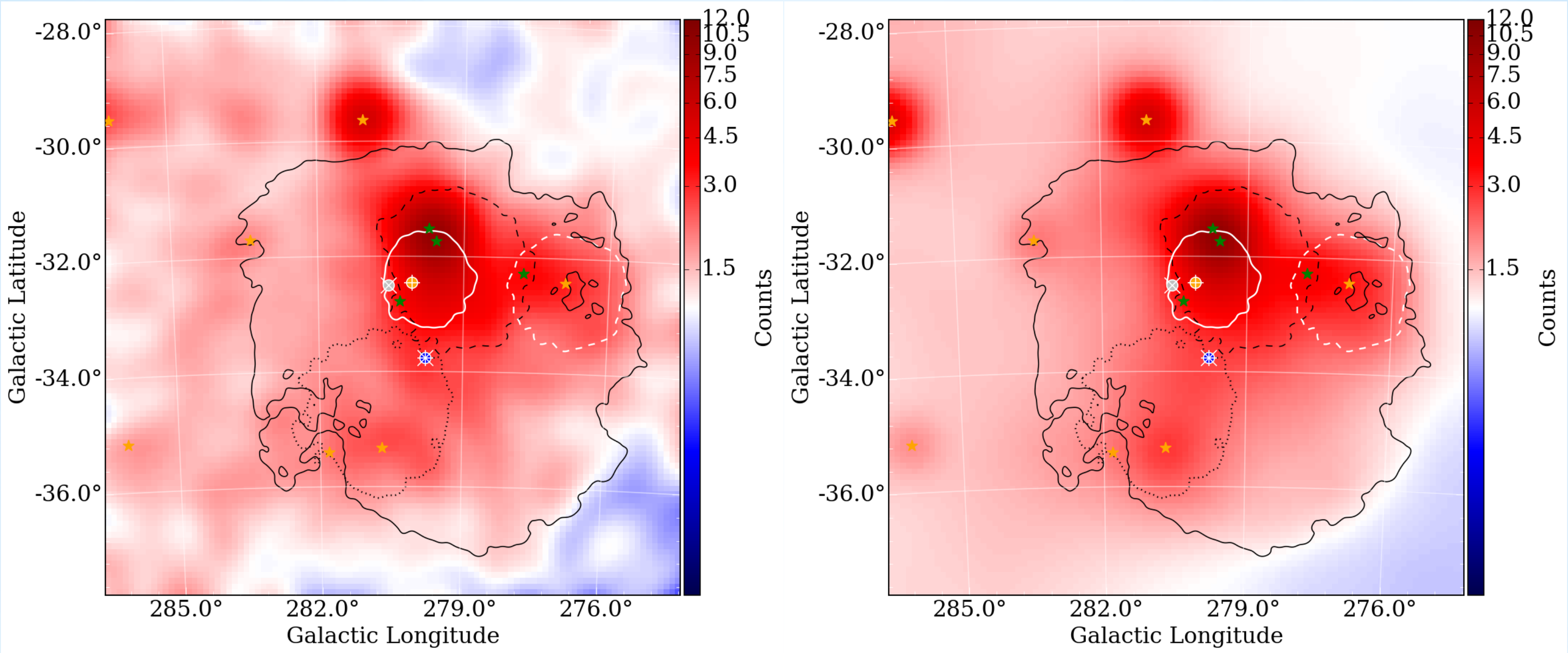


FIG. 6: Left: Counts map of the LMC region, in the energy range from 792 MeV to 12.6 GeV. Right: Model map of the same region and for the same energy range created from the emission model (see text for details). Both maps are binned in $0.^\circ1 \times 0.^\circ1$ pixels and smoothed with a $\sigma = 0.^\circ3$ 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

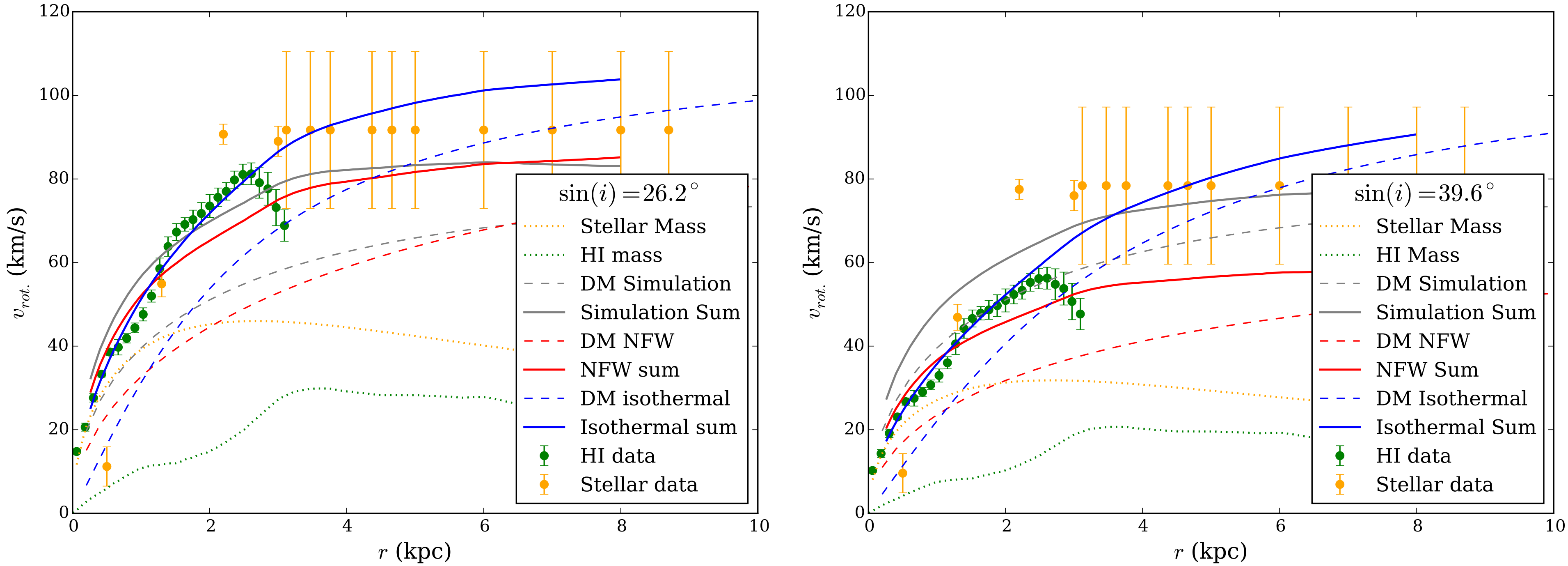
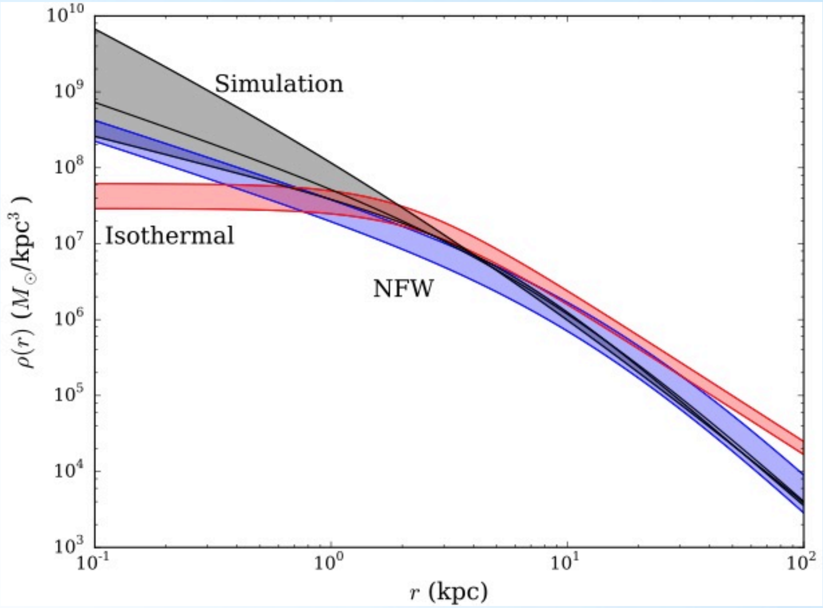


FIG. 1: LMC rotation curve data, assuming an inclination i that maximizes (left) and minimizes (right) the dark matter density. Stellar $v_{\rm rot}$ data are shown with orange points [80], and H I $v_{\rm rot}$ data [79] in green. The orange dotted line denotes the contribution to $v_{\rm rot}$ from 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

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

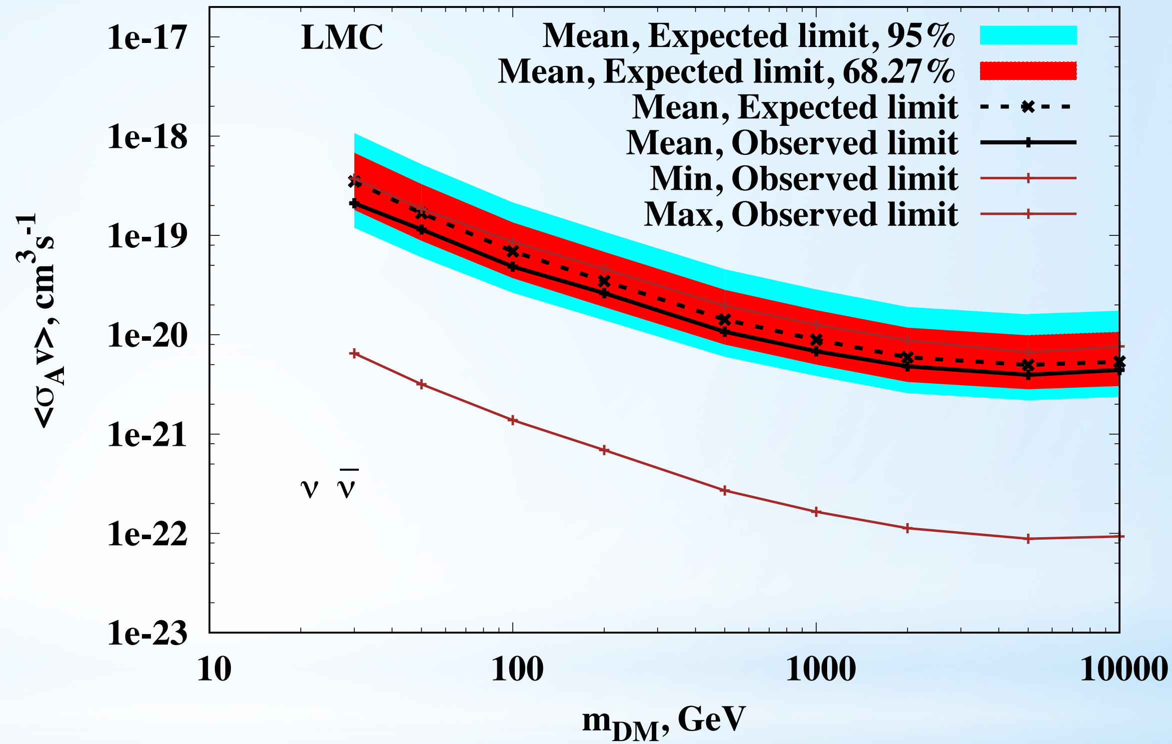
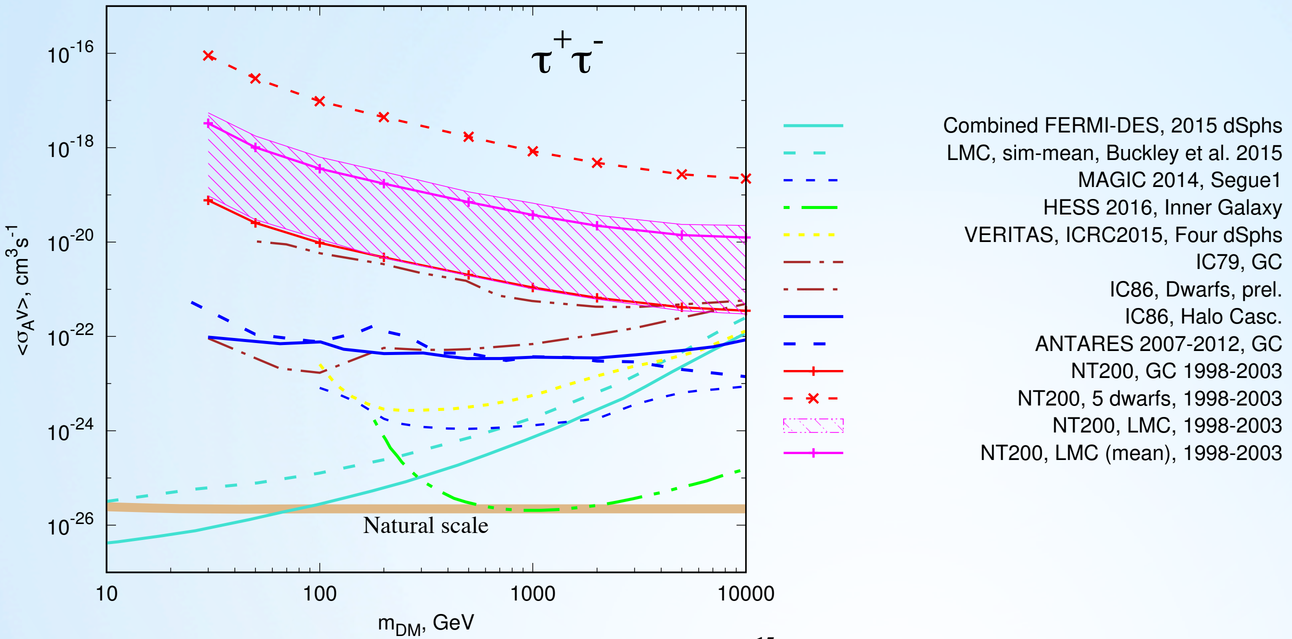
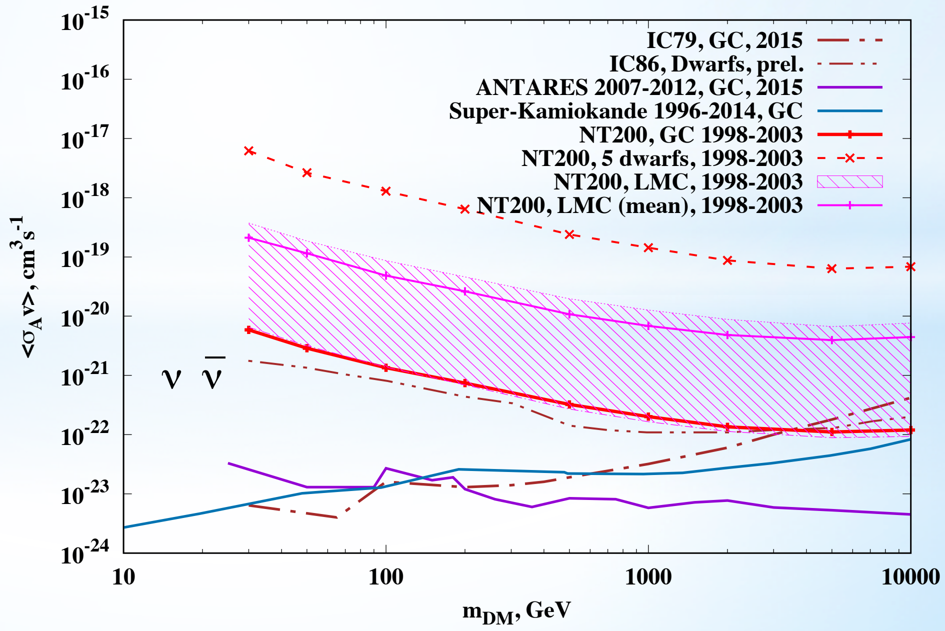


Fig. 8. 90% CL upper limits from the NT200 data assuming different dark matter density profiles for LMC (solid lines) and sensitivity (dashed line) on dark matter annihilation cross section assuming annihilation to $\nu\bar{\nu}$. Colored bands represent 68% (red) and 95% (blue) quantiles.

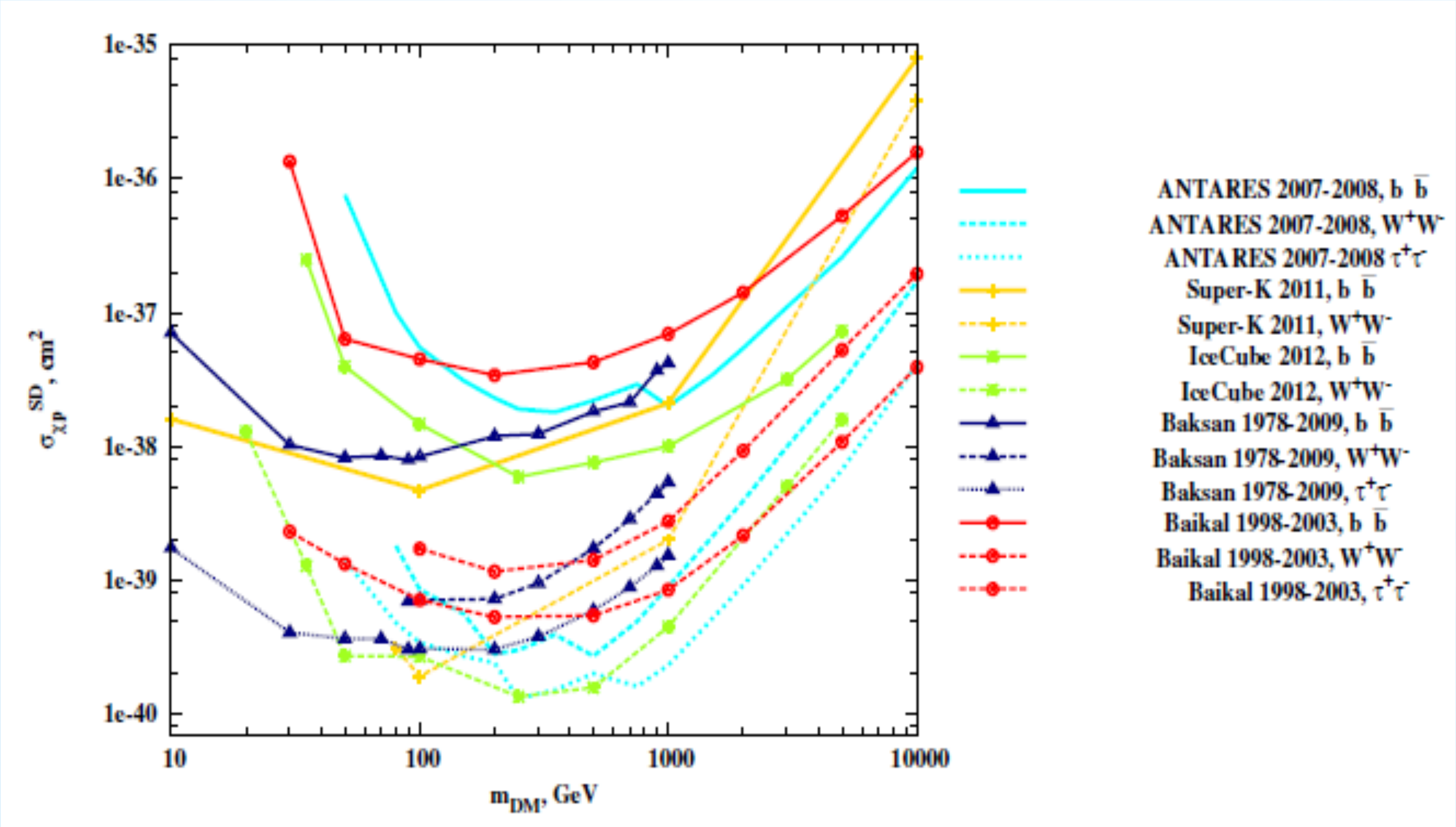
Towards the LMC: upper limits of γamma- and ν- telescopes





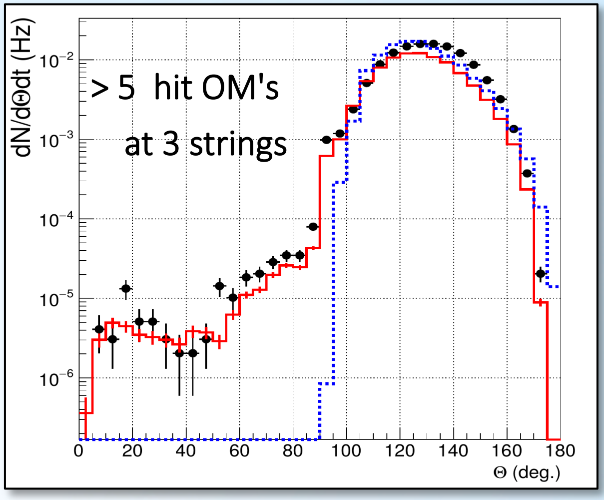
Solar DM: UpL on spin-dependent (SD) cross section DM-p, Baksan, ANTARES, SK, IceCube and Baikal NT200 (result_2014)

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



*Outlook

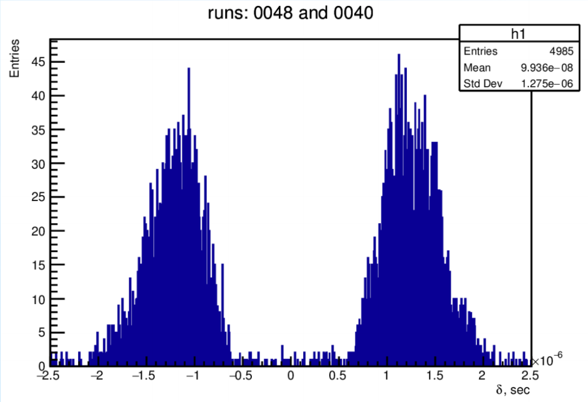
We expect to improve the Baikal results with incoming data of the GVD in search for neutrino signal from expected annihilations of DM particles inside the astrophysical sources



Further progress in track reconstruction

Method of surviving true hits 94% and BDT criteria results to mismath angle ~ 1.2deg median

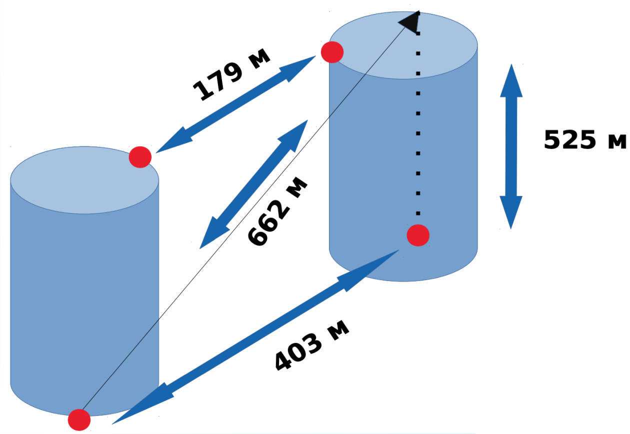
We see potential in multicluster events



Each cluster has 5 ns precision timestamp synchronized with GPS

Muon flight time 0.6 - 2.2 μs through 2 neighbored clusters

Joint event rate is 0.2 Hz



Prospect in combined analysis of GVD data with other NTs

Timeline GVD-1 to reach 0.4 km^3

Year	2016	2017	2018	2019	2020	2021
Nb. of clusters	***1***	***2***	***3***	***5***	***7***	***9***
Nb. of OMs	***288***	***576***	***864***	***1440***	***2016***	***2592***

Baikal-GVD collaboration:

9 institutes, ~60 scientists

RSF grant 17_12_01547
RFBR grant 16-29-13032