Light dark matter in the NMSSM: Upper bounds on direct detection cross sections

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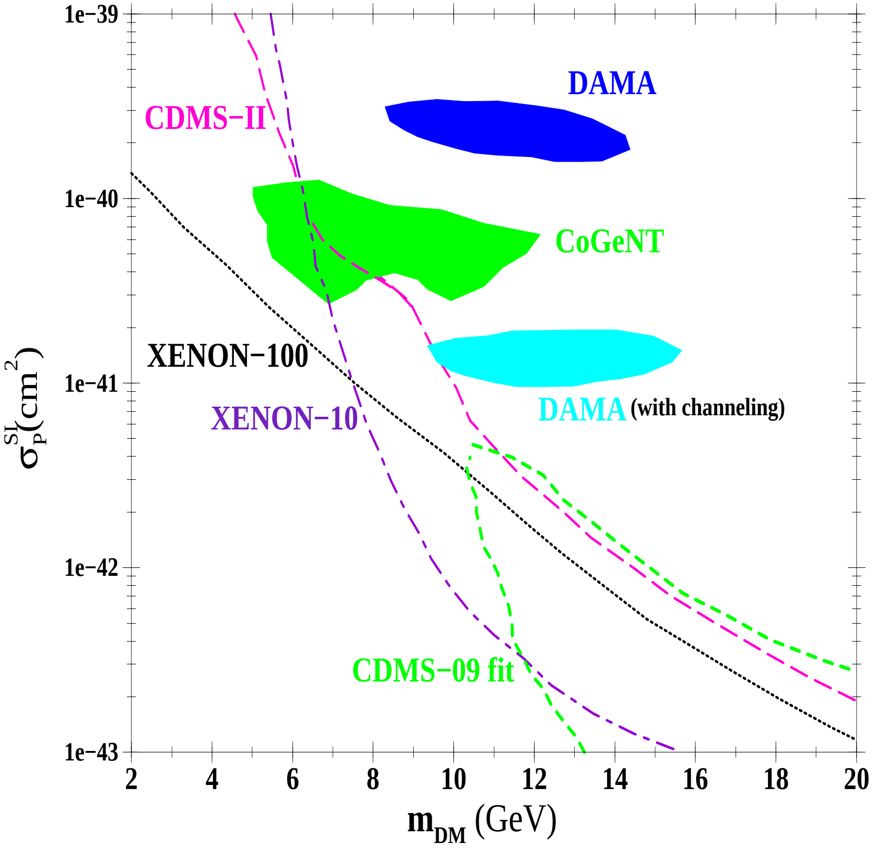
Ref: arXiv:1007.1151

Authors: Debottam Das and Ulrich Ellwanger

Light DM : Direct Detection results



- Light dark matter is getting more and more attractive in the light of recent direct detection results..DAMA.. CoGeNT..$\Rightarrow$ reported events in excess of the expected background $\Rightarrow$ compatible with $m_{DM} \sim 5 - 12$ GeV
- Similarly, CDMS-II experiment reported two events $\Rightarrow$ could be explained by $m_{DM} \gtrsim 10$ GeV
  Ref: J. Kopp, T. Schwetz and J. Zupan,
  JCAP 1002 (2010) 014
- Xenon10 and Xenon100 (also others) provide exclusion limits $\Rightarrow$ set upper bounds on the σ^{SI} $\Rightarrow$ incompatible with the signal events

In general NMSSM, respecting all experimental constraints

we examine the upper limit of σ^{SI} for $m_{\chi_1^0} < 20$ GeV

Light χ_1^0 DM in MSSM

- In the basis of $\left(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0\right)$ neutralino mass matrix:

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} \\ & & 0 & -\mu \\ & & & 0 \end{pmatrix}$$

- In general MSSM, LSP $(\equiv \chi_1^0)$ can be very light $\Rightarrow$ only possibility $\chi_1^0 \simeq \tilde{B}$ with mass $m_{\chi_1^0} \simeq M_1$ $\Rightarrow$ Chargino mass limit puts a lower bound on Wino and Higgsino masses $\Rightarrow Min\{M_2, |\mu|\} \gtrsim 100$ GeV

- WMAP constraint is satisfied via CP-odd Higgs (A) exchange $\Rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \to A^* \to f\bar{f} \Rightarrow$ set a lower bound on $m_{\chi_1^0} \Rightarrow m_{\chi_1^0} \gtrsim 6$ GeV is required

- For large values of $\tan\beta$ (required for large σ^{SI}), $B_s \to \mu^+\mu^-$ ($\propto \frac{\tan^6\beta}{m_A^4}$) is very stringent $\Rightarrow m_{\chi_1^0} \lesssim 20$ GeV is highly constrained

- In NMSSM: χ_1^0 with mass < 10 GeV is possible (consistent with all constraints) $\Rightarrow$ relic density is satisfied via exchange of an additional CP-odd Higgs boson A_1
Ref: John F. Gunion, Dan Hooper, Bob McElrath **Phys.Rev.D73:015011,2006**

NMSSM : Upshots

- W_{MSSM}=$\mu H_u H_d$ +......
  $W_{NMSSM} = \lambda S H_u H_d + \frac{k}{3} S^3$ +.... (S: SM singlet superfield)
- The VEV $< s >$ of the real scalar component of $S \Rightarrow \mu_{eff} = \lambda s \Rightarrow \quad \mu_{eff} \sim M_{SUSY}$
- $S \Rightarrow$ leaves footprints in the Higgs sector and in the neutralino sector$\Rightarrow$
  - 3 CP-even neutral Higgs bosons H_i
  - 2 CP-odd neutral Higgs bosons A_1 and A_2
  - One charged Higgs boson $H^{\pm}$
  - Five neutralinos χ_i^0, $i = 1 \ldots 5$, which are mixtures of the Bino, the neutral Wino, the neutral Higgsinos and the Singlino
- Lightest CP-odd Higgs boson A_1 in the basis (A_{MSSM}, S_I):

$$A_1 = \cos\theta_A A_{MSSM} + \sin\theta_A S_I$$

- A_{MSSM} is the CP-odd scalar in the MSSM sector of the NMSSM
- S_I representing the singlet scalar of the NMSSM

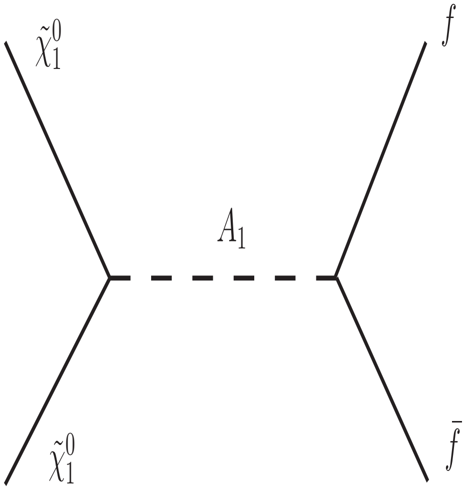
Light χ_1^0 DM in NMSSM

- LSP composition : (An additional state Singlino appears)

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0 + N_{15}\tilde{S}$$

N_{ij}– matrix elements that diagonalizes the neutralino mass matrix

- $\chi_1^0 \sim \tilde{B}$ ($m_{\chi_1^0} \sim M_1$) and additionally $\tilde{S}$ ($m_{\chi_1^0} \sim 2\kappa s$) can be very light ($< 20$ GeV)$\Rightarrow$ WMAP constraint is satisfied via s channel A_1 exchange



$\chi_1^0\chi_1^0 A_1 \simeq \cos\theta_A N_{11} N_{13}$

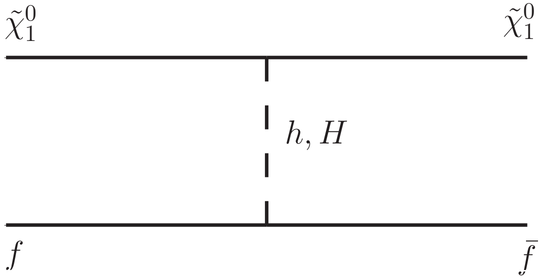
$A_1 b\bar{b} \simeq \cos\theta_A \tan\beta$

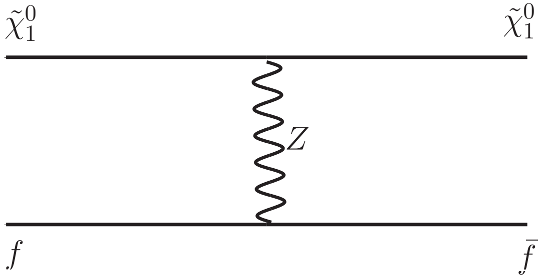
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow A_1^* \rightarrow f\bar{f}$
- A_1 couplings to the SM fermions invlove $\cos\theta_A \Rightarrow C_{A_1\mu^-\mu^+} = C_{A_1\tau^-\tau^+} = C_{A_1 b\bar{b}} = \cos\theta_A \tan\beta$
- $\sigma_{ann} \sim (A_1 b\bar{b})^2 (\chi_1^0\chi_1^0 A_1)^2 \frac{1}{(m_{A_1}^2 - 4\, m_{\chi_1^0}^2)^2}$
- Constraint from $B_s \rightarrow \mu^+\mu^-$ becomes weaker$\Rightarrow$ $A_1 \rightarrow \mu\bar{\mu}$ is suppressed by $\cos^2\theta_A$
- But, A_1 cannot be arbitrary light $\Rightarrow$ Strong bounds from accelerator results,Υ decays and B physics

Dark Matter detection: σ^{SI}, σ^{SD}

- Effective lagrangian for elastic scattering between neutralino-nucleon in SUSY: $\mathcal{L} = \alpha'_q \bar{\chi}\gamma^{\mu}\gamma^{5}\chi \bar{q}_i \gamma_{\mu}\gamma^{5} q_i + \alpha_q \bar{\chi}\chi \bar{q}_i q_i$. α_q and α'_q contain all SUSY model information

  2nd term : WIMP-nucleon SI scattering $\Rightarrow$ Higgs exchange is dominant
  1st one : WIMP-nucleon SD scattering $\Rightarrow$ Z exchange is dominant (A_1 exchange has no contribution)





- σ^{SI} & σ^{SD} become large for $\chi_1^0 \sim \tilde{B} - \tilde{H}$
- $\sigma^{SI} \propto \dfrac{\mathcal{C}^2_{\chi_1^0 \chi_1^0 h(H)} \mathcal{C}^2_{h(H)s\bar{s}}}{m^4_{h(H)}}$
- Usually H plays the dominant role in σ^{SI} (particularly for large $\tan\beta$ and for $h \simeq h_{SM}$) $\sigma^{SI} \sim \dfrac{N_{11}^2 N_{13}^2 \tan^2\beta}{m_H^4}$
- $C_{Z\chi_1^0\chi_1^0}$ depends on the Higgsino components ($\tilde{H}_u^0$ and $\tilde{H}_d^0$) only $\Rightarrow \sigma^{SD} \sim (N_{13}^2 - N_{14}^2)^2$

- Large $\sigma^{SI}, \sigma^{SD} \Rightarrow \mathrm{Max}(\mathrm{N}_{13})$ (small μ_{eff}) required $\Rightarrow$ constrained by LEP
- Similarly, large $\sigma^{SI} \Rightarrow Min(m_H) \Rightarrow$ but $m_H \simeq m_H^{\pm} \Rightarrow$ bounds from the B-physics are quite strong

Light χ_i^0 : LEP Constraints

- For small values of $\mu_{eff} \Rightarrow \chi_2^0$ and χ_3^0 become Higgsino-like with masses $\sim \mu_{eff} \Rightarrow$ production processes $e^+e^- \to \chi_1^0\chi_i^0$ $(i = 2, 3)$ provide stringent constraint
- For very light χ_1^0, the production cross sections of $\chi_1^0\chi_2^0$ and $\chi_1^0\chi_3^0$ should be < 0.05 pb
  Ref: G. Abbiendi et al. [OPAL Collaboration], **Eur. Phys. J. C 35 (2004)**
- Assuming heavy selectrons, $e^+e^- \to \chi_1^0\chi_i^0$ originates from Z^*-exchange only $\Rightarrow$ can be simplied into

$$\sigma_Z(e^+e^- \to \chi_1^0\chi_i^0)[\mathrm{pb}] \simeq 8.3 \times 10^{-7} \frac{(s-\mu^2)^2\mu^2}{u^2+\mu^2}\left(1+\frac{\mu^2}{2s}\right)$$

- Thus the upper OPAL bound $\sigma_Z(e^+e^- \to \chi_1^0\chi_i^0) \simeq 0.05$ pb becomes a lower bound on $|\mu|$ $(\equiv \mu_{eff})$,

$$|\mu_{\mathbf{eff}}| \gtrsim \mathbf{111}\ \mathrm{GeV}$$

- Numerical result: $\boxed{|\mu_{eff}| \gtrsim 120 \text{ GeV}}$ $\Rightarrow$ upper bound on N_{13}^2 $\Rightarrow$ $\boxed{N_{13}^2 \lesssim 0.12}$

Light χ_1^0 : LEP Constraints..contd

- Upper bound on the invisible Z decay width $\Rightarrow \Delta\Gamma_Z^{inv} \lesssim 2.0$ MeV $\Rightarrow$ contribution comes from $Z \to \chi_1^0\chi_1^0$
  Ref: **Phys.Rept.427:257,2006**
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$$\Delta\Gamma_Z^{inv} = \frac{M_Z^3 G_F}{12\sqrt{2}\pi}\left(N_{13}^2 - N_{14}^2\right)^2 \left(1 - \frac{4m_{\chi_1^0}^2}{M_Z^2}\right)^{3/2} \sim 0.165\ \mathrm{GeV}\left(N_{13}^2 - N_{14}^2\right)^2$$

- Then the upper bound on $\Delta\Gamma_Z^{inv}$ implies

$$\left|\mathbf{N_{13}^2 - N_{14}^2}\right| < \mathbf{0.11}$$

- For large $\tan\beta$, where $N_{14}^2 \ll N_{13}^2$, this bound on N_{13}^2 is very similar to the bound obtained from the OPAL limits

Constraint on the A_1 mass : Upsilon decays

- Radiative Upsilon decays ($\Upsilon(ns) \equiv b\bar{b}$ vector like bound state with $m_\Upsilon \geq 9.46$ GeV)$\rightarrow \gamma + X$ searched in B-factories like BaBar, CLEO..
- $\Upsilon \equiv \gamma + A_1$ followed by $A_1 \rightarrow \tau^+\tau^-,\ \mu^+\mu^-$ $\Rightarrow$visible if A_1 is quite light ($A_1 \leq 10$)GeV $\Rightarrow$ put bounds on m_{A_1} and in particular on $\cos\theta_A$
- bottom-eta η_b meson $\equiv$ CP-odd scalar $b\bar{b}$ bound state with $m_{\eta_b} \sim 9.389$ GeV has recently been discovered
- A_1 with mass close to m_{η_b} is constrained (9<m_{A_1}<10 GeV) $\Rightarrow$physical states after mixing should provide the correct mass ~ 9.389 GeV

(Ref: Talk presented by Ulrich Ellwanger & Miguel-Angel Sanchis-Lozano)

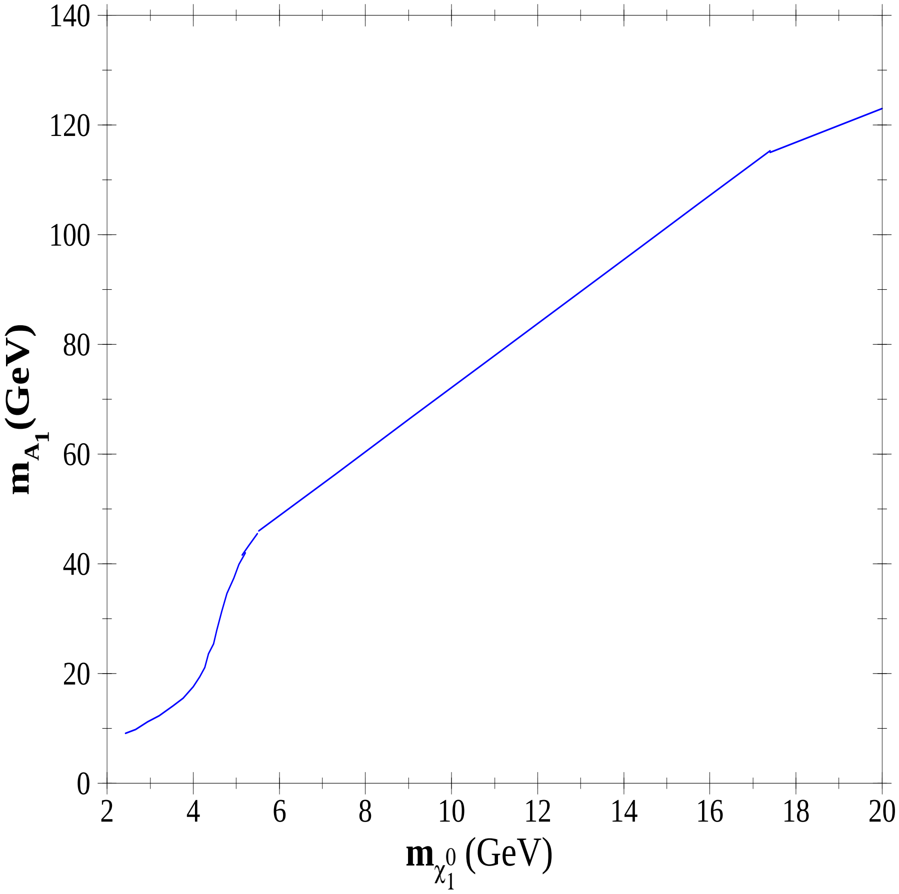
Light A_1 & $H^{\pm}$: Constraints from B physics

- List of the dominant constraints :
  - $Br(b \longrightarrow s\gamma)$
  - ΔM_s, ΔM_d $(\equiv m_{\bar{B}_{s,d}} - m_{B_{s,d}})$
  - $Br(B_s \longrightarrow \mu^+\mu^-)$
  - $Br(B^+ \longrightarrow \tau^+\nu_\tau)$
- A_1 in s channel dominantly contributes to the process like ΔM_s, ΔM_d, and $Br(B_s \rightarrow \mu^+\mu^-)$ via flavor changing vertices $b - s(d) - A_1$
- Other constraints are more dependent on the $m_{H^\pm}$⇒$m_{H^\pm} < 200$ GeV is highly restricted⇒put lower bound on m_H as $m_H \simeq m_{H^\pm}$
- SUSY contribution to the magnetic moment of muon ⇒ $a_\mu^{susy} = a_\mu^{expt} - a_\mu^{SM}$ ⇒ dominant contributions arise principally via the $\tilde{\chi}_1^0 - \tilde{\mu}$ and the $\tilde{\chi}_1^\pm - \tilde{\nu}$ loops ⇒ a_μ^{susy} can be better explained by positive μ values⇒disfavours negative μ values

Results : Parameters for MAX(σ^{SI})

- $\lambda = 0.05 \Rightarrow$ to reduce the negative contribution in $M^2_{H^\pm}$
- $\kappa = 0.55 \Rightarrow$ Singlino and the singlet-like CP-even Higgs state become heavy
- $m_{\tilde{f}_i} \sim$ 1 TeV $\Rightarrow$ $\tilde{l}_i$ contributions to $e^+e^- \to \chi^0_1\chi^0_i$ is negligible
- A_{top} is varied from 300 to 650 GeV$\Rightarrow$ for satisfying $BR(b \to s\gamma)$ constraint
- $\tan\beta \sim 35 - 44$$\Rightarrow$ compromise between the $B-$physics constraints particularly $BR(B_s \to \mu^+\mu^-)$ and Max(σ^{SI})
- $\mu_{eff} \simeq 128$ GeV $\Rightarrow$ for satisfying constraints from $e^+e^- \to \chi^0_1\chi^0_i$ & $\Delta\Gamma^{inv}_Z$
- $A_\kappa \sim -14 \ldots - 4$ GeV$\Rightarrow$ $m_{A_1} \sim 9 - 120$ GeV
- $M_A \sim 260 - 315$ GeV$\Rightarrow$ $m_H \sim 205 - 260$ GeV$\Rightarrow$ $m_{H^\pm} \sim 225 - 280$ GeV

Results : Light pseudo-scalar & WMAP constraint



- Figure depicting $\chi_1^0 - m_{A_1}$ relationship to satisfy WMAP constraint on relic density ($0.091 < \Omega h^2 < 0.129$)
- Neutralino components mostly vary within:

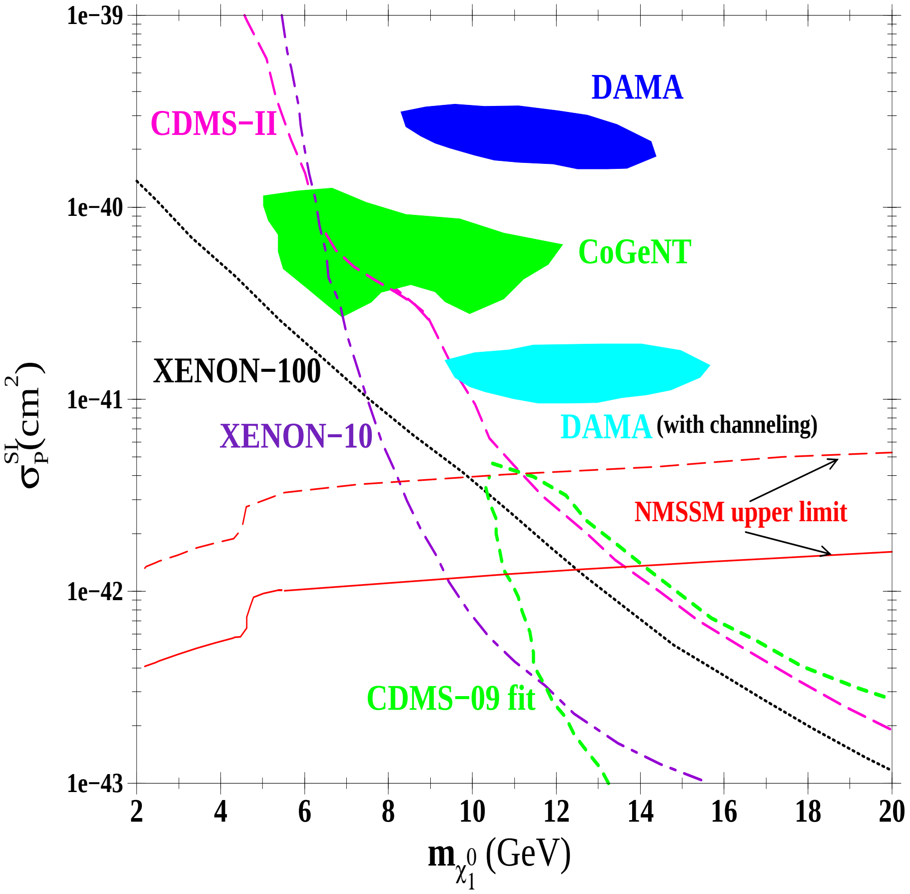
  $N_{11} \sim -0.94\ ,\ N_{12} \sim 0.01 \ldots 0.03$

  $\mathbf{N_{13} \sim -0.32 \ldots -0.34}$

  $N_{14} \sim 0.013 \ldots 0.06\ ,\ N_{15} \sim 0.001$

- Higgsino masses : $m_{\chi_2^0} \sim 105$ GeV and $m_{\chi_3^0} \sim 145$ GeV for all points

Results: Upper limit on σ^{SI}



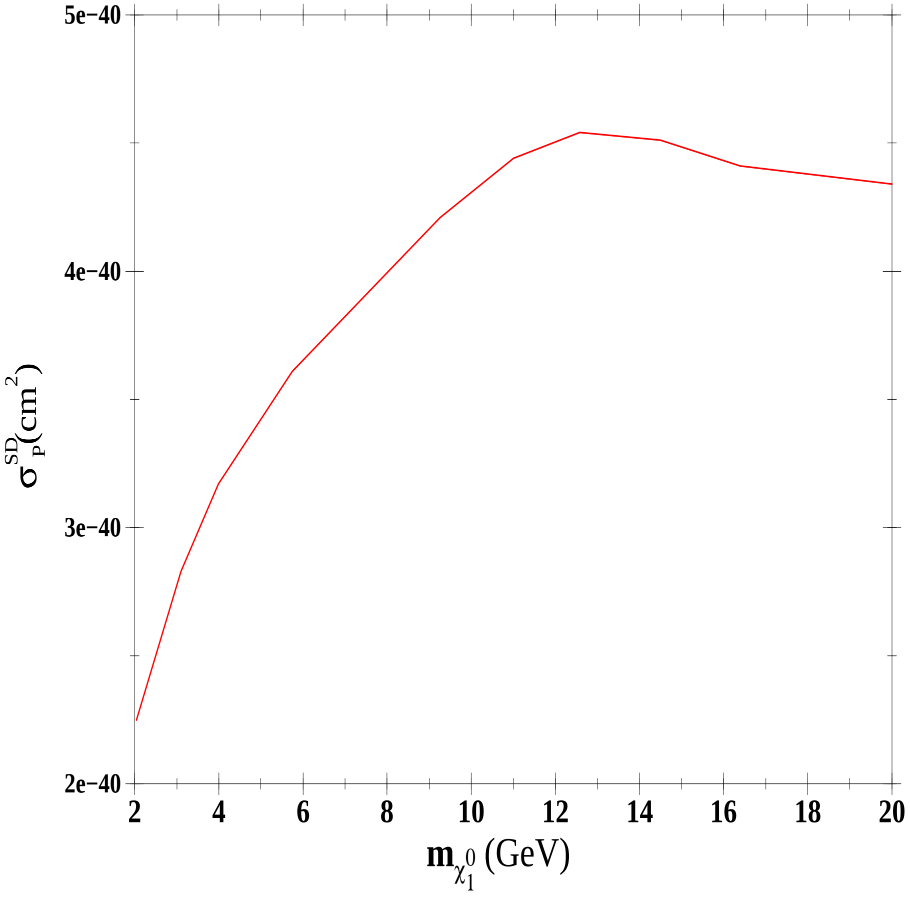
- The upper limit on the σ_P^{SI} for $\sigma_{\pi N} = 55$ MeV and $\sigma_0 = 35$ MeV $\Rightarrow$ shown in red line

- Upper bound on σ_p^{SI} for $\sigma_{\pi N} = 73$ MeV and $\sigma_0 = 30$ MeV shown in red dashed line$\Rightarrow$ choice maximizes strange qurak content of the nucleon

- Explaining the DAMA/CoGeNT results is difficult within the general NMSSM $\Rightarrow$ enhanced contribution in the astrophysical quantities would be required

- Future data from Xenon10, Xenon100 and CDMS-II would test regions of the parameter space of the NMSSM

Results: Upper limit on σ^{SD}



- M_A is set at large value (~ 1000 GeV) $\Rightarrow m_H$ is irrelevant in $\sigma^{SD} \Rightarrow$ helpful to avoid $B-$physics constraints
- μ_{eff} is varied between $\sim 121 - 129$ GeV
- Max(σ_P^{SD}) in NMSSM is still one to two orders of magnitude smaller than the present day experimental sensitivity

Summary

- we have performed a detailed analysis of the WMAP compatible NMSSM parameter space for obtaining Max(σ^{SI}) $\Rightarrow M_1$ is varied to have $m_{\chi_1^0} \sim$ 2 - 20 GeV range
- This part of the parameter space is restricted in the MSSM via sparticles mass limits and by the constraint $B_s \to \mu^+\mu^-$
- Here LSP ($\tilde{B} - \tilde{H}$) satisfies the WMAP constraint via $s-$channel A_1 exchange
- Our results respect all the existing experimental constraints till date
- The resulting upper bounds on $\sigma^{SI} \lesssim 10^{-42}$ cm^2 $= 10^{-6}$ pb

THANK YOU

Direct Detection : Computation of σ^{SI}

- $\sigma^{SI} = \frac{4m_r^2}{\pi} [Z f_p + (A-Z) f_n]^2$; $m_r = \frac{m_\chi m_N}{(m_\chi + m_N)}$
- f_p and f_n contain all the model dependent information and nuclear form factors
- $$\frac{f_{p,(n)}}{m_{p,(n)}} = \sum_{q=u,d,s} f_{Tq}^{(p,(n))} \frac{\alpha_q}{m_q} + \frac{2}{27} f_{TG}^{(p,(n))} \sum_{c,b,t} \frac{\alpha_q}{m_q} ,$$
- Cross-section depends on the co-efficients $f_{Tq}^{(p,(n))}$ and in particularly on $f_{Ts}^{(p,(n))}$
- $f_{Ts}^{(p,(n))} = \frac{\sigma_{\pi N} y}{(1+\frac{m_u}{m_d}) m_{p(n)}} \frac{m_s}{m_d}$

  - $y \Rightarrow$ strange qurak content of the nucleon $\Rightarrow y = 1 - \frac{\sigma_0}{\sigma_{\pi N}}$
  - $\sigma_{\pi N}$ and σ_0 $\Rightarrow$ major sources for uncertainties
  - Default values: $\sigma_{\pi N} = 55\ \mathrm{MeV}$, $\sigma_0 = 35\ \mathrm{MeV}$ used in micrOMEGAs
  - larger values for $\sigma_{\pi N}$ and smaller σ_0 would enhance σ^{SI}

Direct Detection : Computation of σ^{SD}

- $$\sigma_{SD} = \frac{32}{\pi} G_F^2 m_r^2 \Lambda^2 J(J+1).$$

  Here, J is the spin of the nucleus, and

  $$\Lambda = \frac{1}{J}(a_p \langle S_p \rangle + a_n \langle S_n \rangle),$$

  where

  $$a_p = \sum_i \frac{\alpha'_{qi}}{\sqrt{2} G_f} \Delta_i^{(p)}, \text{ and } a_n = \sum_i \frac{\alpha'_{qi}}{\sqrt{2} G_f} \Delta_i^{(n)}.$$

- The quantities $< S_p >$ and $< S_n >$ are the expectation values of the total spin of protons and neutrons respectively, and $\Delta_i^{(p,n)}$ contains the quark spin contribution to the nucleon
- Neutron spin contribution is less than that of proton $\Rightarrow$ $\sigma_n^{SD} < \sigma_p^{SD}$