Neutrino Signals in the Inert Doublet Model

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Work done with P. Agrawal and C. Krenke

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Outline

- Inert doublet model
- Neutrino analysis
  - Capture, annihilation, detector rates
- Results
- Conclusion

Inert Doublet Model

$$H_2 = \begin{pmatrix} H^{\pm} \\ \frac{S+iA}{\sqrt{2}} \end{pmatrix} \qquad H_1 = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

- Add second scalar doublet (H_2) to the SM
- Couples only to gauge bosons (inert)
  - Impose additional discrete symmetry

Good: $(D^{\mu} H_2)^{\dagger} D_{\mu} H_2$

Bad: $(D^{\mu} H_1)^{\dagger} D_{\mu} H_2$

- S is a WIMP dark matter candidate

Inert Doublet Model

- The most general potential we can write is:

$$V = \mu_1 H_1^2 + \mu_2 H_2^2 + \lambda_1 H_1^4 + \lambda_2 H_2^4 + \lambda_3 H_1^2 H_2^2$$
$$+\lambda_4 \left| H_1^\dagger H_2 \right|^2 + \lambda_5 \left[(H_1^\dagger H_2)^2 + h.c. \right]$$

- Tree level Higgs masses

$$m_h^2 = -2\mu_1^2 = 2\lambda_1 v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \tfrac{1}{2}\lambda_3 v^2$$
$$m_A^2 = \mu_2^2 + \tfrac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5) v^2$$
$$m_S^2 = \mu_2^2 + \tfrac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) v^2$$

- Define

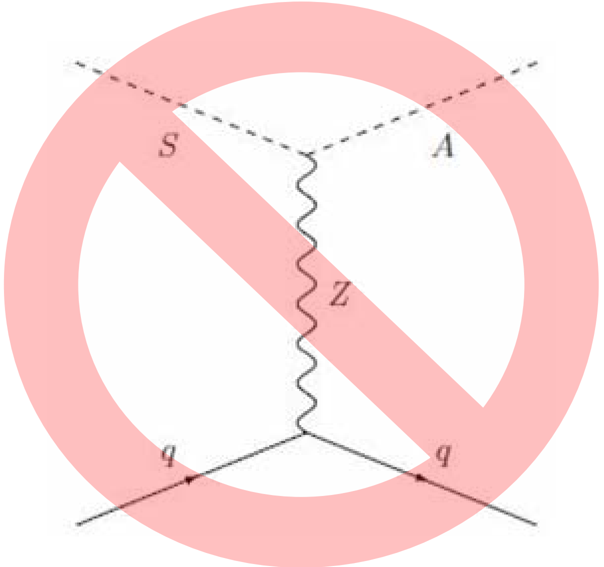
$$\lambda_L = \lambda_3 + \lambda_4 + \lambda_5$$
$$\delta_1 = m_{H^\pm} - m_S$$
$$\delta_2 = m_A - m_S$$

- Free parameters: $v, \lambda_2, m_h, \delta_1, \delta_2, m_S, \lambda_L$

Constraints

- Stability: $$\lambda_{1,2} > 0$$ $$\lambda_{3,L} \geq -2\sqrt{\lambda_1 \lambda_2}$$
- Perturbativity: $$\lambda_2 < 1$$ $$\lambda_3^2 + (\lambda_3 + \lambda_4)^2 + \lambda_5^2 < 12\lambda_1^2$$
- Direct detection: $\delta_2 >$ a few keV
- WMAP

$$\Omega_{CDM} h^2 = 0.112 \pm 0.027$$



Constraints

- LEP I/II

  W/Z width is measured very precisely

  New decay modes cannot contribute to width

  Lundstrom et al. (0810.3924v2)

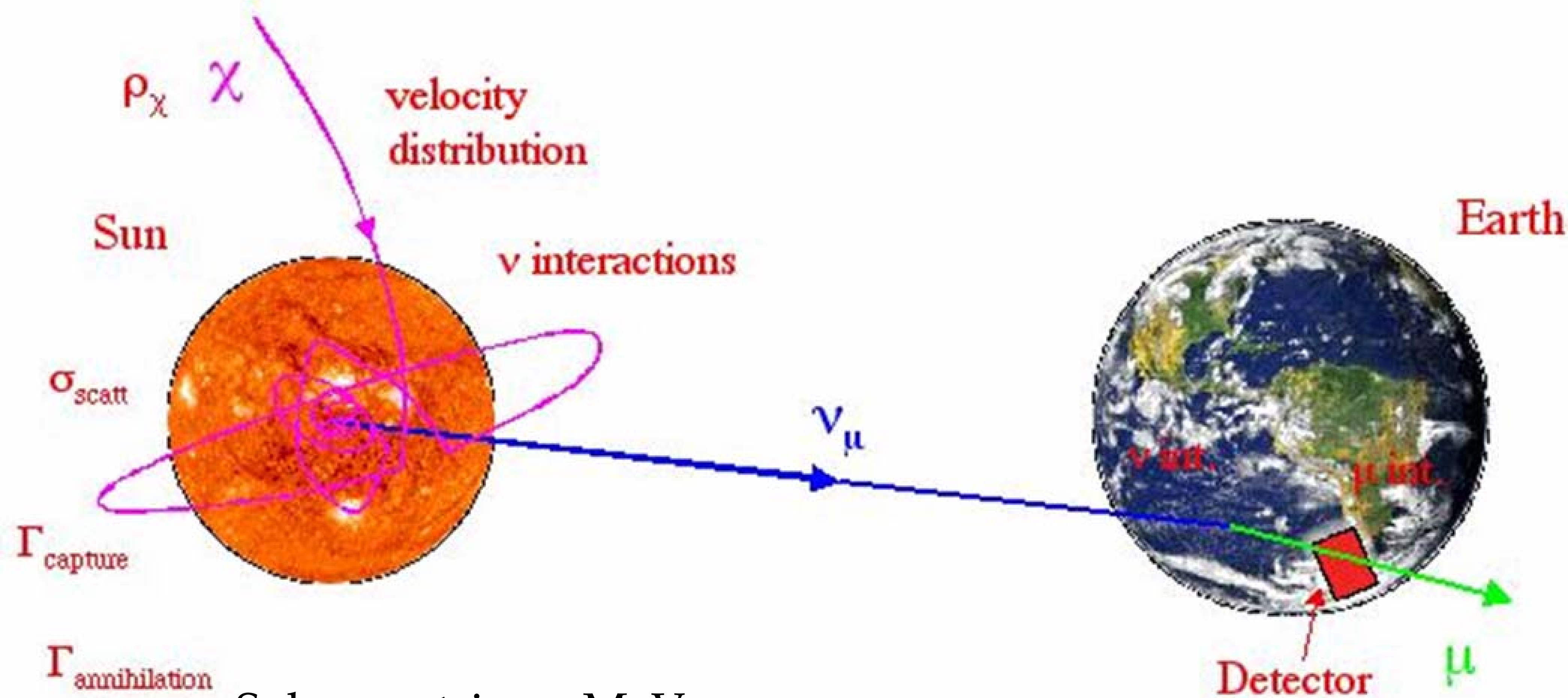
- Precision Electroweak Measurements

  Large contributions to S-T parameters from *h* are cancelled by extra scalars (*S, A, H)*

  Constrained to fall within observed S-T ellipse

  Barbieri et al. (0603188v2)

Analysis: Overview



- Solar neutrinos: MeV
- DM neutrinos: GeV (roughly $m_S/4$)
- Backgrounds: atmospheric neutrinos from cosmic rays

Analysis: Capture Rate

$$C = c\frac{(\rho/0.3\ \mathrm{GeV\ cm^{-3}})}{(m_S/\mathrm{GeV})\ (\bar{v}/270\ \mathrm{km\ s^{-1}})}\sum_i F_i(m_S)\left(\frac{\sigma_0^i}{10^{-4}\mathrm{pb}}\right) f_i\phi_i\frac{S(m_S/m_{N_i})}{m_{N_i}/\mathrm{GeV}}$$

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Earth: $c=4.8\times10^{15}\ s^{-1}$
Sun: $c=4.8\times10^{24}\ s^{-1}$

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Nuclear abundance, distribution, and mass

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Local DM energy density and velocity dispersion

Nuclear abundance, distribution, and mass

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Local DM energy density and velocity dispersion

Nuclear abundance, distribution, and mass

Kinetic form factor suppression

$$S(x) = \left[A^{3/2}/(1+A^{3/2})\right]^{2/3}$$

$$A = \frac{3}{2}\frac{x}{(x-1)^2}\left(\frac{\langle v_{esc}\rangle^2}{\bar{v}^2}\right)$$

Analysis: Capture Rate

$$C = c\,\frac{(\rho/0.3\ \mathrm{GeV\ cm^{-3}})}{(m_S/\mathrm{GeV})(\bar{v}/270\ \mathrm{km\ s^{-1}})} \sum_i F_i(m_S) \left(\frac{\sigma_0^i}{10^{-4}\mathrm{pb}}\right) f_i \phi_i \frac{S(m_S/m_{N_i})}{m_{N_i}/\mathrm{GeV}}$$

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Local DM energy density and velocity dispersion

Form factor suppression

Nuclear abundance, distribution, and mass

Kinetic form factor suppression

Earth: $F_i \approx 1$

$$F_{Fe}(m_S) \approx 1 - 0.26\left(\frac{A}{A+1}\right)$$

Sun: $F_i(m_S) = F_i^{inf} + (1 - F_i^{inf})\exp\left[-\left(\frac{\log(m_S)}{\log(m_c^i)}\right)^{\alpha_i}\right]$

Analysis: Capture Rate

$$C = c\,\frac{(\rho/0.3\ \mathrm{GeV\ cm^{-3}})}{(m_S/\mathrm{GeV})(\bar{v}/270\ \mathrm{km\ s^{-1}})}\sum_i F_i(m_S)\left(\frac{\sigma_0^i}{10^{-4}\mathrm{pb}}\right) f_i\phi_i\,\frac{S(m_S/m_{N_i})}{m_{N_i}/\mathrm{GeV}}$$

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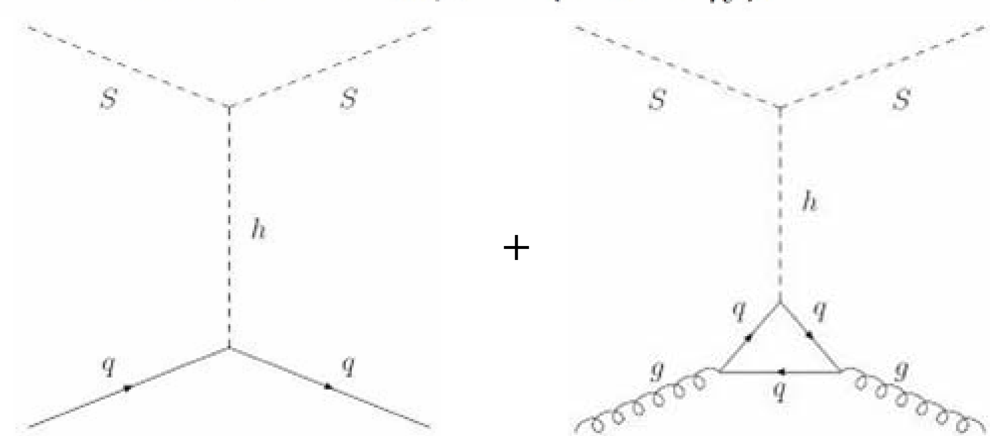
DM-Nucleus cross section

$$\sigma_0^i = \frac{m_S^2 m_{N_i}^2}{4\pi(m_S + m_{N_i})^2}\left(\frac{\lambda_L}{m_S m_h^2}\right)^2 f^2 m_{N_i}^2$$



Analysis: Annihilation Rate

- Number of DM particles as a function of time:

$$\dot{N} = C - C_A N^2 \qquad C_A = \langle \sigma_A v \rangle V_2 / V_1^2$$

$$V_j = (3m_{pl}^2 T/(2j m_S \rho))^{3/2}$$

- Solve to get annihilation rate $\Gamma_A = \frac{1}{2} C \tanh^2(t/\tau)$

  where $\tau = \sqrt{CC_A}$

- If $t \gg \tau$, annihilation rate is maximal: $\Gamma_A = C/2$

Analysis: Detector Rate

$$\Gamma_{detect} = c \left(\frac{\Gamma_A}{s^{-1}} \right) \left(\frac{m_S}{GeV} \right)^2 \sum_i a_i b_i \sum_F B_F \langle N z^2 \rangle_{F,i} (m_S)$$

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Branching fraction: SS => channel F

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Neutrino scattering coefficients and muon range coefficients

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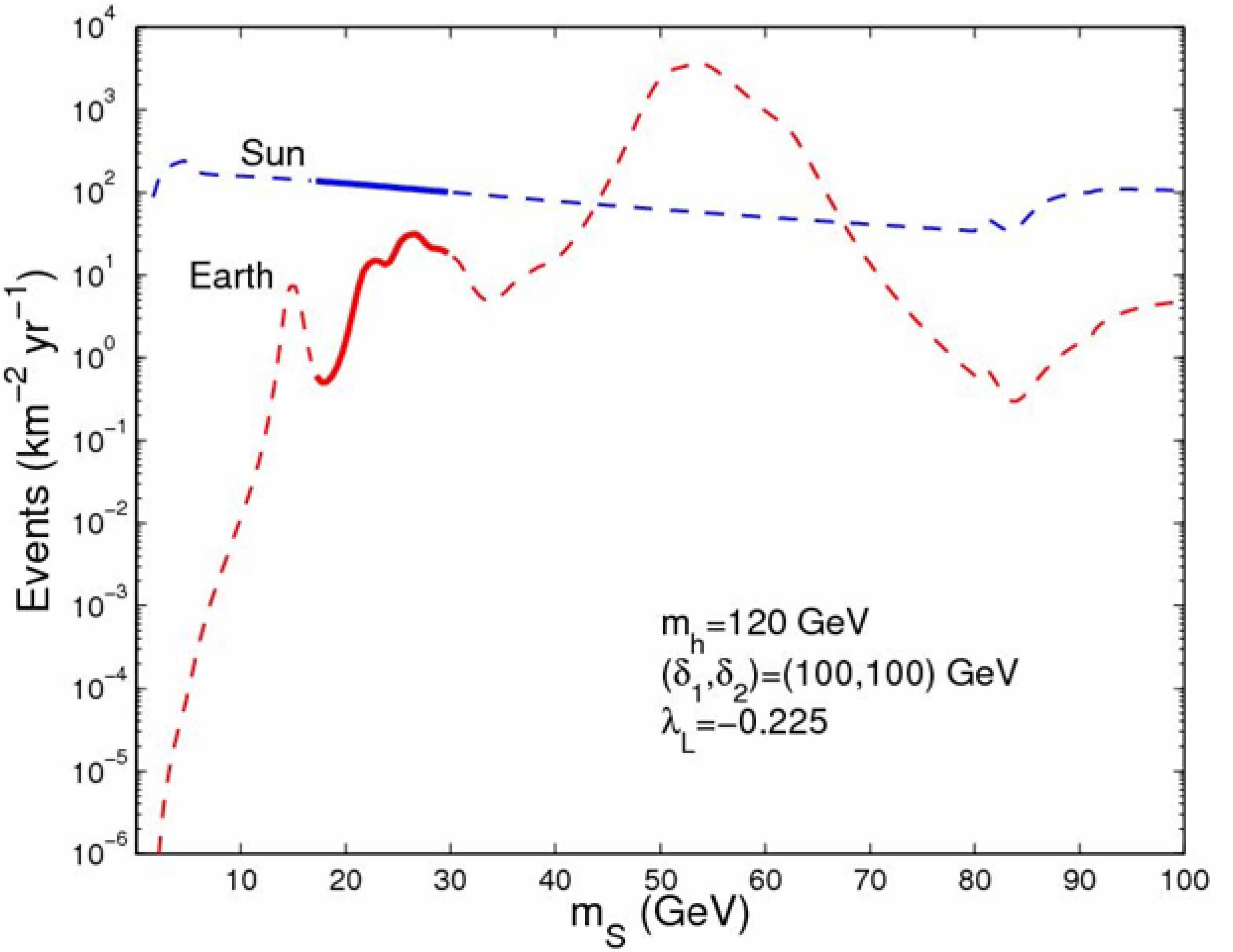
Neutrino scattering coefficients and muon range coefficients

Second moment of neutrino spectrum
- Includes B_F for F=>stuff + neutrinos

Analysis: Results

- Low mass region
- Capture rate enhanced when $m_S = m_N$



Analysis: Results

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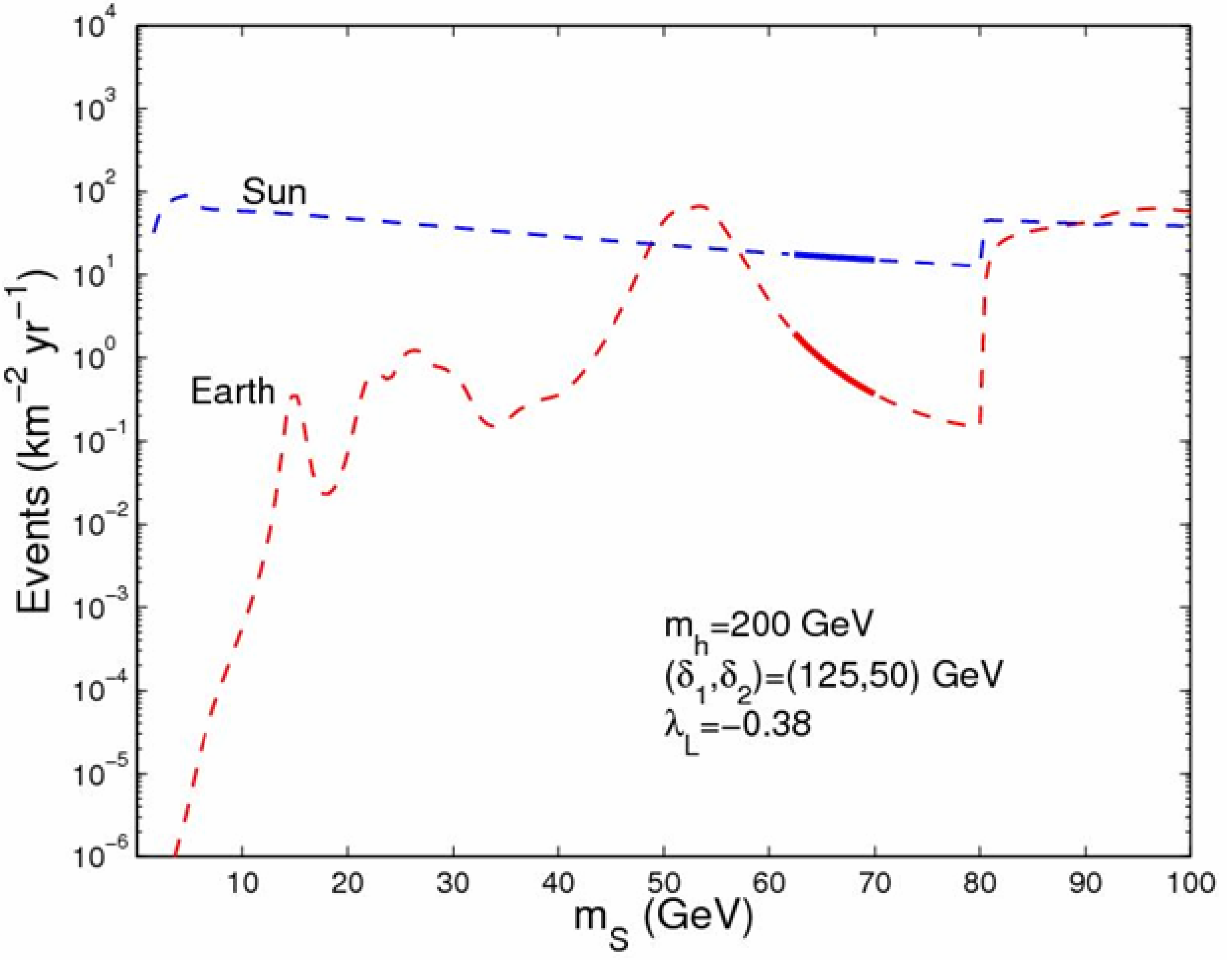
- Capture rate enhanced when $m_S = m_N$
- High m_h compensated by high λ_L



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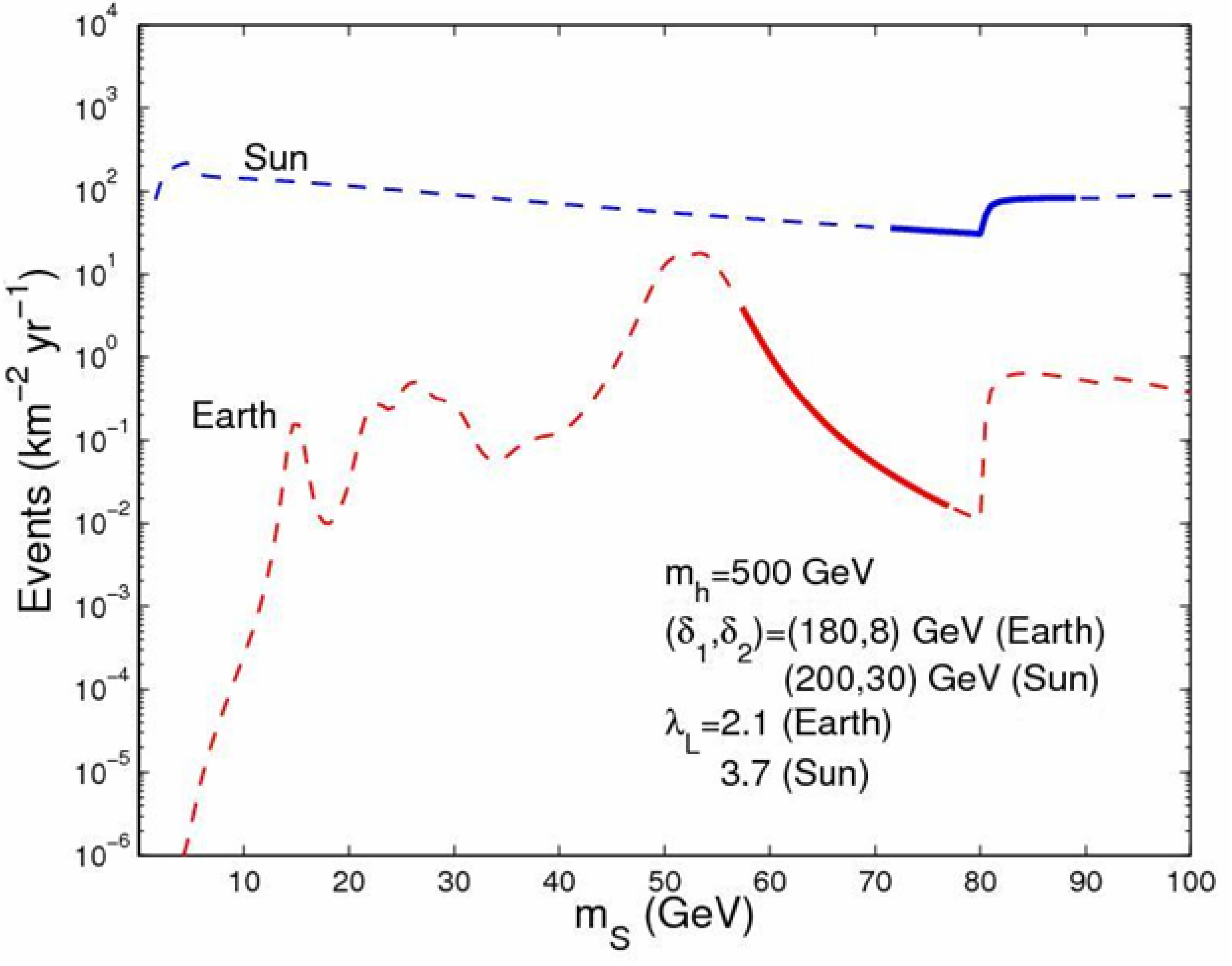
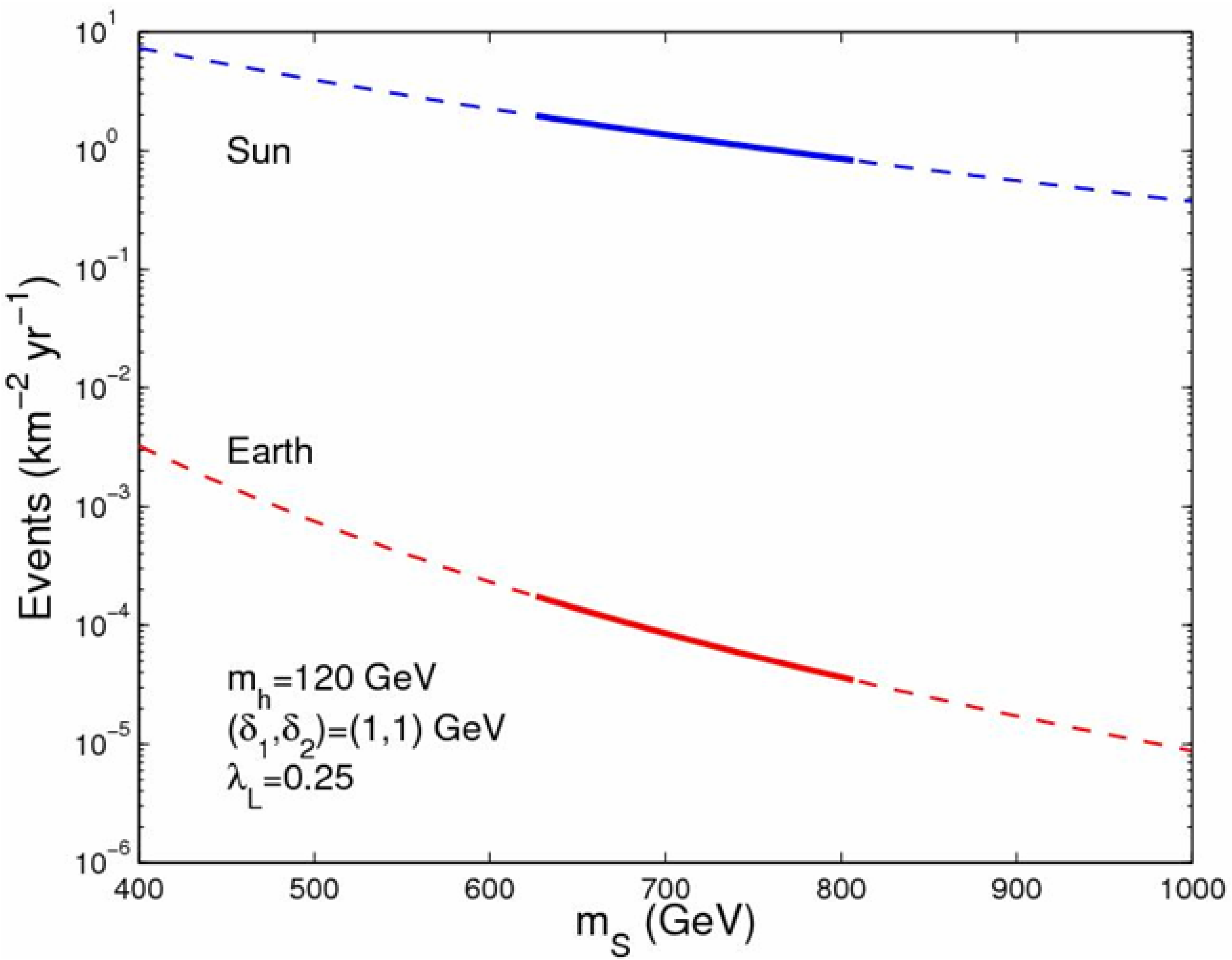


Analysis: Results

- High mass region
- Lower signal due to
  $m_S \gg m_N$



Conclusion

- Barring form factor suppression, the capture rate is governed mainly by the scattering cross section.
- Expect a few to hundreds of events per year at km size detectors (optimistic)
- Things that should be done:

  - Careful signal-background analysis for detection

  - Full three flavor approach with oscillations