Natural Implementation of Neutralino Dark Matter

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- Dark matter fine-tuning
- CMSSM
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- Non-universal gauginos
- Non-universal 3rd family scalars and gauginos
- Conclusion

Based on work with Jonathan Roberts, hep-ph/0603095

Partial list of references:

D. J. H. Chung, L. L. Everett, G. L. Kane, S. F. King, J. D. Lykken and L. T. Wang, Phys. Rept. **407** (2005) 1 [arXiv:hep-ph/0312378].

G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267** (1996) 195 [arXiv:hep-ph/9506380].

J. R. Ellis, S. Heinemeyer, K. A. Olive and G. Weiglein, JHEP **0502** (2005) 013 [arXiv:hep-ph/0411216].

G. Belanger, F. Boudjema, A. Cottrant, A. Pukhov and A. Semenov, Nucl. Phys. B **706** (2005) 411 [arXiv:hep-ph/0407218].

H. Baer, A. Belyaev, T. Krupovnickas and A. Mustafayev, JHEP **0406** (2004) 044 [arXiv:hep-ph/0403214].

M. R. Ramage and G. G. Ross, JHEP **0508** (2005) 031 [arXiv:hep-ph/0307389].

M. Olechowski and S. Pokorski, Phys. Lett. B **344** (1995) 201 [arXiv:hep-ph/9407404].

F. M. Borzumati, M. Olechowski and S. Pokorski, Phys. Lett. B **349** (1995) 311 [arXiv:hep-ph/9412379].

V. Berezinsky, A. Bottino, J. R. Ellis, N. Fornengo, G. Mignola and S. Scopel, Astropart. Phys. **5** (1996) 1 [arXiv:hep-ph/9508249].

P. Nath and R. Arnowitt, Phys. Rev. D **56** (1997) 2820 [arXiv:hep-ph/9701301].

E. Accomando, R. Arnowitt, B. Dutta and Y. Santoso, Nucl. Phys. B **585** (2000) 124 [arXiv:hep-ph/0001019].

R. Arnowitt and B. Dutta, arXiv:hep-ph/0210339.

R. Dermisek, S. Raby, L. Roszkowski and R. Ruiz De Austri, JHEP **0304** (2003) 037 [arXiv:hep-ph/0304101].

V. Bertin, E. Nezri and J. Orloff, JHEP **0302** (2003) 046 [arXiv:hep-ph/0210034].

A. Birkedal-Hansen and B. D. Nelson, Phys. Rev. D **67** (2003) 095006 [arXiv:hep-ph/0211071].

U. Chattopadhyay and D. P. Roy, Phys. Rev. D **68** (2003) 033010 [arXiv:hep-ph/0304108].

D. G. Cerdeno, K. Y. Choi, K. Jedamzik, L. Roszkowski and R. Ruiz de Austri, arXiv:hep-ph/0509275.

L. Covi, L. Roszkowski, R. Ruiz de Austri and M. Small, JHEP **0406** (2004) 003 [arXiv:hep-ph/0402240].

G. W. Bennett *et al.* [Muon g-2 Collaboration], Phys. Rev. Lett. **92** (2004) 161802 [arXiv:hep-ex/0401008].

N. Arkani-Hamed, A. Delgado and G. F. Giudice, arXiv:hep-ph/0601041.

Apologies for the incomplete list…

Introduction to dark matter

Observations (WMAP…) $\Omega_{DM}h^2 = 0.113 \pm 0.009$

$$h \approx 0.7, \quad \Omega_{DM} \approx 0.22 \pm 0.02$$

Qualitatively accounted for by:

- Stable, neutral, colourless, weakly interacting particle with weak scale mass

- In thermal equilibrium, freezes out at temperature $T_f \approx$ 1-100 GeV

- Low energy SUSY with R-parity gives such a particle: the LSP neutralino χ_1

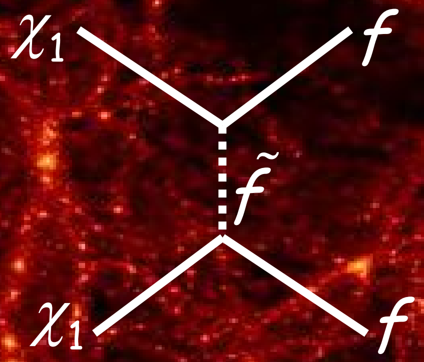
Calculation of relic abundance

$$\Omega_{DM} \approx \frac{T_0^3}{m_P \rho_c} \sqrt{\frac{4\pi^3 g_*}{45}} \left[\int_0^{x_F} \langle \sigma v \rangle dx \right]^{-1}$$

$$x = \frac{T}{m_{LSP}},\ x_F = \tfrac{1}{20},$$

$$T_0 = 2 \times 10^{-13} GeV,\ \rho_c = 4 \times 10^{-47} GeV^4,\ g_* = 100,\ m_P = 10^{19} GeV$$

e.g. t-channel sfermion annihilation



$$\langle \sigma v \rangle \sim \frac{1}{64\pi} x \frac{m_{LSP}^2}{m_{\tilde{f}}^2}$$

$$x_F = \tfrac{1}{24},\ m_{LSP} = m_{\tilde{f}} = 100 GeV \rightarrow \Omega_{DM} \approx 0.4$$

right order of magnitude

SUSY neutralino LSP dark matter

Neutralino mass matrix:

$$\begin{array}{cccc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u \end{array}$$

$$\begin{pmatrix} M_1 & & & \\ & M_2 & & \\ & & 0 & -\mu \\ & & -\mu & 0 \end{pmatrix}$$

The simplest possibility is that the LSP is pure Bino, Wino, or Higgsino

Bino	$\Omega_{\tilde{\chi}_1^0} h^2 \gg 0.1$	$\gg \Omega_{CDM} h^2$
Wino	$\Omega_{\tilde{\chi}_1^0} h^2 \approx 0.13 \left(\frac{M_2}{2.5TeV}\right)^2$	$\ll \Omega_{CDM} h^2$
Higgsino	$\Omega_{\tilde{\chi}_1^0} h^2 \approx 0.1 \left(\frac{\mu}{1TeV}\right)^2$	$\ll \Omega_{CDM} h^2$

For typical SUSY masses

However there are important exceptions…

The Exceptions

SUSY theories **will** satisfy dark matter constraints if:

1. Bino annihilation is enhanced, usually via:
   - t-channel slepton exchange
   - s-channel resonant annihilation (via h^0, Z^0, A^0)
   - co-annihilation (usually with $\tilde{\tau}$ or $\tilde{\mu}_R$, $\tilde{e}_R$)
2. The LSP is a mixed state:
   - Bino/Wino well-tempered $M_1 \approx M_2$
   - Bino/Higgsino well-tempered $M_1 \approx \mu$
   - Bino/Wino/Higgsino maximally tempered. $M_1 \approx M_2 \approx \mu$

Dark Matter Fine-Tuning

Recall the EW fine-tuning sensitivity parameter:

$$\Delta_i^{EW} = \frac{c_i}{M_Z^2}\frac{\partial\left(M_Z^2\right)}{\partial c_i}$$

We study the dark matter fine-tuning sensitivity parameter:

$$\Delta_i^{\Omega} = \frac{c_i}{\Omega_{CDM}h^2}\frac{\partial\left(\Omega_{CDM}h^2\right)}{\partial c_i}$$

A measure of fine-tuning:

$$\Delta^{\Omega} = \mathrm{Max}\left(\Delta_i^{\Omega}\right)$$

We would like to understand how fine-tuned the SUSY dark matter regions are, and see if there are any natural regions in some SUSY models

N.B. The dark matter fine-tuning is logically independent of electroweak fine-tuning

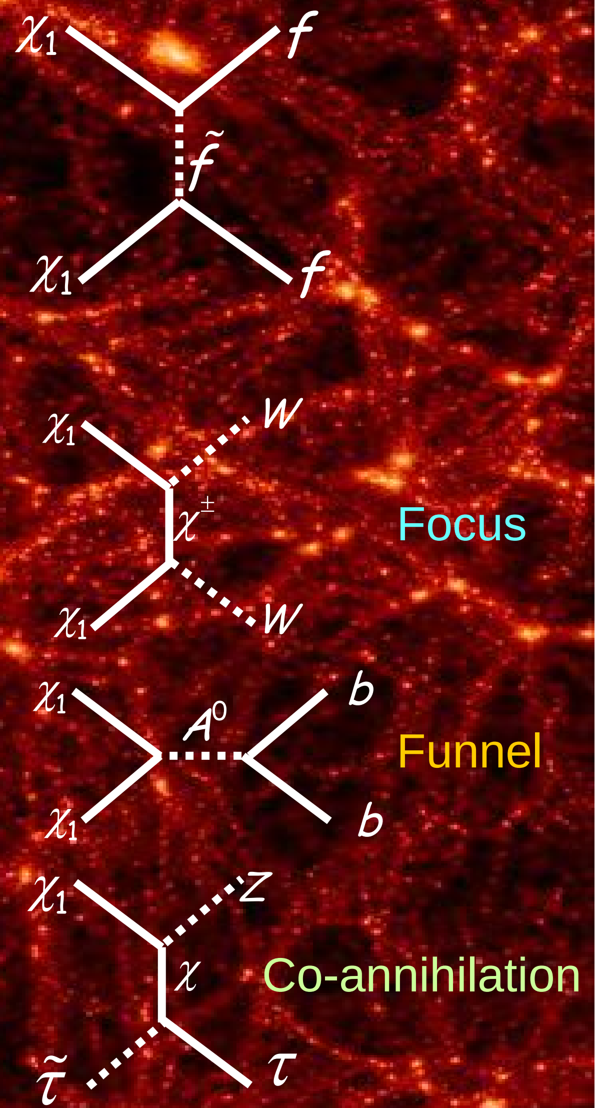
CMSSM

m_0, $m_{1/2}$, $\tan\beta$, A_0, sign(μ)

Over the majority of parameter space the LSP is the bino and Ω_{DM} is too large since the sleptons are too heavy for efficient annihilation

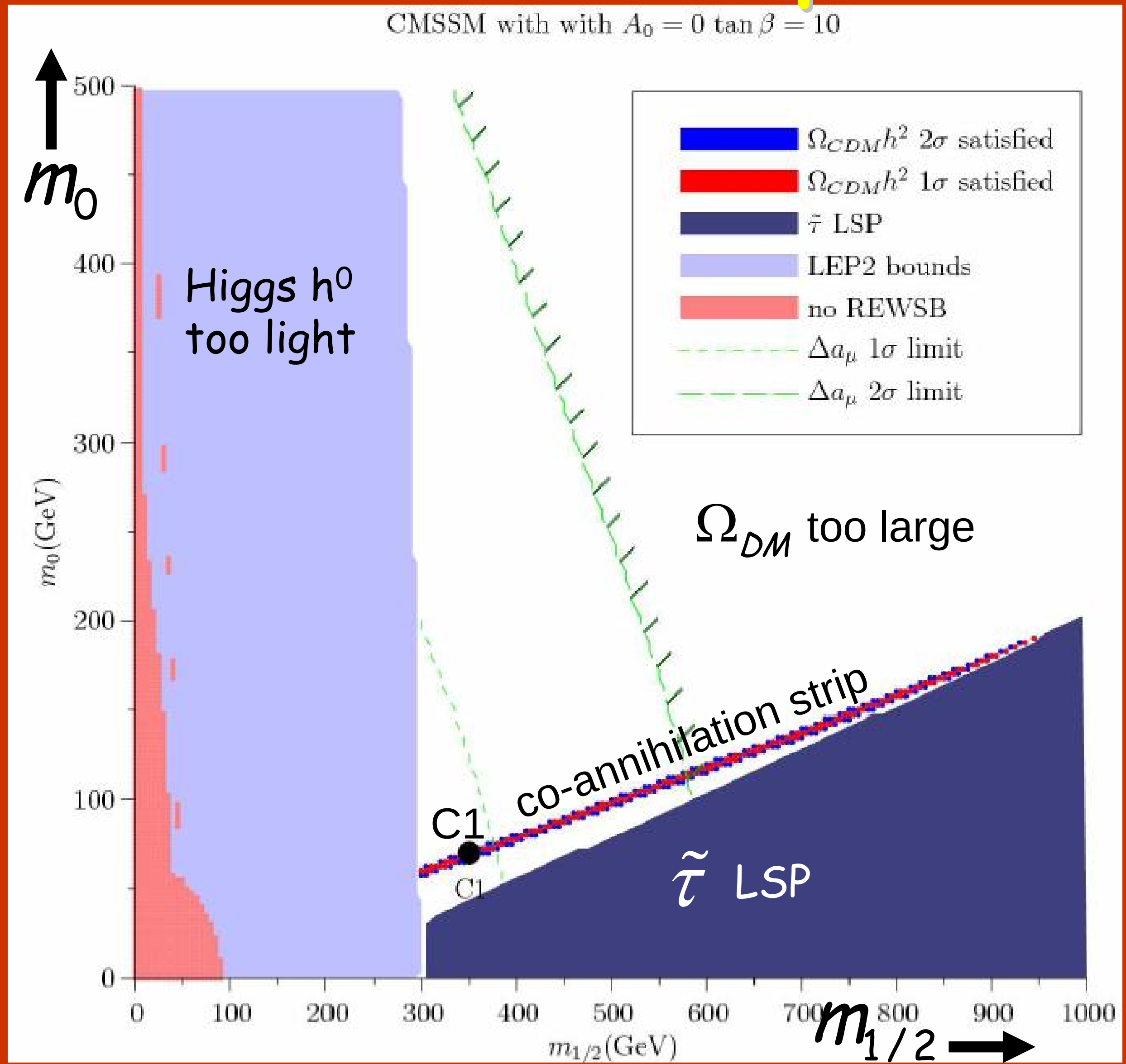
However there are three successful regions:

1. Focus point region: $m_0 > 3$ TeV → low μ → Bino/Higgsino LSP ($\sim$ 2% tuning)
2. Funnel region: large $\tan\beta$ → light A^0 resonance annihilation ($\sim$ 3% tuning)
3. Co-annihilation region: $m_{stau} \approx m\chi$



e.g. CMSSM co-annihilation strip

A_0=0, tan β =10, μ >0



Point C1:
m_0=70 GeV,
$M_{1/2}$=350 GeV

Parameter	Value
$\Delta^{\Omega}_{m_0}$	3.5
$\Delta^{\Omega}_{m_{1/2}}$	3.4
$\Delta^{\Omega}_{\tan\beta}$	1.4
$\Delta^{\Omega}_{A_0}$	0
Δ^{Ω}	3.5
Δ^{EW}	160

30% tuned dark matter in the co-annihil. region

Why so little?

Co-annihilation between 2 particles requires:

$$m_1 \approx m_2 + 10\%$$

But surely $m_{\tilde{\tau}}$ and $m_{\tilde{\chi}_1^0}$ are independent?

Consider the RGEs (at 1-loop):

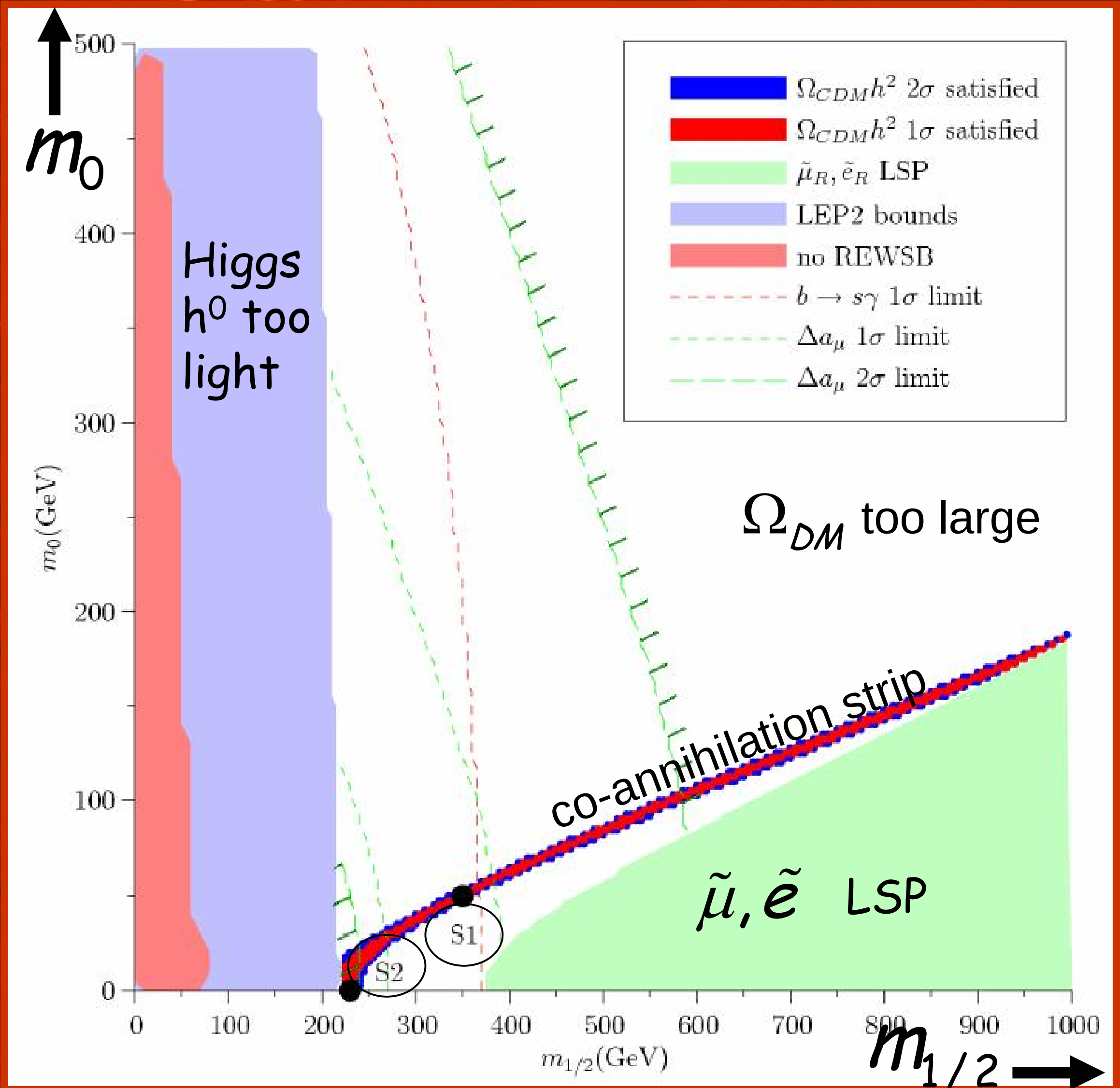
$$\frac{dM_a}{dt} = \frac{2g_a^2}{16\pi^2} b_a M_a$$

$$\frac{dm_{E_3}^2}{dt} = \frac{1}{8\pi^2}\left[\left(3|Y_\tau|^2\left(m_{L_3}^2 + m_{E_3}^2 + m_{H_d}^2 + |A_\tau|^2\right)\right) - \frac{12}{5} g_1^2 |M_1|^2\right]$$

For low m_0, $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ both depend strongly on M_1 and their masses are correlated.

Non-Universal 3rd Family Scalars

$m_{0,3}=m_H=1$ TeV, $A_0=0$, $\tan\beta=10$, $\mu>0$



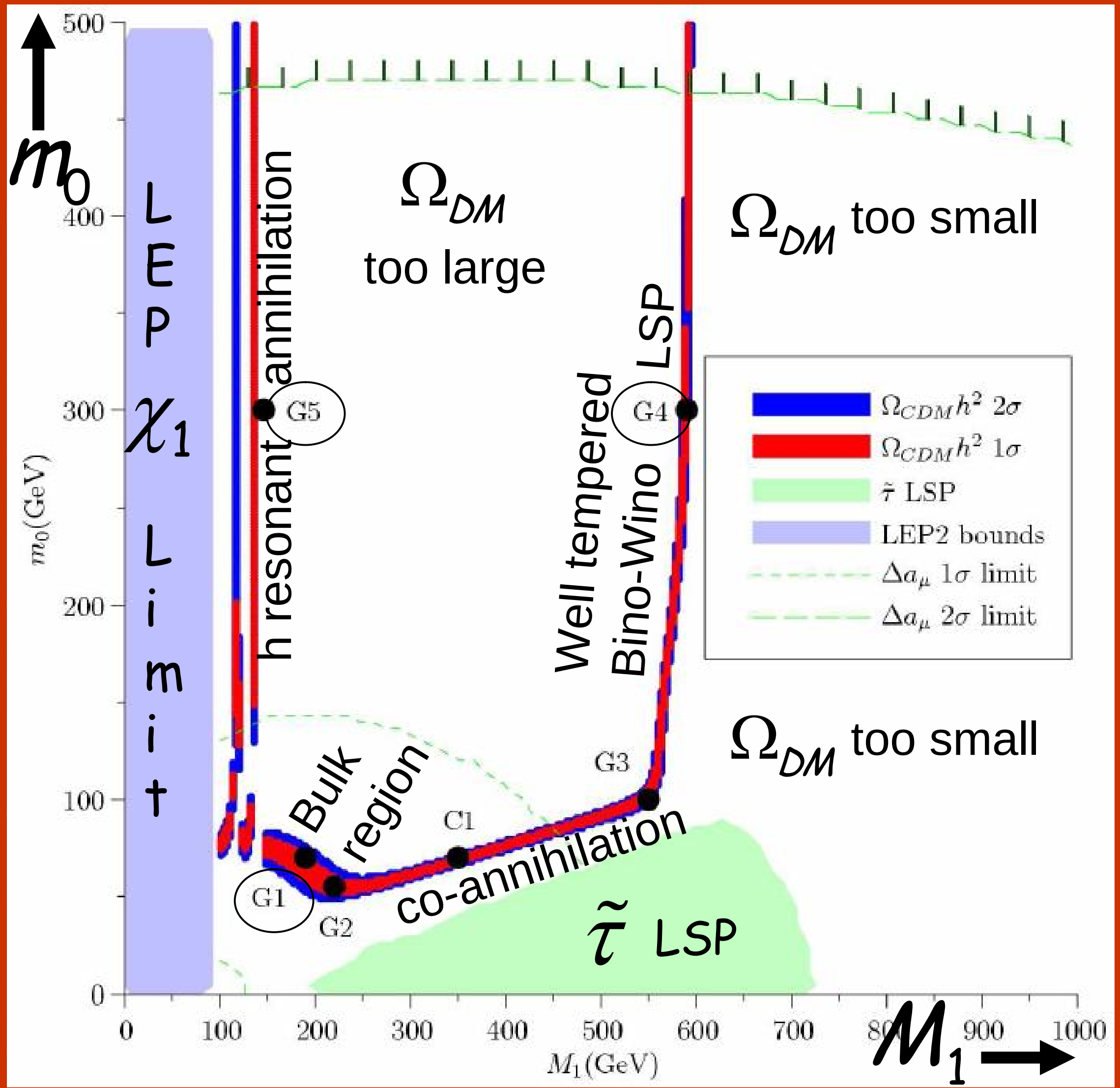
Parameter	Value	
	S1	S2
$\Delta^{\Omega}_{m_0}$	2.4	0
$\Delta^{\Omega}_{m_{0,3}}$	0.15	0.30
$\Delta^{\Omega}_{m_{1/2}}$	4.2	1.8
$\Delta^{\Omega}_{\tan\beta}$	0.061	0.033
$\Delta^{\Omega}_{A_0}$	0	0
Δ^{Ω}	4.2	1.8
Δ^{EW}	240	200

25% tuned dark matter in co-annihil. region

Natural dark matter with 60% slepton ex. 40% co-annihil.

Non-Universal Gauginos

$M_2 = M_3 = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$



Parameter	Value		
	G1	G4	G5
$\Delta^{\Omega}_{m_0}$	0.83	0.65	5.7
$\Delta^{\Omega}_{M_1}$	0.80	28	1100
$\Delta^{\Omega}_{M_2}$	0.23	26	4.8
$\Delta^{\Omega}_{M_3}$	0.24	5.8	91
$\Delta^{\Omega}_{\tan\beta}$	0.20	0.20	4.1
$\Delta^{\Omega}_{A_0}$	0	0	0
Δ^{Ω}	0.83	28	1100
Δ^{EW}	110	111	110

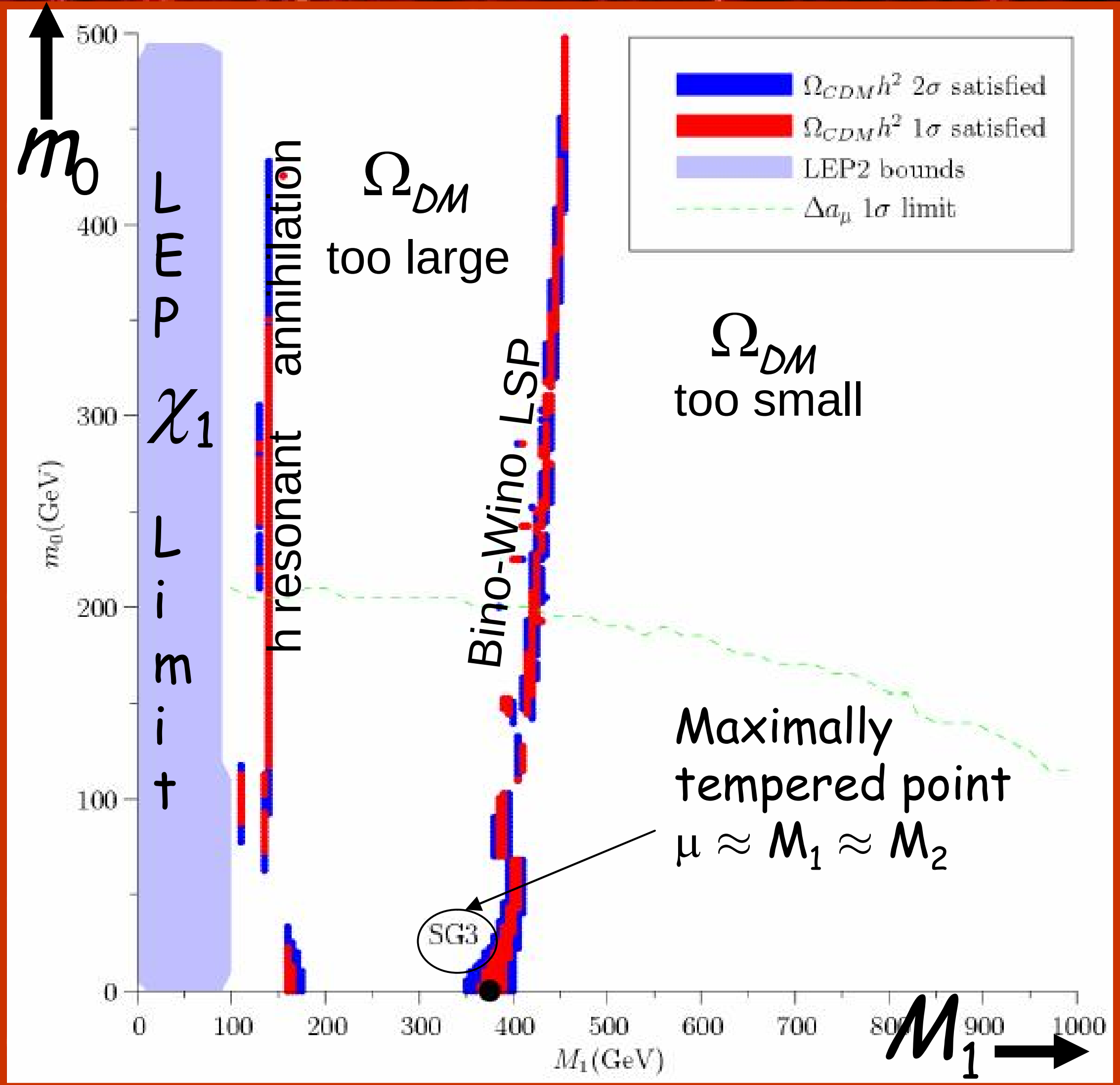
Natural dark matter in bulk region

3% tuned dark matter in well tempered region

0.1% tuned dark matter in res. region

Non-Universal gauginos and 3rd Family Scalars

$M_2 = M_3 = 350$ GeV, $m_{0,3} = 2250$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$



Parameter	Value
	SG3
$\Delta^{\Omega}_{m_0}$	0.064
$\Delta^{\Omega}_{m_{0,3}}$	3.8
$\Delta^{\Omega}_{M_1}$	2.0
$\Delta^{\Omega}_{M_2}$	0.52
$\Delta^{\Omega}_{M_3}$	3.7
$\Delta^{\Omega}_{\tan\beta}$	1.0
$\Delta^{\Omega}_{A_0}$	0.015
Δ^{Ω}	3.8
Δ^{EW}	240

25% tuned dark matter in the maximally tempered region

Conclusions

- The CMSSM funnel and focus point regions are highly tuned, but the co-annihilation region is natural
- Non-universal 3rd family scalar masses allows natural dark matter in the co-annihilation+bulk region with $m_0=0$
- Non-universal gauginos allows access to well tempered Bino/Wino with 3% tuning, and also gives access to the supernatural bulk region
- Non-universal 3rd family + gauginos allows for a maximally tempered Bino/Wino/Higgsino with no fine-tuning
- Electroweak fine-tuning remains, but can be addressed in non-minimal SUSY models