Interpretation of Results from Direct Dark Matter Searches

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Outline

- **Current Direct Detection Experimental Status**
- **Is a light LSP ($m_\chi \lesssim 10\ \mathrm{GeV}$) consistent in the MSSM context**
- **NMSSM scenarios with large σ_{SI} at low m_χ**

Direct Detection Status

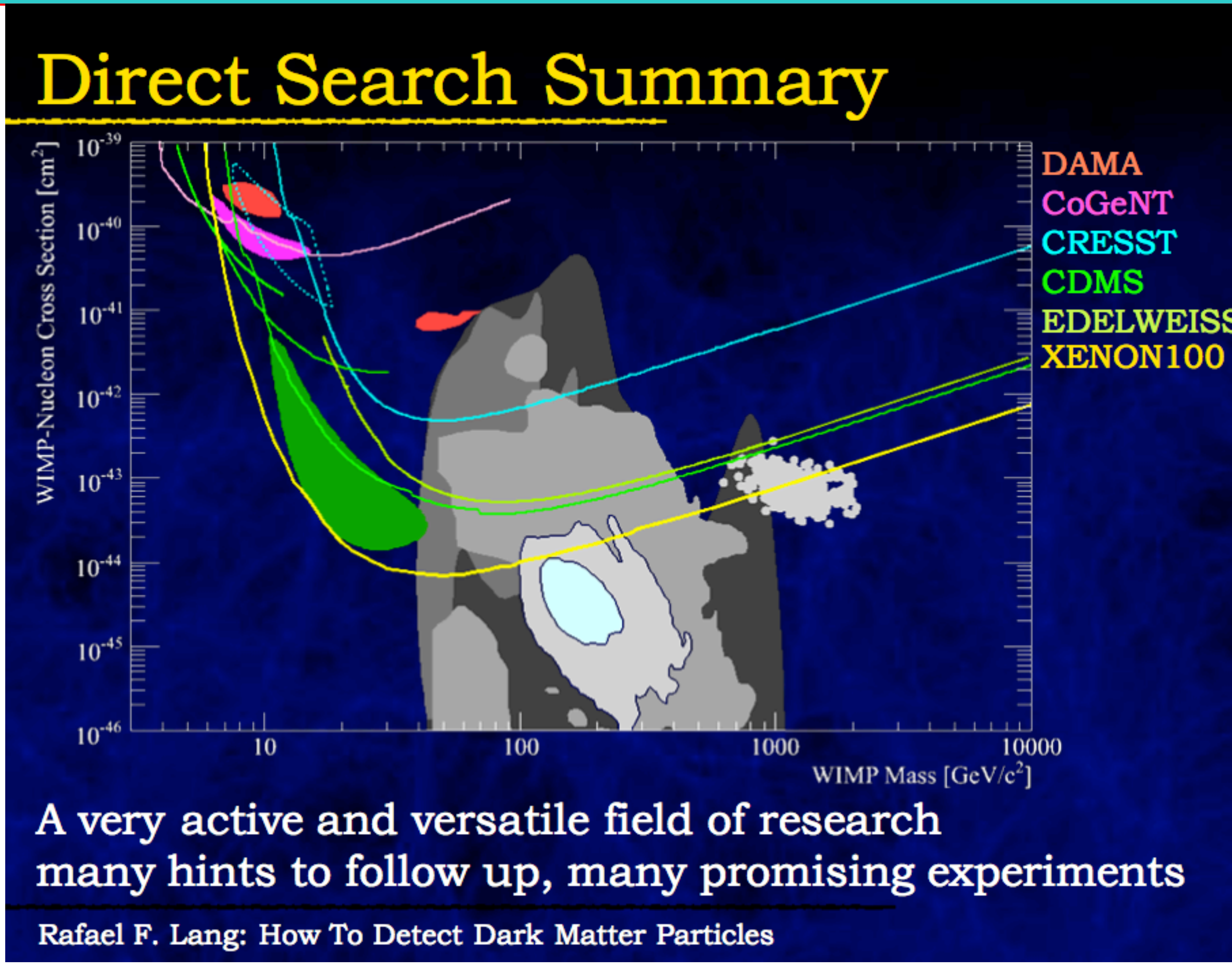


Figure 1: Summary by Lang at Pheno 2011

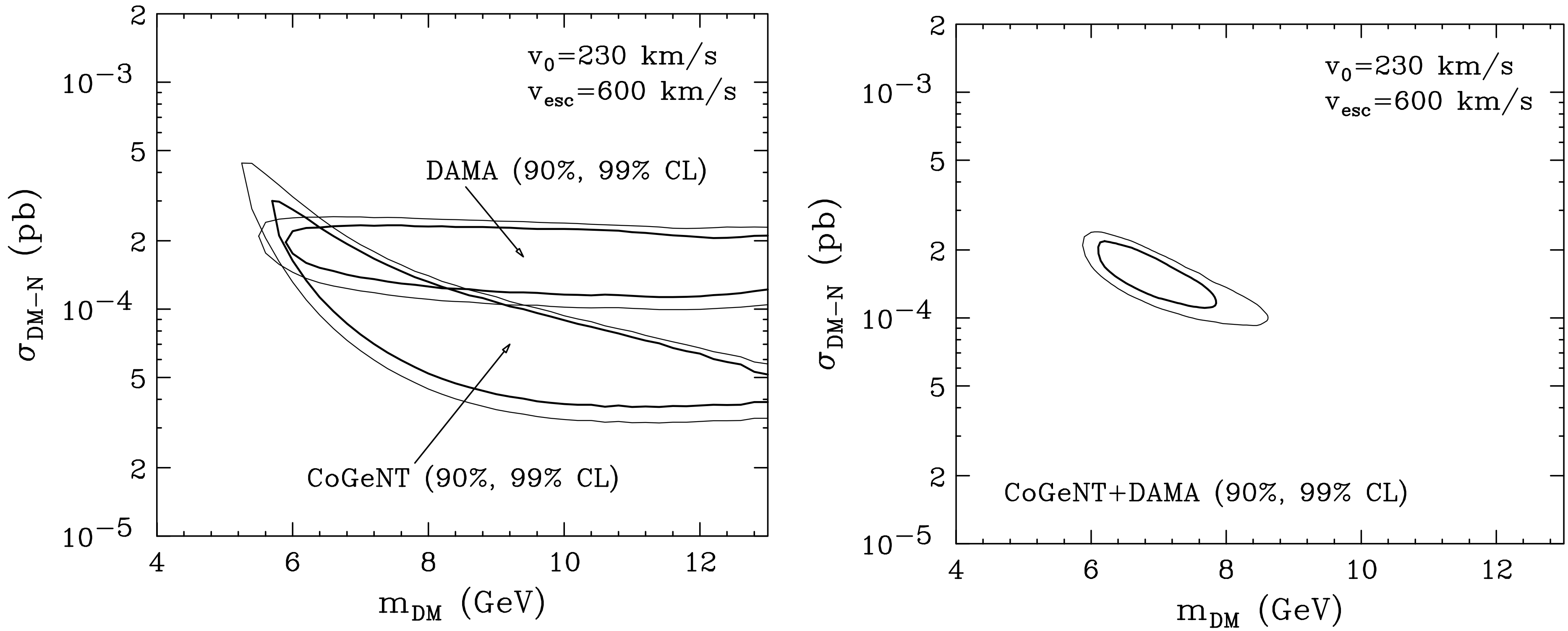


Figure 2: **If you allow for a larger spread in the NaI quenching factor Q, in particular extending to higher values of $Q \sim 0.5$ (vs. "normal" value of $Q \sim 0.2 - 0.3$) then DAMA and CoGeNT can overlap. Note: channeling has been pretty much discredited by theoretical studies, but there is some temperature dependence to this statement. From Hooper et al. arXiv:1007.1005.**

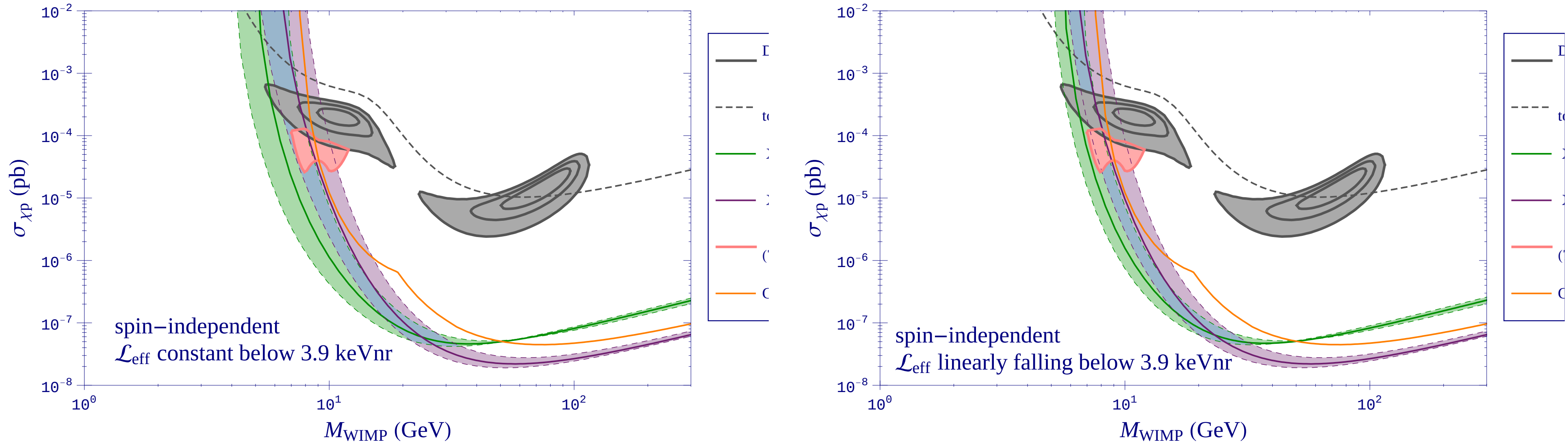


Figure 3: **However, then came XENON10. But the results depend upon how the response $\mathcal{L}_{eff}$ is extrapolated to lower energies than where it is actually measured — the smaller $\mathcal{L}_{eff}$ at low recoil, the less constraining is XENON10. The new green region is XENON10; the purple region is XENON100; the blue region is the overlap between the two. From Savage et al. arXiv:1006.0972.**

And, finally, CoGeNT has now seen oscillations.

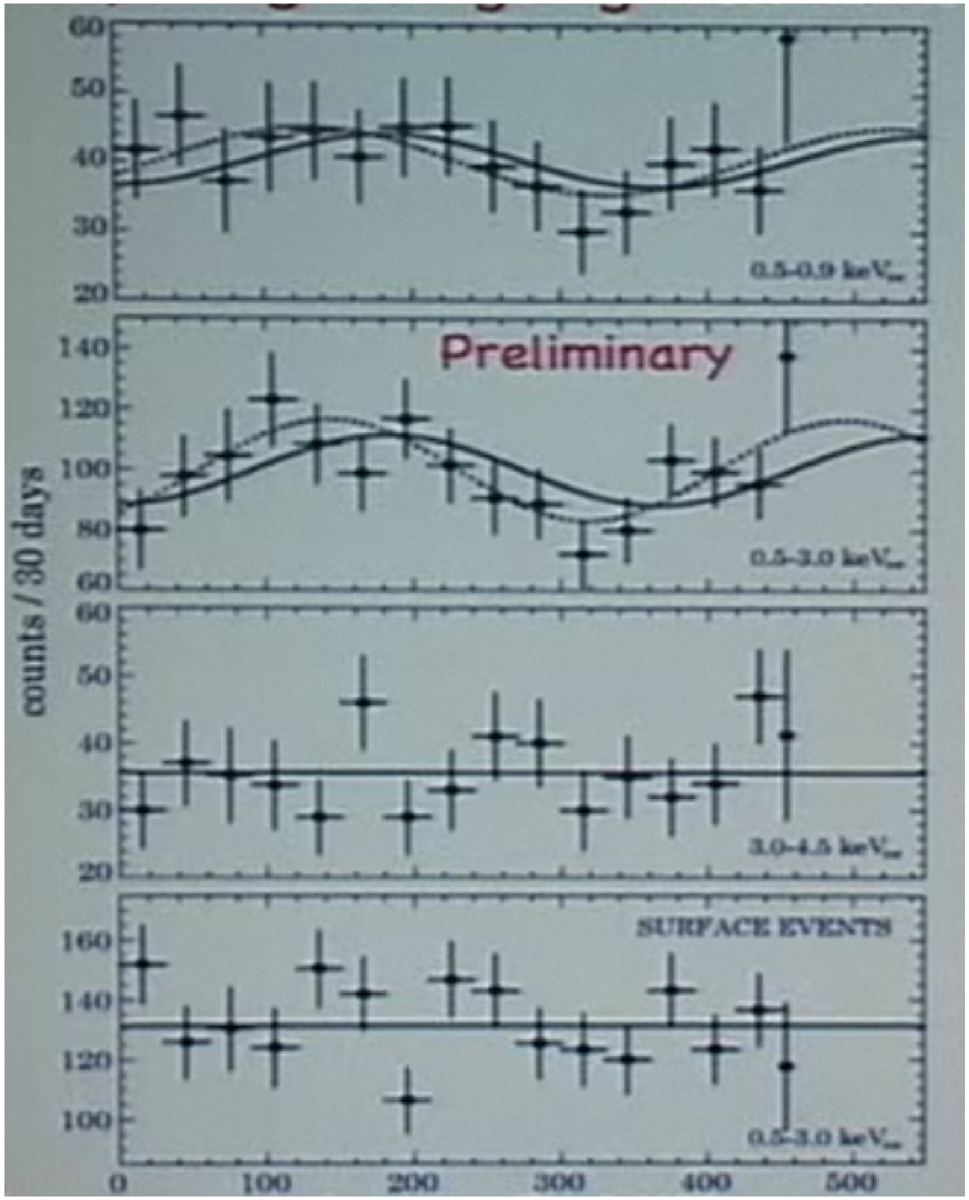


Figure 4: CoGeNT modulation plot from the blogs. Apparently presented at the APS meeting by Collar, but I could not find the APS slides.

If you use only the DAMA and CoGeNT modulation signals to determine the appropriate region of the σ_n — m_χ plane you get:

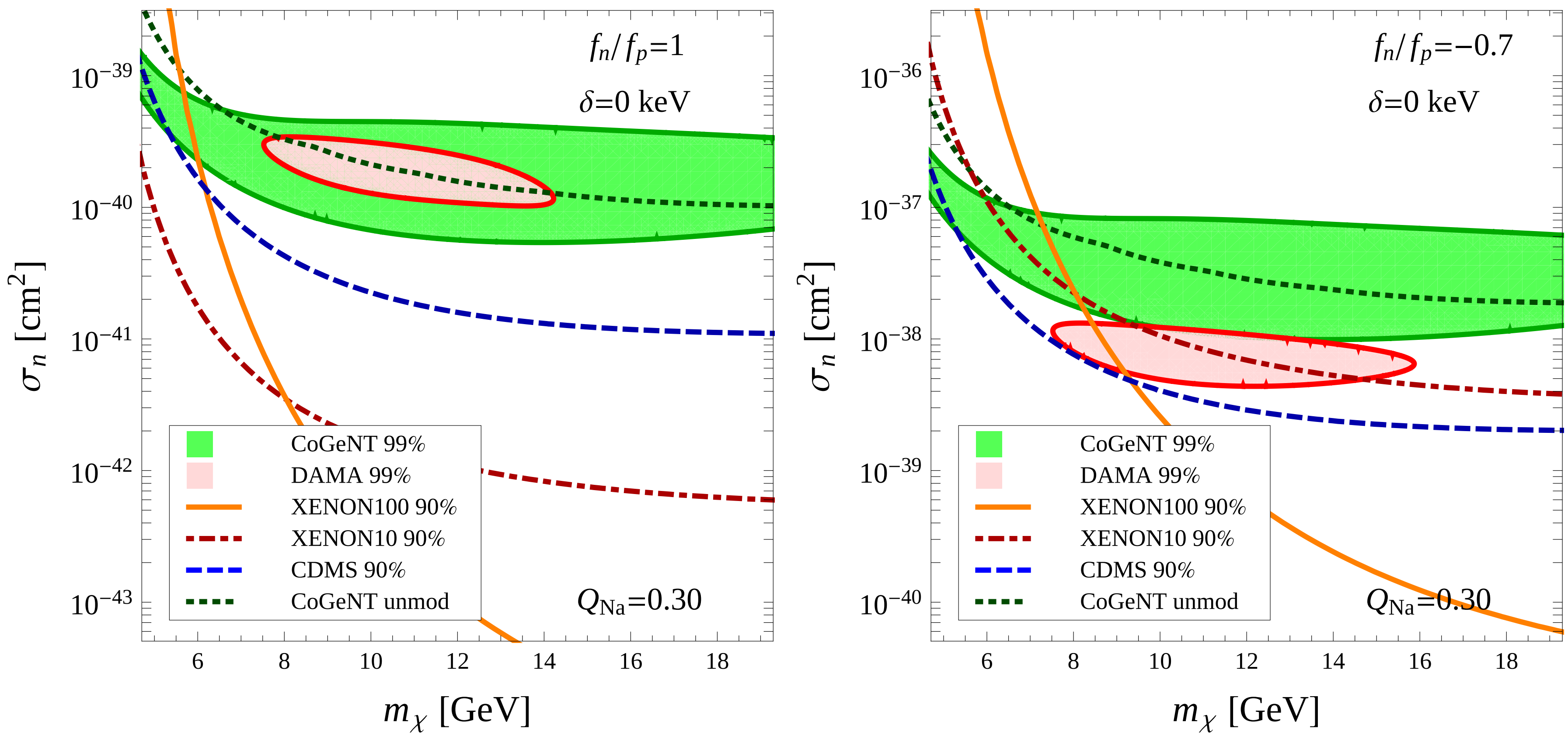


Figure 5: CoGeNTand DAMA modulation region vs. constraints. To the right is shown how taking $f_n = -0.7 f_p$ would eliminate XENON10 constraint and make everything more consistent. From Frandsen et al., arXiv:1105.3734. This agreement does not rely on normalizing the smooth falling spectrum. Note: much bigger σ_n needed if $f_n = -0.7 f_p$ to remove XENON10 and weaken XENON100 constraint.

It won't be long before light dark matter will be toasted or toast.

For now, it seems worth taking seriously the possibility of dark matter with $\sigma_n \sim 1 - 3 \times 10^{-4}$ pb and $m_\chi \lesssim 15$ GeV.

We like to think that we could explain both such a σ_n and the relic density Ωh^2 using a particle physics model.

If this is the case, then, generically, the spin-independent elastic scattering cross section of dark matter with a nucleus is written:

$$\sigma_{SI} \approx \frac{4m_\chi^2 m_N^2}{\pi(m_\chi + m_N)^2}[Zf_p + (A-Z)f_n]^2, \quad (1)$$

where m_N is the mass of the target nucleus (of atomic number Z and mass A) and m_χ is the dark matter mass. f_p and f_n are the dark matter's couplings to protons and neutrons:

$$f_{p,n} = \sum_{q=u,d,s} f_{T_q}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q}, \quad (2)$$

where a_q are the dark matter's couplings to quarks and $f_{T_q}^{(p,n)}$, $f_{TG}^{(p,n)}$ are hadronic matrix elements, $\langle q\overline{q}\rangle, \langle gg\rangle$. These are rather dependent on modeling via sum rules and the πN sigma term, ... — normally, the default values of micrOmegas are employed.

Models for DM

My favorite model, and perhaps yours too, is Supersymmetry.

The big question: can a consistent picture be constructed in Supersymmetry?

I will not consider:

- $f_n = -0.7 f_p$ models.
- Asymmetric Dark Matter models.
- $U(1)'$ models.
- Inelastic Dark Matter.
- $\ldots$.

Minimal Supersymmetric Model

- DM $= \widetilde\chi_1^0$, lightest neutralino is the natural choice. It is a mixture of bino (normally the dominant piece), wino, and higgsinos.

$$\widetilde\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u \,. \tag{3}$$

- $m_{\widetilde\chi_1^0}$ is mainly set by the $U(1)$ gaugino soft-SUSY parameter M_1.

  $m_{\widetilde\chi_1^0} < 20~\mathrm{GeV}$ requires $M_1 \ll$ CMSSM value ($\frac{1}{2}M_2$) since $M_2 \gtrsim 100~\mathrm{GeV}$ is required by $\widetilde\chi_1^\pm$ LEP limits. $\Rightarrow$ gaugino masses will not unify at M_U.

- For light MSSM neutralinos, the neutralino-quark coupling is dominated by scalar Higgs exchange (contributions from squark exchange are typically negligible).

For down-type quarks, the Higgs-quark coupling is given by:

$$
\begin{aligned}
\frac{a_d}{m_d} &= \frac{g_2}{4 m_W \cos\beta}[-g_1 N_{11} + g_2 N_{12}] \\
&\times \left[\left(\frac{N_{13} c_\alpha^2 - N_{14} c_\alpha s_\alpha)}{m_{H^0}^2}\right) + \left(\frac{N_{13} s_\alpha^2 + N_{14} c_\alpha s_{\alpha)}}{m_{h^0}^2}\right)\right],
\end{aligned} \tag{4}
$$

where $s_\alpha \equiv \sin\alpha$ and $c_\alpha \equiv \cos\alpha$ — α is the mixing angle which relates the scalar Higgs boson mass and gauge eigenstates. The corresponding expression for up-type quarks is found by replacing $\cos\beta \leftrightarrow \sin\beta$ and $N_{14} \leftrightarrow N_{13}$.

- The largest elastic scattering cross sections in the MSSM arise in the case of large $\tan\beta$ and $\sin(\beta - \alpha) \sim 1$ (together implying $s_\alpha \sim 0$), significant N_{13}, and relatively light m_{H^0}. In this limit, the lighter Higgs, h^0, is approximately Standard Model-like and the heavier H^0 is approximately

H_d^0, and one finds $\frac{a_d}{m_d} \approx \frac{-g_2 g_1 N_{13} N_{11} \tan\beta\, c_\alpha^2}{4 m_W m_{H^0}^2}$, which yields

$$\sigma_{SI} \approx 1.7 \times 10^{-41} \mathrm{cm}^2 \left(\frac{N_{13}^2}{0.103}\right)\left(\frac{\tan\beta}{50}\right)^2\left(\frac{100\,\mathrm{GeV}}{m_{H^0}}\right)^4\left(\frac{c_\alpha}{1}\right)^4. \quad (5)$$

- The higgsino content of the lightest neutralino is constrained by the invisible width of the Z as measured at LEP. We can translate this result to a limit of $|N_{13}|^2 < 0.103$.
- $\tan\beta = 50$ is the largest value possible without λ_b going into non-perturbative regime.
- $m_{H^0} = 100$ GeV is lightest possible for $m_{h^0} > 92$ GeV (LEP limits).
- If h^0 is SM-like, then $\sin(\beta - \alpha) \sim 1$. If also $\tan\beta$ is large, implying $\beta \sim \pi/2$, then $\alpha \sim 0$ and $c_\alpha \sim 1$.

- m_{H^0} and $\tan\beta$ are constrained by a number of measurements, including those of the rare decays $t \to bH^+$, $B_s \to \mu^+\mu^-$, $B^\pm \to \tau\nu$, $b \to s\gamma$, and direct limits on Higgs production followed by $H^0, A^0 \to \tau^+\tau^-$.

$\Rightarrow \tan\beta \lesssim 30 - 45$ for $m_{H^0}, m_{A^0} \sim 90 - 150$ GeV.

When these limits are taken into account, we find that $\sigma_{SI} \lesssim 10^{-41}\text{cm}^2$, which falls short of that implied by the CoGeNT and DAMA/LIBRA signal by about an order of magnitude.

- Furthermore, in the MSSM it is hard to achieve a thermal relic abundance that is not in excess of the measured dark matter density: $\Omega_{\widetilde{\chi}_1^0} h^2 < 0.1$.

  To briefly review, the density of neutralino dark matter in the universe today can be determined by the particle's annihilation cross section and mass. In the mass range we are considering here, the dominant annihilation channel is to $b\bar{b}$ (and to a lesser extent to $\tau^+\tau^-$) through the s-channel exchange of the pseudoscalar Higgs boson, A^0. The thermally averaged cross sections for these processes are given by

$$\begin{aligned} \langle \sigma_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to A \to b\bar{b}, \tau^+\tau^-} v \rangle &= \frac{(3,1) g_2^2 m_{b,\tau}^2 \tan^2\beta}{8\pi m_W^2} \frac{m_{\widetilde{\chi}_1^0}^2 \sqrt{1 - m_{b,\tau}^2 / m_{\widetilde{\chi}_1^0}^2}}{(4m_{\widetilde{\chi}_1^0}^2 - m_{A^0}^2)^2 + m_A^2 \Gamma_{A^0}^2} \\ &\times \left[(N_{13}\sin\beta - N_{14}\cos\beta)(g_2 N_{12} - g_1 N_{11}) \right]^2, \quad (6) \end{aligned}$$

  where Γ_{A^0} is the width of the pseudoscalar MSSM Higgs.

- **Any additional contributions from scalar Higgs exchange are suppressed by the square of the relative velocity of the neutralinos, and thus are substantially suppressed in the process of thermal freeze-out.**

- **The thermal relic abundance of neutralinos is given by**

$$\Omega_{\widetilde{\chi}_1^0} h^2 \approx \frac{10^9}{M_{\mathrm{Pl}}} \frac{m_{\widetilde{\chi}_1^0}}{T_{\mathrm{FO}}\sqrt{g_\star}} \frac{1}{\langle \sigma_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^0} v \rangle} \tag{7}$$

where $g_\star$ is the number of relativistic degrees of freedom available at freeze-out and T_{FO} is the temperature at which freeze-out occurs:

$$\frac{m_{\widetilde{\chi}_1^0}}{T_{\mathrm{FO}}} \approx \ln\left(\sqrt{\frac{45}{8}} \frac{m_{\widetilde{\chi}_1^0} M_{\mathrm{Pl}} \langle \sigma_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^0} v \rangle}{\pi^3 \sqrt{g_\star m_{\widetilde{\chi}_1^0}/T_{\mathrm{FO}}}}\right). \tag{8}$$

For the range of masses considered here, and for cross sections which will yield approximately the measured dark matter abundance, we find $m_{\widetilde{\chi}_1^0}/T_{\mathrm{FO}} \approx 20$.

For $m_{\widetilde{\chi}_1^0} \sim 5 - 15$ GeV, the relic abundance of MSSM neutralinos is then approximately given by

$$\Omega_{\widetilde{\chi}_1^0} h^2 \approx 0.1 \left(\frac{0.1}{N_{13}^2}\right) \left(\frac{50}{\tan\beta}\right)^2 \left(\frac{m_{A^0}}{100\,\mathrm{GeV}}\right)^4 \left(\frac{9\,\mathrm{GeV}}{m_{\widetilde{\chi}_1^0}}\right)^2 . \tag{9}$$

- Given that LEP limits require $m_{A^0} \gtrsim 90 - 100\ \mathrm{GeV}$ and that $\tan\beta$ as large as 50 is already in the non-perturbative domain for the b-quark coupling, it requires a very extreme choice of parameters to get the measured dark matter density of our universe to be as small as that measured, $\Omega_{\mathrm{CDM}} h^2 = 0.1131 \pm 0.0042$.

- However, it is true that the same extreme choice of parameters that minimizes $\Omega_{\widetilde{\chi}_1^0} h^2$, bringing it close to the observed value, at the same time maximizes σ_{SI}.

  Indeed, detailed scans lead to interesting corners of parameter space.

Some uncertainties in σ_{SI} predictions

1. Normally, assume local density is $\rho \sim 0.3~\mathrm{GeV}/cm^3$.

   Values as high as $0.45 - 0.5~\mathrm{GeV}/cm^3$ are suggested by some theoretical and observational studies. $\Rightarrow$ corresponding decrease in the σ_{SI} needed to get CoGeNT/DAMA signal.

2. Predictions are often given for "default" micrOmegas strange quark matrix elements in nucleons based on "standard" πN sigma term and related.

   It is possible (but many regard the required πN sigma term and related as improbable) to increase the strange quark content $\Rightarrow$ $3\times$ increase in σ_{SI}.

3. Taking a moderate combination of the above effects $\Rightarrow$ might not be unreasonable to suppose that one can bring predicted σ_{SI} and the σ_{SI} required for CoGeNT/DAMA into closer agreement by a factor of 2.

MSSM scans focused on $m_{\widetilde{\chi}_1^0} < 10 \text{ GeV}$

There are a number of competing MSSM scans that have appeared in the literature. The most thorough appear to be:

1. Belanger et al. (arXiv:1009.4380). Conclude $m_{\widetilde{\chi}_1^0} > 28 \text{ GeV}$ (same as Nath and collaborators after putting in $B_s \to \mu^+\mu^-$ limit).

2. Bottino et al. (arXiv:1011.4743 — see also arXiv:1102.4033). Conclude small $m_{\widetilde{\chi}_1^0}$ ok.

3. Calibbi et al. (arXiv:1104.1134). Conclude small $m_{\widetilde{\chi}_1^0}$ ok.

However, in the end the conclusions are pretty much the same once the latest collider Higgs constraints are incorporated.

I will focus on the last paper since their plots are easiest to understand. The constraints they include are typical of the other scans as well.

	Observable	Allowed range	References
WMAP	$\Omega_{\rm DM} h^2$	[0.101, 0.123]	
LEP	m_h	> 92.8 GeV	Nakamura:2010zzi[1]
	m_A	> 93.4 GeV	Nakamura:2010zzi
	$M_{\tilde{\chi}_1^+}$	> 94 GeV	Nakamura:2010zzi
	$\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	< 3 MeV	ALEPH:2005ema
	$\sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_{2,3}^0)$	< 0.1 pb	Abbiendi:2003sc
Group (i)	$R_{B\tau\nu}$	[0.52, 2.61]	Altmannshofer:2009ne,Altmannsho
	$R_{\ell 23}$	[0.985, 1.013]	Antonelli:2010yf
	$R_{D\ell\nu}$	[0.151, 0.681]	Aubert:2007dsa
	$\mathrm{BR}(D_s \to \tau\nu)$	[0.047, 0.061]	Onyisi:2009th,Alexander:2009ux,Ake
Group (ii)	$BR(b \to s\gamma)$	$[2.89,\ 4.21] \times 10^{-4}$	Barberio:2008fa
	$BR(B_s \to \mu^+\mu^-)$	$< 5.1 \times 10^{-8}$	Abazov:2010fs

Table 1: Summary of the constraints.

Group (i) constraints mainly depend on the Higgs sector, with fairly weak dependence on SUSY spectrum.

Group (ii) constraints depend strongly on the Higgs sector, but also strongly constrain the overall SUSY spectrum.

After the scanning they end up with the following SI cross section results.

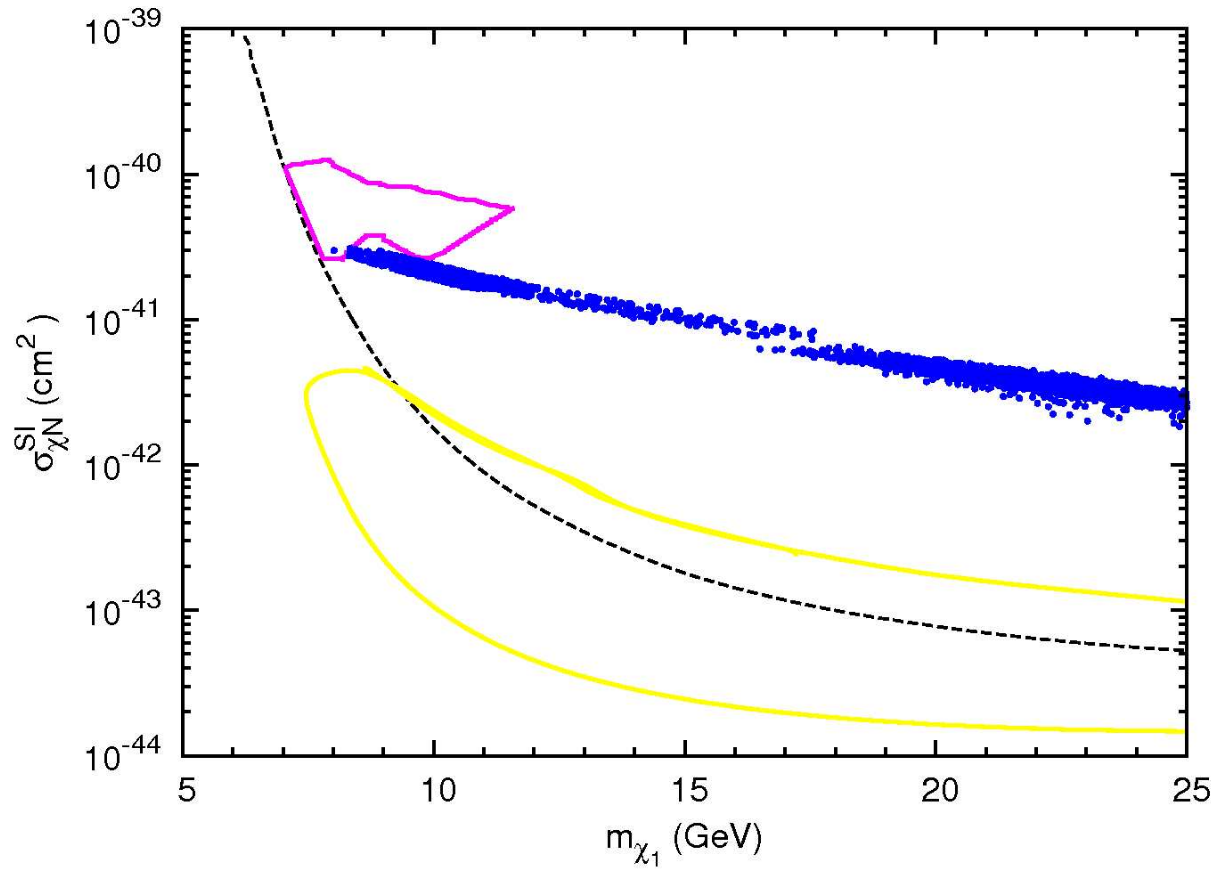


Figure 6: Neutralino-nucleon scattering cross section as a function of the lightest neutralino mass for points which satisfy all the constraints of Table 1. The pink area is the region favored by CoGeNT, the yellow region corresponds to the two CDMS candidates, the dashed line is the 90% C.L. exclusion reported by XENON10. Note that there are actually two sets of blue points — those at low $m_{\widetilde{\chi}_1^0}$ have $\tan\beta \gtrsim 30$.

In the $m_{\widetilde{\chi}_1^0}$–$\tan\beta$ plane, the picture is

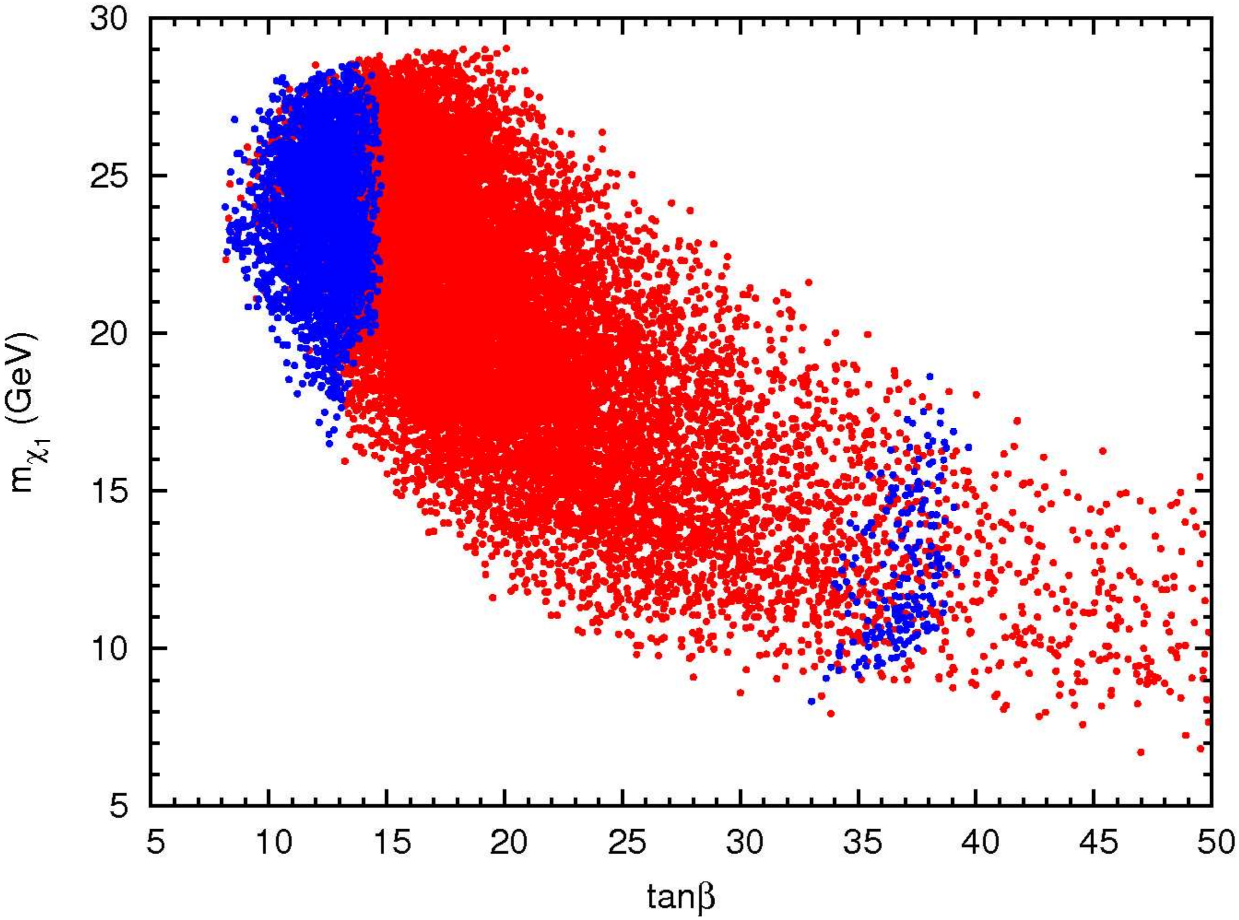
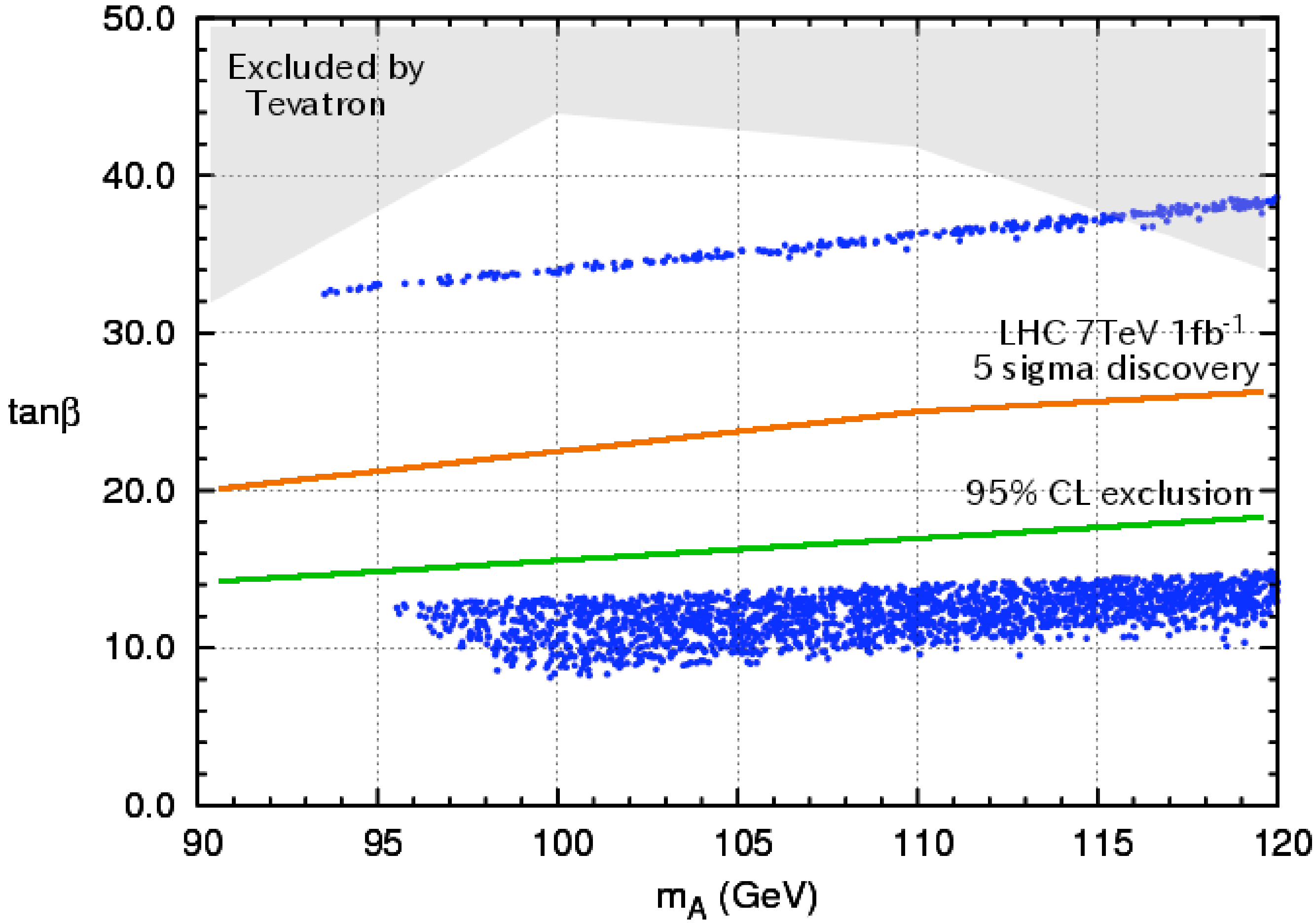


Figure 7: Only blue points satisfy all constraints.

Clearly, only the high-$\tan\beta$ points extend to low $m_{\widetilde{\chi}_1^0}$. The lower $\tan\beta$ points (that do not give large σ_{SI}) start at about $m_{\widetilde{\chi}_1^0} > 18\ \mathrm{GeV}$ (compromise between Belanger et al. and Bottino et al.).

In the space of $\tan\beta$–m_{A^0}, the picture is:



Notes:

- **The maximum σ_{SI} reached agrees roughly with the earlier analytic results and is just barely adequate for CoGeNT.**

- **The $\widetilde{\chi}_1^0$ is allowed to be light.**

- $m_{A^0} \sim 95 - 120$ GeV **is needed for** $\Omega_{\widetilde{\chi}_1^0} h^2 \sim 0.1$.

- **However, the latest LHC constraints on neutral** H^0, A^0 **are not satisfied.**

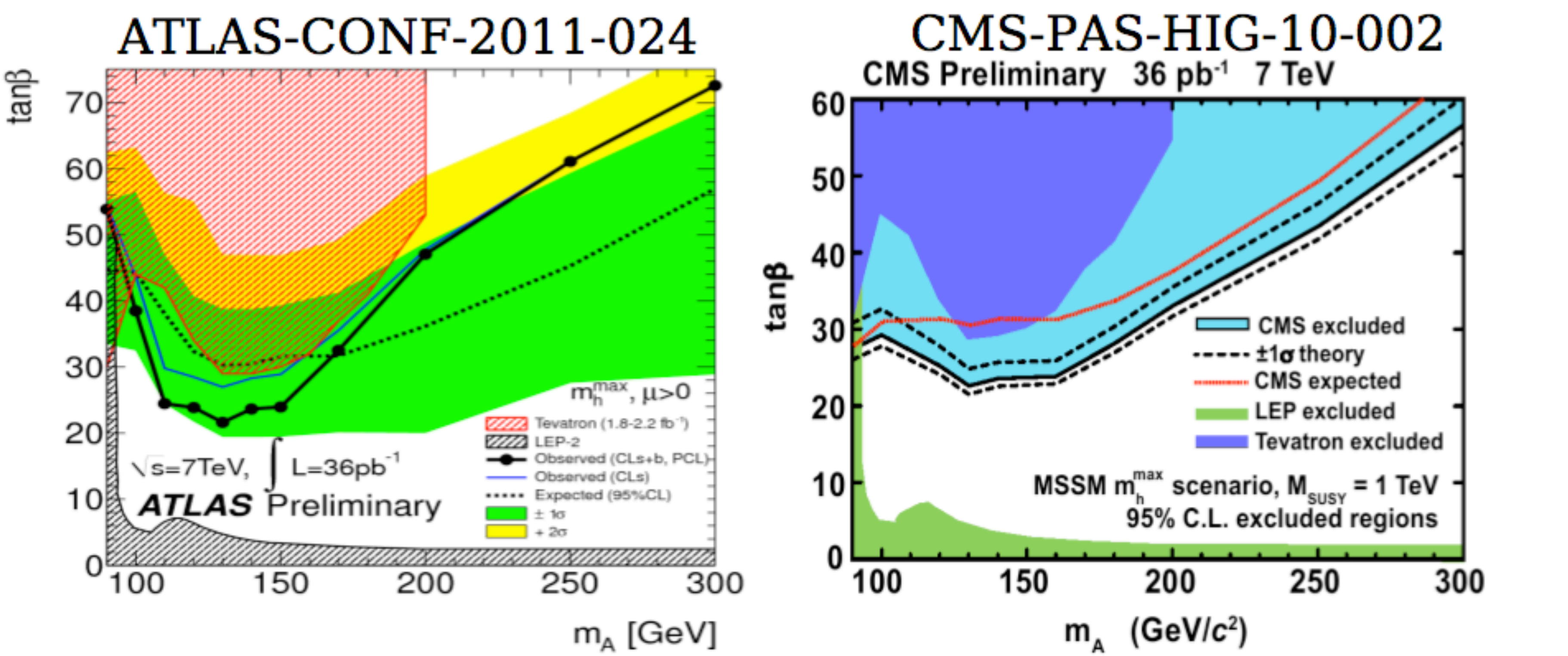


Figure 8: Limits from $36\ \mathrm{pb}^{-1}$ of data at $\sqrt{s} = 7$ TeV from CMS and ATLAS.

These limits assume $m_{H^0} \sim m_{A^0}$, a reasonably good approximation for the range of parameters and m_{A^0} considered, but not absolutely perfect.

$\Rightarrow$ a slight weakening of constraints might be appropriate. Even so, it seems that the required $\tan\beta - m_{A^0}$ values needed for the thin blue strip are excluded.

$\Rightarrow$ The MSSM cannot give large σ_{SI} at low $m_{\widetilde{\chi}_1^0}$.

- One caveat: Djouadi (arXiv:1103.6247) argues that theoretical uncertainties should be treated with a flat prior. This weakens the limits shown somewhat.

  Even if you do this, then CMS and ATLAS will very soon ($L \sim 0.5~\mathrm{fb}^{-1}$) either see the H^0, A^0 or exclude the MSSM CoGeNT/DAMA explanation.

General Lesson There is an integral connection between explaining a large-σ_{SI} signal at low $m_{\widetilde{\chi}_1^0}$ and the Higgs sector. It is either impossible or at the very edge in the MSSM.

Summary It is very likely that the MSSM will either be shown to be inconsistent with CoGeNT/DAMA or the H^0, A^0 will be observed (and

$B_s \to \mu^+\mu^-$, bounded from below by 2×10^{-5} for the high-$\tan\beta$ band, will be seen).

$\Rightarrow$ If CoGeNT/DAMA confirmed, then NMSSM provides a much more comfortable solution — a major reason is the separation of m_{A^0} from m_{h^0}, m_{H^0} so that $\widetilde\chi_1^0\widetilde\chi_1^0 \to A^0 \to \ldots$ can be any strength you like. $\Rightarrow$ correct $\Omega_{\widetilde\chi_1^0}h^2$ is more decoupled from large σ_{SI}.

NMSSM Review

- The NMSSM is defined by adding a single SM-singlet superfield $\widehat{S}$ to the MSSM and imposing a Z_3 symmetry on the superpotential, implying

$$W = \lambda\, \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\, \widehat{S}^3 \tag{10}$$

The reason for imposing the Z_3 symmetry is that then only dimensionless couplings λ, κ enter. All dimensionful parameters will then be determined by the soft-SUSY-breaking parameters. In particular, the μ problem is solved via

$$\mu_{\rm eff} = \lambda\langle S\rangle\,. \tag{11}$$

$\mu_{\rm eff}$ is automatically of order a TeV (as required) since $\langle S\rangle$ is of order the SUSY-breaking scale, which will be below a TeV.

- The extra singlet field $\widehat{S}$ implies: 5 neutralinos, $\widetilde{\chi}^0_{1-5}$ ($\widetilde{\chi}^0_1 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u + N_{15}\tilde{S}$); 3 CP-even Higgs bosons, h_1, h_2, h_3; and 2 CP-odd Higgs bosons, a_1, a_2.

- The soft-SUSY-breaking terms corresponding to the terms in W are:

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \,. \tag{12}$$

  When $A_\lambda, A_\kappa \to 0$, the NMSSM has an additional $U(1)_R$ symmetry, in which limit the a_1 is pure singlet and $m_{a_1} = 0$.

  If, $A_\lambda, A_\kappa = 0$ at M_U, RGE's give $A_\lambda \sim 100~\mathrm{GeV}$ and $A_\kappa \sim 1-20~\mathrm{GeV}$, $\Rightarrow$ small m_{a_1} (including $< 2m_b$) is quite natural and not fine-tuned.

- The NMSSM maintains all the attractive features (GUT unification, RGE EWSB) of the MSSM while avoiding important MSSM problems.

- In particular, there are very attractive scenarios in the NMSSM with no EWSB fine-tuning.

  In those of interest for large-σ_{SI}, low-$m_{\widetilde\chi_1^0}$ dark matter it is h_1 exchange that gives large σ_{SI} and it is h_2 that couples to WW, ZZ. Typically, $m_{h_1} < 100~\mathrm{GeV}$ and $m_{h_2} \gtrsim 105~\mathrm{GeV}$.

Dark Matter and the NMSSM

- **It has long been known (Gunion, McElrath, and Hooper, hep-ph/0509024) that the NMSSM can accommodate light ($m_{\widetilde{\chi}_1^0} < 10\ \mathrm{GeV}$) dark matter with correct relic density by virtue of the ability to choose m_{a_1} so that $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to a_1$ annihilation is of suitable strength.**

- **But, can the NMSSM light dark matter have σ_{SI} as large as suggested by COGENT data, $\sigma_{SI} \sim 2 \times 10^{-4}\ \mathrm{pb}$?**

  We studied this in two papers: Belikov et al. arXiv:1009.2555 and Belikov et al. arXiv:1009.0549.

1. **Type I Scenarios: arXiv:1009.2555**

   - **One has $m_{h_1} \lesssim 100\ \mathrm{GeV}$ and $m_{h_2} > 100\ \mathrm{GeV}$ with $g_{WWh_2} > g_{WWh_1}$ (implies h_1 not subject to LEP limits).**
     The exchange of $h_1 \sim H_d$ gives the dominant contribution to σ_{SI}.

This is sort of like the MSSM case except that in the NMSSM the dominant contribution to σ_{SI} comes from the lightest Higgs as opposed to the heavier H^0 as in the MSSM case.

– Correct $\Omega_{\widetilde{\chi}_1^0} h^2$ is achieved via annihilations through a light a_1 (which often has mass $< 2m_b$).

– σ_{SI} is somewhat larger than the maximum MSSM value simply because the H_d-like h_1 with $\tan\beta$-enhanced couplings to down-type quarks can be lighter than in the more tightly constrained MSSM Higgs sector.

– Problems for Type I that prevent going to full needed σ_{SI}:

(a) LHC limits on $a_2, h_3, h^{\pm}$ (which also have $\tan\beta$-enhanced down-type quark couplings).

(b) $b \to s\gamma$.

(c) $B^+ \to \tau^+ \nu_\tau$. Bad for high-σ_{SI}, $\mu_{\rm eff} < 0$ scenarios.

(d) $(g-2)_\mu$. Bad for high-σ_{SI}, $\mu_{\rm eff} < 0$ scenarios.

$\Rightarrow$ in the end, only $\mu_{\rm eff} > 0$ points can given consistent picture with $\sigma_{SI} \gtrsim 2 \times 10^{-4}$ pb.

– Most importantly, the extra NMSSM freedoms imply that inputting these kind of constraints does not create a gap between large σ_{SI}

solutions and small σ_{SI} solutions.

These constraints only decrease the largest value of σ_{SI} that can be achieved.

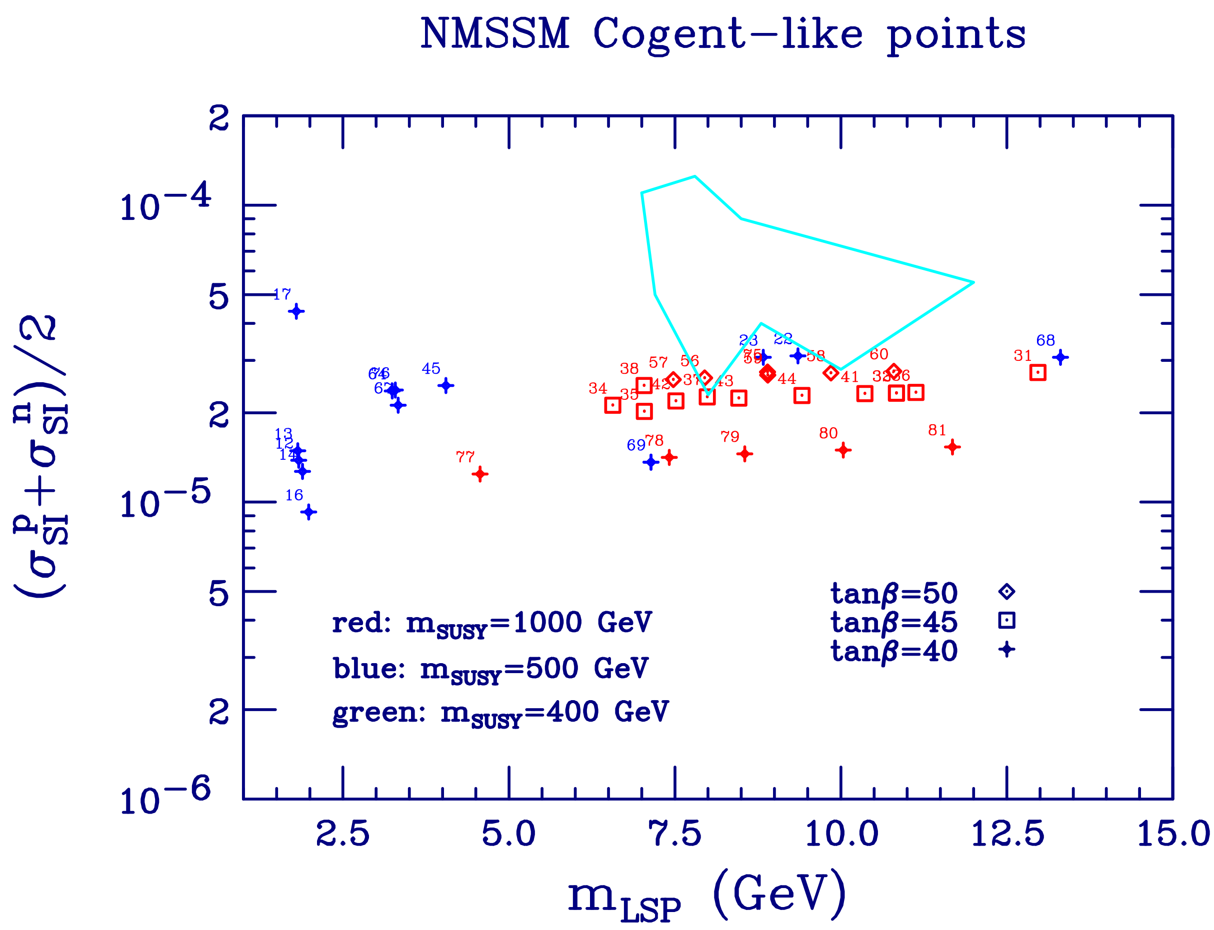


Figure 9: $\mu_{\rm eff} > 0$ **scenarios.**

2. **Type II Scenarios: arXiv:1009.0549**

These are completely unique to the NMSSM since they employ a singlino-like $\widetilde{\chi}_1^0$ and use a singlet-like h_1 (and a_1) to get correct $\Omega_{\widetilde{\chi}_1^0}h^2$ and large σ_{SI}. We term these singlino-singlet scenarios (SS scenarios).

The $h_2, h_3, a_2, h^{\pm}$ form an MSSM-like Higgs sector.

Not unlike the previous MSSM and inverted NMSSM scenarios, there is again a kind of see-saw balance between $\Omega_{\widetilde{\chi}_1^0}h^2$ and σ_{SI} such that when $\Omega_{\widetilde{\chi}_1^0}h^2 \sim 0.1$ then σ_{SI} is largest, but in this case σ_{SI} is very naturally in the CoGeNT/DAMA preferred zone.

Some Details

– The singlino coupling to down-type quarks is given by:

$$\frac{a_d}{m_d} = \frac{g_2 \kappa N_{15}^2 \tan\beta F_s(h_1) F_d(h_1)}{8 m_W m_{h_1}^2} \tag{13}$$

where $h_1 = F_d(h_1)H_d^0 + F_u(h_1)H_u^0 + F_s(h_1)H_S^0$ and the crucial trilinear coupling that couples a singlino pair to the singlet Higgs H_S^0 comes from the $\frac{1}{3}\kappa\widehat{S}^3$ superpotential term and is thus proportional to κ. This leads to

$$\sigma_{SI} \approx 2.2 \times 10^{-4}\,\mathrm{pb}\left(\frac{\kappa}{0.6}\right)^2\left(\frac{\tan\beta}{50}\right)^2\left(\frac{45\,\mathrm{GeV}}{m_{h_1}}\right)^4\left(\frac{F_s^2(h_1)}{0.85}\right)\left(\frac{F_d^2(h_1)}{0.15}\right),$$

which is consistent with the value required by CoGeNT and DAMA/LIBRA for the indicated κ, m_{h_1} and h_1 component values. (Of course, one really sums coherently over all the CP-even Higgs bosons.)

– The large singlet fraction $F_s^2(h_1) \sim 0.85$ of the h_1 will allow it evade the constraints from LEP II and the Tevatron.

– Meanwhile, the thermal relic density of neutralinos is determined by the annihilation cross section and the $\widetilde{\chi}_1^0$ mass.
In the mass range we are considering here, the dominant annihilation channel is to $b\bar{b}$ and $\tau^+\tau^-$ through the s-channel exchange of the same scalar Higgs, h_1, as employed for elastic scattering, yielding:

$$\sigma_{\chi_1^0\chi_1^0\to b\bar{b},\tau^+\tau^-}v = (3,1)\frac{N_c g_2^2\kappa^2 m_b^2 F_s^2(h_1)F_d^2(h_1)}{64\pi m_W^2\cos^2\beta}\frac{m_{\chi_1^0}^2(1-m_b^2/m_{\chi_1^0}^2)^{3/2}\,v^2}{(4m_{\chi_1^0}^2-m_{h_1}^2)^2+m_{h_1}^2\Gamma_{h_1}^2}, \quad (14)$$

where v is relative velocity between the annihilating neutralinos

This yields the thermal relic abundance of neutralinos (using the standard formula with $m_{\chi_1^0}/T_{\rm FO} \approx 20$ for this scenario)

$$\Omega_{\chi_1^0} h^2 \approx 0.11 \left(\frac{0.6}{\kappa}\right)^2 \left(\frac{50}{\tan\beta}\right)^2 \left(\frac{m_{h_1}}{45\,\text{GeV}}\right)^4 \left(\frac{7\,\text{GeV}}{m_{\chi_1^0}}\right)^2 \left(\frac{0.85}{F_s^2(h_1)}\right) \left(\frac{0.15}{F_d^2(h_1)}\right), \quad (15)$$

i.e. naturally close to the measured dark matter density, $\Omega_{\rm CDM} h^2 = 0.1131 \pm 0.0042$ for the same choices for κ, m_{h_1} and composition fractions as give CoGeNT/DAMA-like σ_{SI}.

– The only question is can we achieve the above situation without violating LEP and other constraints.

  Basically, one wants a certain level of decoupling between the singlet sectors and the MSSM sectors, but not too much since we must have $F_d(h_1)$ coupling to the quarks.

  We found it necessary to extend the NMSSM superpotential and soft-SUSY-breaking potential to:

$$v_0^2 \hat{S} + \frac{1}{2}\mu_S \hat{S}^2 + \mu \hat{H}_u \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 \,, \quad (16)$$

and the soft Lagrangian is

$$B_\mu H_u H_d + \frac{1}{2} m_S^2 |S|^2 + B_S S^2 + \lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + H.c. \qquad (17)$$

We find points for $15 < \tan\beta < 35$ with $\sigma_{SI} = few \times 10^{-4}$ and $m_{\widetilde\chi_1^0} \sim 7~\mathrm{GeV}$ that are consistent (within the usual $\pm 2\sigma$ combined theory plus experimental windows).
Points at higher $\tan\beta$ with similar σ_{SI} have excursions in $b \to s\gamma$ and $b\bar{b}h, h \to \tau^+\tau^-$ that fall slightly outside the $\pm 2\sigma$ window.

– Let us illustrate using a particular point. The following table shows:

(a) Large σ_{SI} with $m_{\widetilde\chi_1^0} = 5~\mathrm{GeV}$ is achieved with correct $\Omega_{\widetilde\chi_1^0} h^2$.

(b) The roughly degenerate and very singlet h_1, a_1 (mass $\sim 82~\mathrm{GeV}$) have separated off from something that is close to an MSSM-like Higgs sector with $h_2 \sim h^0$ being SM-like and $h_3 \sim H^0$, $a_2 \sim A^0$ and $h^+ \sim H^+$.

(c) Detection of the h_2 would be possible via the usual SM-like detection modes planned for the MSSM h^0.

(d) One sees that h_1 and a_1 decay primarily to $\widetilde\chi_1^0 \widetilde\chi_1^0$ but that there also decays to $b\bar{b}$ and $\tau^+\tau^-$ with reduced branching ratios of 0.33 and 0.03 compared to the normal $B(b\bar{b}) \sim 0.85$ and $B(\tau^+\tau^-) \sim 0.12$.

(e) At this large $\tan\beta$, detection of the h_3 and a_2 would certainly be possible in $gg \to b\bar{b}h_3 + b\bar{b}a_2$ in the $h_3, a_2 \to \tau^+\tau^-$ decay channel.

Table 2: Properties of a typical ENMSSM point with $\tan\beta = 45$ and $m_{\rm SUSY} = 1000~{\rm GeV}$.

λ	κ	λs	A_λ	A_κ	M_1	M_2	M_3	A_{soft}
0.011	0.596	-0.026 GeV	3943 GeV	17.3 GeV	150 GeV	300 GeV	900 GeV	679 GeV

B_S	μ_S	v_S^3	μ	B_μ	$\mu_{\rm eff}$	B_μ^{eff}
0	7.8 GeV	4.7 GeV	164 GeV	658 GeV	164 GeV	556 GeV

m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	m_{h^+}
82 GeV	118 GeV	164 GeV	82 GeV	164 GeV	178 GeV

$F_S^2(h_1)$	$F_d^2(h_1)$	$F_S^2(h_2)$	$F_u^2(h_2)$	$F_S^2(h_3)$	$F_d^2(h_3)$	$F_S^2(a_1)$	$F_S^2(a_2)$
0.86	0.14	0.0	0.996	0.14	0.86	0.86	0.14

$C_V(h_1)$	$C_V(h_2)$	$C_V(h_3)$	$C_{h_1b\bar{b}}$	$C_{h_2b\bar{b}}$	$C_{h_3b\bar{b}}$	$C_{a_1b\bar{b}}$	$C_{a_2b\bar{b}}$
-0.0096	0.999	-0.041	16.8	2.9	41.7	-16.9	41.7

$m_{\widetilde{\chi}_1^0}$	N_{11}^2	$N_{13}^2 + M_{14}^2$	N_{15}^2	σ_{SI}	$\Omega_{\widetilde{\chi}_1^0}h^2$
4.9 GeV	0.0	0.0	1.0	2.0×10^{-4} pb	0.105

$B(h_1 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$	$B(h_1 \to 2b, 2\tau)$	$B(h_2 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$	$B(h_2 \to 2b, 2\tau)$	$B(h^+ \to \tau^+\nu)$
0.64	$0.33, 0.03$	0.003	$0.88, 0.092$	0.97

$B(a_1 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$	$B(a_1 \to 2b, 2\tau)$	$B(a_2, h_3 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$	$B(a_2, h_3 \to 2b, 2\tau)$
0.64	$0.33, 0.03$	0.05	$0.85, 0.095$

– A few final notes regarding this scenario.

(a) First, it is the very large value of A_λ and the very small λ that keep the singlet and MSSM Higgs sectors fairly separate.

(b) Second, the new parameters of the ENMSSM, μ and B_μ must be substantial.

This is generally the case if you desire an SS scenario with σ_{SI} in the CoGeNT/DAMA region and $m_{h_1} > few~\mathrm{GeV}$.

3. **Alternative Type II Scenarios**

Several other groups have also developed SS scenarios, including Draper et al. (arXiv:1009.3963), Winkler et al. (arXiv:1010.0553) and Cao et al. (arXiv:1104.1754).

Let me discuss just the first of these papers. They call their scenario the Dark Light Higgs (DLH) scenario.

- Their preferred region is one where an approximate $U(1)_{PQ}$ symmetry is realized by virtue of very small κ and κA_κ.
  This guarantees that both h_1 and a_1 will be very light.
- In order to achieve CoGeNT/DAMA-like values for σ_{SI} while maintaining consistency with current experimental constraints, $m_{h_1} \lesssim 1~\mathrm{GeV}$ is required, in which case a considerable degree of finetuning for the couplings is necessary.

– However, they do not need to go to the ENMSSM in order to achieve a phenomenologically viable separation between the singlet Higgs sector and the MSSM Higgs sector.

– Some properties of their typical point appear in the following Table.

Table 3: DLH point with $\tan\beta = 13.77$, $m_{\tilde{q}} = 1000$ GeV and $m_{\tilde{\ell}} = 200$ GeV.

λ	κ	λs	A_λ	A_κ	M_1	M_2	M_3	A_{soft}
0.1205	0.00272	168 GeV	2661 GeV	−24.03 GeV	100 GeV	200 GeV	660 GeV	750 GeV

m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	m_{h^+}
0.811 GeV	116 GeV	2.44 TeV	16.7 GeV	2.44 TeV	2.44 TeV

$F_S^2(h_1)$	$F_d^2(h_1)$	$F_S^2(h_2)$	$F_u^2(h_2)$	$F_S^2(h_3)$	$F_d^2(h_3)$	$F_S^2(a_1)$	$F_S^2(a_2)$
0.997	0.00017	0.0036	0.99	0.0	0.994	1.00	0.00

$C_V(h_1)$	$C_V(h_2)$	$C_V(h_3)$	$C_{h_1 b\bar{b}}$	$C_{h_2 b\bar{b}}$	$C_{h_3 b\bar{b}}$	$C_{a_1 b\bar{b}}$	$C_{a_2 b\bar{b}}$
0.06	0.998	0.0	0.183	0.994	13.77	−0.12	13.77

$m_{\tilde{\chi}_1^0}$	N_{11}^2	$N_{13}^2 + N_{14}^2$	N_{15}^2	σ_{SI}	$\Omega_{\tilde{\chi}_1^0} h^2$
7.2 GeV	0.0036	0.017	0.98	2.34×10^{-4} pb	0.112

$B(h_1 \to \mu^+\mu^-)$	$B(h_1 \to u\bar{u} + d\bar{d}, gg)$	$B(h_2 \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	$B(h_2 \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	$B(h_2 \to 2b, 2\tau)$
0.087	$0.047, 0.044$	0.05	0.45	$0.37, 0.038$

$B(h^+ \to t\bar{b})$	$B(h^+ \to \tilde{\chi}_{1,2}^+\tilde{\chi}_{1,2,3,4,5}^0)$
0.138	0.80

$B(a_1 \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	$B(a_1 \to 2b, 2\tau, 2\mu)$
0.25	$0.70, 0.042, 0.00015$

$B(a_2, h_3 \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	$B(a_2, h_3 \to 2t, 2b, 2\tau)$	$B(a_2, h_3 \to \tilde{\chi}_{1,2,3,4,5}^0\tilde{\chi}_{1,2,3,4,5}^0)$	$B(a_2, h_3 \to \tilde{\chi}_{1,2}^+\tilde{\chi}_{1,2}^-)$
0.00	$0.013, 0.126, 0.023$	0.32	0.48

– Note that the simple formula given earlier for the SS scenario still applies here and that

$$\frac{\sigma_{SI}(DLH)}{\sigma_{SI}(SS)} = \left(\frac{0.000272}{0.6}\right)^2 \left(\frac{82}{0.81}\right)^2 \left(\frac{13.8}{50}\right) \left(\frac{0.00017}{0.14}\right) \left(\frac{0.997}{0.86}\right) = 0.23 \quad (18)$$

which is in acceptable agreement with unity that one can see that both models have a common nature.

– Once again large A_λ is needed to achieve appropriate near decoupling of the MSSM-like Higgs sector from the h_1, a_1 singlet Higgs sector.

– In combination, these two points suggest that one can also anticipate a variety of intermediate models between these two extreme cases of large κ and very small κ.

– Higgs phenomenology:

In the DLH case, the MSSM sector heavy Higgs, $h_3, a_2, h^\pm$ have very large mass of order $2.4~\mathrm{TeV}$. There will be no accessible phenomenology related to them.

At the same time, the h_2 will be completely SM-like in couplings to SM particles but will have $h_2 \to \widetilde\chi_1^0 \widetilde\chi_1^0, \widetilde\chi_1^0 \widetilde\chi_2^0$ decays that will help to identify this scenario.

Conclusions

- **If CoGeNT/DAMA survive, then it seems very likely that the MSSM must be extended to the NMSSM if we are to explain light Dark Matter in the context of "standard" supersymmetry models.**

- **If σ_{SI} is as large as indicated, it cannot be explained in NMSSM scenarios of Type I without pushing the strange quark and other parameters affecting σ_{SI} to some extremes.**

- **The net result is some preference for the singlino-singlet scenarios in which Dark Matter is primarily related to light singlet $\widetilde{\chi}_1^0, h_1, a_1$ while EWSB is primarily associated with the $h_2, h_3, a_2, h^{\pm}$ (heavier) Higgs sector.**