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STATUS OF INDIRECT DARK MATTER SEARCH WITH NEUTRINO TELESCOPES

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We discuss here the latest results of high-energy neutrino experiments with neutrino telescopes in search for neutrino emissions from astrophysical sources where there is every likelihood that relic Dark Matter has been clumped and annihilates till present time, e.g., in the Sun, the Galaxy Center, and the Dwarfs.

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INTRODUCTION

Measurements of the Cosmic Microwave Background (CMB), that is, relic radiation from the Early Universe, prove stringent constraints on the matter and energy densities, assuming the ΛCDM (Lambda Cold Dark Matter) model. The baryonic matter of the Universe weighs only 4.9%, while there are 26.8% of relic Dark Matter, which might be nonrelativistic and collisionless, and 68.3% of dark energy, which is consistent with a cosmological constant.

Why ΛCDM? The CMB data from the nine-year Wilkinson Microwave Anisotropy Probe [1] alone and in combination with the first-year Planck satellite measurements [2] are well described by the cosmological parameters of the ΛCDM, each determined to a high precision (less than 1.5%). Implying the ΛCDM model, the size of the matter fluctuations derived from data of the CMB temperature and polarization and joined with measurements of the Hubble constant and the baryon acoustic oscillation scale is consistent with all observed matter variances over a large range of scales, including redshift cluster abundances, gravitational lensing and peculiar velocities. Certainly, there is no convincing evidence for deviations from this cosmological model.

What is Dark Matter? In astronomy and cosmology, Dark Matter phenomena is well known as a "hidden mass" of matter that offered to exit from gravitational effects on visible matter and radiation. DM itself is invisible by emitted or scattered electromagnetic radiation. The first Dark Matter conception was suggested

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by F. Zwicky to explain unexpected fast Doppler velocities of galaxies within the Coma cluster and estimated a large mass-to-light ratio (about 50), thirty years later, in 1970, V. Rubin discovered flat rotation curves in observations of the orbital speeds of stars in about sixty spiral galaxies. These observations make compelling evidence for Dark Matter and claim an existence of a Dark Matter halo around spiral galaxies like the Milky Way (MW). Presently a preferable density profile of the DM distribution in the MW halo is not determined as will be discussed below. However, N-body simulations have shown that the Galaxy Center is the brightest DM annihilation signal in the sky, compared to the Dwarfs (dSphs) or the sub-halos of DM and other possible clumped structures. For an observer on the Earth the presence of invisible clumped matter along the line of sight at the distant galaxy or cluster of galaxies have to play a role of a gravitational lens, which was predicted by Einstein on the basis of his theory of general relativity hundred yeas ago. Later, in 1979, a gravitational lens was first discovered with a double image of the same distant quasar. A gravitational lensing is a powerful tool in cosmology, which allows one to estimate the amount of Dark Matter contained in the lens mass. First direct proof of Dark Matter existence was found by the Chandra Observatory in 2006 from observation of hot gas collisions in the bullet galaxy cluster 1E0657-56 using a joint analysis with optic telescopes data. The total mass in gravitational lensing was found to be much greater than X-rays emission of hot gas. Moreover, lack of acceleration by Dark Matter in collisions between galaxy clusters supports for its nonbaryonic nature, while lack of DM deceleration constrains its self-interaction cross section.

What Dark Matter for ΛCDM? The DM density Ω_χ expressed in units of critical density proves to be a very narrow bind $0.1198 < \Omega_\chi h^2 < 0.1187$ [3], where h is the Hubble parameter in 100 (km/s)/Mpc. If Dark Matter is relics produced thermally in the Early Universe, their annihilation strength ensures density Ω_χ naturally at electroweak scale. The "natural scale" for Maxwellian-averaged self-annihilation cross sections $\langle\sigma_{\rm ann}v\rangle$ is determined to be $\sim 3 \cdot 10^{-26}$ cm$^3 \cdot$ s^{-1}. In particle physics, so far in the Standard Model (SM), there is no candidate on particle-like DM except of neutrino in role of hot or warm DM moving at relativistic velocities since freeze-out time. However, active neutrinos (hot DM) have too light masses (at least less than eV) to explain the observed large-scale structures (LSS). Sterile neutrinos with keV masses (warm DM) could be good DM candidate if they exist, but they alone would not be enough for LSS formations. Therefore, particle-like DM might be some "neutrino" beyond the SM, like a Weakly Interacting Massive Particle (WIMP) being the lightest particle in a supersymmetry (SUSY neutralino) or in the unified field theories with its predicted mass in GeV–TeV range. Also, it could be SuperWIMPs as gravitino and axino, either Peccei–Quinn axions in QCD or many other new particle-like fields in the extensions of the SM (for review see, for example, [4]). The WIMPs have a preference in experimental searches among the "particles zoo", since its all three strengths — production, scattering, and annihilation — are testable at the electroweak scale. Correspondently, there are methods of direct detection by missing energy measurements at TeV colliders of particle productions as with the LHC or in low-radioactivity background experiments of scattering reactions on nuclear targets. In dependence on a target composition and energy recoil transmission there are numerous detectors and projects (for review see, for example, [5]). The targets being studied for indirect methods of DM searches are astrophysical objects mentioned above. The annihilations of DM particles generate copies of ordinary matter particles which are searched for by the ground-based and the satellite on-board gamma-ray telescopes and for the neutrino telescopes of high-energy neutrino detection.

Is Dark Matter a Particle? According to present status of searches for the Dark Matter signature, no DM particle was found in direct searches; for light DM masses there are placed upper bounds on cross sections of scalar elastic scattering on nucleons at the level of neutrino coherent cross sections at MeV; the LHC data at 7 TeV with 20 fb^{-1} luminosity results in stringent limits on existence of new SUSY particles; and finally, there is increasing importance of indirect detections. Namely, studies with the gamma rays and neutrino telescopes. In particular, the recent FERMI-LAT results [12] with a joint likelihood analysis of the Galactic Center and dwarfs present limits on annihilation cross section $\langle\sigma_{\rm ann}v\rangle$ which is lower than expectation for a Dark Matter as thermal relics for its mass less than 100 GeV.

1. HIGH-ENERGY NEUTRINO EXPERIMENTS

The feature of a DM search with high-energy neutrino telescopes (NTs) is their measurements of penetrating relativistic particles produced in neutrino interactions with medium at more than kilometer depth of water equivalent reducing the atmospheric background fluxes. Dark Matter neutrino origin itself could be identified by an excess in number of events coming from the directions of supposed DM source. Charged particles generated in neutrino interactions in water and ice emit Cherenkov light since its velocity $\beta > 1/n$, where n is a coefficient of medium refraction. Cherenkov radiation of neutrino-induced muons and electromagnetic showers are collected by optical modules (OM) with photomultiplier tubes (PMTs) configurated in 3D arrays of photodetectors on strings. Its detection efficiency is determined by that of Cherenkov photon emitted at fixed angle (θ_C) relatively the track of moving relativistic particle at each point of its path. Therefore, it is a helpful directional signal in reconstruction of arrival time of particle and its angular coordinates, while optical properties of medium play its basic role in attenuation of light. In Fig. 1, one can see absorption and scattering coefficients of water and ice in appropriate photon wavelength range at three sites of neutrino telescope deployment: in Lake Baikal (the NT200 [7] and

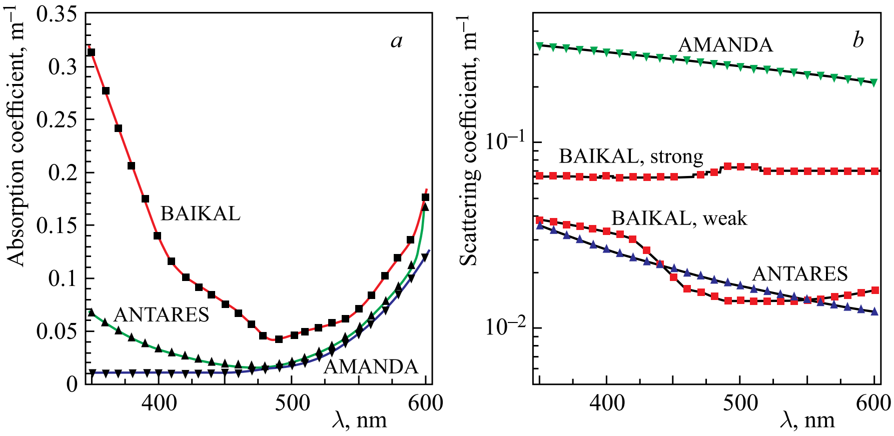

Fig. 1. Spectral dependence of absorption (*a*) and scattering (*b*) coefficients of the Baikal water, the Mediterranean Sea water, and Antarctic ice (from [7])

first cluster of the GVD [6]), in the Mediterranean Sea (the ANTARES, see [19] and references therein), and in Antarctic ice at the South Pole (the IceCube of km^3-sizes and early the AMANDA, see [20] and references therein). Although the Cherenkov angle θ_C in water and ice is approximately the same, about $42°$, the signal attenuation is essentially different and affects the angular resolution and so far the configuration of the photodetector arrays and its energy threshlods in total. Note a large scattering coefficient and a short attenuation length (less than 30 m) of the deep-ice layers. Defined reason are the plural inhomogeneities of ancient atmospheric sediments inside ice at the depths of 1500–2500 m. Their presence results in angular uncertainty of $\sim 15°$ for shower directions even at PeV energies. The shown characteristics of the Baikal pure water at a depth of 1100 m and the Mediterranean deepwater at about 2500 m provide a good accuracy in directional measurement both of muon and showers. In particular, the Baikal GVD project [6] with 2304 OMs estimate muon angular resolutions to be 0.25 deg with muon effective area 0.3 km^2 above 1 TeV and 3–6 deg with shower effective volume 0.4–2.4 km^3 above 10 TeV. The tenth part of the giga volume detector efficiencies is reached by the GVD first cluster (named "Dubna") deployed in Lake Baikal in April 2015. A factor of hundred is gained by the Dubna in the muon and showers detection efficiencies compared to the Baikal first-generation detector NT200. However, a low-energy neutrino threshold of 10 GeV allows the NT200 to search for signature of light WIMPs much more effectively than the expanded telescope, starting of 20 GeV for annihilation spectra of either leptons or quarks. The better sensitivity is presented by the ANTARES. This telescope is configured by 900 OMs and detects upgoing neutrino events above 15 GeV, while its neutrino effective area is about 0.1 m^2 above 10 TeV. The compatible parameters and sensitivity are for the DeepCore cluster inside the IceCube whose 79 strings are composed by 5160 OMs along 1 km at depth down to 2450 m. In dataset analysis the IceCube selects neutrino events from both hemisphers, but with different efficiencies.

Since the energies of neutrinos arising from a DM annihilation cover a range of GeV–TeV, there is a strong energy dependence o angular resolutions on neutrino directions. Following kinematics of neutrino scattering in charged current interactions and further multiple scattering of produced low-energy muons, the corresponding r.m.s. angle of $\nu{-}\mu$ angular distribution increases up to a few degrees for GeV neutrino, while it is a part of a degree for TeV energies. There is a challenge of sophisticated reconstruction of the lower energy part of events comoved by dominating atmospheric muon and neutrino background from upper and lower hemispheres, respectively, as well as by isotropical kHz noise of water/ice medium. There are different strategies in event reconstruction applied by each experiment. They include minimization of a chi-square or a likelihood ratio test of parameter distribution functions from hitted time-causing photodetectors. Analysis of data is subdivided into lower (LE) and higher energetic events (HE) and is followed by a joined analysis. Separations are either on a single- and a multi-string events, as it was done by the ANTARES [19], or on contained, partially-contained, and through-going events, as it was used by the Super-K [22] for upwardgoing muons and also the IceCube for downgoing muons by using its inner cluster of 10-GeV neutrino threshold and the veto conditions [14].

Among the operating neutrino telescopes only non-Cherenkov detector is the aged underground telescope at the Baksan with 300 t of liquid scintillator in 3150 tanks arranged into four-floor building (see [17] and references therein). The telescope is measuring the ionization trajectories of penetrating particle by the time-of-flight method. Neutrino events analysis is based on selected dataset of the upgoing through-going muons. The muon energy threshold is about 1 GeV, while the angular resolution determined by its geometrical sizes and structures is $\sim 1.5^\circ$. Due to a long-term observation with 24.12 yr of live time (l.t.) [17] the Baksan exposure is comparable with current very large volume detectors, whose data are obtained for five years with the ANTARES in structures of 5 to 12 strings [19], also with the Baikal NT200 of 8 strings for 2.6 yr of l.t. [18], and for different time periods of working configurations of the polar telescopes, from one to nine years [20]. Also underground installation is the Super-Kamiokade (see [22] and references therein) which is using 50 kt of pure water for Cherenkov light detection. The Super-K dataset analysis has been done for more than 12 yr of l.t. Their recent preliminary results on DM searches [22] present the most stringent upper bounds within systematic errors on a WIMP scattering and self-annihilation cross sections for the masses lower 100 GeV and down to 1 GeV due to included analysis of a sub-GeV range of measured upgoing muons. Let us consider how these results are complementary.

2. SEARCH FOR DARK MATTER IN THE GALAXY

A diffuse gamma-ray excess in the Galactic Center (GCE) in FERMI-LAT data is seen as significant central and spatially extended excess in Fig. 2. Shown are maps in galactic coordinates within window of $5 \times 5^\circ$ of fluxes in units of 10^{-4} γ/cm^2/s/sr for raw data (*a*) and for the residual after subtracting all estimated background (*b*) [8]. The detection of the GCE has been discussed in many recent papers with its intepretations by a DM annihilation in the MW halo, whose profile was fit by a generalized Navarro–Frenk–White (NFW) model [9] with inner slope of 1.1–1.4 [8]. As illustrated in Fig. 2, *b*, spectral shape of the GCE is harder at low energies than that of emmisions from globular clusters and

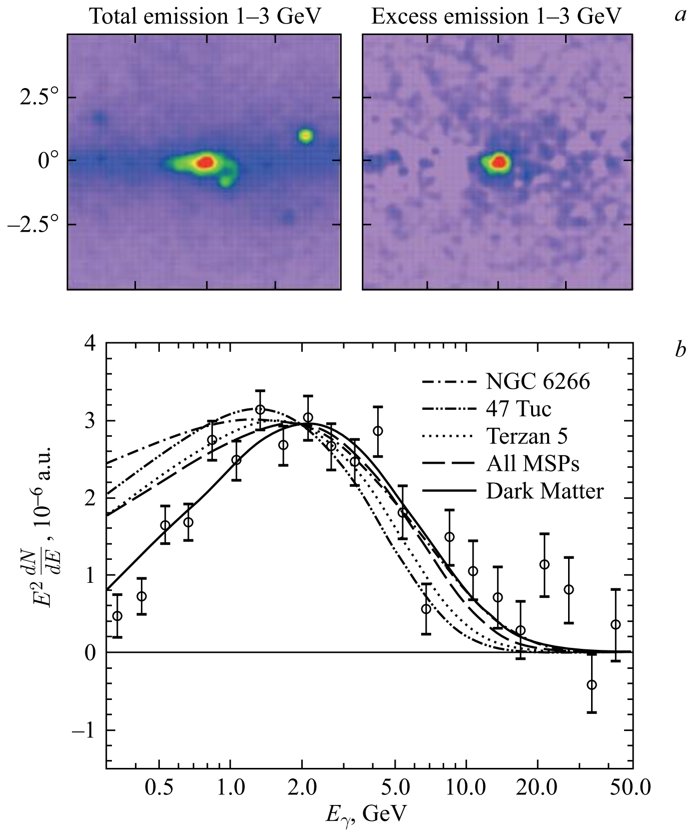

Fig. 2. Observed 1–3 GeV excess in FERMI-LAT data toward the Galactic Center (*a*) and a comparison (*b*) of the GCE with emission from globular clusters and from the sum of resolved millisecond pulsars. The best fit of data by DM annihilations is shown by the solid line (from [8], see the text)

from the sum of millisecond pulsars detected by the FERMI-LAT as individual point sources. Moreover, the GCE spectrum can be well fit by annihilation spectra either in $b\bar{b}$ branch (WIMP of 30–60 GeV) or $\tau^+\tau^-$ branch (WIMP of 5–15 GeV), while the normalization of the signal is in remarkable agreement with annihilation cross section for a thermal relic. Recent improved analysis of FERMI-LAT data

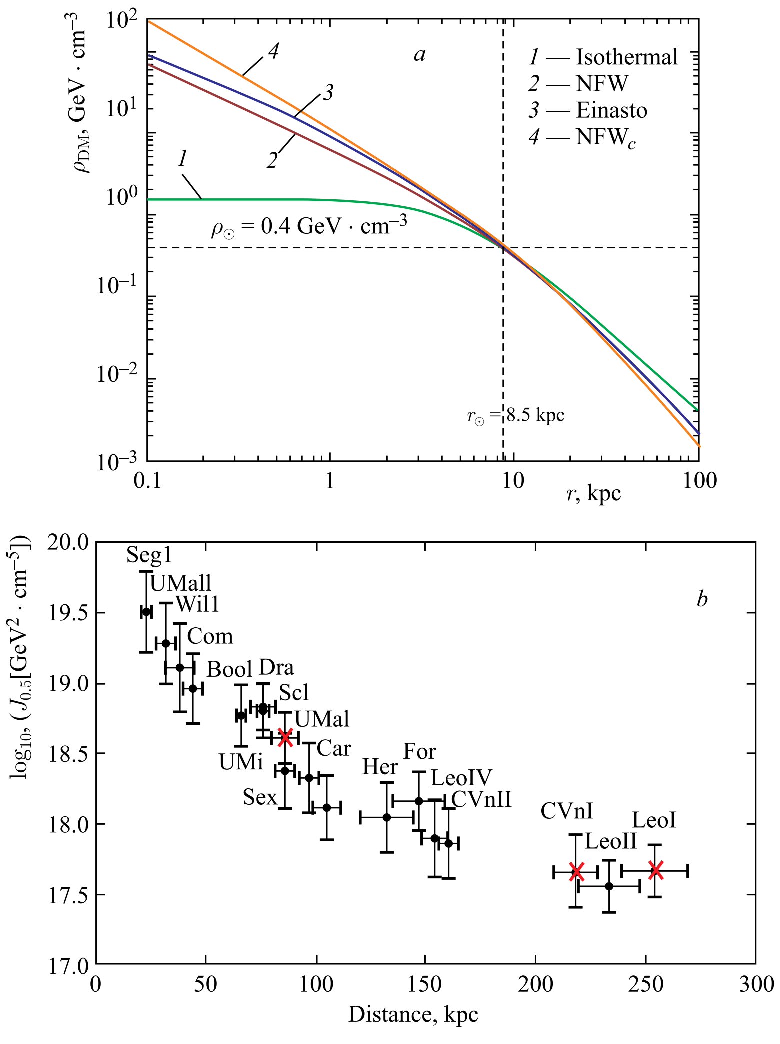

Fig. 3. *a*) Density profiles of the MW Dark Matter halo in several models (from [10]). The top line is for the NFW$_c$ model and the bottom line is for the isothermal model. *b*) J-factor of 15 dwarfs versus distance (from [11])

(pass 8) [12] with new dwarf limits indicate some tension in consistency of Dark Matter interpretations with the GCE, either it indicates a steeper inner slope for a MW density profile or preferable value of a local DM density ($\rho_{\rm loc}$, in the solar system) is rather 0.4–0.5 $\rm GeV \cdot cm^{-3}$. There are different modeling distributions of a DM density in central halo region of the MW, which could be shaped with or without core or spike as shown in Fig. 3, *a* for some of them. A convinient model in ΛCDM is the NFW. It is used for comparison of results from different experiments. Theoretical uncertainties of modeling halo profile are involved in the astrophysical factor, J-factor, which is integrated square of the DM density in the Galaxy (ρ^2) along the line of sight. In Fig. 3, *b*, dimension astrophysical J-factors for fifteen dwarfs, determined with data of stars velocities, are shown. Rescaled to the distance R_0, a dimensionless J-factor at the angular distance ψ from the source to the direction of observation is written as follows:

$$J(\psi) = \int\limits_0^{L_{\rm max}} \frac{dr}{R_0} \, \frac{\rho^2\left(\sqrt{R_0^2 - 2rR_0\cos\psi + r^2}\right)}{\rho_{\rm loc}^2}, \tag{1}$$

where $L_{\rm max}$ is a length exceeding the size of the Galaxy. One might expect equal fluxes of gamma rays and neutrinos (hereinafter we mean neutrino and antineutrino) from the DM annihilation in the MW or dwarfs, since they are defined by the same astrophysical factor and spectra of particle decays in annihilation branches. The fluxes being proportional to annihilation rate, which is determined by annihilation cross section and a DM mass, are written in the form

$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v\rangle}{2} J(\psi) \, \frac{R_0 \rho_{\rm loc}^2}{4\pi m_{\rm DM}^2} \, \frac{dN_\nu}{dE}, \tag{2}$$

where $\langle \sigma_A v\rangle$ is annihilation cross section averaged over DM velocity distribution; dN_ν/dE is neutrino or gamma-ray spectrum per one annihilation in given branch (channel). Note a dependence on ρ^2 (in J-factor) and inverse dependence on $m_{\rm DM}^2$, square of a DM mass, in Eq. (2). Propagating the galactic distances from a DM source a flavor content of neutrino fluxes is not affected by their oscillations. Also small is attenuation of the fluxes in the Earth for GeV–TeV neutrino energies. Therefore, the spectral shapes of neutrino energy distribution in each annihilation channel are very close to the decay spectra at the production and can be calculated with a number of numerical codes. Expected number of neutrino events for time observation in the detector towards a DM source is the integrated product of neutrino affective area and flux from Eq. (2) over neutrino energies from threshold to $m_{\rm DM}$ inside a cone around the source direction. In the search region the background of atmospheric neutrino is estimated by scrambling data and is followed by optimization of a signal-to-background (S/B) ratio (see, e.g., [13,14]). Note that the Galactic Center is a spread source and its region of a signal search is not less than a few degrees, as was discussed above. In a lack of event excess inside the cone the upper limits on neutrino flux are set in the Bayesian or frequentist approaches. Finally, a conversion of upper limits on neutrino flux to upper limits on annihilation cross section $\langle\sigma_A v\rangle$ is resolved by Eq. (2) for each annihilation channel. In Fig. 4, one can see a comparison of upper limits/sensitivities at 90% C.L. on $\langle\sigma_A v\rangle$ in tau-lepton annihilation channel obtained by gamma-ray and neutrino telescopes, i.e., FERMI-LAT, MAGIC, H.E.S.S. (see [14] and references therein) — shown are dwarfs limits (dSphs, dark spheroidal galaxies) and also the results of DM interpretation of positron excess [24]; IceCube with DeepCore (IC79) [14], ANTARES [13] — shown are GC limits and also GC sensitivity of the GVD [15]. The upper bounds on annihilation cross section $\langle\sigma_A v\rangle$ of a DM in dwarfs should be definitely weaker than GC limits with the same detector. Here there are Virgo limits of the IceCube which concern the results with their incomplete configuration (IC59) for longer livetime observations than it was with IC79. More stringent bounds on $\langle\sigma_A v\rangle$ with the NTs are placed obviously in branch of monochromatic neutrinos from DM annihilations (not SUSY WIMP) as is presented in Fig. 5. Other stringent limits on $\langle\sigma_A v\rangle$ in neutrino channel are in preliminary results of the Super-Kamiokande [22] respond to 90% C.L. of about 10^{-24} cm$^3\cdot$s^{-1} for $m_{\rm DM} \sim 1$ GeV and 10^{-22} cm$^3\cdot$s^{-1} for 10 TeV of a DM mass.

Systematics errors are incorporated in all shown results. There are uncertainties above 10% in the cross sections of neutrino interactions as well as in oscillation parameters. Contribution of experimental systematics erros could be 30% defined by photodetector functions and as well depends on medium characteristics. So far there is a wide errors belt in sensitivity of neutrino telescopes (shown, e.g., in [14]). Nevertheless, J-factor uncertainties are much bigger as discussed above. Note also that shown results in Figs. 4 and 5 imply the NFW halo

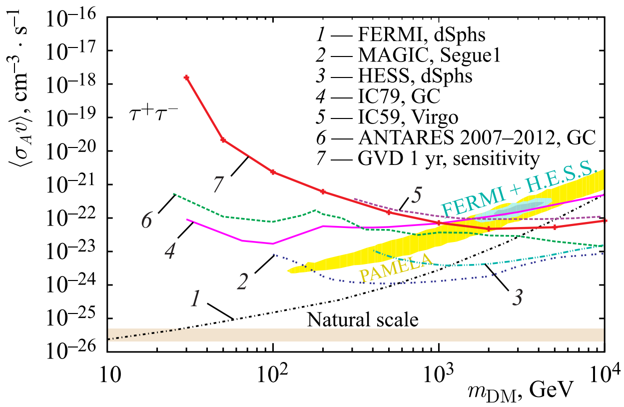

Fig. 4. Upper limits and sensitivities on DM annihilation cross section in tau-lepton channel from NTs and gamma-ray telescopes (see the text)

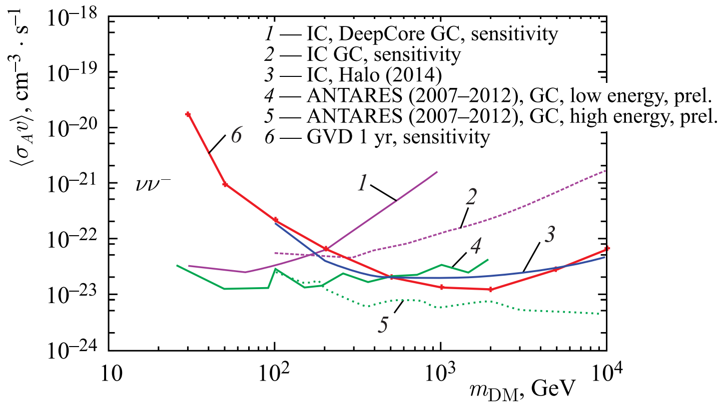

Fig. 5. Upper limits and sensitivities of neutrino telescopes on DM annihilation cross section in neutrino–antineutrino channel

profile and $\rho_{\rm loc}$ of 0.3 GeV $\cdot$ cm^{-3}. In general, the neutrino telescope searches for galactic Dark Matter present compatible limits, while their sensitivity even of most harder energy spectrum is weaker than present dwarfs limits of gamma-ray telescopes.

3. SEARCH FOR SOLAR WIMPs

Dark matter local density in the Solar System $\rho_{\rm loc}$ estimated by N-body simulations is rather small to appear a DM presence. Assuming the speeds of halo WIMPs crossing the ecliptic plane are nonrelitivistic with mean velocity of ~ 270 km/s (root-mean-square of the dispersion of Maxwellian–Boltzmann distribution) these particles could be gravitationaly trappered by the Sun. Further multiple scattering of WIMP off solar matter is likely happened with energy losses. Due to these interactions, WIMPs can be captured inside the Sun. Their orbital motion changes to spiral falling down to the dense center, where they finally settle and accumulate as well as self-annihilate at a distance smaller than annihilation length. During a live time of the Sun these two processes of capture and annihilation may reach approximate equilibrium, and thus accumulated number of WIMP does not change with time. Solving known Boltzmann evolution equation for the number of WIMPs in the Sun, it is easy to show that annihilation rate Γ_A is a half of capture rate C_C when equilibrium time is less than age of the Solar System, $4.5 \cdot 10^9$ yr. Expected neutrno flux from Dark Matter annihilations in the Sun under condition of equilibrium is related to the captute rate and neutrino spectra at the detector level, i.e., is written in the form

$$\frac{d\phi_\nu}{dE} = \frac{C_C}{2}\,\frac{1}{4\pi R_d^2}\,\frac{dN_\nu}{dE}, \tag{3}$$

where $R_d = 1$ a.u. is a distance to the Sun. Calculation of the capture rate C_C is numerical. In simplified model of the solar potential which can be parameterized by escape velocity on distance from the center of the Sun it was found an analytical form of the capture rate C_C which shows its direct functional dependence on values of scattering cross sections, velocity distribution, local DM density and solar model. There are related big uncertainties in these quantities, exceeding experimental systematics. Also, note the inverse dependence on square of a DM mass within a function C_C in Eq. (3). Emphasize that expected signal rate has direct dependence on scattering cross section that is complementary to the direct detection experiments. Since solar chemical composition consists of hydrogen in more than 73%, WIMP could scatter off proton in axial-vector (spin-dependent, SD) and in scalar (spin-independent, SI) interaction, dominanting a contribution to the capture rate and annihilation rate. In the case of exact equilibrium, annihilation rate can be divided into two corresponding parts of SD or SI type of contributions (see, e.g., [16]). Further, the conservative upper limits on SD and SI elastic cross section of DM particles on proton can be obtained from conversion of found upper limits on number of events in the signal region around the Sun, using Eq. (3) for each annihilation channel and DM mass. The same way as for galactic Dark Matter searches there is determination of a size of the cones toward the Sun for given annihilation channel and mass by optimization of a signal-to-background ratio along the Sun trajectory. As mentioned above, the expected number of neutrino events in the telescopes is defined by their effective areas averaged over given neutrino sprectra. During the propagation of neutrinos from the center of the Sun to the level of the detector the neutrino sprectra are modified, since three-flavor neutrino oscillations happen in the Sun, in the vacuum, and in the Earth including matter effects, absorption of neutrinos due to charged current interactions with the interior of the Sun and the Earth and the change of the energy spectrum due to neutrino neutral current elastic scattering and τ-regeneration. It was shown by Monte Carlo simulations (see, e.g., [17]) there is a decrease of neutrino flux from $b\bar{b}$ branch and ν flux increasing from W^+W^- and more essential ν flux enhance from $\tau^+\tau^-$ channel compared to their spectra in generation point. Present searches for solar WIMP with operating neutrino telescopes found a lack of event excess over background toward the Sun. Resulted upper limits have been set at 90% C.L. on SI and SD elastic scattering cross sections of WIMP on proton in selected annihilation channels $\tau^+\tau^-$, $b\bar{b}$, W^+W^-, where systematic and statistical errors have been taken into account. In range of low WIMP mass (about 10 GeV) there are a number of results from direct searches of a DM, which claim on WIMP signatures in a number of experiments, i.e., DAMA, CoGeNT, CRESSTII, CDMS-II (see [21, 22] and references therein). Corresponding bounds from latest larger projects as LUX and XENON-100 (also shown in Fig. 6 as in [22] and [21]) almost fully exclude the DM interpretations of the excesses, as is seen from Fig. 6, a [21]. A challenge

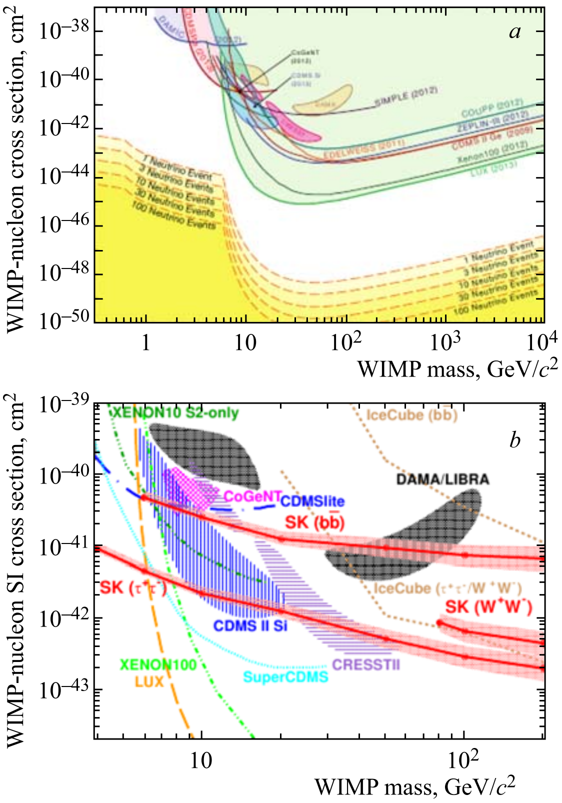

Fig. 6. A comparison of results of direct detection experiments (*a*, [21]) on SI elastic cross section of WIMP scattering off nucleon with the upper limits presented by neutrino experiments (*b*, [22]) (see the text)

in further increasing of detector exposure at lighter DM mass is a presence of irreducible background from MeV neutrino coherent scattering off nuclear target [21]. There are compatible limits on SI scattering of WIMP on proton obtained with neutrino telescopes of low energy threshold, the Baksan [17] and Super-Kamiokande [22]. As shown in Fig. 6 [22], Super-Kamiokande upper limits on SI cross-sections scattering of WIMP on proton strongly exclude most part of “signal-lands” starting from lightest WIMP mass. If consider the upper limits on SD cross sections, there are not so many results from direct searches of WIMP in its SD scattering off nucleon. The most stringent limits on SD elastic scattering of Dark Matter are presented by Super-Kamiokande also in [22], while there is the Baikal NT200 analysis [18] for six annihilation channels including three pairs of active neutrino–antineutrino shown in Fig. 7. Also shown are results in direct searches with DAMA, PICASSO, KIM, SIMPLE, COUPP (see [18] and

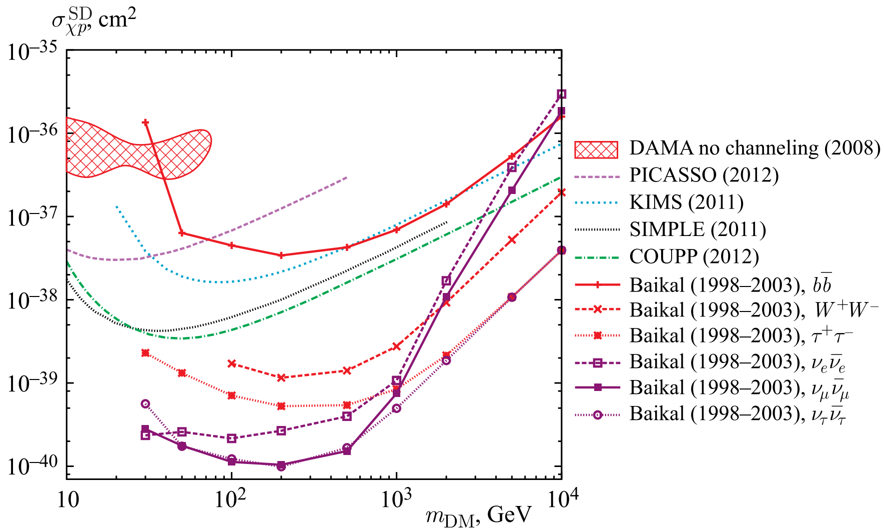

Fig. 7. Comparison of the upper limits at 90% C.L. on SD elastic cross section of a DM scattering off proton in six annihilation channels obtained with Baikal NT200 with results of the direct detection experiments

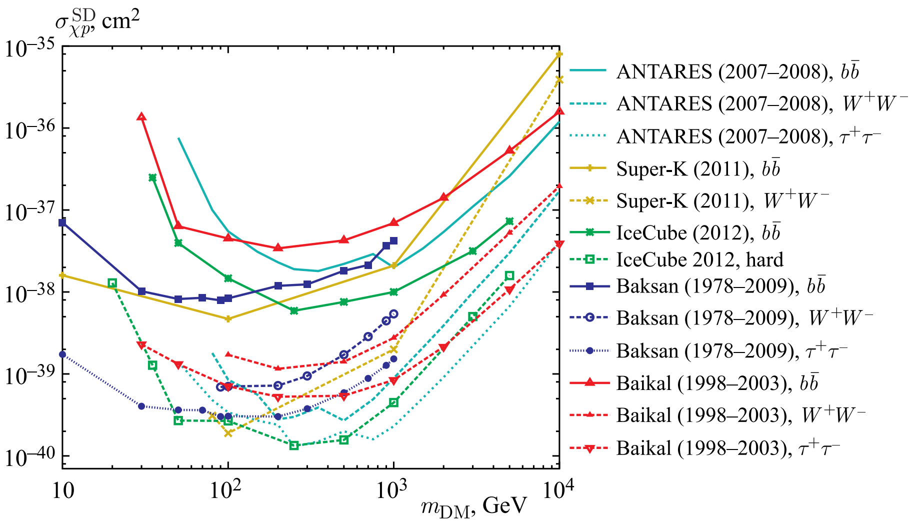

Fig. 8. Upper limits at 90% C.L. on SD elastic cross section of a DM scattering off proton obtained with a number of neutrino telescopes

references therein). Exclusion of DAMA [23] results and the strongest bounds are provided by neutrino telescopes. Most stringent upper limits are in annihilation branches of monochromatic neutrinos producing hardest neutrino spectra related to each DM mass, and thus a better detection sensitivity to a signal in DM searches. The obtained level of 10^{-40} cm^2 for SD cross section of a DM scattering off proton is stringent value among the upper limits with neutrino telescopes and considered annihilation channels, that is presented in Fig. 8.

4. SUMMARY

Searches for Dark Matter with neutrino telescopes are complementary to searches with other astrophysical messangers, also to direct detections, and between each other. Being stringent in the lepton branches, the obtained upper limits by NTs on Dark Matter strengths of scattering both in scalar and spin-dependent interactions close ranges of event excess or annual modulation signals reported by some direct detection experiments. The NTs limits on annihilation cross sections are not so strong as combined limits by the gamma-ray telescopes, which have crossing a nonthermal relics region for light DM masses. For future searches the new frontier for DM detection with NTs could be still related both with light and heavy Dark Matter.

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