Dark Matter Searches at Baksan Underground Scintillator Telescope

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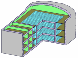
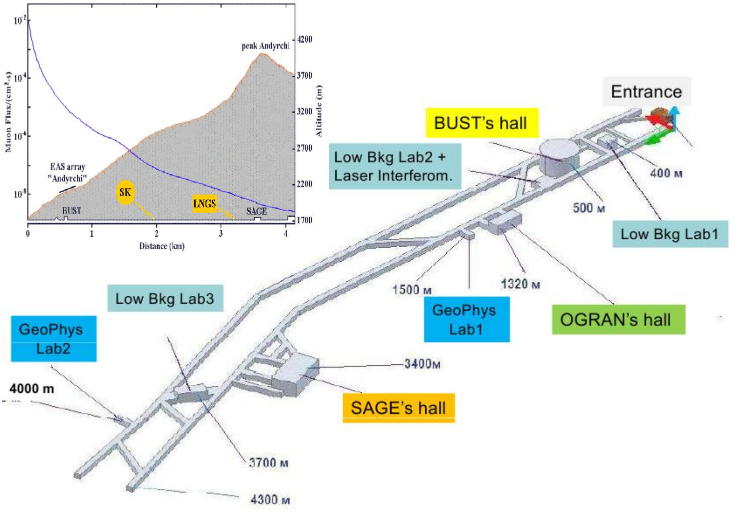


Outline

Signal from DM annihilations in the Sun

- DM particles scatter off nuclei in the Sun
- DM can become gravitationally trapped
- Accumulation and annihilation of DM in the center of the Sun
- Neutrino flux from the direction towards the Sun

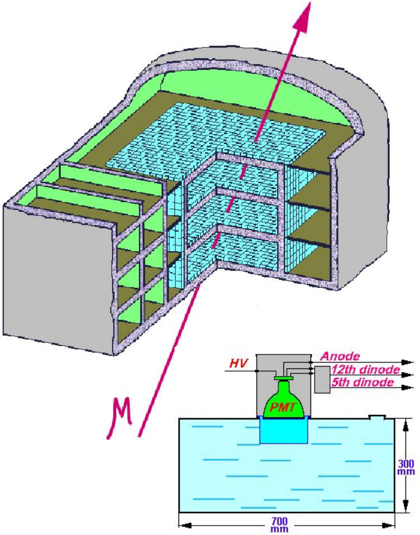
Baksan Neutrino Observatory



Baksan Underground Scintillator Telescope

Baksan Underground Scintillator Telescope

General view



- depth: 850 hg/cm^2
- size: 17 m × 17 m × 11 m
- 3150 tanks of size 70 cm × 70 cm × 30 cm
- angular resolution: about 1.5°
- time resolution: 5 ns
- general trigger rate: 17 Hz
- muon fluxes upward/downward ratio: $\sim 10^{-7}$

In operation since 18 December 1978

Baksan Underground Scintillator Telescope

Time-of-flight method and event selection

- time resolution is about 5 ns (Yu. Andreyev et al., 1979, S.P.Mikheev, 1984)
- probability of imitation of “wrong” direction is considerably diminished if more then two planes involved
- two special triggers for upward muons: T1 - for zenith angle range $95^\circ \div 180^\circ$, T2 - for almost horizontal events: $80^\circ \div 100^\circ$

Trigger T1

- ≥ 3 scintillator planes
- ≥ 2 negative Δt
- ≤ 3 external scintillator planes

Trigger T2

- $= 2$ vertical scintillator planes
- $= 0$ horizontal scintillator planes
- $\Delta t \geq 30$ ns (pathlength ≥ 10 m)

trigger rate 0.02 Hz (1800 events per day)

Event selection: additional cuts

Cuts Level 1

- Only one reconstructed track with $\beta < 0$
- Enter point should be below exit point
- For T2: exclude events with $0 < \phi < 180$ with respect to least shallow depth

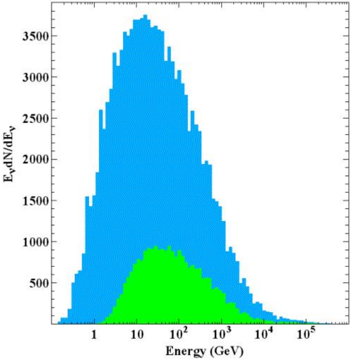
Cuts Level 2

- Only through going tracks (no stopping muons or neutrino interactions inside)
- Muon range inside detector > 500 g/cm^2 (excluded muons with $E_\mu < 1$ GeV)
- Geometrical cuts to exclude events close to plane edge (1.5 m)
- $-1.3 < 1/\beta < -0.7$ (from MC: 95% of upward-going events)

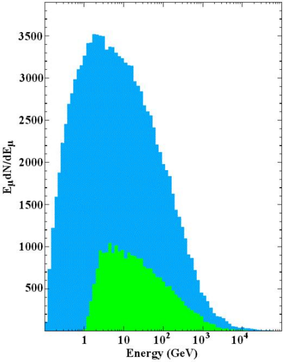
December 1978 – November 2009; livetime 24.12 yrs;
1700 muons after Cuts Level 1; 1255 muons after Cuts Level 2

MC simulation and reconstruction

O.Suvorova, M.Boliev, S.Mikheev et al., 1996



Neutrino



Muon

Muon energy threshold $E_\mu > 1$ GeV

Efficiency of registration upward-going muon with $E > E_{th}$ is about 0.3

Signal simulation

- DM particles can become gravitationally trapped in the Sun
- (Anti)Neutrinos are produced in the result of DM annihilations produced in the center of the Sun
- Propagation of neutrinos in the Sun and Earth
- Expected muon flux from dark matter annihilation in the Sun

$$\Phi_\mu = \frac{\Gamma_A}{4\pi R^2} \times \sum_{\nu_j,\bar{\nu}_j} \int_{E_{th}}^{m_{DM}} dE_{\nu_j} P(E_{\nu_j}, E_{th}) \frac{dN_{\nu_j}}{dE_{\nu_j}}$$

$P(E_{\nu_j}, E_{th})$ - probability of neutrino-muon conversion,

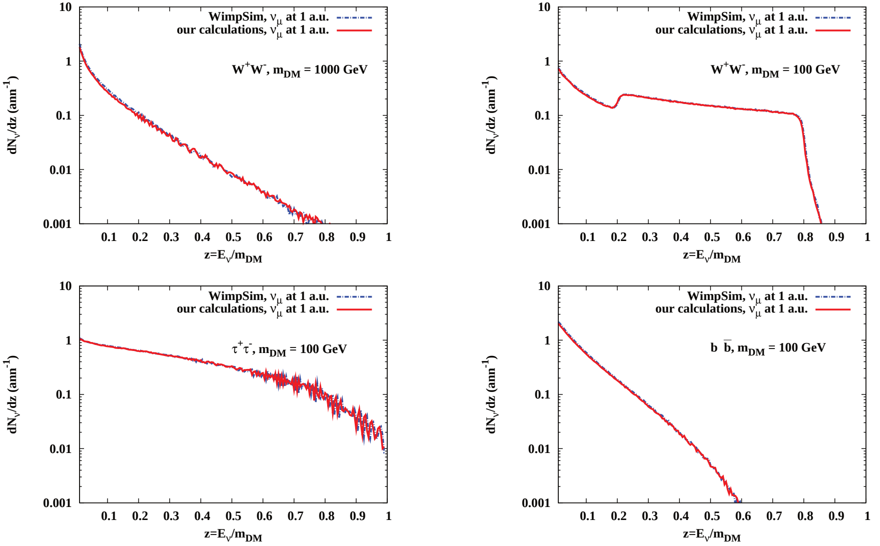
- $\frac{dN_{\nu_j}}{dE_{\nu_j}}$ - spectra of neutrino at production point - depend on annihilation channel: $\chi\bar{\chi} \to \ldots$
- Benchmark channels: $b\bar{b}$ (soft spectrum), W^+W^- and $\tau^+\tau^-$ (hard spectrum)

Signal simulation: overview and parameters

- We use our C program; compare results with WIMPsim (M.Blennow, J.Edsjo, T.Ohlsson, 2008)
- Initial neutrino spectra at the center of the Sun (M.Cirelli, N.Fornengo et al., Nucl.Phys. B727 (2005) 99)
- Annihilation point near the center of the Sun
- Neutrino oscillations, 3×3 scheme ($\Delta m_{21} = 7.63 \cdot 10^{-5}$ eV^2, $|\Delta m_{31}| = 2.55 \cdot 10^{-3}$ eV^2, $\delta_{CP} = 0$, $\sin^2\theta_{12} = 0.32$, $\sin^2\theta_{23} = 0.49$, $\sin^2\theta_{13} = 0.026$, D.V. Forero, M. Tortola, J.W.F. Valle, arXiv:1205.4018)
- Matter effects: solar model, J.N.Bahcall, A.M.Serenelli,, S.Basu (2005)
- NC and CC interactions (including τ-mass effects) in the Sun and the Earth: change in neutrino fluxes and spectra
- ν_τ regeneration: $\nu_\tau \to \tau^- + ...$, $\tau^- \to \nu_\tau, \bar{\nu_e}, \bar{\nu_\mu} + ...$ - secondary neutrinos

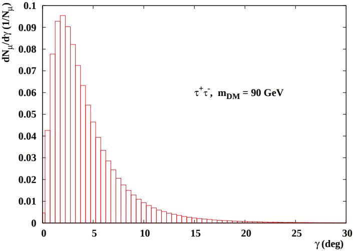
Comparison with WIMPsim: ν_μ spectra at 1 a.u.

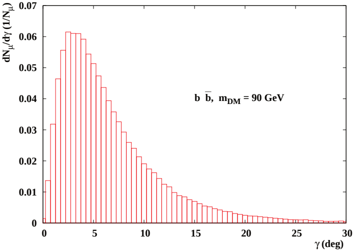
For the same initial neutrino spectra



Muon flux calculation

- Muons are produced in neutrino CC interactions
- Mean muon energy losses in rock (D.E.Groom, N.V.Mokhov, S.I.Striganov, 2001)
  $\langle \frac{dE}{dx} \rangle = -(\alpha(E) + \beta(E)E)\rho$
- Multiple Coulomb scattering



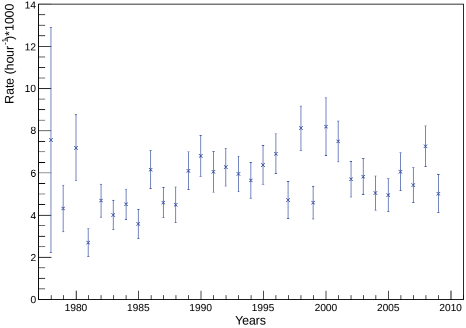


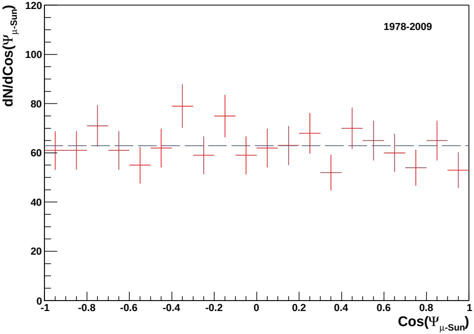
Upward going muons:

December 1978 - November 2009; livetime 24.12 yrs, 1255 events

Event rate

Muon distribution with respect to position of the Sun





About 50 events per year

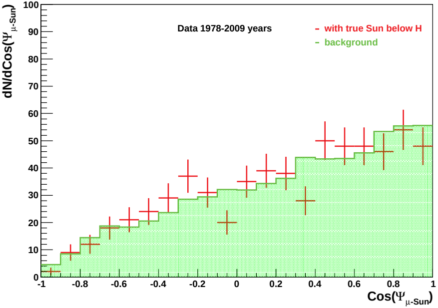
Direction to the Sun corresponds to $\cos\Psi_{\mu-\mathrm{Sun}} = 1$

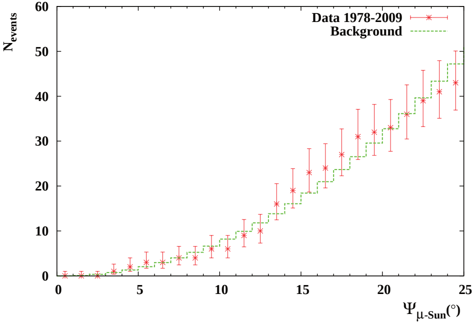
Data and expected background

December 1978 - November 2009; livetime 24.12 yrs

Sun below horizon

Number of signal and background events inside cone half-angle γ





Background – from data with shifted position of the Sun

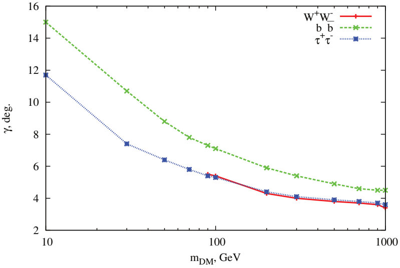
Optimization of analysis

In previous analysis we used cone half-angle γ which contains 90% of signal events

Optimization (Hill, Rawlins, 2003); expected limit on muon flux:

$$\text{sensitivity} = \frac{\bar{N}^{90}(\gamma)}{x(\gamma) \times S_{eff}(x) \times T},$$

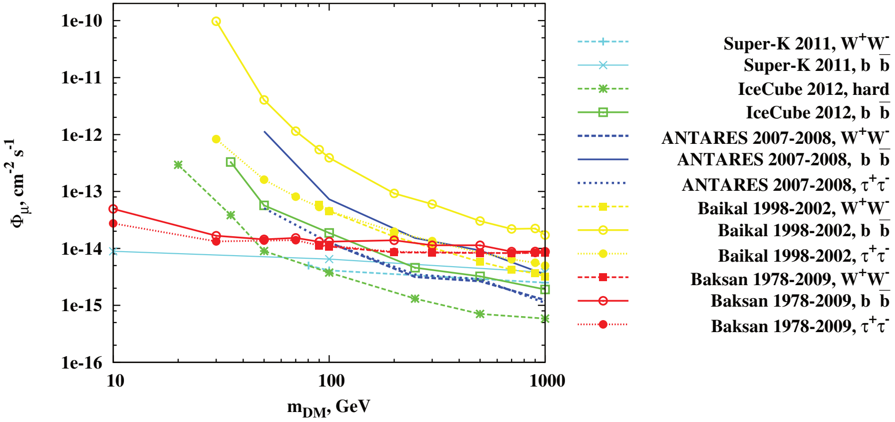
where $x(\gamma)$ is a fraction of event inside cone half-angle γ, $\bar{N}^{90}$ - mean expected upper limit



The effective area: $S_{eff}(E_{th}) = \frac{\int dEd\theta\ S(E,\theta) \times \epsilon(E_{th},E,\theta) \times \Phi_\mu(E,\theta)}{\int dEd\theta\ \Phi(E,\theta)}$

Upper limits on muon fluxes from DM annihilations

$$\Phi_\mu^{lim} = \frac{N^{90}(\gamma)}{x(\gamma) \times S_{eff} \times T}, \quad E_\mu > 1 \text{ GeV};$$



Recalculation to upper limits on SD

G. Wikstrom, J. Edsjo, 2009

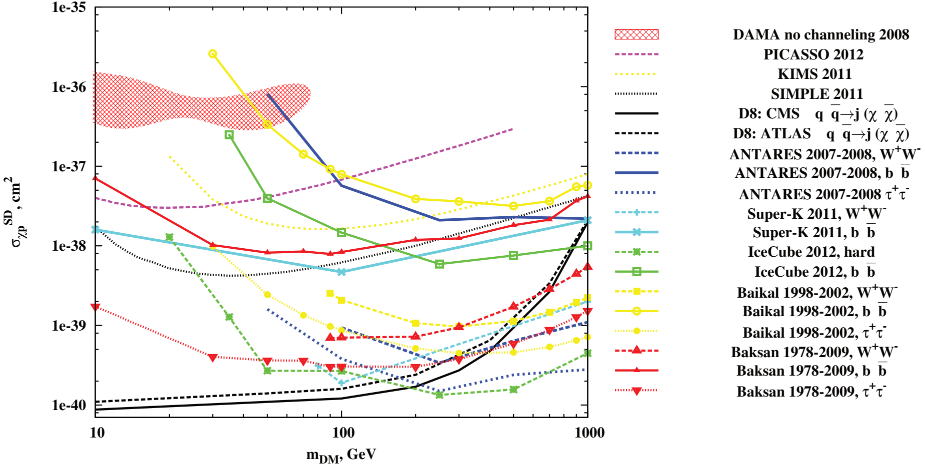
- Firstly, we recalculate $\Phi_\mu \to \Gamma_A$
- In equilibrium between capture and annihilation processes: $\Gamma_A = C_{DM}/2$
- Capture rate is determined by the SI and SD elastic cross section of DM particles on nucleons (Gould, 1987)
- Recalculation $\Gamma_A \to \sigma_p^{SD}, \sigma_p^{SI}$ (Olga Suvorova, S.D., 2010)

$$\Gamma_A = \Gamma_A^{SD} + \Gamma_A^{SI},$$

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

- Upper limits on SD cross sections are strong - a lot of hydrogen in the Sun

Upper limits on SD elastic cross section



Summary

- Analysis of upward-going muon data collected for 24.11 years of livetime by neutrino experiment at Baksan Underground Scintillator Telescope has been performed
- No significant excess was found in search for muon signal from dark matter annihilations in the Sun
- New limits on muon flux, annihilation rate, elastic cross sections

Thank you!

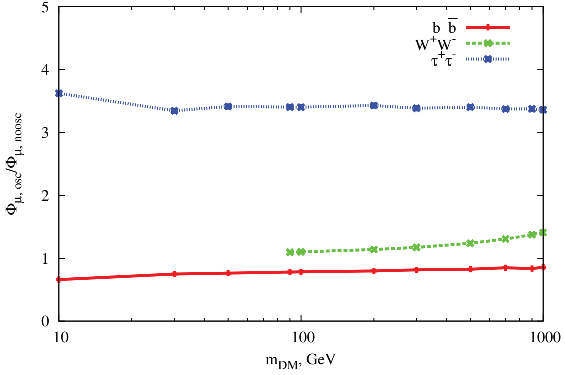
Backup slides

Systematic uncertainties

- Experimental uncertainties: $\approx 8\%$ (instability of work of photomultipliers, season variations, dead tanks, ...).
- Neutrino oscillation parameters: $\approx 5\%$ for W^+W^- and $b\bar{b}$, $\approx 8\%$ for $\tau^+\tau^-$
- Neutrino nucleon cross section - up to 10% (even higher for $E_\nu < 10$ GeV)
- For limits on SD and SI cross sections: astrophysical uncertainties (chemical composition of the Sun, local dark matter density ρ_χ, DM velocity distribution, ...)

Comparison of upper limits for W^+W^- and $\tau^+\tau^-$ channels

- Comparable limits on muon fluxes
- Number of neutrinos (and antineutrinos) per annihilation: ≈ 1.0 for W^+W^- and ≈ 2.6 for $\tau^+\tau^-$
- Effect of oscillations



Upper limits on SI elastic cross section