Dark Matter Prospects in Deflected Mirage Mediation

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arXiv:0905.0674
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June 6, 2009
Outline

- Deflected Mirage Mediation
  - Outline model setup
- Parameter Space
  - Allowed regions in specific framework
  - Neutralino properties
- Dark Matter Signatures
  - Direct detection, muons & gamma rays
- Summary
Deflected Mirage Mediation

- DMM: string motivated scenario where modulus, anomaly and gauge mediation all present and of similar size

\[
\left\langle \frac{F^T}{T + \bar{T}} \right\rangle \sim \frac{1}{16\pi^2} \left\langle \frac{F^C}{C} \right\rangle \sim \frac{1}{16\pi^2} \left\langle \frac{F^X}{X} \right\rangle
\]

- Naturally realized in type IIB string theory with flux compactification (KKLT)
- Below SUSY breaking scale (GUT scale): MSSM field content + messenger sector
- Messenger sector: gauge singlet $X$ and $N$ messenger fields $\Psi$, $\bar{\Psi}$ in complete GUT representation of SM gauge groups to preserve gauge coupling unification $g_a^{-2}(\mu_{GUT}) = g_{GUT}^{-2} - \frac{N}{8\pi^2} \ln \left( \frac{\mu_{GUT}}{\mu_{mess}} \right)$ with $g_{GUT}^2 \approx 1/2$

- Soft terms get contribution from modulus mediation (universal) and anomaly mediation ($\propto b_a$) at SUSY breaking scale ($\mu_{GUT}$)
- At $\mu_{mess} < \mu_{GUT}$ soft terms recieve contribution from messengers
A priori have three mass scales

\[ M_0 = F^T / (T + \bar{T}), \quad m_{3/2} = F^C / C, \quad \Lambda_{\text{mess}} = F^X / X \]

High scale soft terms combination of \( M_0 \) and \( m_{3/2} \)

\[ M_a (\mu_{\text{GUT}}) = M_0 + g^2_a (\mu_{\text{GUT}}) \frac{b'_a}{16\pi^2} m_{3/2} \quad b'_a = b_a + N \]

Evolve down to messenger scale \( \mu_{\text{mess}} < \mu_{\text{GUT}} \)

\[ M_a (\mu_{\text{mess}}) = M_0 \left[ 1 - g^2_a (\mu_{\text{mess}}) \frac{b'_a}{8\pi^2} \ln \left( \frac{\mu_{\text{GUT}}}{\mu_{\text{mess}}} \right) \right] + g^2_a (\mu_{\text{mess}}) \frac{b'_a}{16\pi^2} m_{3/2} \]

Integrate out messengers gives threshold correction

\[ \Delta M_a = -N \frac{g^2_a (\mu_{\text{mess}})}{16\pi^2} (\Lambda_{\text{mess}} + m_{3/2}) \]

Evolve \( M_a (\mu_{\text{mess}}) + \Delta M_a \) to low scale

\[ M_a (\mu_{\text{EW}}) = g^2_a (\mu_{\text{EW}}) \frac{b_a}{16\pi^2} m_{3/2} + \left[ 1 - g^2_a (\mu_{\text{EW}}) \frac{b_a}{8\pi^2} \ln \left( \frac{\mu_{\text{mess}}}{\mu_{\text{EW}}} \right) \right] \]

\[ \times \left[ M_0 \left( 1 - g^2_a (\mu_{\text{mess}}) \frac{b'_a}{8\pi^2} \ln \left( \frac{\mu_{\text{GUT}}}{\mu_{\text{mess}}} \right) \right) - N \frac{g^2_a (\mu_{\text{mess}})}{16\pi^2} \Lambda_{\text{mess}} \right] \]
DMM Gaugino Masses

- Introduce two dimensionless ratios ($M_P = 2.4 \times 10^{18}$ GeV):
  
  $$\alpha_g = \frac{\Lambda_{\text{mess}}}{m^{3/2} \alpha_g} \quad \& \quad \alpha_m = \frac{m^{3/2}}{M_0 \ln \left( \frac{M_P}{m^{3/2}} \right)}$$

- Re-arrange to find (Choi)
  
  $$M_a (\mu_{\text{EW}}) = M_0^{\text{eff}} \left\{ 1 + \beta_a (\mu_{\text{EW}}) \ln \left( \frac{\mu_{\text{EW}}}{\mu_{\text{mir}}} \right) \right\}$$

  $$\beta_a (\mu_{\text{EW}}) = \frac{b a g^2 (\mu_{\text{EW}})}{8\pi^2} \quad M_0^{\text{eff}} = R M_0$$

  $$R = 1 - \frac{N g^2_{\text{GUT}}}{8\pi^2} \left\{ \frac{\alpha_m \alpha_g}{2} \ln \left( \frac{M_P}{m^{3/2}} \right) + \ln \left( \frac{\mu_{\text{GUT}}}{\mu_{\text{mess}}} \right) \right\}$$

- Gaugino masses unify at a scale
  
  $$\mu_{\text{mir}} = \mu_{\text{GUT}} \left( \frac{m^{3/2}}{M_P} \right)^{\alpha_m / 2R}$$
Following Choi introduce variables $x$ and $y$

$$x = \frac{1}{R + \alpha_m} \quad & \quad y = \frac{\alpha_m}{R + \alpha_m}$$

- $xy$ plane; move between various limits
  - MM $(1, 0)$, GM: $(0, 0)$
  - AM: $(0, 1)$
  - Mirage: $x + y = 1$
  - KKLT $(0.5, 0.5)$

- Gaugino masses in terms of $\{x, y, M_0\}$

$$M_a (\mu_{EW}) = M_0 \frac{1 + \beta_a (\mu_{EW}) t}{x} \left\{ 1 + y \left[ \frac{\beta_a (\mu_{EW}) t'}{1 + \beta_a (\mu_{EW}) t} - 1 \right] \right\}$$

scaling variables: $t = \ln \left( \frac{\mu_{EW}}{\mu_{GUT}} \right) \quad & \quad t' = \frac{1}{2} \ln \left( \frac{M_P}{m_{3/2}} \right)$
Model Dependent Scenario

- Gaugino masses determine large portion of dark matter phenomenology. Need a full model framework to specify full soft SUSY Lagrangian in order to determine $\mu$, etc.
- Type IIB compactified on Calabi-Yau orientifold with flux (KKLT)
- Assume Kähler potential with modular weights $n_i$ for superfields $\Phi_i$

$$K = \sum_i (T + \bar{T})^{-n_i} \Phi_i \bar{\Phi}_i$$

- Soft terms at high scale

$$A_{ijk}(\mu_{GUT}) = M_0 \left[ (3 - n_i - n_j - n_k) - \frac{\gamma_i + \gamma_j + \gamma_k}{16\pi^2} \alpha_m \ln \left( \frac{M_P}{m_{3/2}} \right) \right]$$

$$m^2_i(\mu_{GUT}) = M_0^2 \left[ (1 - n_i) - \frac{\theta_i'}{16\pi^2} \alpha_m \ln \left( \frac{M_P}{m_{3/2}} \right) - \frac{\gamma_i'}{16\pi^2} \left( \alpha_m \ln \left( \frac{M_P}{m_{3/2}} \right) \right)^2 \right]$$

- $m^2_i$ receives threshold correction, $A_{ijk}$ does not
- Gaugino masses in $xy$ plane specified by $\{x, y, M_0\}$: slices of $xy$ plane for specific $M_0$
- Assume: $\tan \beta = 10$, $N = 3$, $\mu_{mess} = 10^{10}$ GeV and
  $\{n_Q, n_U, n_D, n_L, n_E, n_{Hu}, n_{Hd}\} = \{1/2, 1/2, 1/2, 1/2, 1/2, 1, 1\}$
Parameter Space

- Use RGE analysis + Suspect to determine low scale physical masses
- Model dependent scenario $M_0 = 500, 1000$ GeV

Mass bounds: $m_{\tilde{N}_1} \geq 46$ GeV, $m_{\tilde{C}_1} \geq 103$ GeV, $m_{\tilde{g}} \geq 200$ GeV

- Model independent scenario. Determine gaugino masses using $\{x, y, M_0\}$, set $\mu = m_A = 1$ TeV, other soft terms $= \max(1$ TeV, $M_3)$
Neutralino Properties

- Model dependent scenario neutralino mass contours and wave function composition

- $m_{\tilde{g}}$ (solid), $m_{\tilde{C}_1}$ (dashed) and $m_A/m_{\tilde{N}_1}$ (shaded) contours
Relic Density

- WMAP 5 yr data $\Omega_\chi h^2 = 0.1099 \pm 0.0124 \ (2\sigma)$ Komatsu et al. arXiv:0803.0547
- Thermal relic density and all dark matter calculations done using DarkSUSY

<table>
<thead>
<tr>
<th>$\Omega_\chi h^2$</th>
<th>[0, 0.025)</th>
<th>[0.025, 0.07)</th>
<th>[0.07, 0.14)</th>
<th>[0.14, 1)</th>
<th>(1, $\infty$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>color</td>
<td>yellow</td>
<td>blue</td>
<td>red</td>
<td>green</td>
<td>gray</td>
</tr>
</tbody>
</table>

- Rescale local halo density $\rho_\chi = 0.3 \text{ GeV/cm}^3$ by $r_\chi = \min \left(1, \frac{\Omega_\chi h^2}{0.025} \right)$ for all dark matter observables
Random Scan

- Random scan to see effects of other parameters
- Generated 1000 points in the DMM scenario

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Parameter</th>
<th>Min Value</th>
<th>Max Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_0$</td>
<td>100 GeV</td>
<td>2000 GeV</td>
<td>$\mu_{\text{mess}}$</td>
<td>$10^8$ GeV</td>
<td>$10^{14}$ GeV</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>0</td>
<td>5</td>
<td>$\alpha_g$</td>
<td>-5</td>
<td>5</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>2</td>
<td>40</td>
<td>$N$</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

$n_Q = n_U = n_D = n_L = n_E = 0$ or $1/2$ & $n_{H_u} = n_{H_d} = 0$ or $1/2$ or $1$

- Also generated 1000 points with $\alpha_m = \alpha_g = 0$ and vanishing modular weights to represent unified modulus mediation models

![Graph showing DMM and unified models](image)

- Blue circles = DMM models, green circles = unified models
- $x = $ DMM models with $0.07 \leq \Omega_\chi h^2 \leq 0.14$
Direct Detection

Detection of neutralino's via terrestrial DM experiments looking for interactions of LSP with nucleons. Differential rate of interaction:

\[
\frac{dR}{dE} = \sum_i c_i \frac{\rho_x \sigma_{\chi_i} |F_i(q_i)|^2}{2m_x \mu_{\chi_i}^2} \int_{v_{\text{min}}}^{\infty} \frac{f(\vec{v}, t)}{v} d^3v
\]

Focus on two detector types: cryogenic germanium bolometer & dual-phase liquid/gas xenon

Currently experiments are running and placing bounds on interactions (XENON 10, CDMS II) with planned upgrades to larger installations

Calculate recoil rates on Xe & Ge via:

\[
R = \int_{E_{\text{min}}}^{E_{\text{max}}} \left( \frac{dR}{dE} \bigg|_{\text{SI}} + \frac{dR}{dE} \bigg|_{\text{SD}} \right) dE
\]

\( E_{\text{min}}^{\text{Xe}} = 5 \text{ keV}, \quad E_{\text{max}}^{\text{Xe}} = 25 \text{ keV}; \quad E_{\text{min}}^{\text{Ge}} = 10 \text{ keV}, \quad E_{\text{max}}^{\text{Ge}} = 100 \text{ keV} \)

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>Fiducial Mass [kg]</th>
<th>Exposure Time [yr]</th>
<th>( R_{10} ) [counts/(kg yr)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>XENON10(^a)</td>
<td>5.4</td>
<td>0.16</td>
<td>11.54</td>
</tr>
<tr>
<td>XENON100</td>
<td>170 × 0.8</td>
<td>1</td>
<td>7.35 × 10^{-2}</td>
</tr>
<tr>
<td>LUX</td>
<td>350 × 0.8</td>
<td>3</td>
<td>1.19 × 10^{-2}</td>
</tr>
<tr>
<td>XENON1T</td>
<td>1000 × 0.8</td>
<td>5</td>
<td>2.50 × 10^{-3}</td>
</tr>
<tr>
<td>CDMS II(^b)</td>
<td>3.75</td>
<td>0.29</td>
<td>9.18</td>
</tr>
<tr>
<td>SuperCDMS (SNOlab)</td>
<td>27 × 0.8</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>SuperCDMS (DUSEL)</td>
<td>1140 × 0.8</td>
<td>5</td>
<td>2.19 × 10^{-3}</td>
</tr>
</tbody>
</table>


\(^b\) Z. Ahmed et al. [CDMS Collaboration], Phys. Rev. Lett. 102, 011301 (2009)
DD Rates $xy$ Plane

Rates in units of counts/(kg year)

XENON100 1 yr (green), LUX 3 yr (red)

XENON1T 5 yr (blue), not seen (yellow)

SuperCDMS (SNOlab) 3 yr (green), SuperCDMS (DUSEL) 3 yr (red)

not seen (yellow)
DD Rates Random Scan

blue circles = DMM models, green circles = unified models

$\times = \text{DMM models with } 0.07 \leq \Omega_X h^2 \leq 0.14$

- Xe target: (a) Xenon10 (reported), (b) Xenon100 (1 year), (c) LUX (3 year) and (d) Xenon1T (5 year)
- Ge target: (a) CDMS II (reported), (b) SuperCDMS (SNOLab - 3 year) and (c) SuperCDMS (DUSEL - 5 year)
Muons

- Detect neutrinos from neutralino annihilation in the earth and sun. Conversion of $\nu_\mu$ to $\mu$ detected at IceCube
- Integrate differential flux of conversion muons from the earth and sun over range $50 \text{ GeV} \geq E_\mu \geq 300 \text{ GeV}$
- Estimate flux to observe 10 signal events at IceCube in a given exposure (km$^2$ yr)

\[ 0.2 \text{ km}^2 \text{ yr (red)}, 0.5 \text{ km}^2 \text{ yr (green)} \]
\[ 1.5 \text{ km}^2 \text{ yr (blue)}, 10 \text{ km}^2 \text{ yr (yellow)} \]

gray not seen
Diffuse Gammas

- Diffuse gamma ray signal depends on SUSY model as well as halo profile
- Consider Fermi/GLAST with angular resolution of $\Delta \Omega = 10^{-5}$ sr
- $\tilde{J}(\Delta \Omega) = 1.2644 \times 10^4$ (NFW), $\tilde{J}(\Delta \Omega) = 1.0237 \times 10^6$ (NFW+AC)
- Integrate differential flux of photons from 1 GeV to 200 GeV

<table>
<thead>
<tr>
<th>Exposure [m$^2$ yr]</th>
<th>Halo Profile</th>
<th>$\Phi_{100}$ [counts/(cm$^2$ s)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NFW</td>
<td>$5.79 \times 10^{-10}$</td>
</tr>
<tr>
<td>5</td>
<td>NFW</td>
<td>$1.16 \times 10^{-10}$</td>
</tr>
<tr>
<td>1</td>
<td>NFW+AC</td>
<td>$7.15 \times 10^{-12}$</td>
</tr>
<tr>
<td>5</td>
<td>NFW+AC</td>
<td>$1.43 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

1 m$^2$yr NFW (red), 5 m$^2$yr NFW (green)
1 m$^2$yr NFW (blue), 5 m$^2$yr NFW (yellow)
gray not seen

solid = NFW
dash = NFW+AC
Monochromatic Gammas

- Air Cherenkov telescopes to detect monochromatic gamma rays from $\chi\chi \rightarrow \gamma\gamma$ or $\gamma Z$
- Typical ACT energy resolution 15% $\rightarrow$ combine to treat as 1 line

<table>
<thead>
<tr>
<th>Exposure [m$^2$ yr]</th>
<th>Halo Profile</th>
<th>$\Phi_{10}$ [counts/(cm$^2$ s)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>NFW</td>
<td>$31.7 \times 10^{-15}$</td>
</tr>
<tr>
<td>100</td>
<td>NFW+AC</td>
<td>$3.92 \times 10^{-15}$</td>
</tr>
<tr>
<td>500</td>
<td>NFW+AC</td>
<td>$7.83 \times 10^{-16}$</td>
</tr>
<tr>
<td>1000</td>
<td>NFW+AC</td>
<td>$3.92 \times 10^{-16}$</td>
</tr>
</tbody>
</table>

1000 m$^2$ yr NFW (red), 100 m$^2$ yr NFW+AC (green), 500 m$^2$ yr NFW+AC (blue), 1000 m$^2$ yr NFW+AC (yellow), gray not seen.

solid = NFW
dash = NFW+AC
Summary

- DMM: rich framework with 3 mediation mechanisms present simultaneously
- Investigated parameter space of DMM model within a specific framework
  - Plenty of allowed space where have 3 mediation mechanisms present
  - Space offers many different possible signatures of neutralino DM
  - Lower mass scale models will soon be probed at DM experiments
- More combinations of parameters which give WMAP preferred $\Omega_\chi h^2$ than original mirage mediation
  - WMAP preferred regions favor $m_\chi \sim \mathcal{O}(1)$ TeV with significant wino/Higgsino content
  - Favored region will be probed by direct and indirect searches
- Interesting to investigate collider signatures in DMM model (work in progress)
Detect Deflection?

- Can one distinguish mirage models from deflected mirage models using dark matter?
- At low scale can rewrite gaugino masses as

\[
\frac{M_a (\mu_{EW})}{g_a^2 (\mu_{EW})} = \tilde{M}_0 (\tilde{\alpha} + b_a)
\]

\[
\tilde{\alpha} \equiv \left[ \alpha_m \frac{g_a^2 (\mu_{GUT})}{16\pi^2} \ln \left( \frac{M_P}{m_{3/2}} \right) \right]^{-1} - N_m \alpha_g; \quad \tilde{M}_0 \equiv \alpha_m \frac{M_0}{16\pi^2} \ln \left( \frac{M_P}{m_{3/2}} \right) = \frac{m_{3/2}}{16\pi^2}
\]

⇒ For mirage models with \(N = 0\), have DMM models with same gaugino masses at low scale

- Only differences in dark matter phenomenology due to other soft terms and resulting EWSB parameters

- Example of degenerate points: mirage model has \(n_i = 1/2\) & \(\tan \beta = 2.5\) while DMM model has \(n_i = 0\) & \(\tan \beta = 27.8\)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(\tilde{\alpha})</th>
<th>(\tilde{M}_0) [GeV]</th>
<th>(M_0) [GeV]</th>
<th>(\alpha_m)</th>
<th>(N \times \alpha_g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirage</td>
<td>6.52</td>
<td>587</td>
<td>1976</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>DMM</td>
<td>6.52</td>
<td>599</td>
<td>889</td>
<td>3.4</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Quantities</th>
<th>(H%)</th>
<th>(m_\chi) [GeV]</th>
<th>(\Omega_\chi h^2)</th>
<th>(\sigma_{SI}^p) [cm(^2)]</th>
<th>(\Phi_{\gamma \ge 1\text{ GeV}}) [cm(^{-2})s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirage</td>
<td>98.1%</td>
<td>1247</td>
<td>0.13</td>
<td>(0.63 \times 10^{-45})</td>
<td>(6.51 \times 10^{-12})</td>
</tr>
<tr>
<td>DMM</td>
<td>99.5%</td>
<td>1040</td>
<td>0.10</td>
<td>(2.86 \times 10^{-45})</td>
<td>(2.41 \times 10^{-12})</td>
</tr>
</tbody>
</table>
Detect Deflection?

- Generated 1000 points in Mirage scenario

  blue = DMM, green = Mirage
Detect Deflection?

Combined monochromatic flux
Detect Deflection?

- Low scale gaugino masses in terms of explicit mass scales

\[
M_a (\mu_{EW}) = M_0 \left\{ 1 + \beta_a (\mu_{EW}) \left[ t - \frac{N}{b_a} \ln \left( \frac{\mu_{GUT}}{\mu_{mess}} \right) \right] \right\} - \frac{\beta_a (\mu_{EW}) N}{2b_a} \Lambda_{mess} + \frac{\beta_a (\mu_{EW})}{2} m_{3/2}
\]

\[
M_a (\mu_{EW}) = M_0 \left[ 1 + \beta_a (\mu_{EW}) t \right] + m_{3/2} \frac{\beta_a (\mu_{EW})}{2} \left[ 1 - \frac{\alpha'}{b_a} \right]
\]

\[
\alpha' = N \left[ \alpha_g + \frac{2}{\alpha_m} \ln \left( \frac{\mu_{GUT}}{\mu_{mess}} \right) \ln \left( \frac{M_P}{m_{3/2}} \right) \right]
\]