Indirect searches for dark matter at Baksan and Baikal

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Prospects of Particle Physics:
Neutrino Physics and Astrophysics
Valdai, 30 January 2014

Outline

I Introduction: idea

II Neutrinos from dark matter annihilations in the Sun: simulation of neutrino propagation

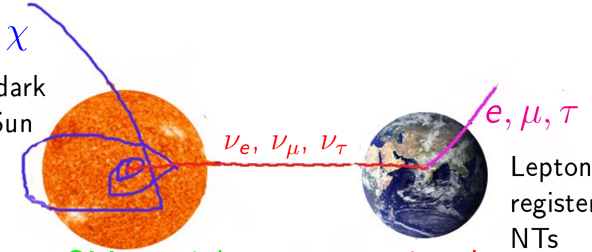
III Sun survey at Baksan and Baikal

IV Results

V Conclusions

Signal from DM annihilations in the Sun

Capture of dark matter in the Sun



Leptons are registered at NTs

if $\chi\chi \to$ SM particles $\to$ neutrinos!

- DM particles scatter off nuclei in the Sun
- DM can become gravitationally trapped ($m_{DM} \gtrsim 5$ GeV)
- Accumulation and annihilation of DM in the center of the Sun
- Neutrino flux should be observed from the direction towards the Sun
- IceCube, SuperKamiokande, ANTARES, BUST (Baksan) and BDUNT (Baikal)

Neutrino signal from DM annihilations in the Sun

- Capture of DM particles by the Sun: $\sigma_{\chi p}^{SD}$ and $\sigma_{\chi p}^{SI}$.
- $\chi\bar{\chi} \to \ldots$???
- Benchmark channels: $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$
- (Anti)Neutrinos are produced $\frac{dN_{\nu_j}^{\text{prod}}}{dE_{\nu_j}}$
- Propagation of neutrinos in the Sun and Earth (oscillations, interactions)
- Expected muon neutrino and muon fluxes from dark matter annihilation in the Sun

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

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

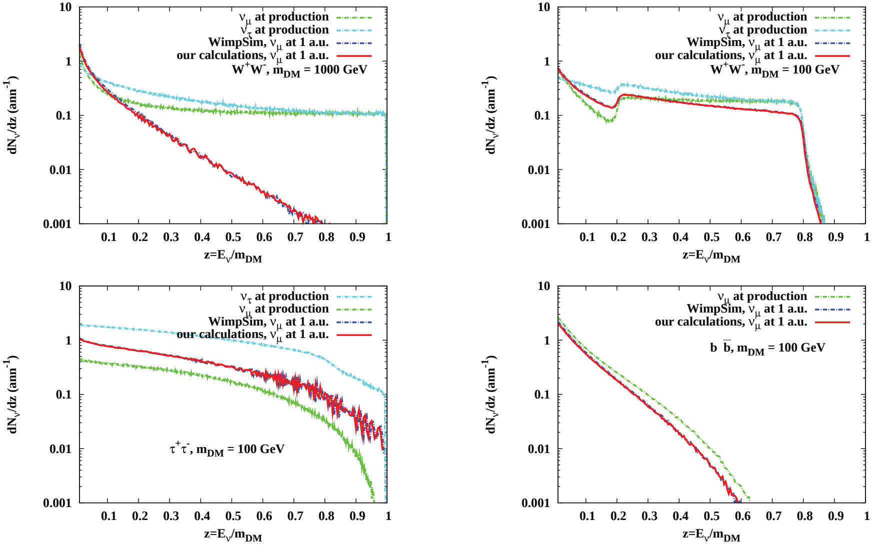
$P_{\nu_\mu}(E_{\nu_j}, E_{th})$ and $P_{\mu}(E_{\nu_j}, E_{th})$ - probabilities to obtain neutrino or muon at the detector level

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: PYTHIA or Ref. Cirelli, Fornengo et al., NPB727 (2005) 99
- Annihilation point near the center of the Sun
- Neutrino oscillations, 3×3 scheme
- 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.

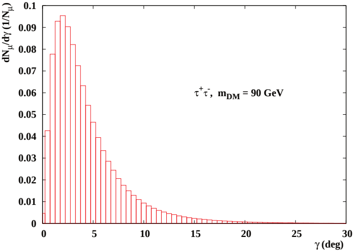
For the same initial neutrino spectra

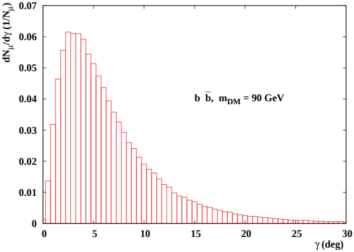


Neutrino signal

Muon flux calculation

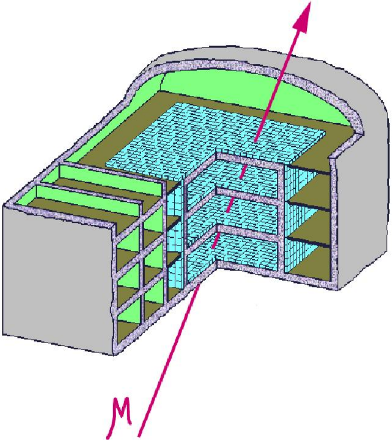
- Muons are produced in neutrino CC interactions
- Mean muon energy losses in rock (D.E.Groom, N.V.Mokhov, S.I.Striganov, 2001)
  $\langle \frac{dE}{dx} \rangle = -(\alpha(E) + \beta(E)E)\rho$
- Multiple Coulomb scattering





Baksan Underground Scintillator Telescope

General view



- depth: 850 hg/cm^2
- size: 17 m $\times$ 17 m $\times$ 11 m
- 3150 tanks of size 70 cm $\times$ 70 cm $\times$ 30 cm
- angular resolution: about 1.5°
- time-of-flight method, resolution: 5 ns
- Energy threshold $E_{th} \approx 1$ GeV
- muon fluxes upward/downward ratio: $\sim 10^{-7}$

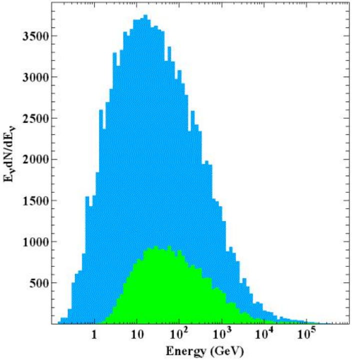
December 1978 - November 2009; livetime 24.12 years

1255 upward-going muons after selection

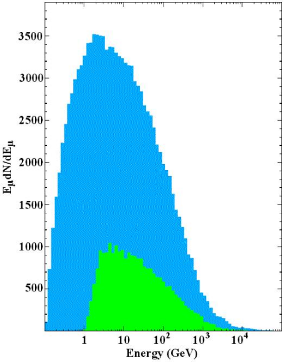
MC simulation and reconstruction

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

Neutrino



Muon



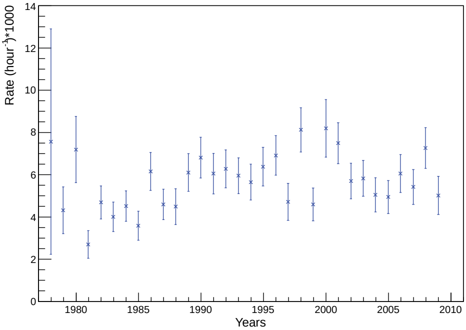
Muon energy threshold $E_\mu > 1$ GeV

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

Upward going muons:

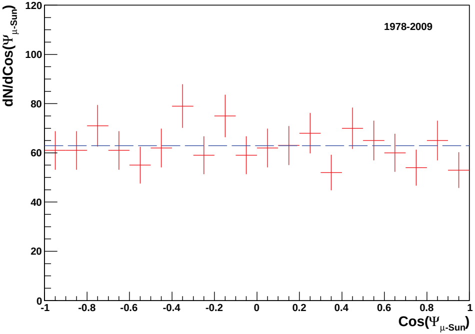
December 1978 - November 2009; livetime 24.12 yrs, 1255 events

Event rate



About 50 events per year

Muon distribution with respect to position of the Sun



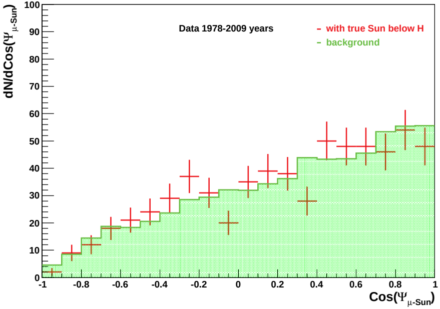
Direction to the Sun corresponds to $\cos\Psi_{\mu-\mathrm{Sun}} = 1$

Baksan data

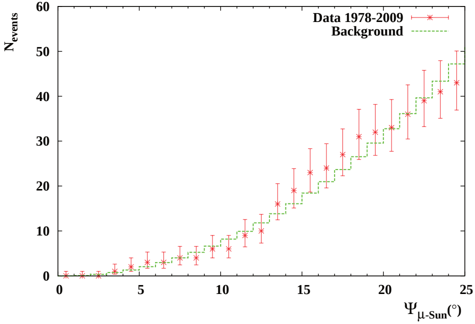
Data and expected background

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

Baksan data

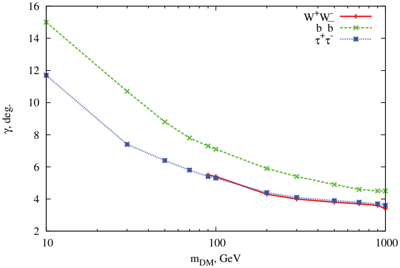
Optimization of analysis

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

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

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

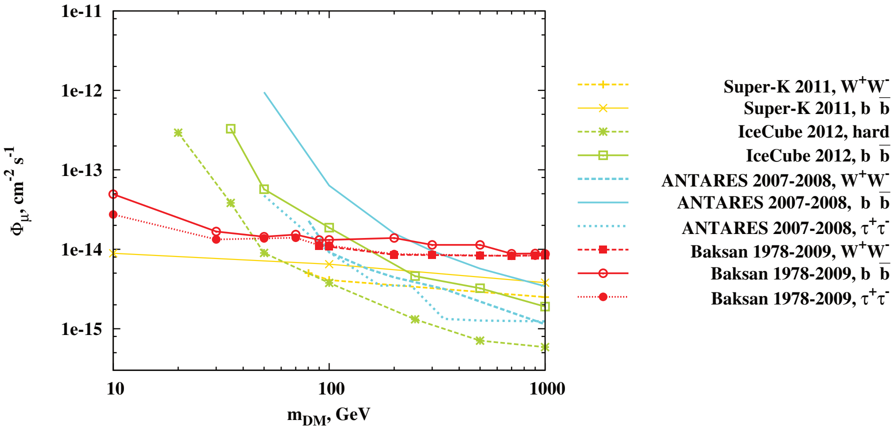
where $x(\gamma)$ is a fraction of event inside cone half-angle γ, $\bar{N}^{90}$ - mean expected upper limit



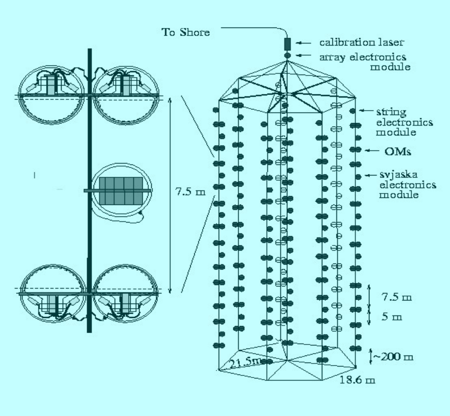
The effective area: $A_{eff}(\gamma) = \frac{\int dEd\theta\ A(E,\theta)\times\epsilon(E_{th},E,\theta)\times\Phi_\mu(E,\theta,\gamma)}{\int dEd\theta\ \Phi_\mu(E,\theta,\gamma)}$

Upper limits on muon fluxes from DM annihilations

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



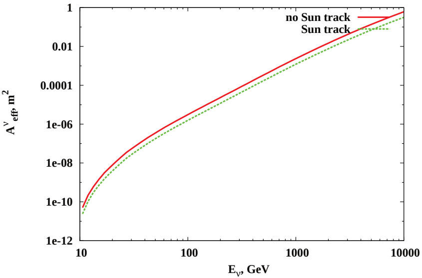
Baikal Neutrino Telescope (NT200)



- 8 strings and 192 OM
- Angular resolution 4-5°
- Energy threshold $E_{th} \approx 10$ GeV
- data from April 1998 to February 2003
- Events towards the Sun

Expected number of events

$$N_\mu = \int_{E_{th}}^{M_{DM}} dE_\nu d\Omega A^\nu_{eff}(E_\nu, \Omega) \frac{d^2 N_\nu}{dE_\nu d\Omega}$$

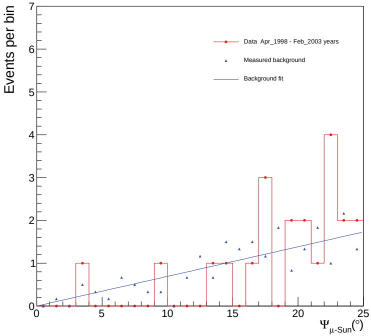


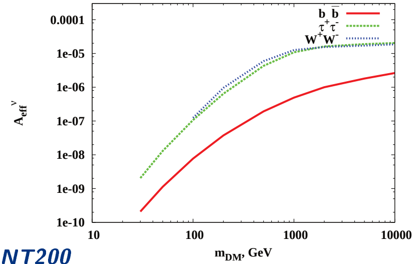
Neutrino from the Sun and optimization

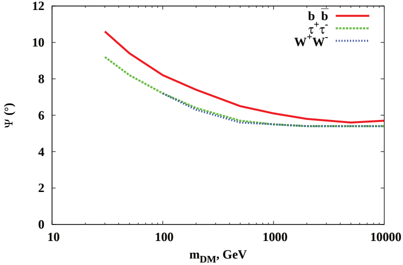
expected limit on neutrino flux $\approx \frac{\bar{N}^{90}(\gamma)}{A^{\nu}_{eff}(\gamma)\times T}$

The effective area for given spectrum

$$A^{\nu}_{eff}(\gamma) = \frac{\int_{E_{th}}^{m_{DM}} dE_\nu A(E_\nu, E_{th}) P_\mu(E_\nu, \theta) \frac{dN_\nu(E_\nu)}{dE_\nu}}{\int_{E_{th}}^{m_{DM}} dE_\nu P_\mu(E_\nu, \theta) \frac{dN_\nu(E_\nu)}{dE_\nu}}$$



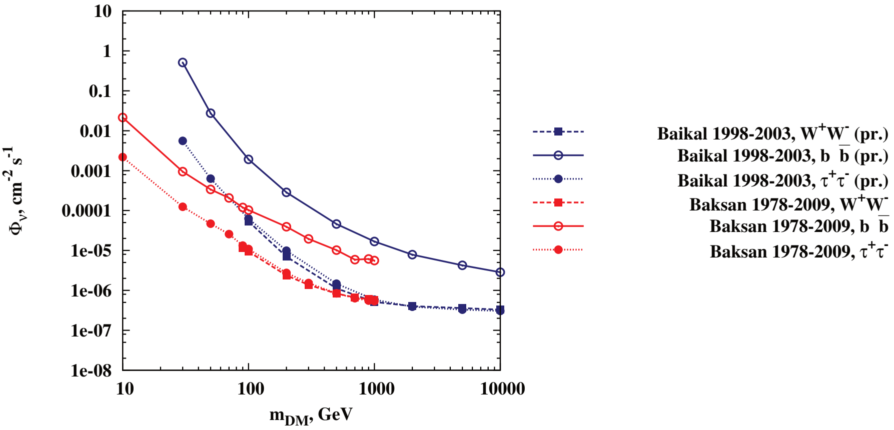




NT200

Upper limits on neutrino flux

$$\Phi_{\nu}^{lim} = \frac{N^{90}(\gamma)}{A_{eff}^{\nu} \times T}, \quad \text{recalculated on } E_{\nu} > 1 \text{ GeV};$$



Upper limits on neutrino flux

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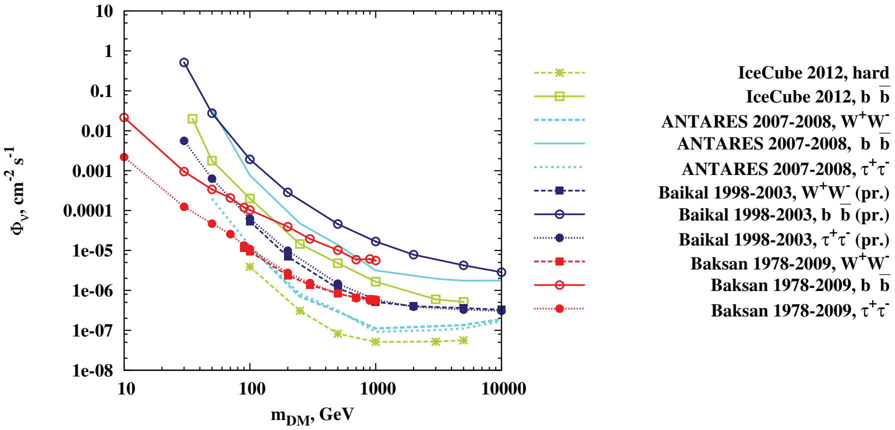


Recalculation to upper limits on SD

G. Wikstrom, J. Edsjo, 2009

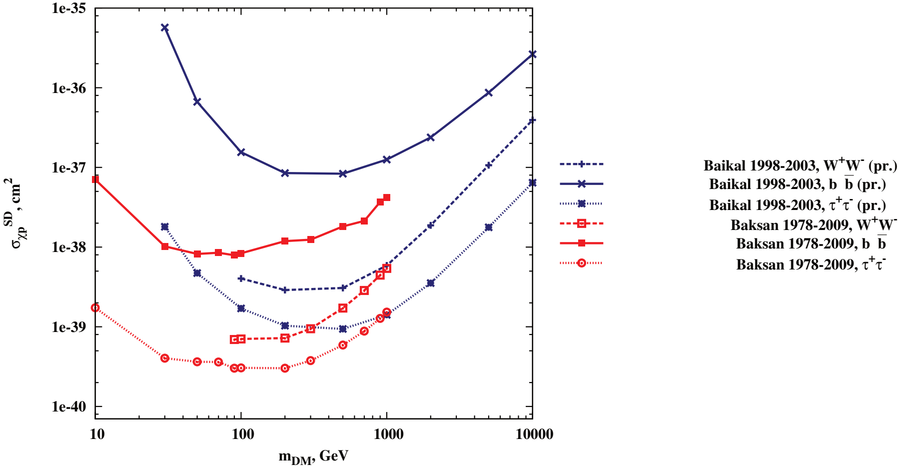
- Firstly, we recalculate $\Phi_\mu \to \Gamma_A$
- In equilibrium between capture and annihilation processes: $\Gamma_A = C_{DM}/2$
- Capture rate is determined by the SI and SD elastic cross section of DM particles on nucleons (Gould, 1987)
- Recalculation $\Gamma_A \to \sigma_p^{SD}, \sigma_p^{SI}$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

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

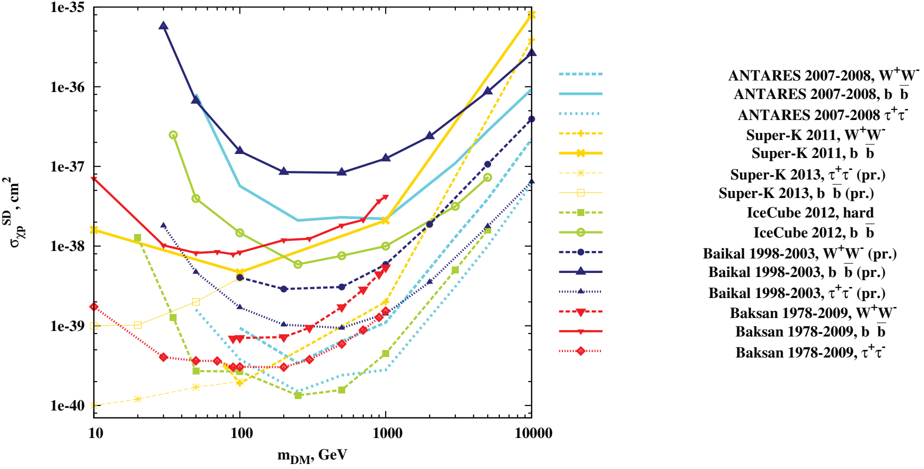
$$\frac{\sigma_p^{SD}}{\Gamma_A^{SD}} \cdot \Gamma_A^{Upp.Lim.} = \sigma_p^{SD,Upp.Lim.}, \quad \frac{\sigma_p^{SI}}{\Gamma_A^{SI}} \cdot \Gamma_A^{Upp.Lim.} = \sigma_p^{SI,Upp.Lim.}$$

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

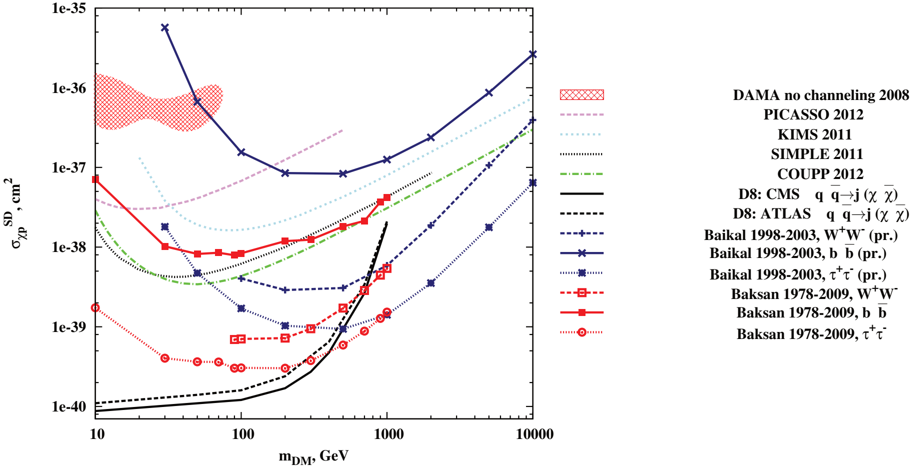
Upper limits on SD elastic cross section: Baksan and Baikal



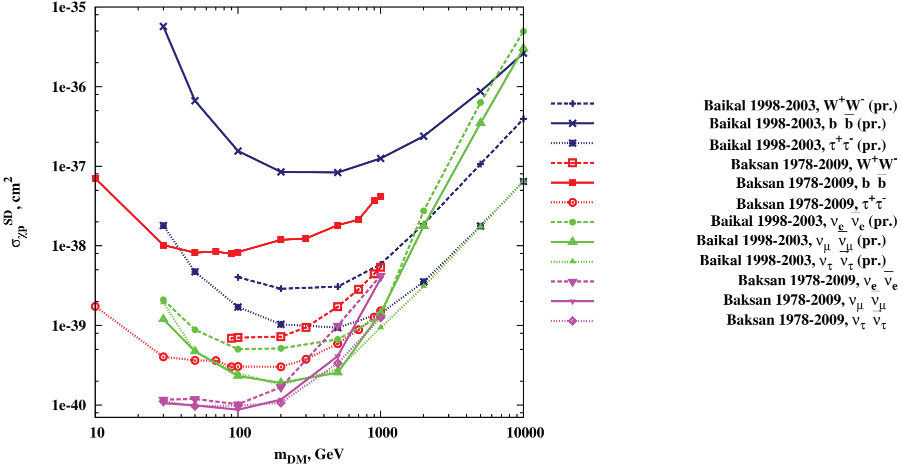
Upper limits on SD elastic cross section: indirect searches



Upper limits on SD: direct and collider searches



Upper limits on SD: neutrino channels



Baksan data

Summary

- Simulation of neutrino signal from dark matter annihilations in the Sun has been performed
- New analysis of upward-going muon data collected for more than 24 years at Baksan and more than 1000 days at Baikal (NT200) has been performed
- New limits on muon flux, annihilation rate, elastic cross sections

Thank you!

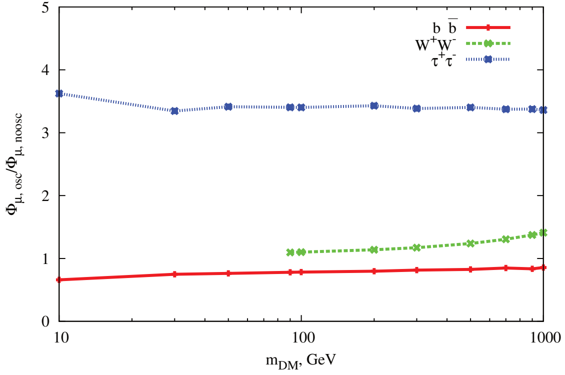
Backup slides

Systematic uncertainties

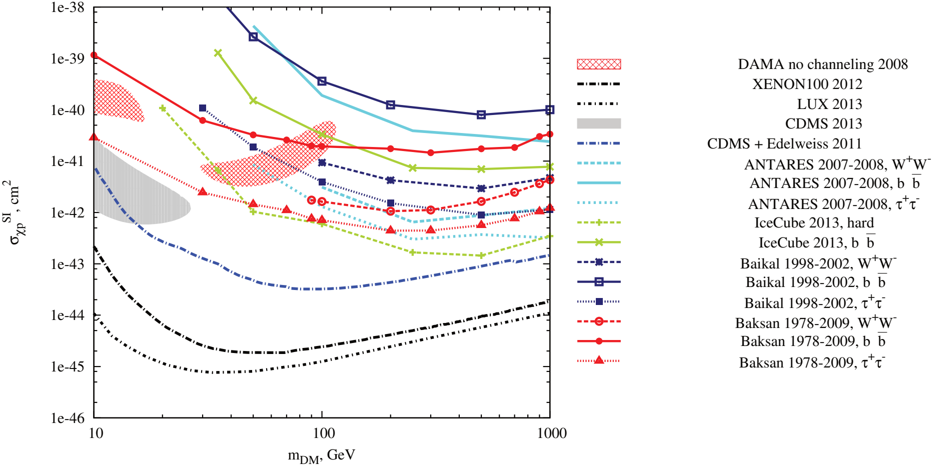
- Experimental uncertainties: Baksan: $\approx 8\%$ (instability of work of photomultipliers, dead tanks, ...), Baikal: $\approx 30\%$.
- Neutrino oscillation parameters: $\approx 5\%$ for W^+W^- and $b\bar{b}$, $\approx 8\%$ for $\tau^+\tau^-$
- Neutrino nucleon cross section - up to 10% (even higher 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

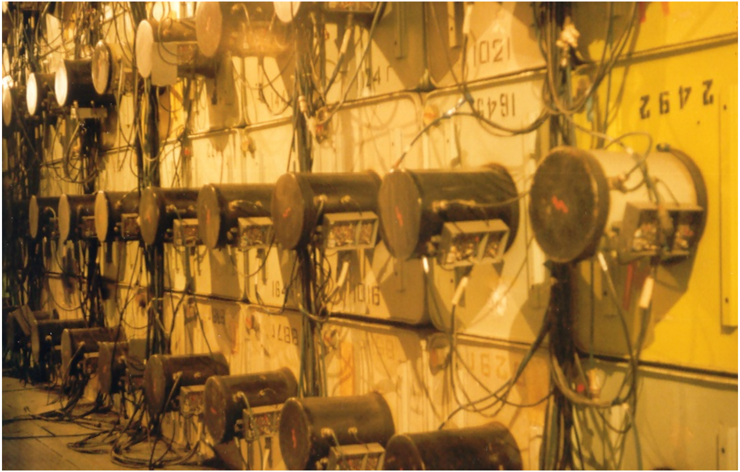
- Comparable limits on muon fluxes
- Number of neutrinos (and antineutrinos) per annihilation: ≈ 1.0 for W^+W^- and ≈ 2.6 for $\tau^+\tau^-$
- Effect of oscillations



Upper limits on SI elastic cross section



Baksan Underground Scintillator Telescope



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)
- Geometrical cuts to exclude events close to plane edge (1.5 m)
- Muon range inside detector > 500 g/cm^2 (excluded muons with $E_\mu < 1$ GeV)
- $-1.3 < 1/\beta < -0.7$ (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