Higgses and Light Dark Matter in the NMSSM

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hep-ph/0509024 [J. Gunion, D. Hooper, B. McElrath]

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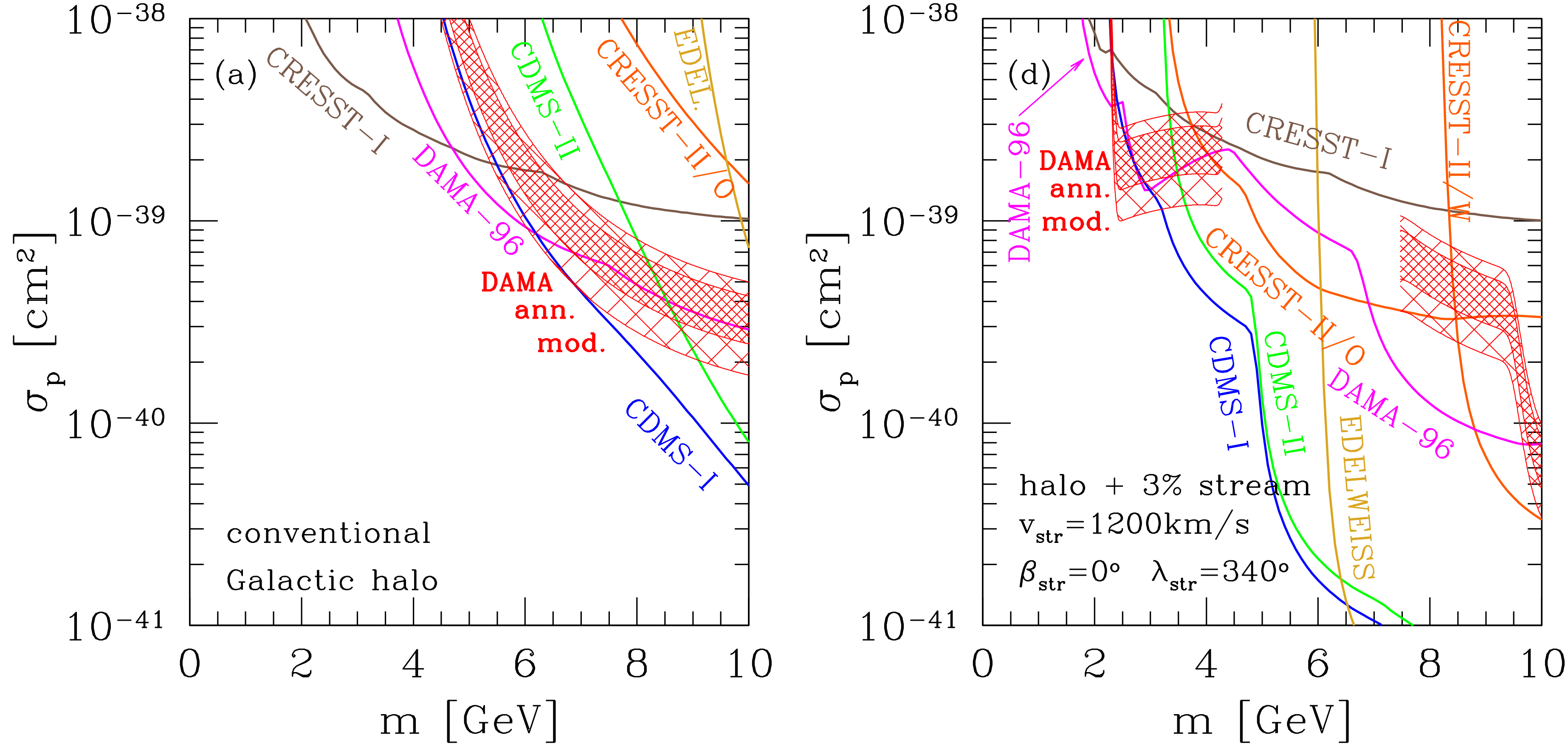
DAMA Evidence

DAMA is a 100kg NaI detector. They observed an annual modulation signal consistent with a WIMP with mass $M_{\chi^0} = 52^{+10}_{-8}$ GeV and a cross section $\sigma = 7.2^{+0.4}_{-0.9} \times 10^{-6}$ pb. [Phys.Lett.B480:23-31,2000]

This is inconsistent with recent CDMS results using Si and Ge. [astro-ph/0405033]

It was pointed out that Na has a lower detection threshold than Si and Ge, making DAMA more sensitive to light dark matter. Furthermore, a "wind" passing through our local region can make DAMA and CDMS compatible. [Gondolo, Gelmini, Savage, Freese]

DAMA/CDMS Compatability



[Gondolo, Gelmini, hep-ph/0504010]

INTEGRAL Evidence

The SPI spectrometer aboard the INTEGRAL satellite observes a gaussian profile of 511 keV γ-rays coming from the inner kiloparsec of our galaxy. Attempt to explain this from astrophysical sources have failed thus far.

If this is coming from dark matter annihilation, the dark matter must be in the range $m_e < m_{\chi^0} < 207$ MeV. This annihilation must not produce any π^0 or high-energy electrons, due to COMPTEL and EGRET limits on gamma rays.

Annihilation through Z^0 and MSSM higgses is not efficent enough to prevent a neutralino this light from over-closing the universe.

$\Rightarrow$ A new SM-DM annihilation mediator is required.

Pseudoscalars make the best mediators since the annihilation cross section is non-zero at zero velocity (S-wave).

The NMSSM and μ-solvable models

The NMSSM was originally designed to solve the μ problem in the MSSM by adding a single chiral supermultiplet that is uncharged under SM gauge symmetries. Its superpotential is

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \quad (1)$$

when the scalar compnent of S gets a vev, $\mu = \lambda \langle S \rangle$ is dynamically generated, solving the μ problem.

The matter spectrum is extended to have one extra neutralino (called the singlino), one extra CP-even higgs, and one extra CP-odd higgs.

After SUSY is broken, trilinears and soft masses are generated for S:

$$V_{\text{soft}} \subset A_\lambda \lambda S H_u H_d + A_\kappa \kappa S^3 + m_S^2 S^2 \quad (2)$$

There are other ways to add a singlet and also solve the μ problem. (e.g. MNSSM, singlets to break extra gauge groups, etc) We take the NMSSM to be a prototype for "μ-solvable" models. The necessary features for light dark matter should be found in any μ-solvable model.

Light Neutralinos in the NMSSM

The MSSM can allow a massless neutralino. Solving $\det M_{\chi^0} = 0$:

$$M_1 = \frac{M_Z^2 \sin^2 \theta_W \sin(2\beta) M_2}{M_2 \mu - M_W^2 \sin(2\beta)} \qquad (3)$$

This gives 80MeV $< M_1 <$ 16GeV for reasonable parameters.

By a similar analysis, the NMSSM can also allow a massless neutralino (with M_1 as large as 55 GeV).

To evade $Z \to invisible$ constraints, a neutralino lighter than $M_Z/2 \simeq$ 45 GeV must be mostly bino or mostly singlino.

The lightest neutralino (LSP) can be any linear combination of bino and singlino, since for a given singlino mass we can tune M_1 to be near it, and therefore get any singlino-bino mixing angle we want.

Light A_1 in the NMSSM

There are two CP-odd A bosons in the NMSSM. After removing the goldstone corresponding to the Z, we can write the lightest as:

$$A_1 = \cos\theta_A A_{\text{MSSM}} + \sin\theta_A A_S. \tag{4}$$

In either the large $\tan\beta$ limit or large $\langle S\rangle$ limits, $M_{A_1}^2 \simeq 3\kappa A_\kappa \langle S\rangle$. (Alternatively: $M_{A_1}^2 = 3\frac{\kappa}{\lambda} A_\kappa \mu$)

Thus, A_1 will be light and mostly singlet in the small κ and/or small A_κ limits.

The light A_1 can also be MSSM-like if the angle $\cos\theta_A$ is large. This is possible but constrained. For $M_{\chi^0} < 5$ GeV:

$\cos\theta_A \tan\beta < 5$	LEP $Z \to b\bar{b}b\bar{b}$ or $\tau^+\tau^-\tau^+\tau^-$
$\cos\theta_A \tan\beta < 3$	$b \to s\gamma$, $B_s \to \mu\mu$, and $(g-2)_\mu$
$\cos\theta_A \tan\beta < 0.5$	$\Upsilon \to \gamma\chi^0\chi^0$ ($M_{\chi^0} < 1.5$ GeV)

$U(1)$ symmetries give a small M_A

$$W = \lambda S H_u H_d + \kappa S^3 \qquad V_{soft} = \lambda A_\lambda S H_u H_d + \kappa A_\kappa S^3 \tag{5}$$

$$Q_{H_u} = 1 \qquad Q_{H_d} = 1 \qquad Q_S = -2 \tag{6}$$

This is a Peccei-Quinn symmetry. Superpotential λ term is symmetric, soft M_i are symmetric, Yukawa's are symmetric. Broken explicitly by κ and A_κ. Symmetry is approximate in $\kappa \ll 1, A_\kappa \ll M_{SUSY}$ limit. [Miller, Moretti, Nevzorov, `hep-ph/0501139` (among others)]

$$Q_{H_u} = 1 \qquad Q_{H_d} = 1 \qquad Q_S = 1 \tag{7}$$

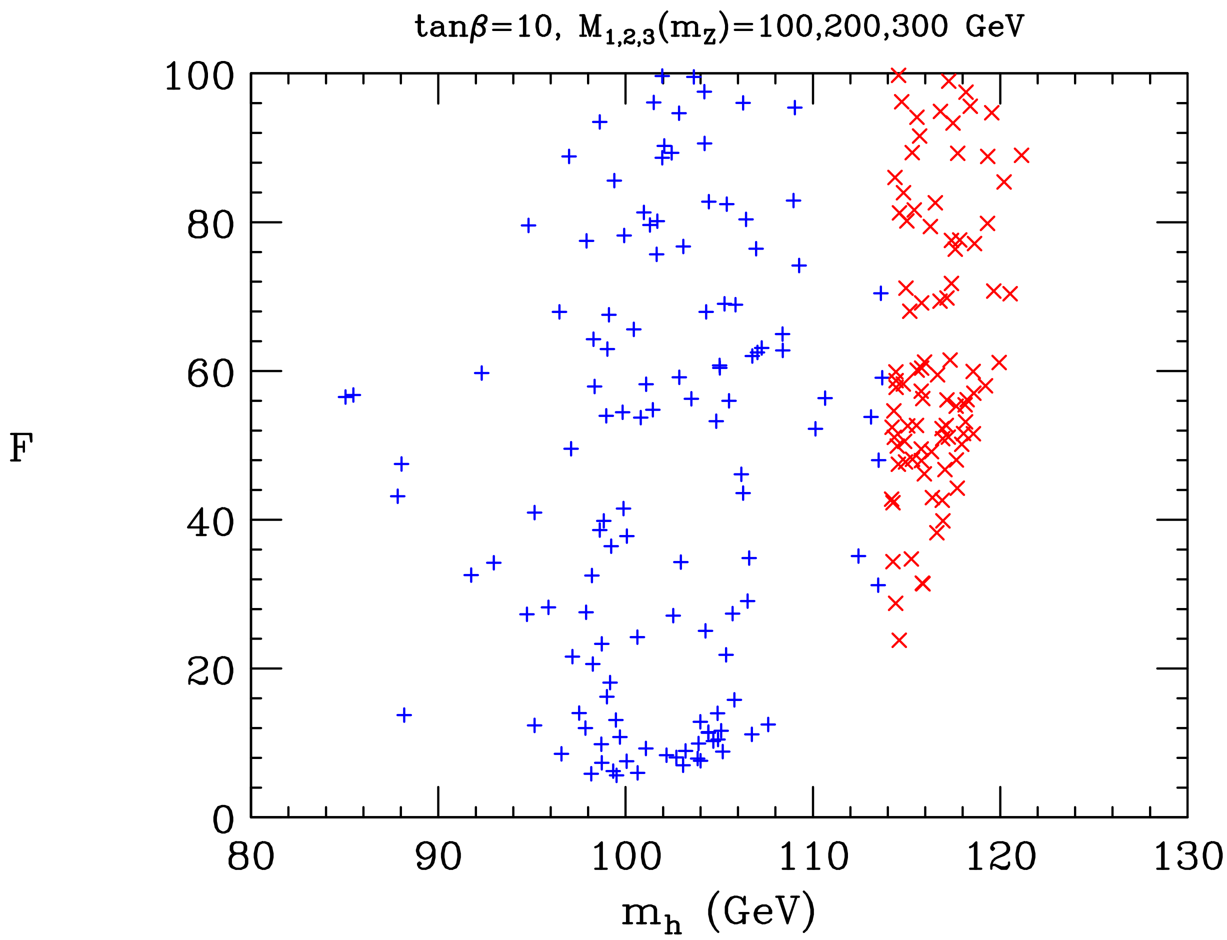
This is an R-symmetry (not respected by supersymmetry). Broken by soft SUSY breaking trilinear terms A_λ, A_κ. Symmetry is approximate in $\kappa A_\kappa, \lambda A_\lambda \ll M_{SUSY}$ limit. [Dobrescu, Matchev `hep-ph/0008192`]

In *both* cases, A_1 is the PNGB of the broken symmetry.

R-symmetry also broken by radiative corrections.

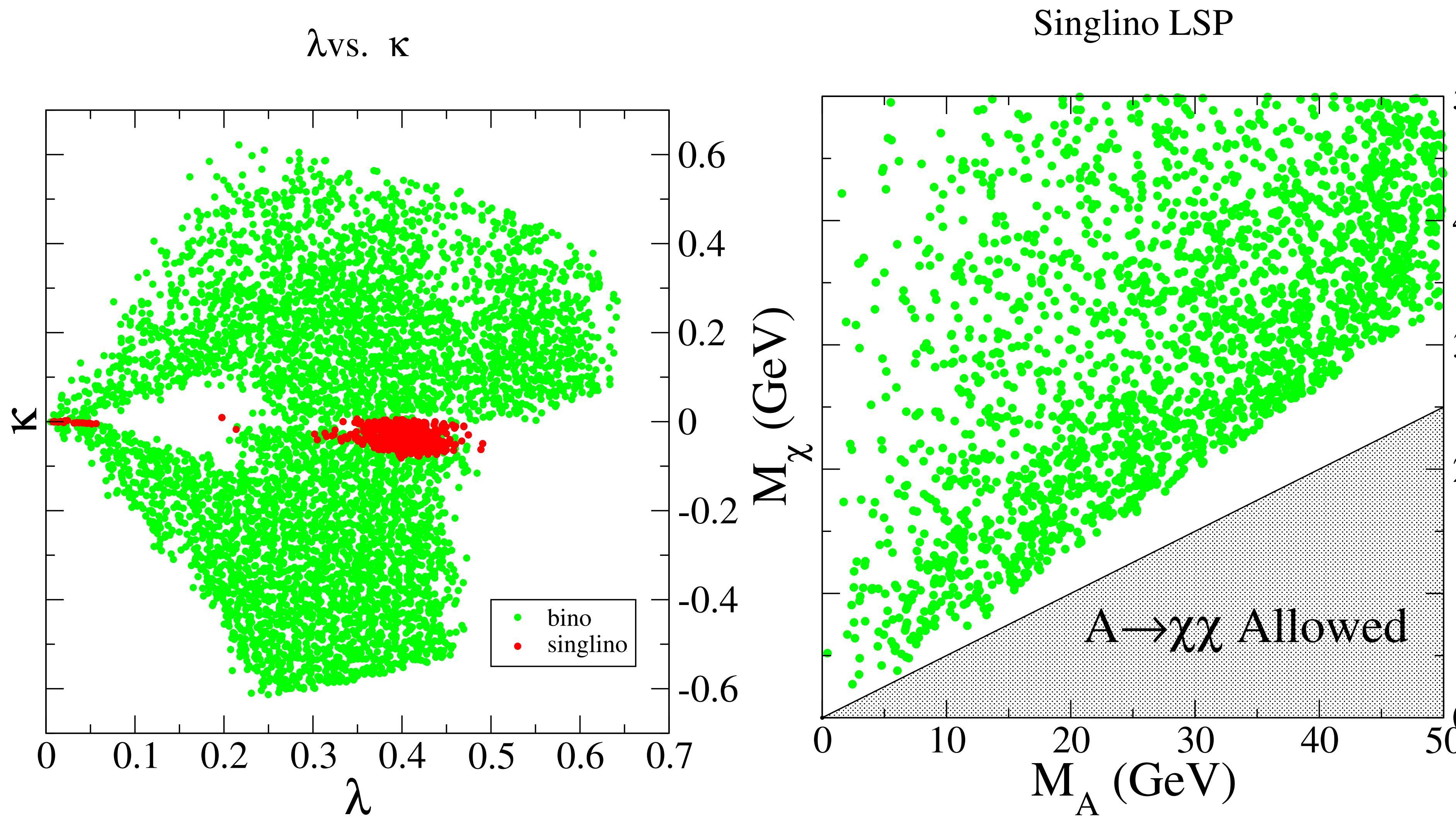
We *want* a light A_1

A light A_1 can eliminate the fine-tuning problem in the MSSM.



Dermisek, Gunion, hep-ph/0502105

Parameter Space



When both singlet A_1 and singlino are light, mass relationships do not allow $A_1 \rightarrow \chi^0\chi^0$. ($M_{\chi^0} \simeq 2\kappa x$, $M^2_{A_1} \simeq 3\kappa A_\kappa x$) Up to 80% singlino can be allowed with appropriate relic density.

Indirect Constraints

Binos, winos and singlinos do not couple to the Z directly. $\Rightarrow Z \to invisible$ only constrains the higgsino component of the LSP. Given an LSP with an eigenvector:

$$\chi^0 = \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}, \tag{8}$$

the invisible Z decay constraint limits $|\epsilon_u^2 - \epsilon_d^2| \lesssim 6\%$.

The wino component of the LSP is limited by direct chargino searches, which force M_2 large. $\Rightarrow$ The LSP must be a linear combination of bino and singlino.

We computed $(g-2)_\mu$, $b \to s\gamma$, $B_s \to \mu\mu$, Z invisible width, all LEP constraints on higgses, and $\Upsilon \to A_1\gamma$ where the A_1 decays visibly or invisibly, in a 2-body or 3-body decay.

Constraints generally limit the product $\cos\theta_A \tan\beta$, but a light A_1 or bino generally have small effects that can be compensated or cancelled by other things in the theory (e.g. squarks, H^+, χ^+, etc).

Trade-off: lighter A_1/χ^0 or improved constraints $\Rightarrow$ must be closer to relation $M_{A_1} \simeq 2M_{\chi^0}$.

Direct Detection Prospects

Direct detection occurs dominantly through t-channel exchange of a CP-even higgs.

Very light dark matter generally has problems with detection thresholds.

$$\sigma \approx \sum_H \frac{16 G_F^2 m_z^2 v^2 \cos^2\theta_W}{\pi m_H^4 g_2^2 \sin^2\beta} \left(C_{\chi^0\chi^0 H} C_{ffH}\right)^2 \left(\frac{m_p m_{\chi^0}}{m_p + m_{\chi^0}}\right)^2 \left(\sum_q \langle N|q\bar{q}|N\rangle\right)^2$$

Where

$$\begin{aligned} C_{\chi^0\chi^0 H} &= (g_1\epsilon_B - g_2\epsilon_W)(\epsilon_d\xi_u - \epsilon_u\xi_d) \\ &+ \sqrt{2}\lambda\epsilon_s(\epsilon_d\xi_d + \epsilon_u\xi_u) + \sqrt{2}\xi_s(\lambda\epsilon_u\epsilon_d - \kappa\epsilon_s^2) \end{aligned}$$

$$C_{ffH} = \frac{m_f}{\sqrt{2}v}\frac{\xi_d}{\cos\beta}$$

Muon anomalous magnetic moment

The one-loop contribution to $(g-2)_\mu$ comes from a triangle diagram with a smuon on two sides, and the neutralino on the third. This leads to:

$$\delta a_\mu^{\chi^0} \sim 2.3 \times 10^{-11} (\frac{m_{\chi^0}}{10\,\mathrm{GeV}})(\frac{200\,\mathrm{GeV}}{m_{\tilde{\mu}}})^4 (\frac{\mu \tan\beta - A_{\tilde{\mu}}}{1000\,\mathrm{GeV}}). \tag{9}$$

The light A_1 can contribute at 1-loop and 2-loops:

$$\begin{aligned} \delta a_\mu^{A\,1+2\,\mathrm{loop}} &\approx -7 \times 10^{-11} \times \cos^2\theta_A \tan^2\beta \quad \text{for } \mathrm{m_A} = 1\,\mathrm{GeV}, \\ \delta a_\mu^{A\,1+2\,\mathrm{loop}} &\approx 1.7 \times 10^{-12} \times \cos^2\theta_A \tan^2\beta \quad \text{for } \mathrm{m_A} = 10\,\mathrm{GeV}. \end{aligned}$$

The experimental limits are:

$$\begin{aligned} \delta a_\mu(e^+e^-) &= 23.9 \pm 7.2_{\mathrm{had-lo}} \pm 3.5_{\mathrm{lbl}} \pm 6_{\mathrm{exp}} \times 10^{-10} \\ \delta a_\mu(\tau^+\tau^-) &= 7.6 \pm 5.8_{\mathrm{had-lo}} \pm 3.5_{\mathrm{lbl}} \pm 6_{\mathrm{exp}} \times 10^{-10} \end{aligned}$$

Thus only for a light smuon, or large $\cos\theta_A \tan\beta$ are we in danger of violating $(g-2)_\mu$. Contributions from other SUSY particles can also be arranged to cancel these contributions, if they were too large.

Rare kaon decays

The decay $K^+ \to \pi^+ \nu\bar{\nu}$ was recently measured by the E787 and E949 experiments (*Holy Tiny Number Batman!*):

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \tag{10}$$

is nearly twice the predicted Standard Model branching ratio

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.67^{+0.28}_{-0.27}) \times 10^{-10}. \tag{11}$$

The leading process involves a loop of W^+ bosons, and *two* A_1's in the final state since there is no $W^+W^-A_1$ vertex. This means *four* χ^0 in the final state, with a mass less than 88.5 MeV to be kinematically allowed.

$\Rightarrow M_\chi^0 < 88.5$ MeV is ruled out.

However if this is the explanation of the INTEGRAL signal and $\chi^0\chi^0 \to A_1 \to e^+e^-$, $M_{\chi^0} \lesssim 20$ MeV by COMPTEL and EGRET gamma ray constraints. [Beacom, Bell, Bertone, astro-ph/0409403]

Rare B-Meson Decays

CDF places an upper limit $BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-7}$.

$b \to s\gamma$ has been measured by BaBar, Belle, CLEO, and ALEPH, giving $BR(B \to X_s\gamma) = (3.25 \pm 0.37) \times 10^{-4}$. SUSY processes that contribute to this must involve either a charged Higgs boson or chargino, which we can take to be heavy to evade all constraints.

These constraints, taken together, generally restrict $|\cos\theta_A \tan\beta| < 12$, and are not very strong.

$B^+ \to K^+ + invisible$ also provides a constraint. In scalar dark matter scenarios, this may be 50 times larger than the SM process. [Bird, Jackson, Kowalewski, Pospelov, `hep-ph/0401195`]

Υ and J/Ψ Decays

If kinematically allowed, vector resonances can decay into a photon and A_1.

$$\frac{\Gamma(V \to \gamma A)}{\Gamma(V \to \mu\mu)} = \frac{G_F m_b^2}{\sqrt{2}\alpha\pi}\left(1 - \frac{M_H^2}{M_V^2}\right)\cos^2\theta_A x^2. \qquad (12)$$

where $x = \tan\beta$ for Υ and $x = \cot\beta$ for J/Ψ.

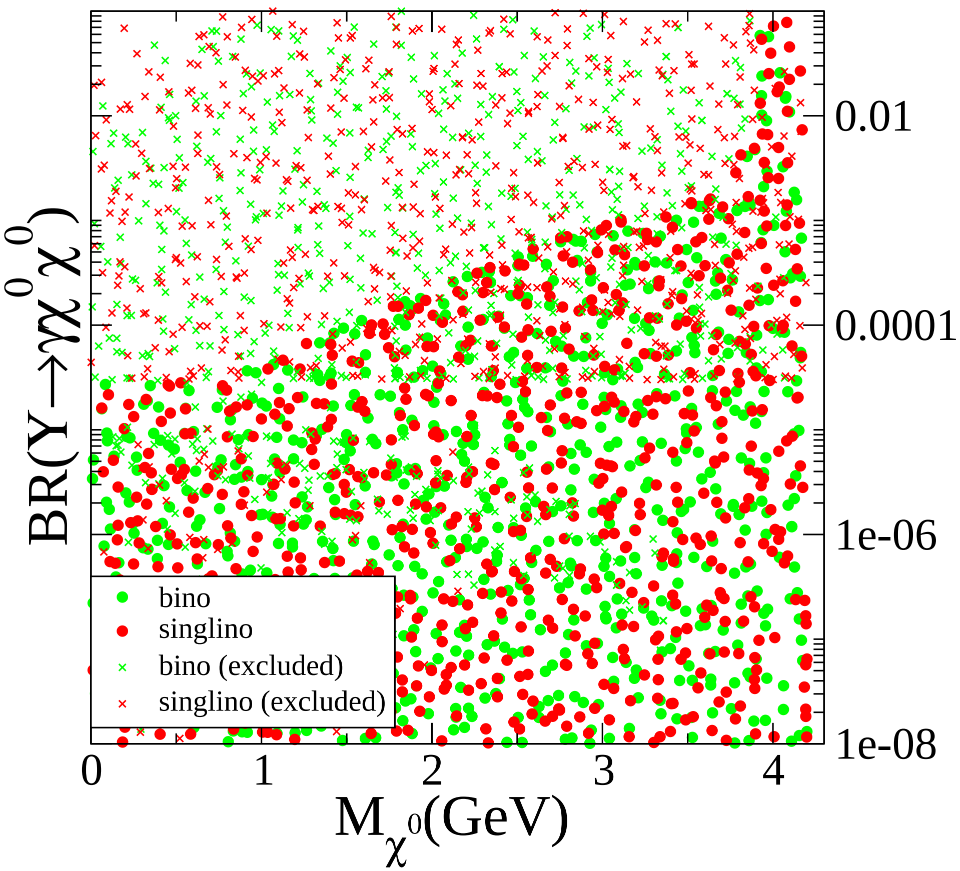
The 3-body decay $\Upsilon \to \chi^0\chi^0\gamma$ is also measured.

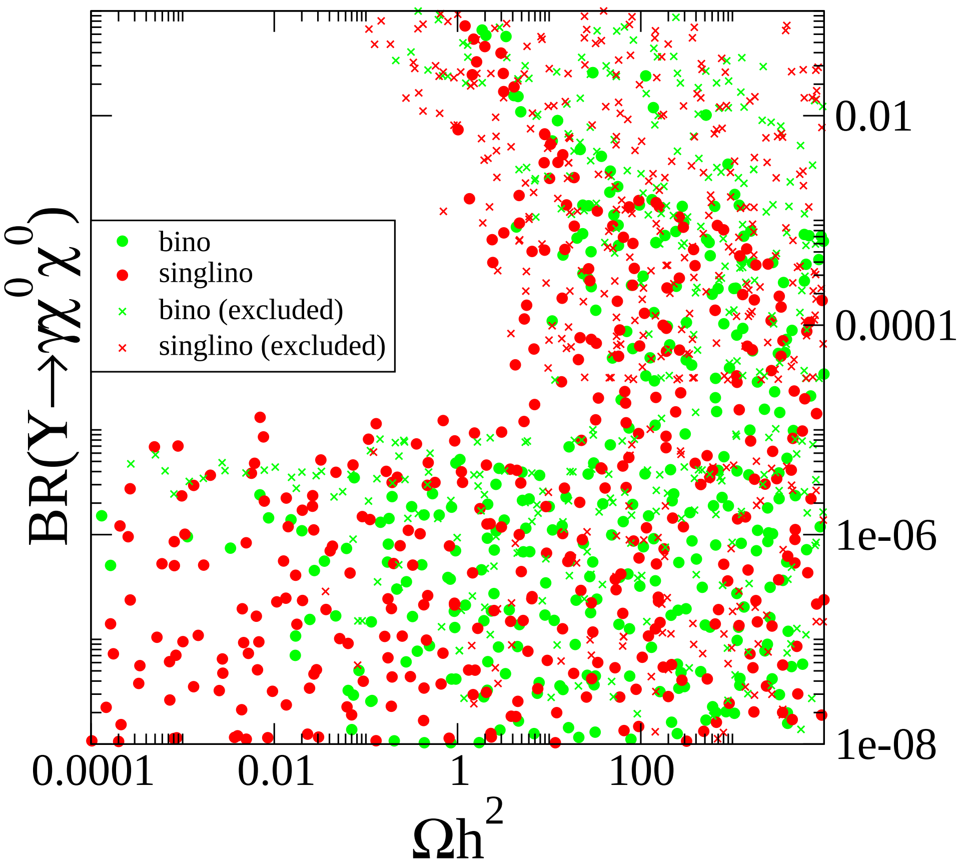
It is claimed that by measuring both $\Upsilon \to A_1\gamma$ and $J/\Psi \to A_1\gamma$, the standard axion is ruled out. However

$$BR(\Upsilon \to A_1\gamma) \times BR(J/\Psi \to A_1\gamma) \propto \cos^4\theta_A \qquad (13)$$

which is generally quite small. Thus we can evade these limits even for $M_\chi^0 < M_{J/\Psi}/2$.

Υ decays and relic density

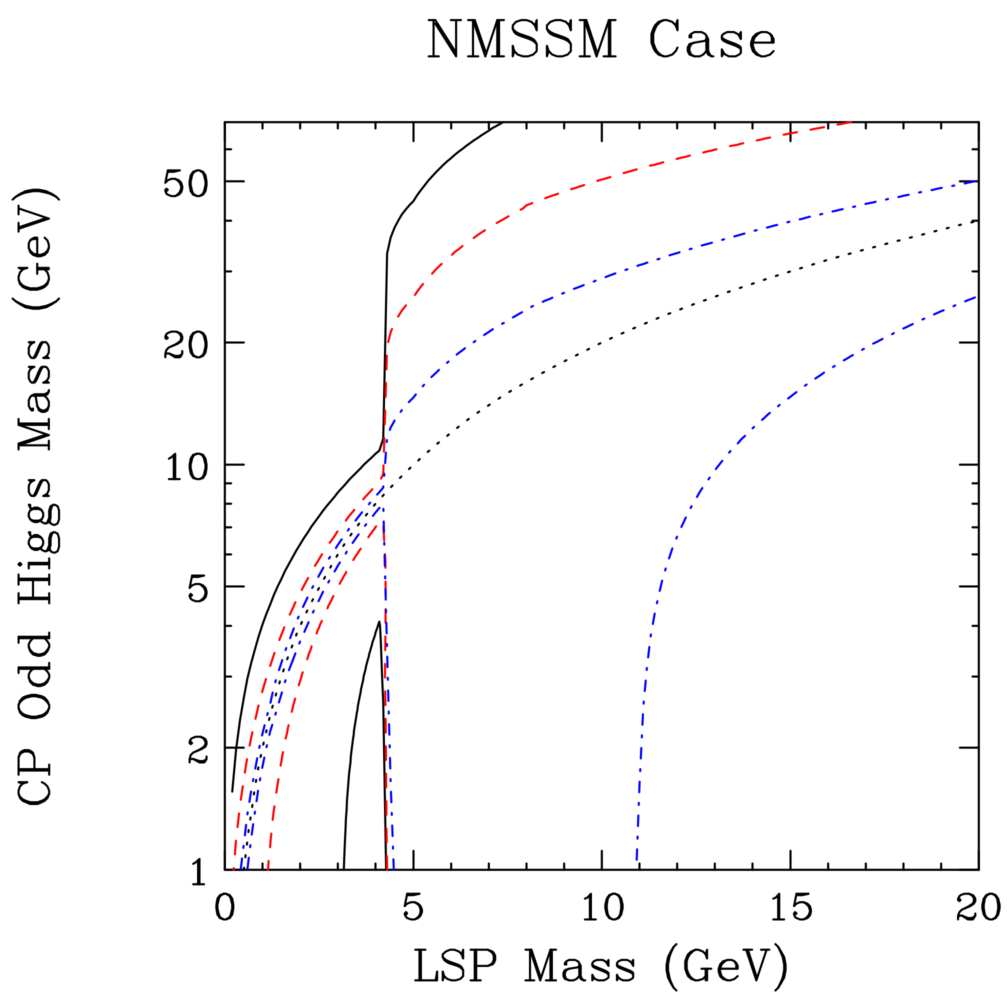


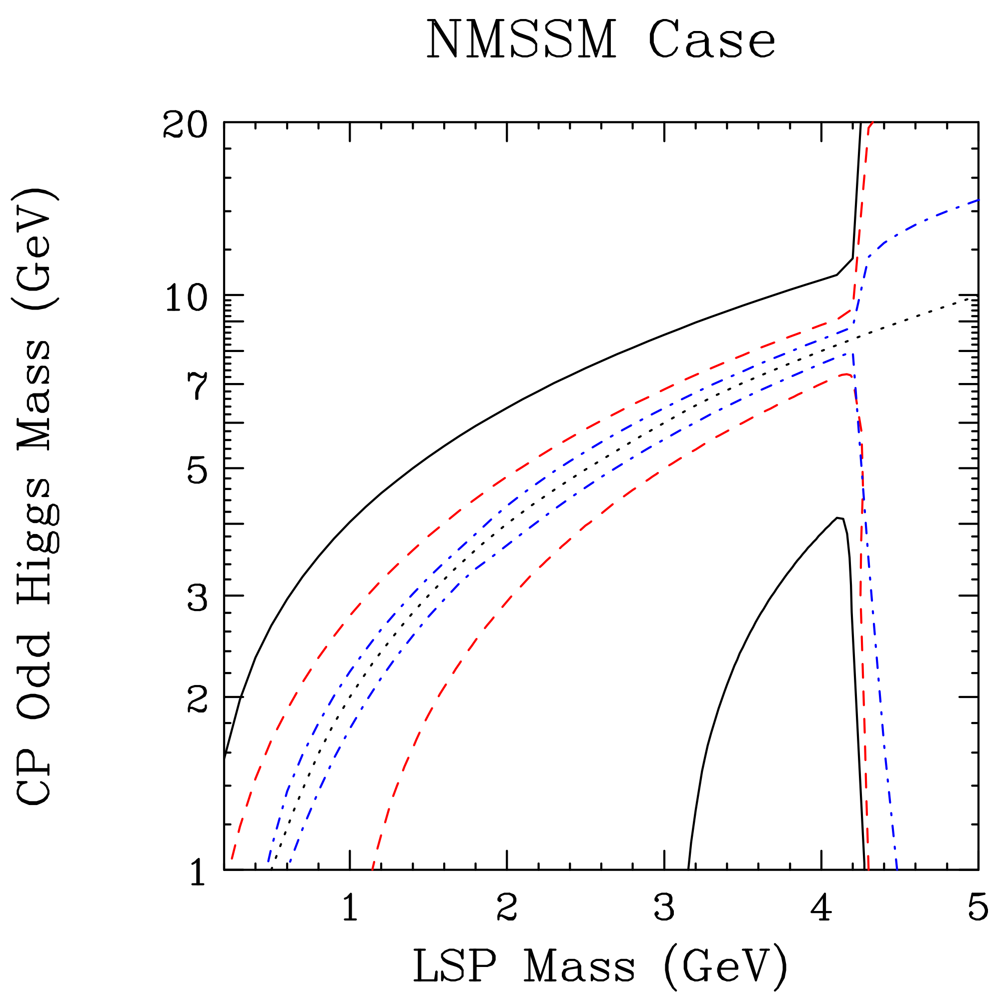


CLEO limits are $BR(\Upsilon \to \gamma\chi^0\chi^0) \simeq 3 \times 10^{-5}$ for $M_{\chi^0} < 1.5$ GeV. CLEO used only 48 pb^{-1} of data (about 1M $\Upsilon(1S)$). They have 20 times this recorded. BaBar and Belle have produced about 5M $\Upsilon(1S)$ each with ISR.

This measurement can be drastically improved with existing data!

Relic Density figures



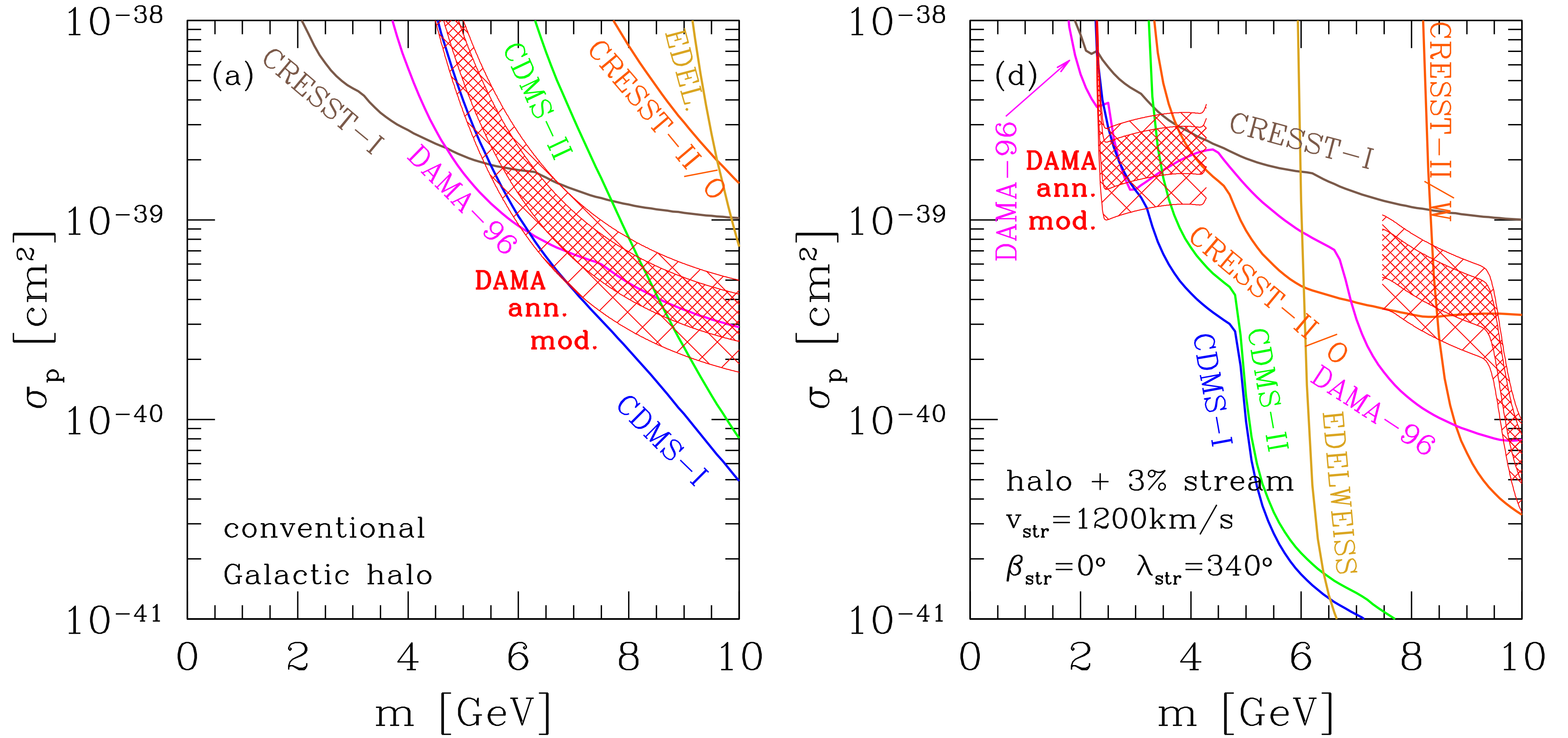


These results are for ($\epsilon_B^2 = 0.94$, $\epsilon_u^2 = 0.06$). $\tan\beta$=(50, 15 and 3) are shown as solid black, dashed red, and dot-dashed blue lines, respectively. Also shown as a dotted line is the contour corresponding to $2m_{\chi^0} = m_A$. For each set of lines, we have set $\cos^2\theta_A = 0.6$.

Direct Detection Prospects and DAMA

$$\sigma_{\rm elastic} \sim 4 \times 10^{-45}{\rm cm}^2 \left(\frac{120{\rm GeV}}{M_H}\right)^4 \left(\left(\frac{M_H}{120{\rm GeV}}\right)^{3/2} + 0.1\right)^2 \left(\frac{\tan\beta}{10}\right)^2 {\rm F}_\lambda$$

where $F_\lambda = 1$ for a bino-like neutralino and $F_\lambda = 2\lambda^2/g'^2 \simeq 0.67 \times (\lambda/0.2)^2$ for singlino. ϵ_H is the higgsino fraction of the χ^0.



A solution to INTEGRAL?

Anihilation to electrons requires $M_{\chi^0} < 20$ MeV from gamma-ray considerations [Beacom]. Since annihilation mediator is a higgs, annihilation is extremely inefficent due to small electron Yukawa.

Consider instead annihilation to muons, which decay to electrons. Need $M_\mu < M_{\chi^0} < M_{\pi^+} + M_{\pi^0}/2$ or $106\text{MeV} < M_{\chi^0} < 207$ MeV.

Therefore $212\text{MeV} \lesssim M_A \lesssim 414\text{MeV}$.

Also need $\cos\theta_A \tan\beta < 0.13$ to evade $\Upsilon \to A_1\gamma$.

Correct relic density can be obtained for $M_{A_1} \simeq 2M_{\chi^0} \pm 10$ MeV.

Can be confirmed by improving the $\Upsilon \to A_1\gamma$ measurement with existing data from CLEO, BaBar, Belle!

A new measurement, $\eta \to invisible$ can also confirm this [McElrath, Phys.Rev.D72:103508,2005 `hep-ph/0506151`]

Sample Model Point #1

The first has a singlet-like H_1, which would have escaped detection at LEP due to this singlet nature. In addition, the mass of the more SM-like H_2 is beyond the LEP reach. It also has a sizable BR($\Upsilon \to \gamma + A_1$) which could be discovered by a re-analysis of existing CLEO data.

λ	κ	$\tan\beta$	μ		
0.436736	-0.049955	1.79644	-187.931		
A_λ	A_κ	M_1	M_2		
-458.302	-40.4478	1.92375	390.053		
M_{A_1}	$\cos\theta_A$				
7.17307	-0.193618				
M_{H_1}	ξ_u	ξ_d	ξ_s		
73.8217	0.1127	-0.0277	0.9932		
$M_{\tilde{\chi}_1^0}$	ϵ_B	ϵ_W	ϵ_u	ϵ_d	ϵ_s
3.49603	-0.781466	-0.00595	0.11476	0.26493	0.553099
$BR(\Upsilon \to \gamma + A_1)$	$\langle \sigma v \rangle$	Ωh^2			
8.12331e-06	4.55841e-26 cm^3/s	0.107689			

Sample Model Point #2

The second point has an MSSM-like H_1, but due to the presence of the light A_1 and the large λ coupling, this MSSM-like H_1 decays dominantly to a pair of A_1's [$BR(H_1 \to A_1 A_1) = 99.6\%$ for this point]. Such an H_1 would not be easily detected at the LHC.

λ 0.224982 A_λ -421.908	κ -0.47912 A_κ -30.6106	$\tan\beta$ 7.58731 M_1 21.0909	μ -174.624 M_2 984.116		
M_{A_1} 46.6325	$\cos\theta_A$ -0.570716				
M_{H_1} 117.72	ξ_u 0.9823	ξ_d 0.1848	ξ_s 0.0316		
$M_{\widetilde{\chi}_1^0}$ 22.37	ϵ_B -0.9715	ϵ_W -0.0024	ϵ_u 0.0020	ϵ_d 0.2366	ϵ_s 0.0128
$BR(\Upsilon \to \gamma + A_1)$ 0	$\langle \sigma v \rangle$ 2.17478e-25 cm^3/s	Ωh^2 0.108649			

Sample Model Point #3

The third point has a singlino-like $\tilde{\chi}_1^0$ as well as a singlet-like H_1. As for point #1, this point has a $BR(\Upsilon \to \gamma + A_1)$ that might be excluded by an appropriate re-analysis of existing data.

λ A_λ 0.415867 -455.387	κ A_κ -0.029989 -39.671	$\tan\beta$ M_1 1.78874 7.1098	μ M_2 -175.622 289.115		
M_{A_1} 8.35008	$\cos\theta_A$ -0.187349				
M_{H_1} 63.3851	ξ_u -0.1412	ξ_d -0.1810	ξ_s 0.9733		
$M_{\tilde{\chi}_1^0}$ -3.98	ϵ_B -0.3697	ϵ_W -0.0262	ϵ_u 0.2524	ϵ_d 0.2560	ϵ_s 0.8564
$BR(\Upsilon \to \gamma + A_1)$ 3.96e-6	$\langle \sigma v \rangle$ 4.12241e-26 cm^3/s	Ωh^2 0.119239			

Conclusions

Can $\lambda << 1$ and/or $\kappa << 1$ be natural?
SUSY breaking models which generate small trilinears

A light A_1 and bino or singlino χ^0 is technically natural in μ-solvable models such as the NMSSM.

An arbitrarily light A_1 and χ^0 are allowed.

A light bino/singlino in the NMSSM can reconcile DAMA and CDMS-II, especially if there is some "wind" of dark matter through our local area, and the H_1 is also light.

A light bino/singlino can explain the INTEGRAL observation.

Direct detection prospects look bleak unless H_1 is very light.

Reference Formulae

$$M_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{\sqrt{2}}g'v\cos\beta & \frac{1}{\sqrt{2}}g'v\sin\beta & 0 \\ 0 & M_2 & \frac{1}{\sqrt{2}}gv\cos\beta & -\frac{1}{\sqrt{2}}gv\sin\beta & 0 \\ -\frac{1}{\sqrt{2}}g'v\cos\beta & \frac{1}{\sqrt{2}}gv\cos\beta & 0 & -\lambda x & -\lambda v\sin\beta \\ \frac{1}{\sqrt{2}}g'v\sin\beta & -\frac{1}{\sqrt{2}}gv\sin\beta & -\lambda x & 0 & -\lambda v\cos\beta \\ 0 & 0 & -\lambda v\sin\beta & -\lambda v\cos\beta & 2\kappa x \end{bmatrix}$$

$$M_A^2 = \begin{bmatrix} \frac{2\lambda x(\kappa x + A_\lambda)}{\sin 2\beta} & -2\lambda v\kappa x + \lambda A_\lambda v \\ -2\lambda v\kappa x + \lambda A_\lambda v & \left(2\kappa\lambda v^2 + \lambda A_\lambda \frac{v^2}{2x}\right)\sin 2\beta + 3\kappa A_\kappa x \end{bmatrix}$$

$$\tan 2\theta_A = \frac{4\sin(2\beta)\lambda v x(2\kappa x - A_\lambda)}{2x^2(2\lambda\kappa x - 3\kappa A_\kappa \sin(2\beta) + 2\lambda A_\lambda) - \lambda v^2 \sin^2(2\beta)(4\kappa x + A_\lambda)}$$

Relic Density Calculation

The relic density is given by:

$$\langle \sigma v \rangle = \frac{1}{m_{\chi^0}^2}[1 - \frac{3T}{m_{\chi^0}}]\omega(s)|_{s \to 4m_{\chi^0}^2 + 6m_{\chi^0}T} + \mathcal{O}(T^2),$$

The squared amplitudes for the processes, $\chi^0\chi^0 \to A \to f\bar{f}$ and $\chi^0\chi^0 \to H \to f\bar{f}$, averaged over the final state angle are given by:

$$\omega_{f\bar{f}}^A = \frac{C_{ffA}^2 C_{\chi^0\chi^0 A}^2}{(s - m_A^2)^2 + m_A^2\Gamma_A^2} \frac{s^2}{16\pi}\sqrt{1 + \frac{4m_f^2}{s}},$$

where

$$\begin{aligned}
C_{\chi^0\chi^0 A} &= \cos\theta_A \left[(g_2\epsilon_W - g_1\epsilon_B)(\epsilon_d \cos\beta - \epsilon_u \sin\beta)\right] \\
&+ \cos\theta_A \left[\sqrt{2}\lambda\epsilon_s(\epsilon_u \sin\beta + \epsilon_d \cos\beta)\right] \\
&+ \sin\theta_A \sqrt{2}\left[\lambda\epsilon_u\epsilon_d - \kappa\epsilon_s^2\right] \\
C_{ffA} &= \frac{m_f}{\sqrt{2}v}\cos\theta_A \tan\beta. \\
A_1 &= \cos\theta_A A_{\mathrm{MSSM}} + \sin\theta_A A_s \\
\chi^0 &= \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}
\end{aligned}$$