NSI and neutrino signal from dark matter annihilations in the Sun

Quarks-2014:
Suzdal, Russia, 2-8 June, 2014

S.V.Demidov INR RAS

Outline

I Introduction: neutrinos from DM annihilations in the Sun, what signal can be expected, which processes are involved

II Non-Standard Interactions (NSI) of neutrinos and bounds

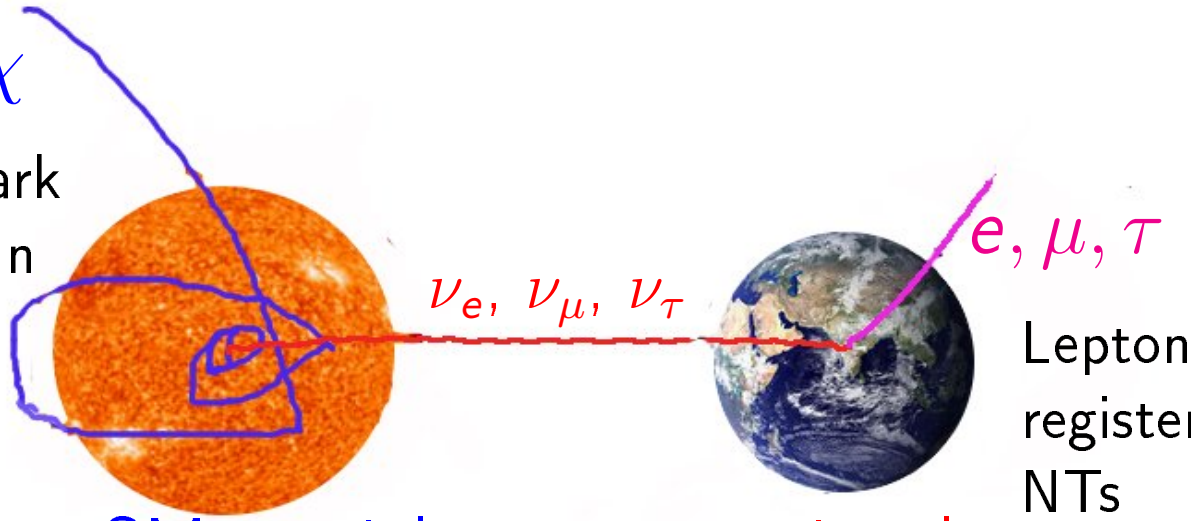
III Propagation of neutrinos from the Sun to the Earth: how NSI could affect it, numerical simulations

IV Influence of NSI on upper limit on muon neutrino flux

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

- DM scattering on nucleons (σ^{SD} and σ^{SI})
- DM space distribution in the Sun: $n(r) = n_0 \exp(-r^2/R_{\rm DM}^2)$, where $R_{\rm DM} \sim 0.01 R_{Sun}\sqrt{100\ GeV/m_{DM}}$
- Energy distribution and flavour composition at production depend on annihilation channel. Benchmark channels: $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, $\nu\bar{\nu}$
- Expected muon neutrino fluxes from dark matter annihilation in the Sun

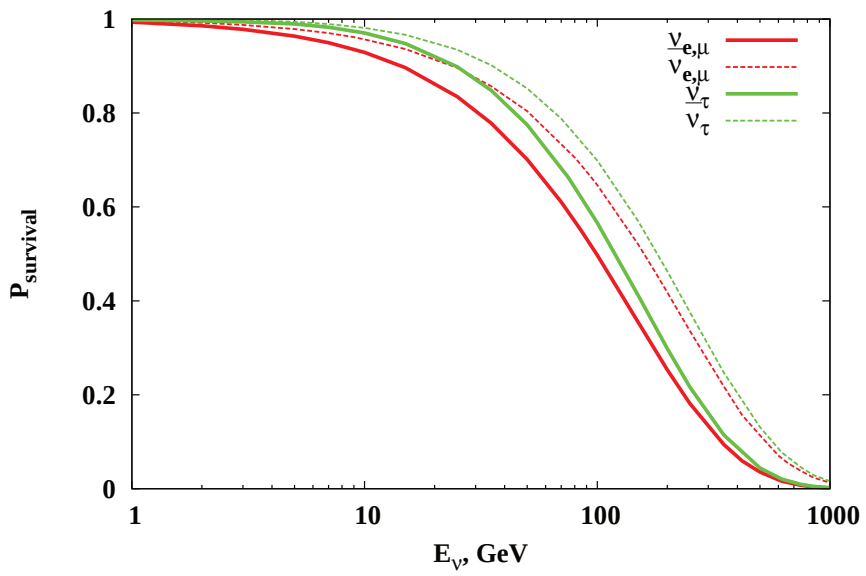
$$\Phi_{\nu_\mu} = \frac{\Gamma_A}{4\pi R^2} \times \sum_{\nu_j,\bar{\nu}_j} \int_{E_{th}}^{m_{DM}} dE_{\nu_j} P_{\nu_\mu}(E_{\nu_j}, E_{th}) \frac{dN_{\nu_j}^{\rm prod}}{dE_{\nu_j}}$$

$P_{\nu_\mu}(E_{\nu_j}, E_{th})$ - probability to obtain muon neutrino at the detector level: depends on neutrino interactions (NC and CC) and oscillations in vacuum and in the media of the Sun and Earth

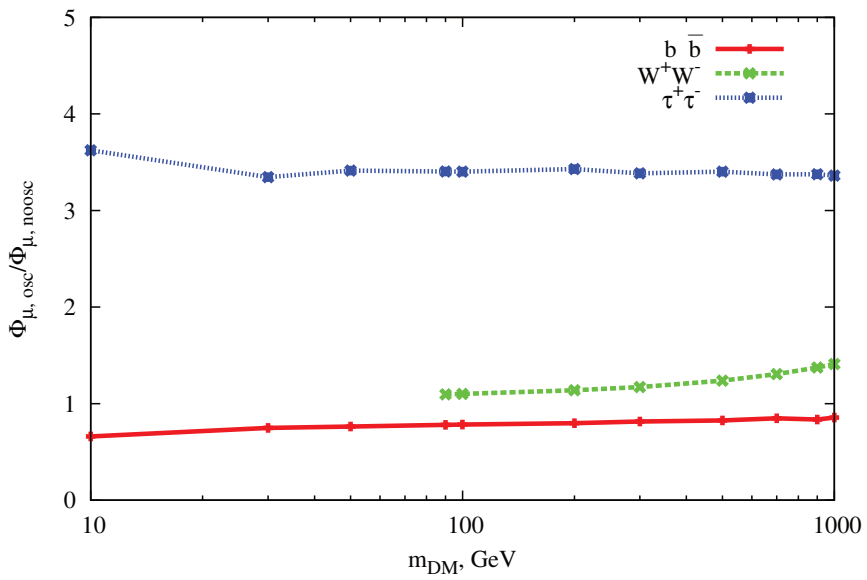
Neutrino signal from DM annihilations: interactions and oscillations

NC, CC interactions, ν_τ regeneration

Survival probability (at the same E_ν)



Ratio of muon fluxes



Changes of neutrino interactions due to New Physics could affect the neutrino signal from DM annihilations!

Non-Standard Interactions of neutrino

Effective four-fermion SM lagrangian ($Q \ll m_W$)

$$\mathcal{L}_{eff} = \left[-2\sqrt{2}G_F(\bar{\nu}_\beta\gamma^\mu P_L l_\beta)(\bar{f}\gamma^\mu P_L f') + h.c.\right]$$

$$-2\sqrt{2}G_F \sum_{P=P_L,P_R} g_P^\beta(\bar{\nu}_\beta\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu Pf)$$

Non-standard neutral current neutrino interactions (conserve electric charge and color) can result from the SM extensions

$$\mathcal{L}_{eff}^{NSI} = -\sum_{P=P_L,P_R} \epsilon_{\alpha\beta}^{fP} 2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu Pf)$$

One of the consequences – modification of matter effects in neutrino oscillations

Matter NSI

$$\hat{H} = \frac{1}{2E} U \mathrm{diag}(m_1^2, m_2^2, m_3^2) U^\dagger + \mathrm{diag}(V_e, 0, 0) + V_e \epsilon^m,$$

$$\epsilon^m = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ & & \epsilon_{\tau\tau} \end{pmatrix}, \quad \epsilon_{\alpha\beta} = \sum_{f, P=P_L, P_R} \epsilon_{\alpha\beta}^{fP} \frac{N_f}{N_e}, \quad V_e = \pm\sqrt{2} G_F N_e$$

The values of ϵ-s depend on the matter content (Sun, Earth, ...)
Biggio, Blennow, Fernandez-Martinez (2009), Ohlsson (2013)

$$|\epsilon_{\alpha\beta}^{Earth}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ ... & 0.068 & 0.33 \\ ... & ... & 21 \end{pmatrix}, \quad |\epsilon_{\alpha\beta}^{Sun}| < \begin{pmatrix} 2.5 & 0.21 & 1.7 \\ ... & 0.046 & 0.21 \\ ... & ... & 9.0 \end{pmatrix}$$

Recently, Esmali & Smirnov 2013 (IceCube, atmospheric neutrinos)

$$|\epsilon_{\mu\tau}| \lesssim 0.018, \quad |\epsilon_{\mu\mu} - \epsilon_{\tau\tau}| \lesssim 0.09 \text{ (90\% CL)}$$

Standard picture of the oscillations of WIMP neutrinos

- Let us neglect neutrino interactions
- At production: Lehnert, Weiler (2007)

  $\rho_\nu(0) = \sum_\alpha w_\alpha |\alpha\rangle\langle\alpha| = w_e|\nu_e\rangle\langle\nu_e| + w_\mu|\nu_\mu\rangle\langle\nu_\mu| + w_\tau|\nu_\tau\rangle\langle\nu_\tau|$

  $$i\frac{d}{dx}\nu_f = \left[2\Delta_{31} U \begin{pmatrix} 0 & & \\ & \alpha & \\ & & 1 \end{pmatrix} U^\dagger + \begin{pmatrix} V_e(r) & & \\ & 0 & \\ & & 0 \end{pmatrix}\right]\nu_f,$$

  where $\Delta_{ij} = \frac{\delta m^2_{ij}}{4E}$, $\alpha = \frac{\Delta_{21}}{\Delta_{31}}$
- In the center of the Sun:

  $|1, r=0\rangle = |\nu_e>; \quad |2, r=0\rangle, |3, r=0\rangle \approx \frac{1}{\sqrt{2}}(|\nu_\mu\rangle \pm |\nu_\tau\rangle)$
- Instantaneous eigenstates: $H_m(r)|m, r\rangle = E_m(r)|m, r\rangle$

$$|\alpha\rangle = \sum_k (U_m)_{\alpha k}(r=0)|k, r=0\rangle$$

$$\rho_\nu(0) = \sum_\alpha w_\alpha (U^*_m)_{\alpha k}(U_m)_{\alpha l}|l, r=0\rangle\langle k, r=0|$$

WIMP Neutrinos in the Sun

In the adiabatic regime: $|\psi_m(r)\rangle$ – evolution states.

$$\rho_\nu(r) = \sum_\alpha w_\alpha (U_m^*)_{\alpha k}(U_m)_{\alpha l}|l, r\rangle\langle k, r| e^{-i\int_0^r dr(E_l(r)-E_k(r))}$$

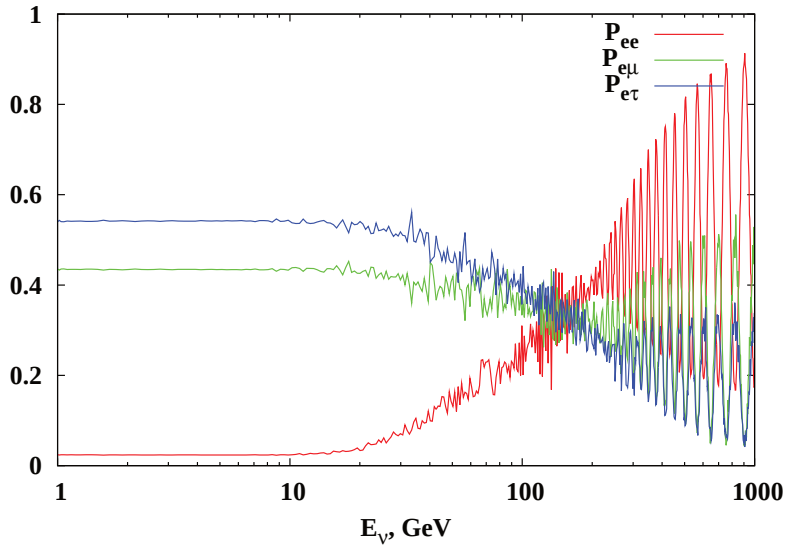
Phase factors are large - decoherence

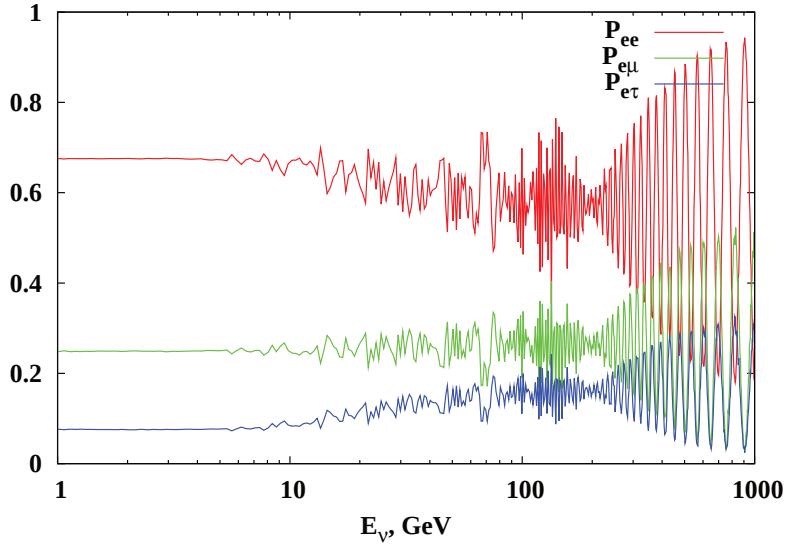
$$\rho_\nu(r) \approx \sum_k (U_m^*)_{\alpha k}(U_m)_{\alpha k}|k, r\rangle\langle k, r|$$

The probability to find a muon neutrino
$P_{\nu_{Sun}\to\nu_\mu} = \langle\mu|\rho(Earth)|\mu\rangle = \sum_{\alpha,i} w_\alpha |U^m_{\alpha i}|^2 |U_{\mu i}|^2$
Adiabaticity is violated in the Sun for $E \gtrsim 10 - 30$ GeV near level crossing (MSW resonances)
$P_{\nu_{Sun}\to\nu_\mu} = \langle\mu|\rho(Earth)|\mu\rangle = \sum_{\alpha,i} w_\alpha |U^m_{\alpha i}|^2 P_{ji} |U_{\mu j}|^2$,
where P_{ji} are probabilities of level crossing.
Normal hierarchy: 1-3 and 1-2 resonances for neutrino
Inverse hierarchy: 1-2 resonance in neutrino and 1-3 for antineutrino

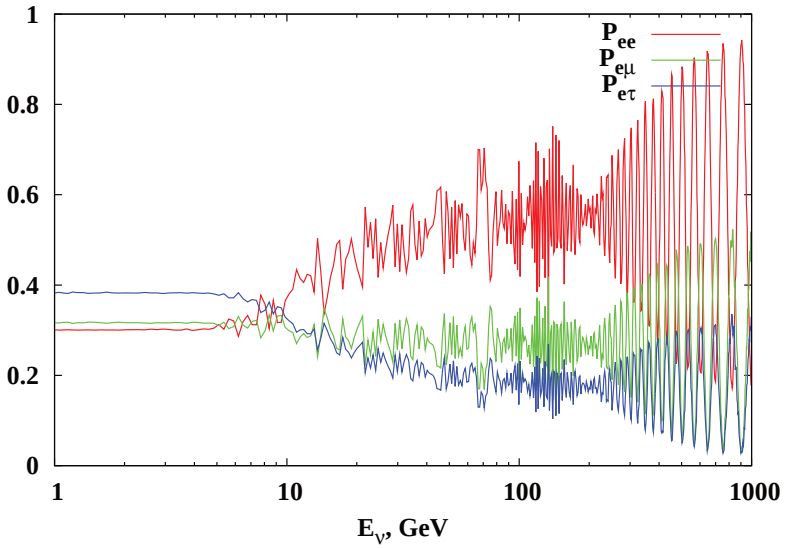
Examples

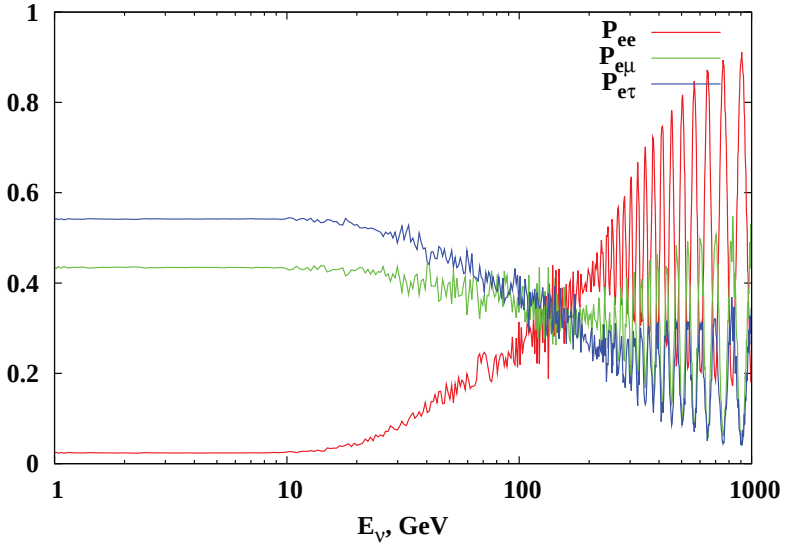
Normal ν_e (up) and $\bar{\nu}_e$ (down)





Inverse ν_e (up) and $\bar{\nu}_e$ (down)





NSI: $\epsilon_{e\tau}$ and $\epsilon_{\tau\tau}$

$$H_f = 2\Delta_{31} U \begin{pmatrix} 0 & & \\ & \alpha & \\ & & 1 \end{pmatrix} U^\dagger + V_e \begin{pmatrix} 1 & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\nu_f = R_{13}(\tilde{\theta}_\epsilon)\tilde{\nu}, \quad \tan 2\tilde{\theta}_\epsilon = -\frac{2\epsilon_{e\tau}}{1-\epsilon_{\tau\tau}}$$

$$\tilde{H} = 2\Delta_{31} \tilde{U} \begin{pmatrix} 0 & & \\ & \alpha & \\ & & 1 \end{pmatrix} \tilde{U}^\dagger + V_e \begin{pmatrix} 1+\epsilon_{e\tau}^2 & & \\ & 0 & \\ & & \epsilon_{\tau\tau} - \epsilon_{e\tau}^2 \end{pmatrix},$$

where $\tilde{U} = R_{13}^\dagger(\tilde{\theta}_\epsilon) U$

Center of the Sun: flavour states are mass states. For $\epsilon << 1$ the state $|e\rangle$ decouples

$$\tilde{H}_{23} = 2\Delta_{32} R_{23}(\tilde{\theta}_{23}) \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} R_{23}^\dagger(\tilde{\theta}_{23}) + (\epsilon_{\tau\tau} - \epsilon_{e\tau}^2) V_e \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

Diagonalize it by $\tilde{\nu} = R_{23}(\theta'_{23})\nu'$

$$\tan 2\theta'_{23} = \frac{2\Delta_{32} \sin 2\tilde{\theta}_{23}}{2\Delta_{32} \cos 2\tilde{\theta}_{23} + (\epsilon_{\tau\tau} - \epsilon_{e\tau}^2) V_e}$$

New $2-3$ resonanse!

NSI: $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$

$$H_f = 2\Delta_{31} U \begin{pmatrix} 0 & & \\ & \alpha & \\ & & 1 \end{pmatrix} U^\dagger + V_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & \epsilon_{\mu\tau} \\ 0 & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

Matter term can be diagonalized by $\nu_f = R_{23}(\tilde{\theta}_{23})\tilde{\nu}$, where $\tan 2\tilde{\theta}_{23} = \frac{2\epsilon_{\mu\tau}}{\epsilon_{\tau\tau}}$
At $\epsilon \ll 1$ the state $|\nu_e\rangle$ decouples in the center of the Sun

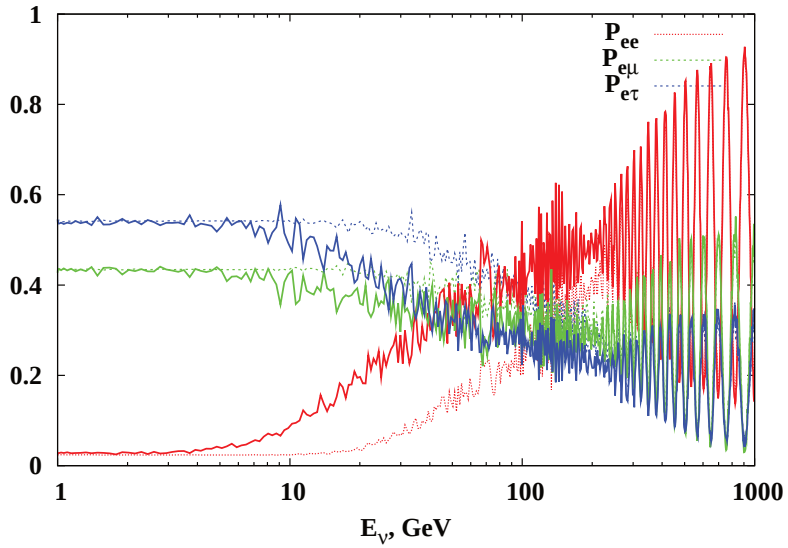
$$\tilde{H}_{32} = 2\Delta_{32} R_{23}(\theta_{23} - \tilde{\theta}_{23}) \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} R^\dagger(\theta_{23} - \tilde{\theta}_{23}) + V_e \sqrt{4\epsilon_{\mu\tau}^2 + \epsilon_{\tau\tau}} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

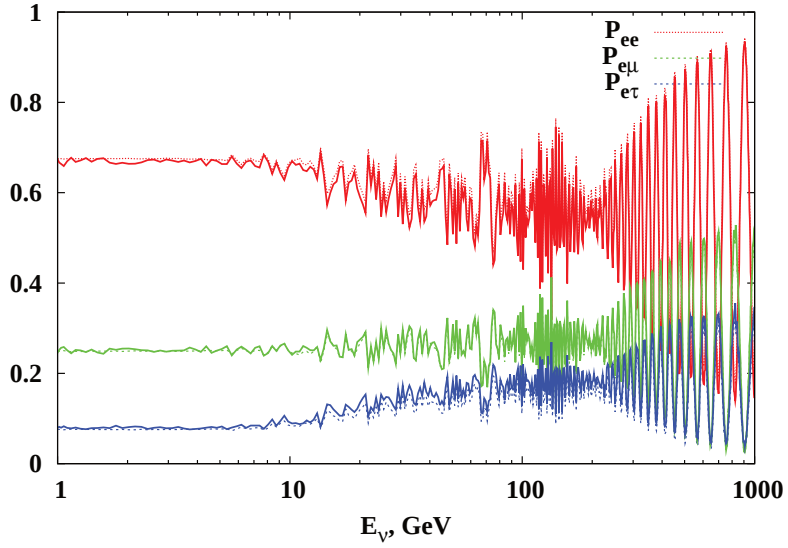
Diagonalized by $\tilde{\nu} = R_{23}(\theta_{23}^m)\nu^m$

$$\tan 2\theta_{23}^m = \frac{2\Delta_{32} \sin 2(\theta_{23} - \tilde{\theta}_{23})}{2\Delta_{32} \cos 2(\theta_{23} - \tilde{\theta}_{23}) + V_e}$$

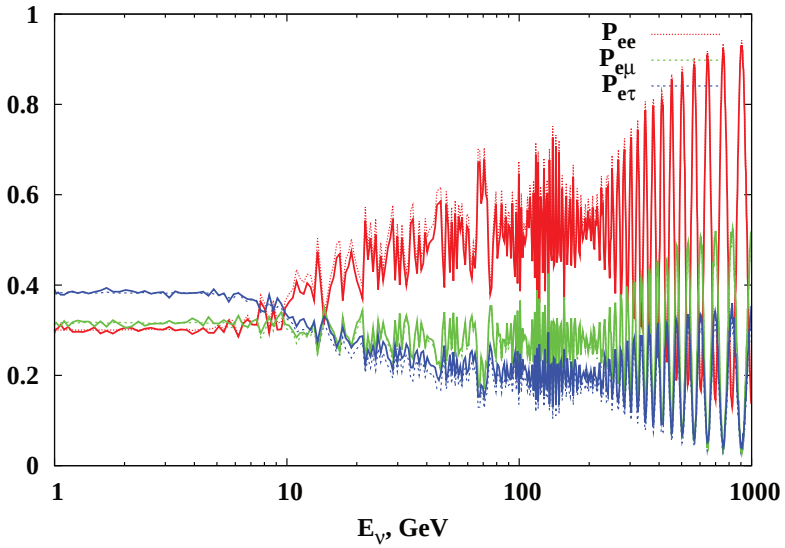
Examples: $\epsilon_{e\tau} = -0.1$

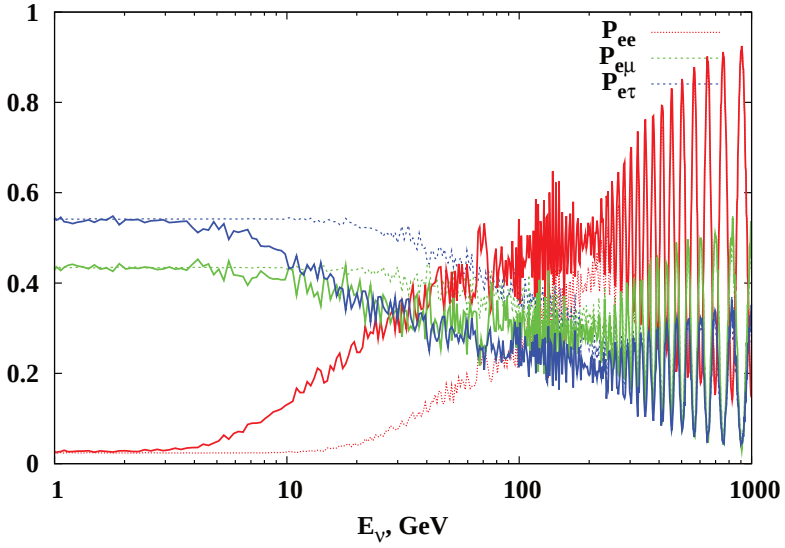
Normal ν_e (up) and $\bar{\nu}_e$ (down)



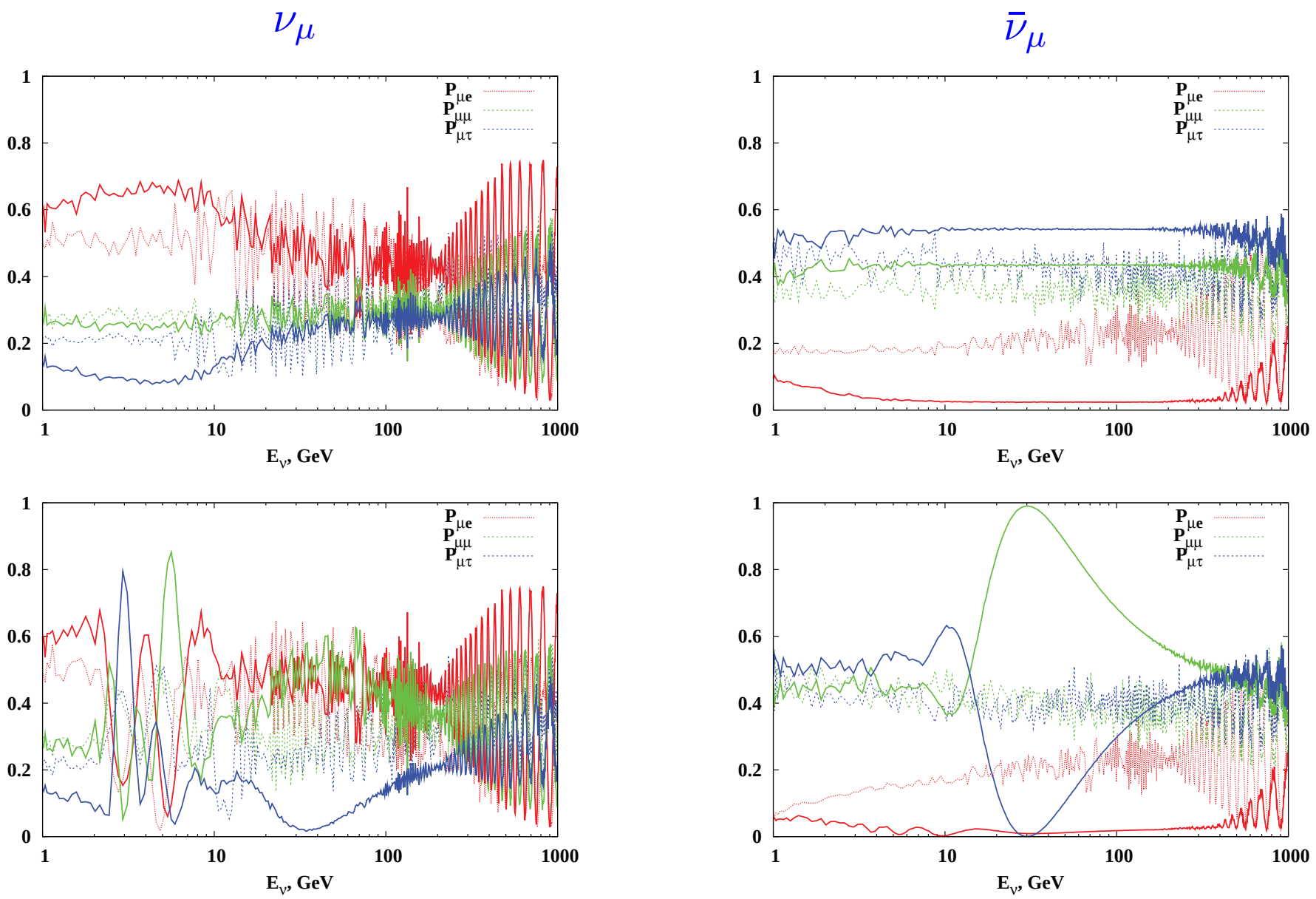


Inverse ν_e (up) and $\bar{\nu}_e$ (down)





Effect of the Earth: $\epsilon_{\tau\tau} = 0.1$

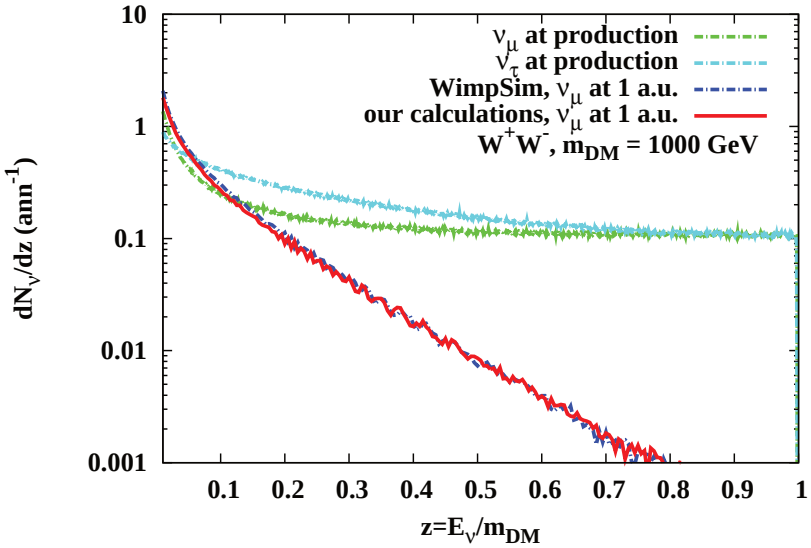


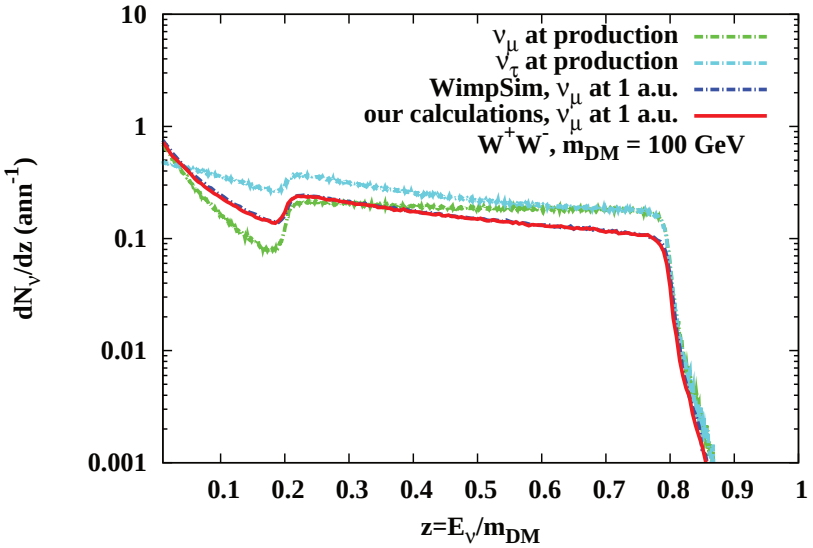
Full signal simulation: overview

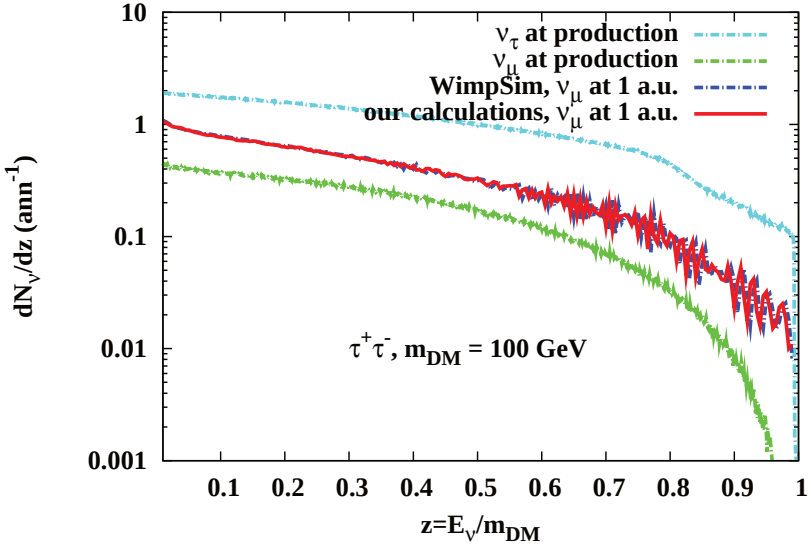
- We use our C program; compare results with WIMPsim
- Initial neutrino spectra at the center of the Sun: PYTHIA
- Annihilation point near the center of the Sun
- Neutrino oscillations, 3×3 scheme
- Matter effects: solar model, J.N.Bahcall, A.M.Serenelli,, S.Basu (2005); earth PREM model.
- NC and CC 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

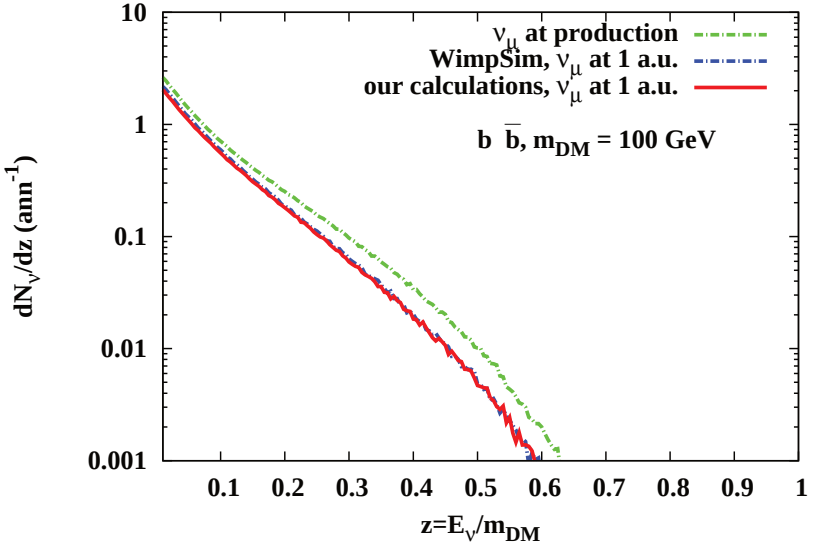
Comparison with WIMPsim: ν_μ spectra at 1 a.u.

For the same initial neutrino spectra

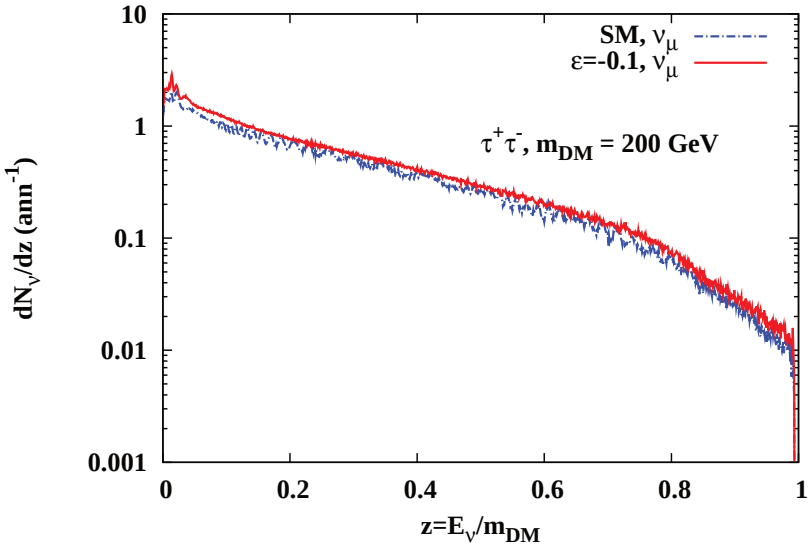


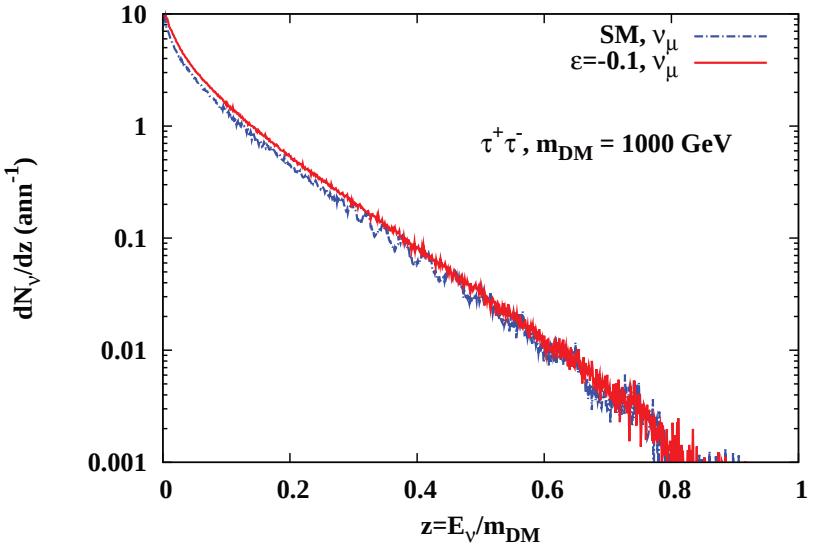


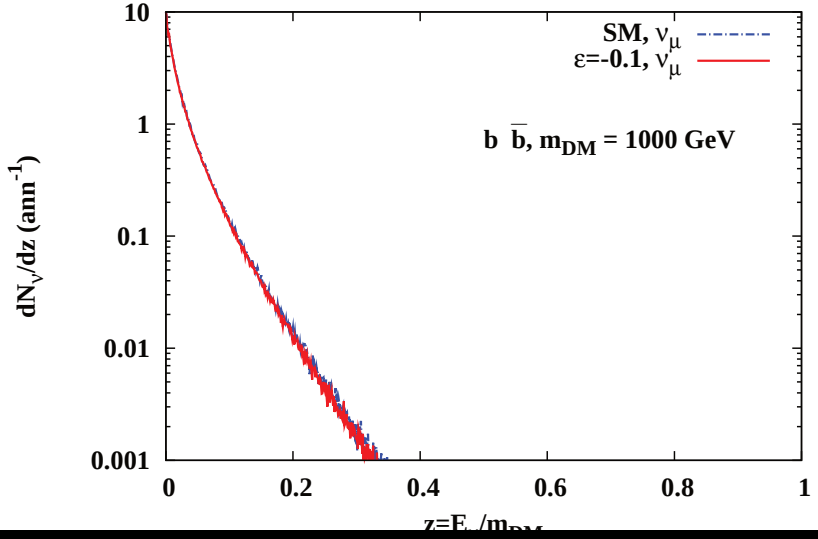


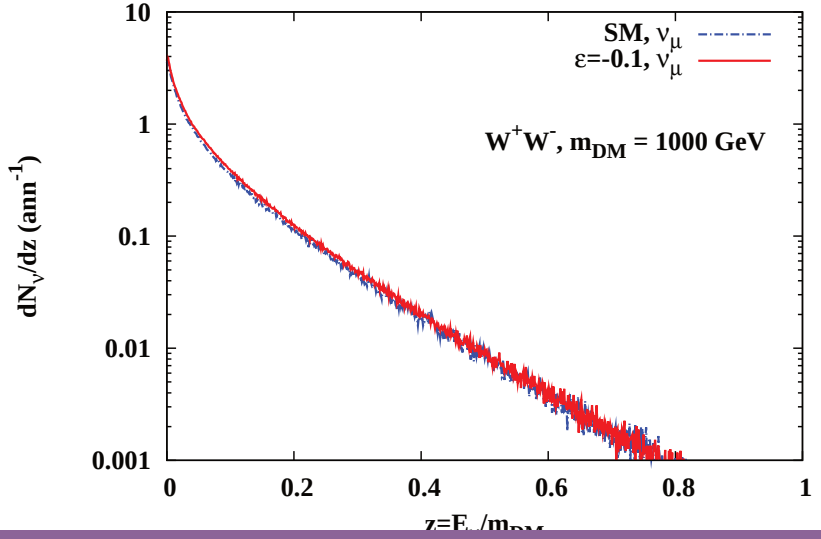


NSI: $\epsilon_{e\mu} = -0.1$, normal hierarchy

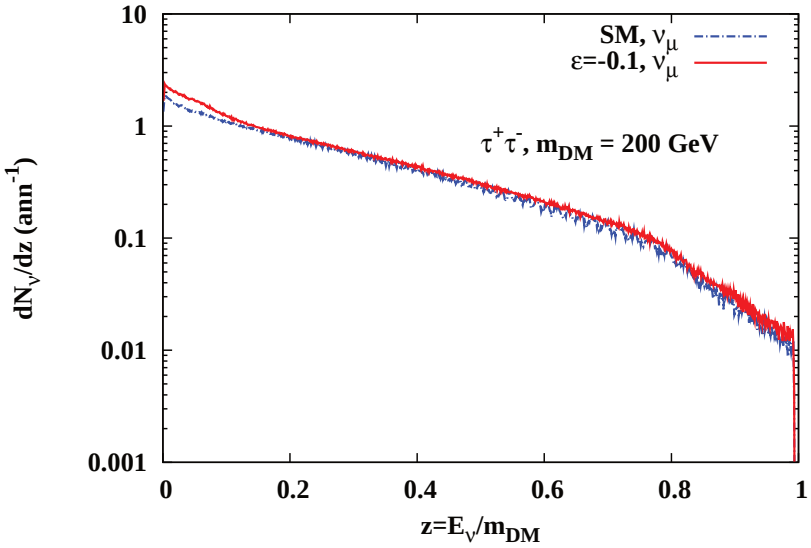


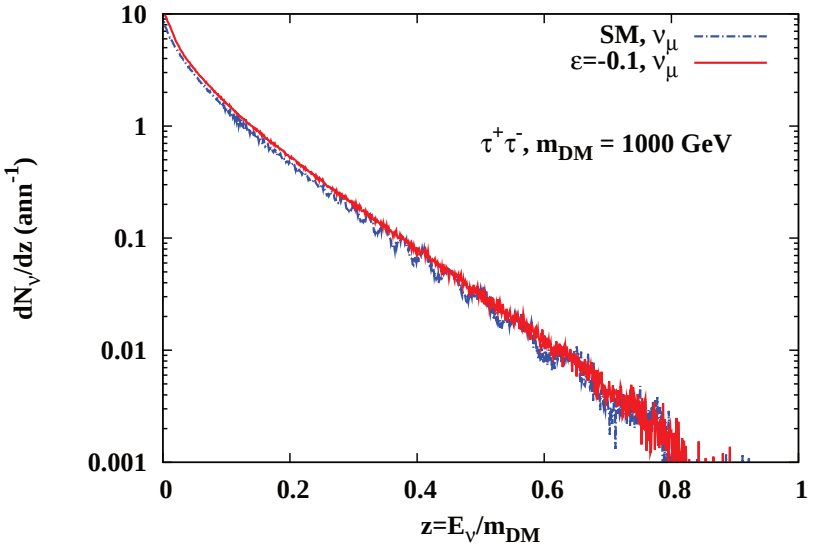


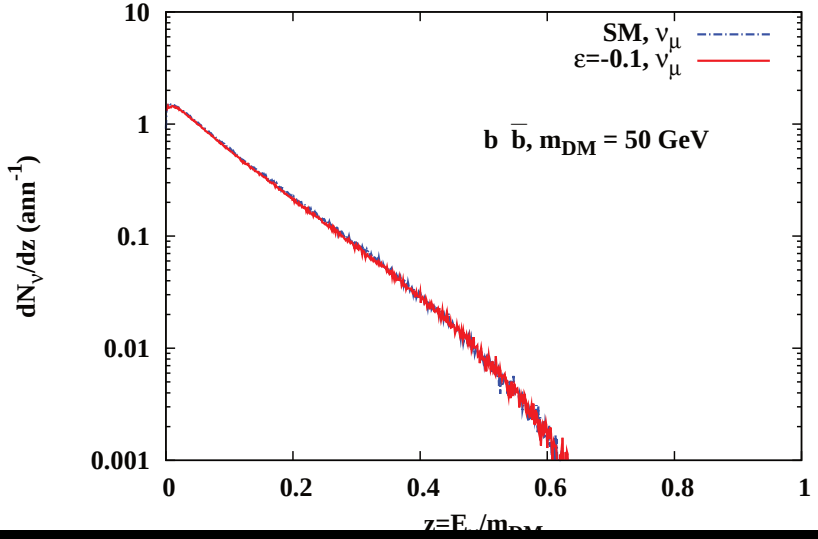


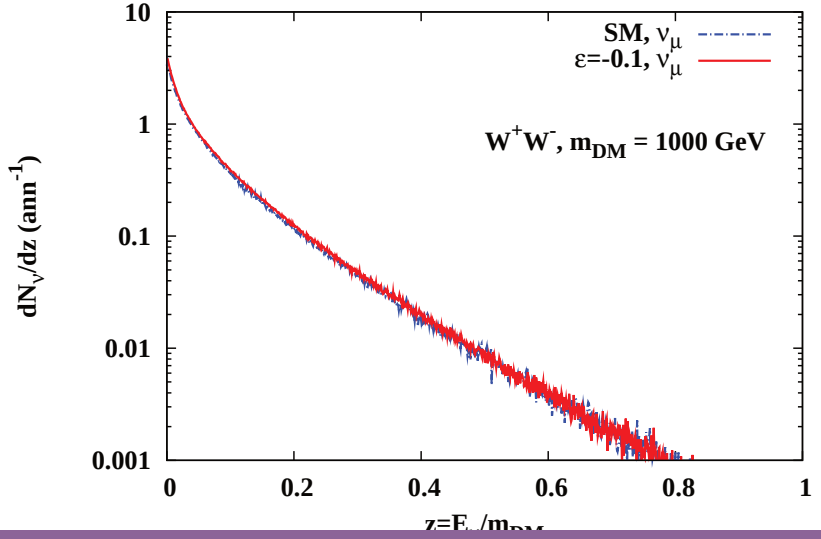


NSI: $\epsilon_{e\tau} = -0.1$, inverse hierarchy

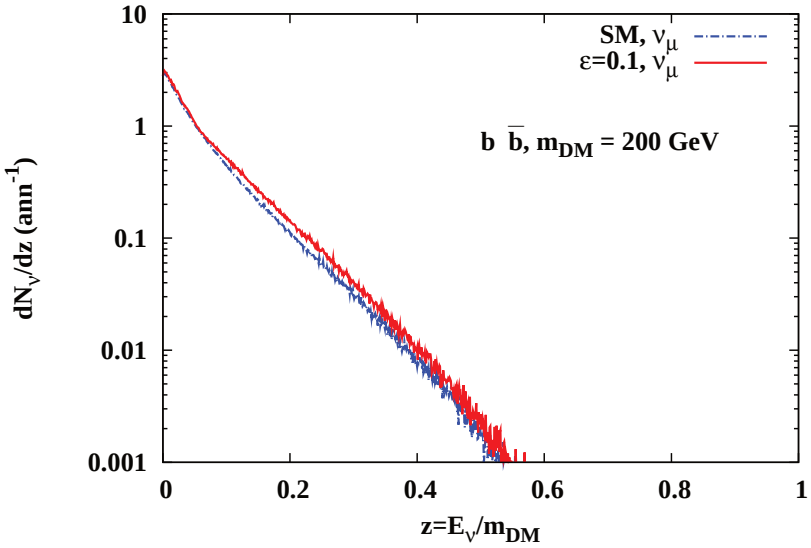


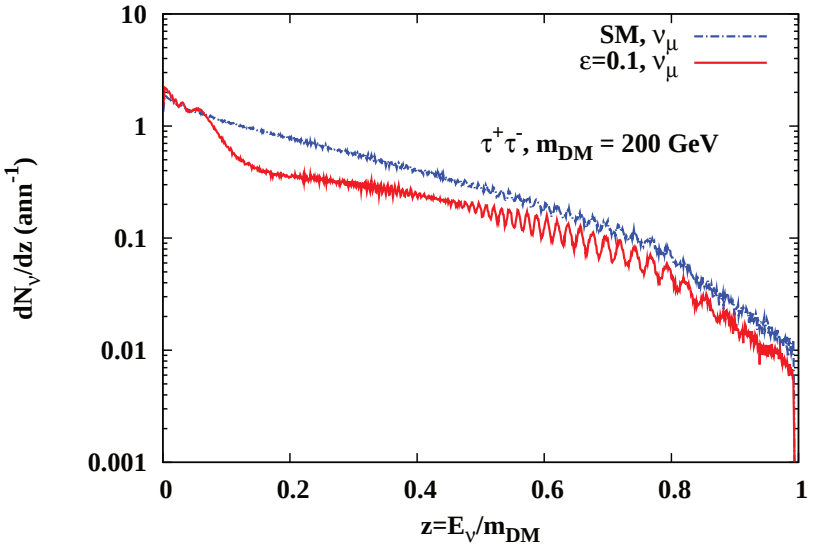


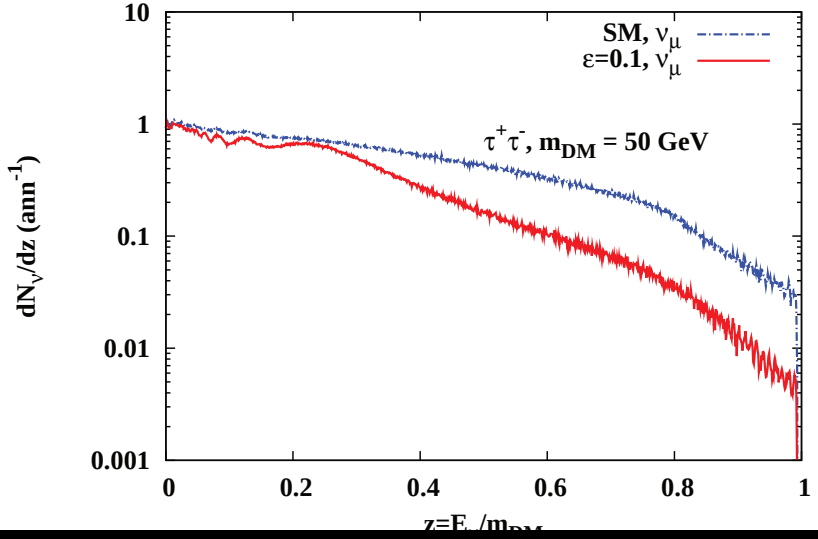


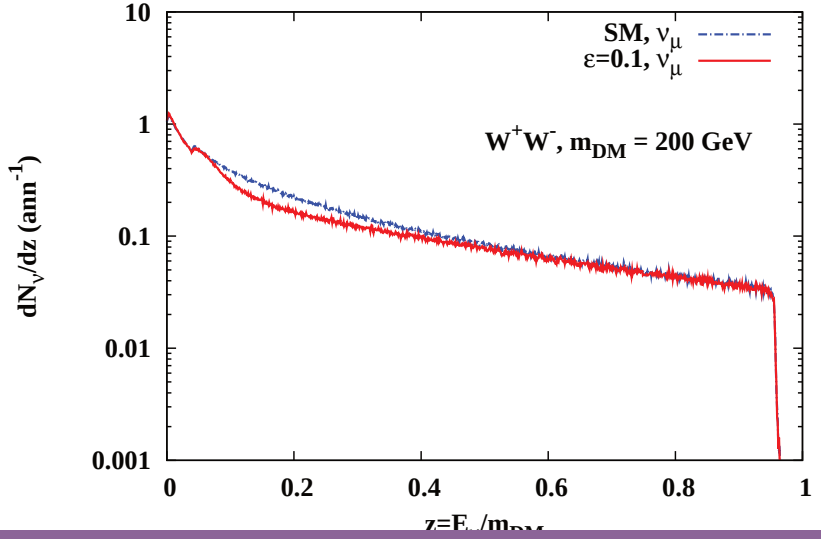


NSI: $\epsilon_{\tau\tau} = 0.1$, inverse hierarchy

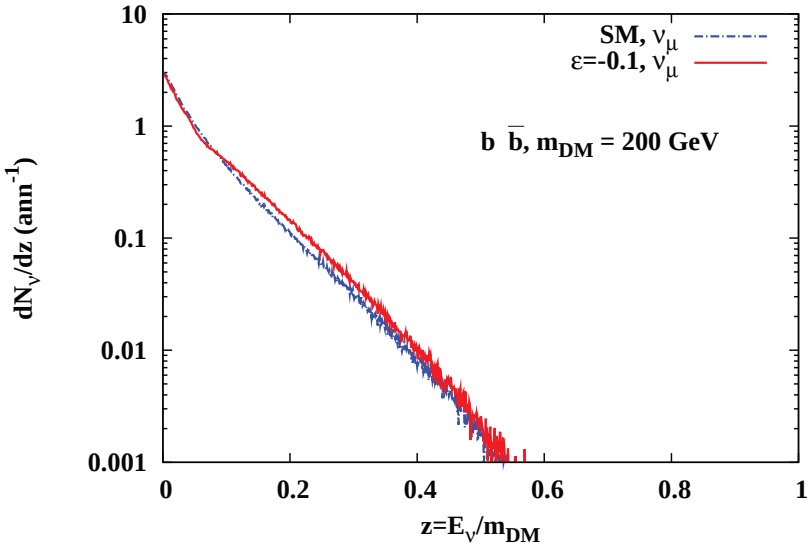


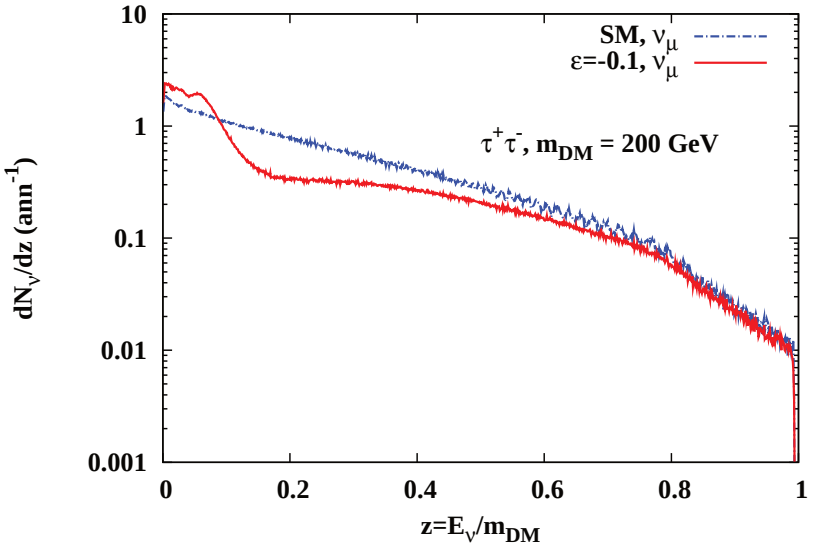


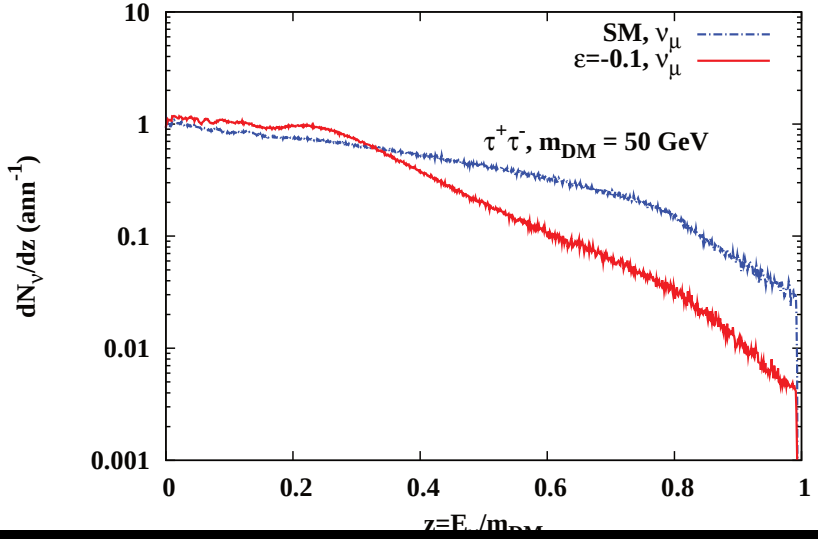


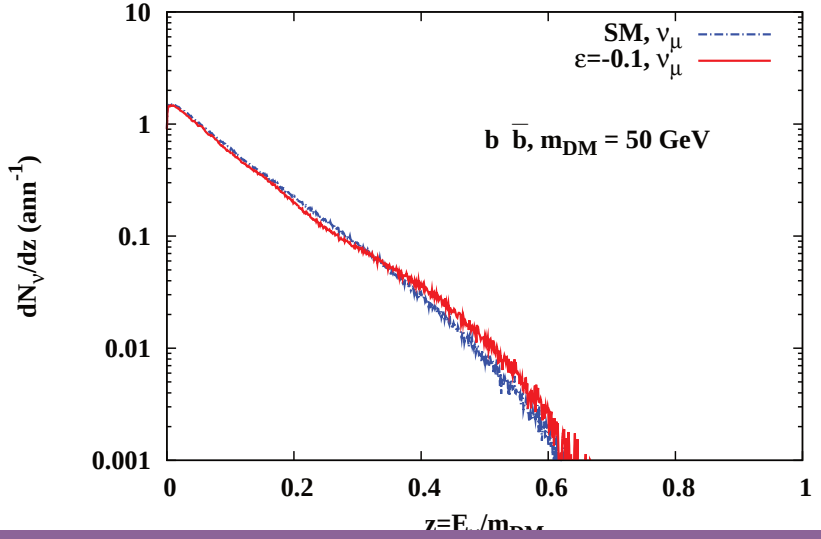


NSI: $\epsilon_{\tau\tau} = -0.1$, inverse hierarchy





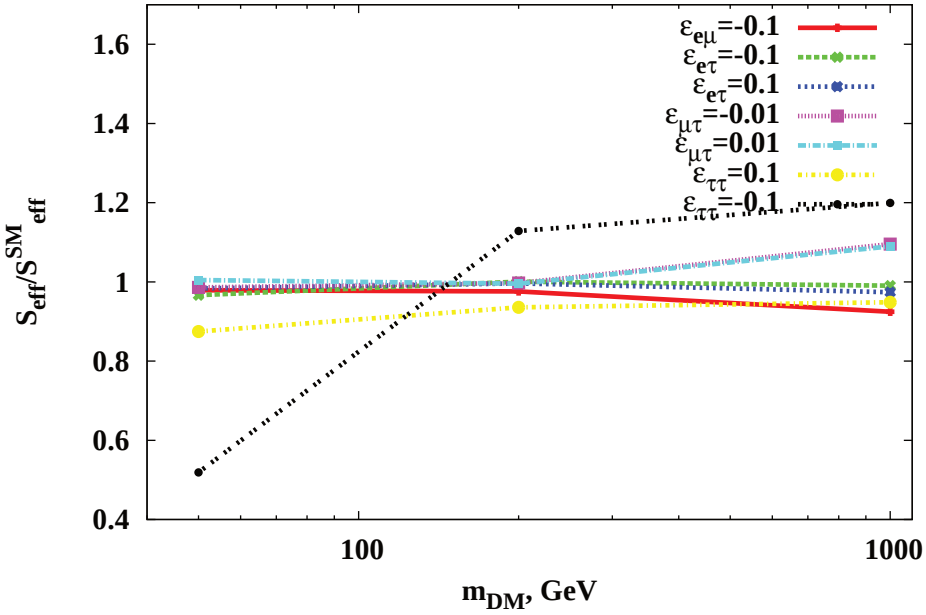




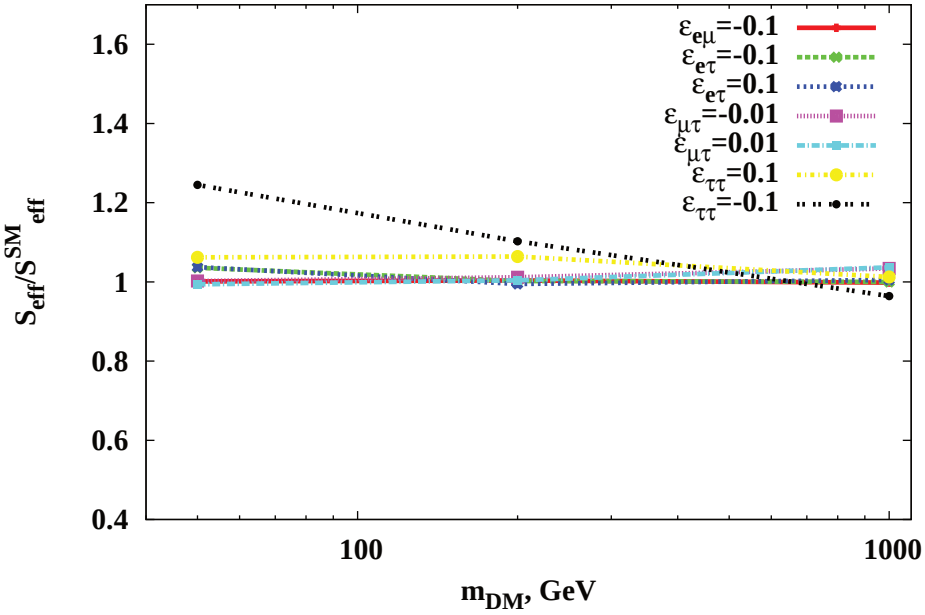
Muon neutrino flux

- Expected limit on neutrino flux $\approx \frac{\bar{N}^{90}}{S^{\nu}_{eff} \times T}$
- Effective area $S^{\nu}_{eff} = \frac{\int_{E_{th}}^{m_{DM}} dE_\nu S(E_\nu, E_{th}) \frac{dN_\nu(E_\nu)}{dE_\nu}}{\int_{E_{th}}^{m_{DM}} dE_\nu \frac{dN_\nu(E_\nu)}{dE_\nu}}$
- We use effective area for NT-200: $\tau^+\tau^-$ and $b\bar{b}$ (normal)

$\tau^+\tau^-$ (normal)



$b\bar{b}$ (normal)



Summary

- Analysis of influence of NSI on neutrino signal from dark matter annihilations in the Sun has been performed
- It is shown that NSI can considerably change the propagation of WIMP neutrino
- We can expect 10-50% corrections to the upper limits on neutrino flux for $b\bar{b}$, W^+W^- and $\tau^+\tau^-$ annihilation channels due to NSI

Thank you!

Systematic uncertainties from neutrino interactions

- Neutrino oscillation parameters: $\lesssim 4-5\%$ for W^+W^- and $b\bar{b}$, $\lesssim 7-8\%$ for $\tau^+\tau^-$
- Neutrino nucleon cross section - up to 10%, larger for $E_\nu < 10$ GeV but smaller for higher energies
- NSI can result in larger uncertainties!