Neutralino Dark Matter in non-universal and non-minimal SUSY

- MSSM neutralino dark matter
- Dark matter sensitivity and the CMSSM
- NU Higgs Mass
- NU Third family scalar mass
- NU Gaugino mass
- NU Gauginos in SU(5)
- NU Gauginos and third family scalar mass
- Singlet SUSY Models: the USSM, E_6SSM

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

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 Sensitivity

Recall the EW sensitivity parameter:

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

Introduce the dark matter sensitivity parameter:

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

N.B. The dark matter sensitivity is logically independent of electroweak sensitivity

It is a measure of the sensitivity of the WMAP allowed regions to the underlying parameters

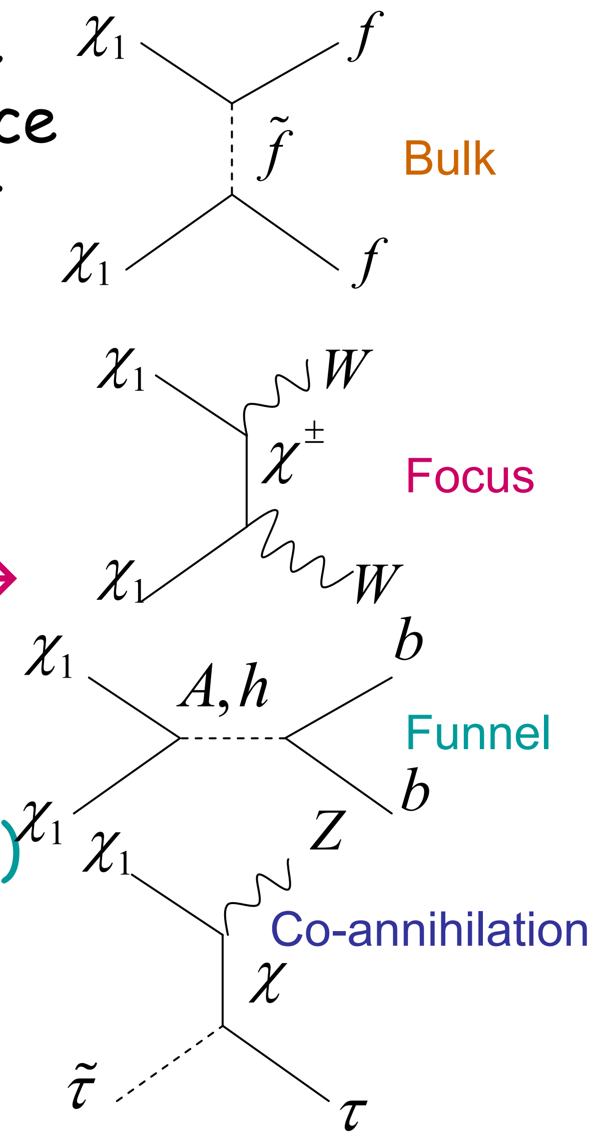
CMSSM sensitivity

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

Two of the three successful regions have large dark matter sensitivity:

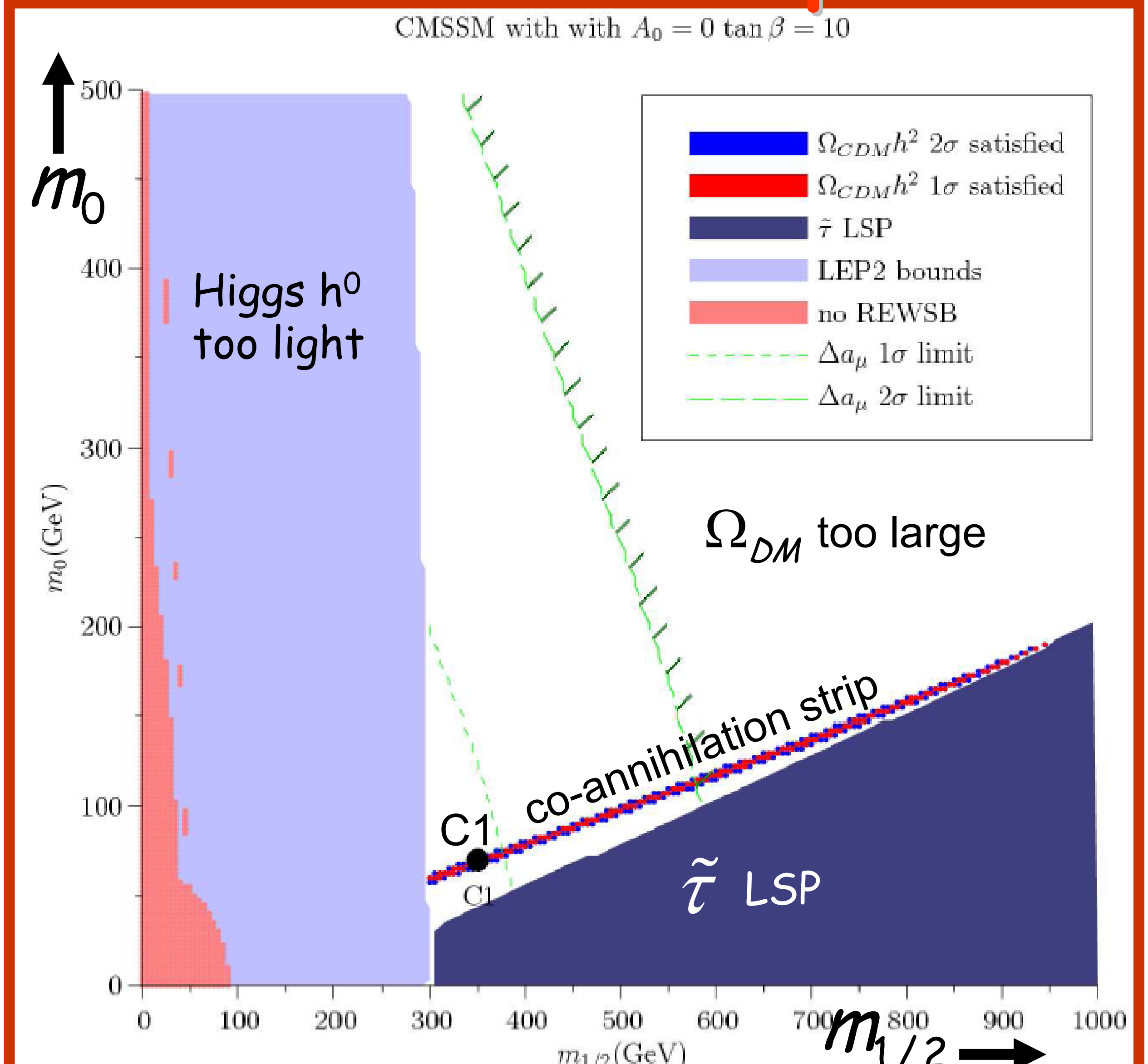
1. Focus point region: $m_0 > 3$ TeV → low μ → Bino/Higgsino LSP ($\sim$ 2% sensitivity)
2. Funnel region: large $\tan\beta$ → light A^0 resonance annihilation ($\sim$ 3% sensitivity)
3. Co-annihilation region: $m_{stau} \approx m\chi$ (none)



CMSSM co-annihilation strip

SFK, Roberts

$A_0=0$, $\tan\beta=10$, $\mu>0$



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

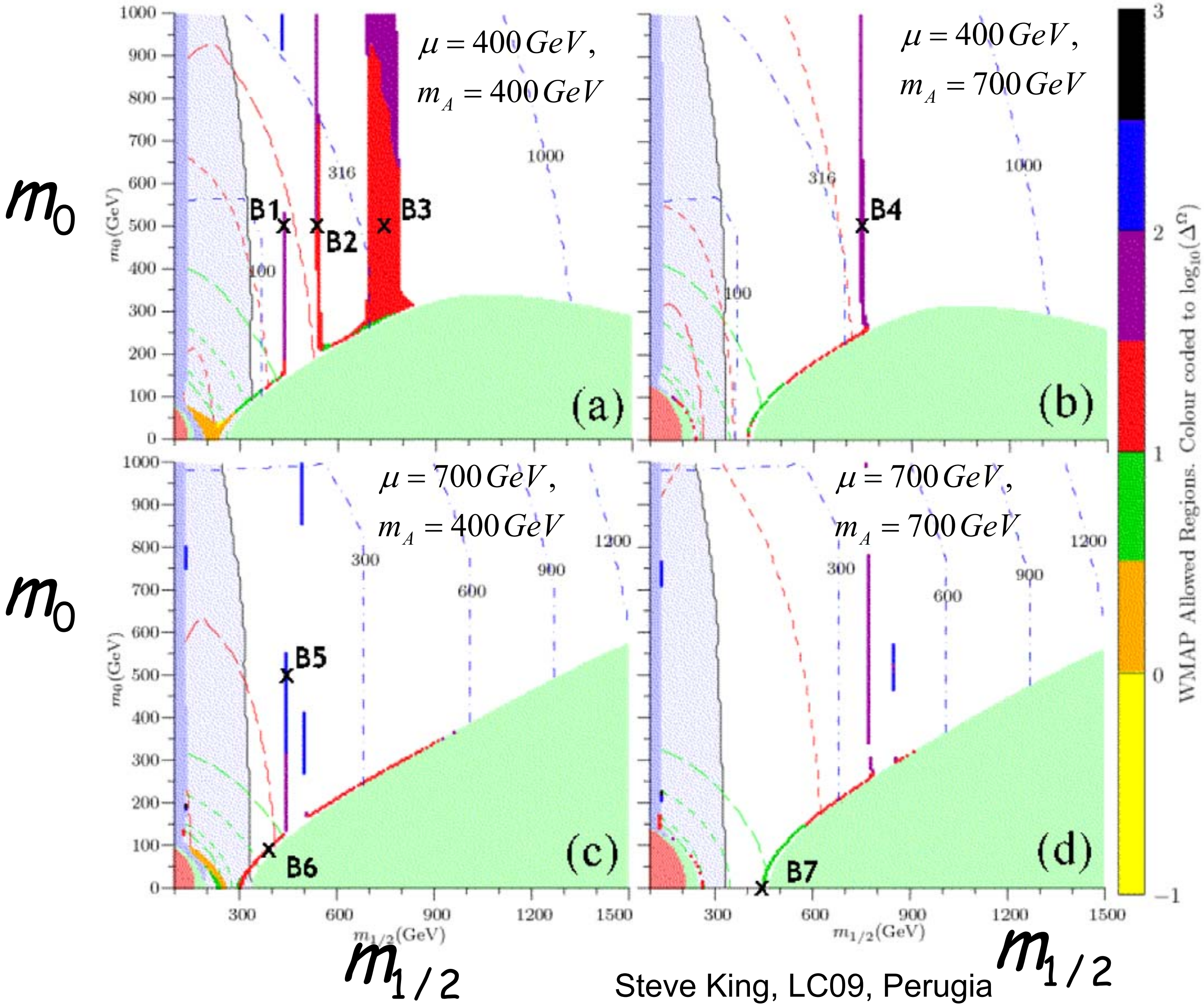
Parameter	Value
$\Delta^{\Omega}_{m_0}$	3.5
$\Delta^{\Omega}_{m_{1/2}}$	3.4
$\Delta^{\Omega}_{\tan\beta}$	1.4
$\Delta^{\Omega}_{A_0}$	0
Δ^{Ω}	3.5
Δ^{EW}	160

30% sensitivity in the co-annihil. region

NUHM $a_{NUHM} = \{m_0,\ m_{H_1},\ m_{H_2},\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)\}$

Ellis, SFK, Roberts

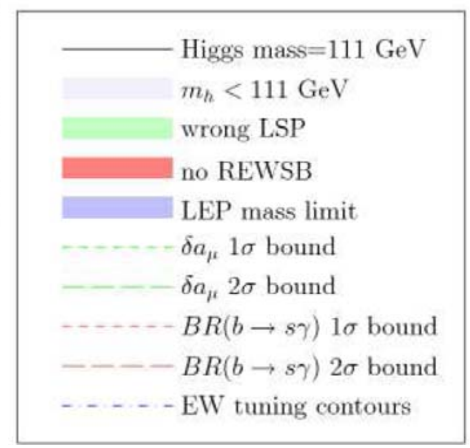
$A_0 = 0, \quad \tan\beta = 10,$
$\mathrm{sgn}(\mu) = +$



CPodd Higgs funnel: B1,2,4,5

Bino-Higgsino LSP: B3

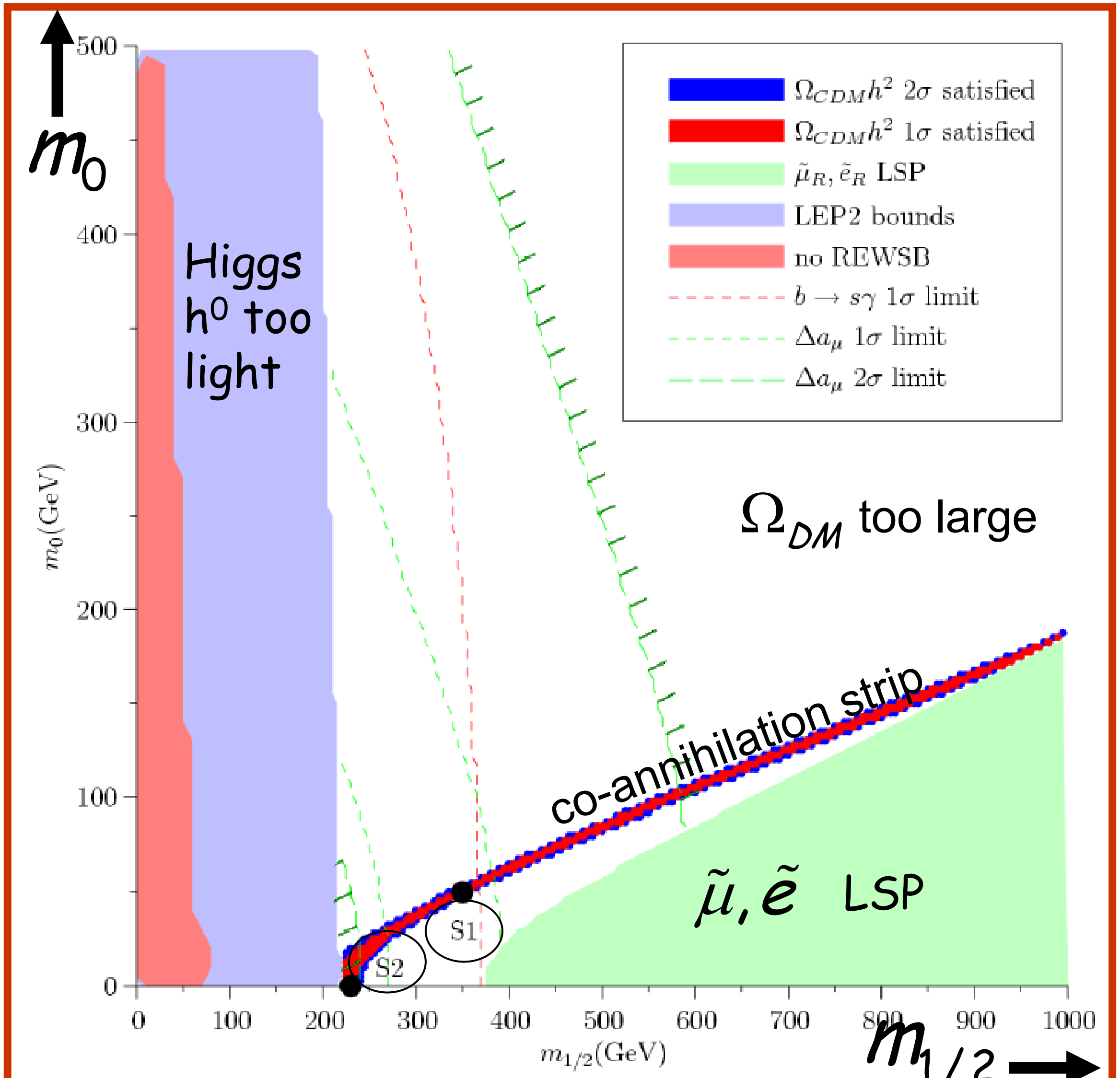
Stau co-ann: B6,7



NU 3rd Family Scalars

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

SFK, Roberts



Parameter	Value S1	Value 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

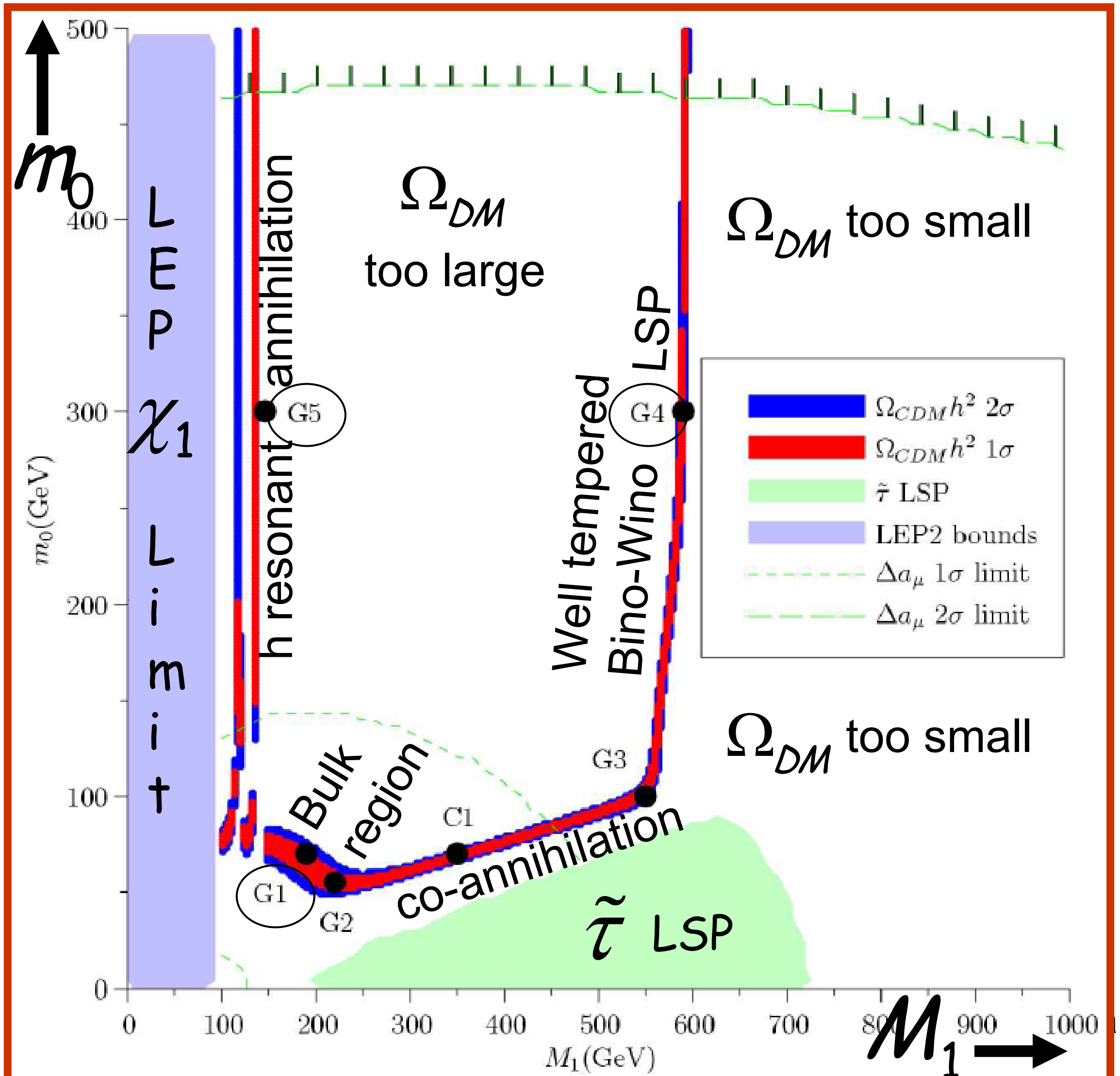
25% tuned dark matter in co-annihil. region

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

NU Gauginos

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

SFK, Roberts



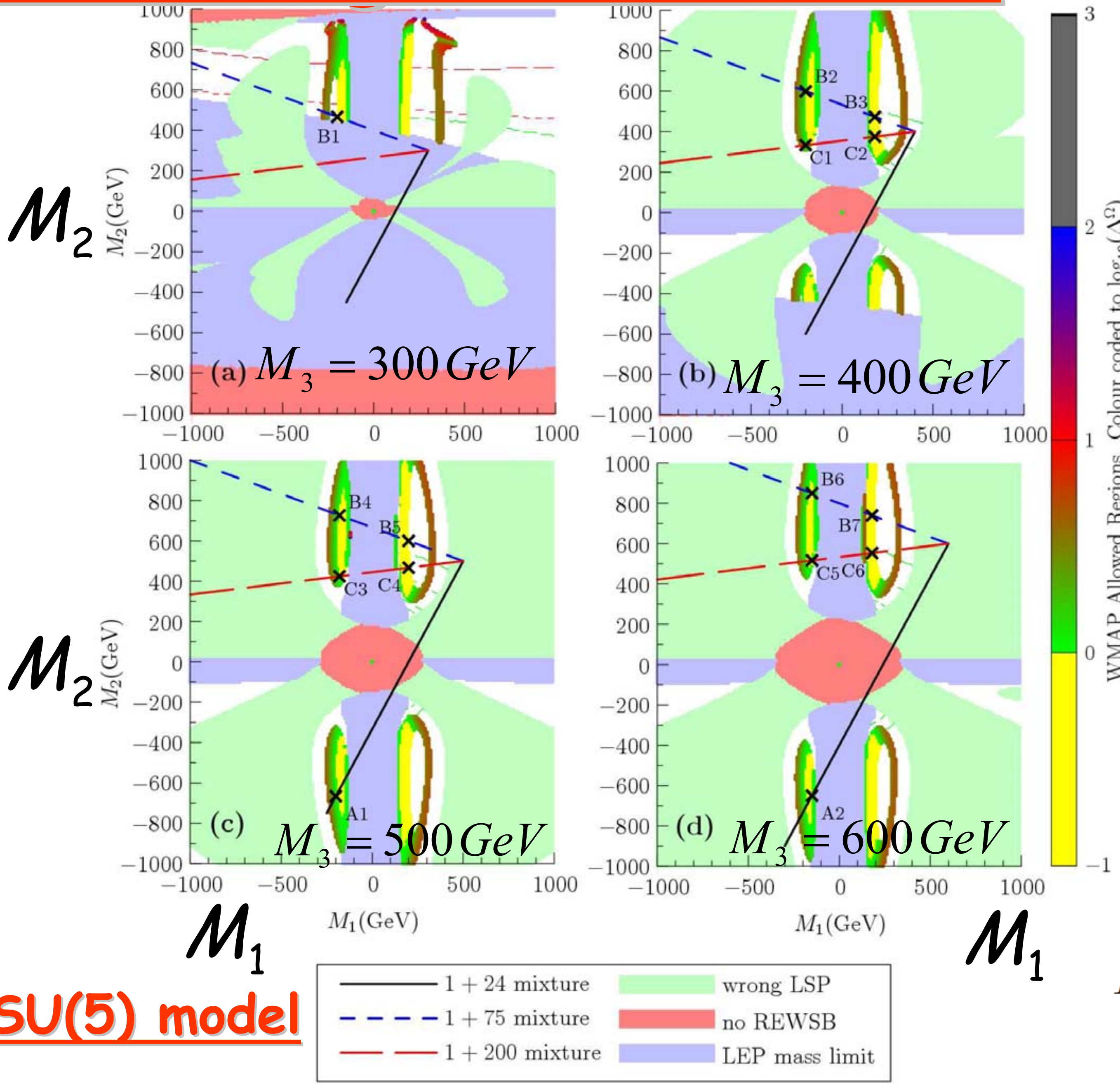
Parameter	Value G1	Value G4	Value G5
$\Delta^{\Omega}_{m_0}$	0.83	0.65	5.7
$\Delta^{\Omega}_{M_1}$	0.80	28	1100
$\Delta^{\Omega}_{M_2}$	0.23	26	4.8
$\Delta^{\Omega}_{M_3}$	0.24	5.8	91
$\Delta^{\Omega}_{\tan\beta}$	0.20	0.20	4.1
$\Delta^{\Omega}_{A_0}$	0	0	0
Δ^{Ω}	0.83	28	1100
Δ^{EW}	110	111	110

Natural dark matter in bulk region

3% tuned dark matter in well tempered region

0.1% tuned dark matter in res. region

NU Gauginos in SU(5)



SFK, Roberts, Roy

$$A_0 = 0, \quad \tan\beta = 10, \quad m_0 = 70\,GeV$$

All points A,B,C are for the bulk region with very low sensitivity "supernatural dark matter"

SU(5) 1+24: A1,2

SU(5) 1+75: B1-7

SU(5) 1+200: C1,2,3

$$L = \frac{< F_\Phi >_{ij}}{M_{Planck}} \lambda_i \lambda_j$$

SU(5) model

Singlet SUSY Models

To solve the μ problem and reduce fine tuning consider:

$W = \lambda SHuHd$ where singlet $\langle S \rangle \sim \mu$

But leads to weak scale axion due to global U(1) PQ symmetry

Need to remove axion somehow

In NMSSM we add S^3 to break U(1) PQ to Z_3 – but this results in cosmological domain walls (or tadpoles if broken)

In USSM we gauge the U(1) PQ symmetry to eat the axion resulting in a massive Z' gauge boson – but not anomaly free

In E_6SSM the anomalies of the USSM are cancelled by three complete 27's of E_6 at the TeV scale with U(1) PQ $\in E_6$

de Carlos, Espinosa, Cvetic, Demir, Everett, Langacker; Barger, Lewis, McCaskey,Shaughnessy, Yencho, Kalinowski, SFK, Roberts

USSM Neutralino Dark Matter

$$W_{USSM} = \lambda S H_u H_d + W_{Yuk} + U(1)'_{gauge} \rightarrow MSSM\ \ states + S + Z'$$

Solves μ problem of MSSM

Plus extra states for anomaly cancellation (see later)

$$\begin{array}{cccccc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u & \tilde{S} & \tilde{B}' \end{array}$$

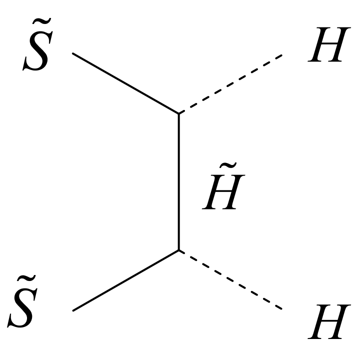
$$\begin{pmatrix} M_1 & & & & & \\ & M_2 & & & & \\ & & 0 & -\lambda s & & \\ & & -\lambda s & 0 & & \\ & & & & 0 & \sim M_{Z'} \\ & & & & \sim M_{Z'} & M_1' \end{pmatrix}$$

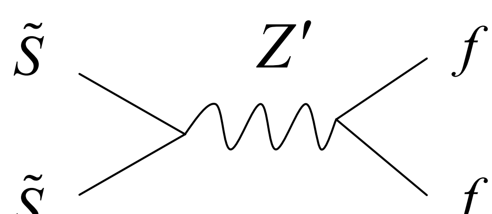
$$\chi_1 = N_1\tilde{B} + N_2\tilde{W} + N_3\tilde{H}_d + N_4\tilde{H}_u + \underbrace{N_5\tilde{S} + N_6\tilde{B}'}_{\text{New}}$$

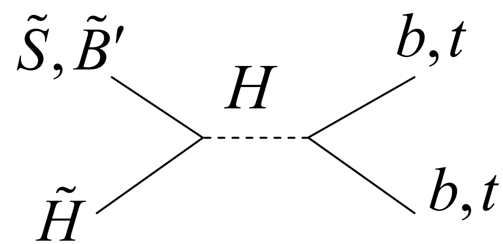
$$M_1' \rightarrow \infty \qquad M_{\tilde{S}} \approx \frac{M^2_{Z'}}{M_1'} \rightarrow 0$$

mini-see-saw gives singlino LSP as $M_1' \rightarrow \infty$

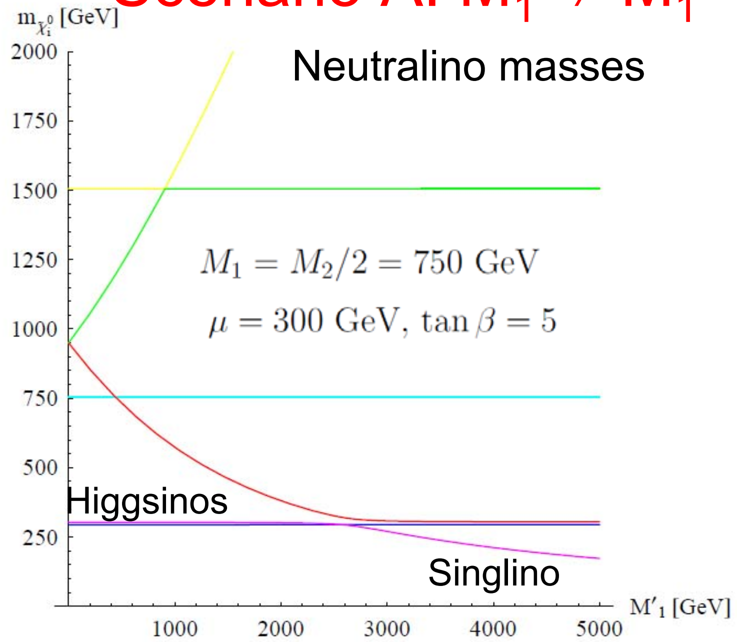
How can a singlino LSP annihilate? Via λSHH and Z' couplings

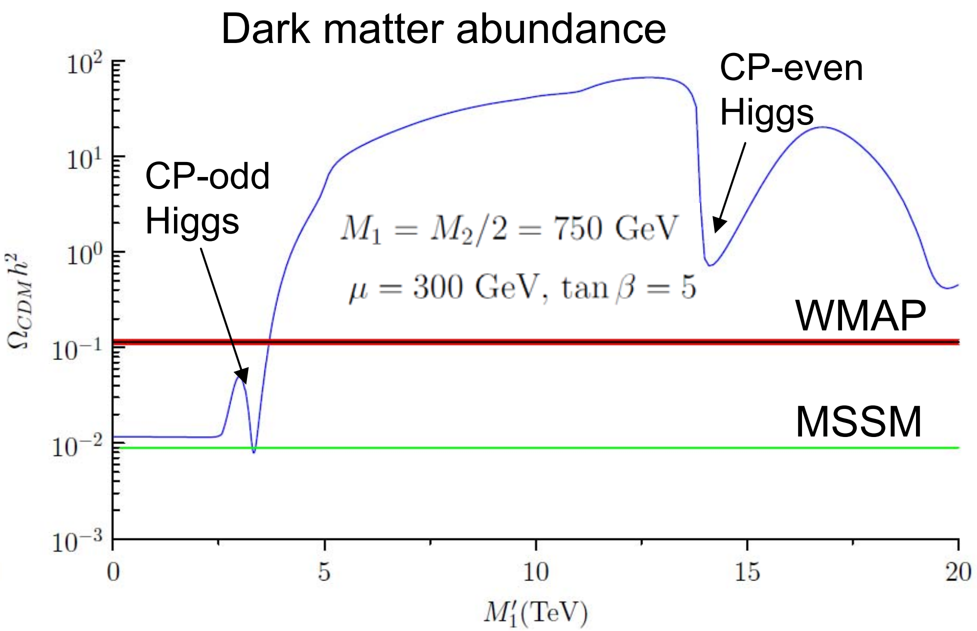


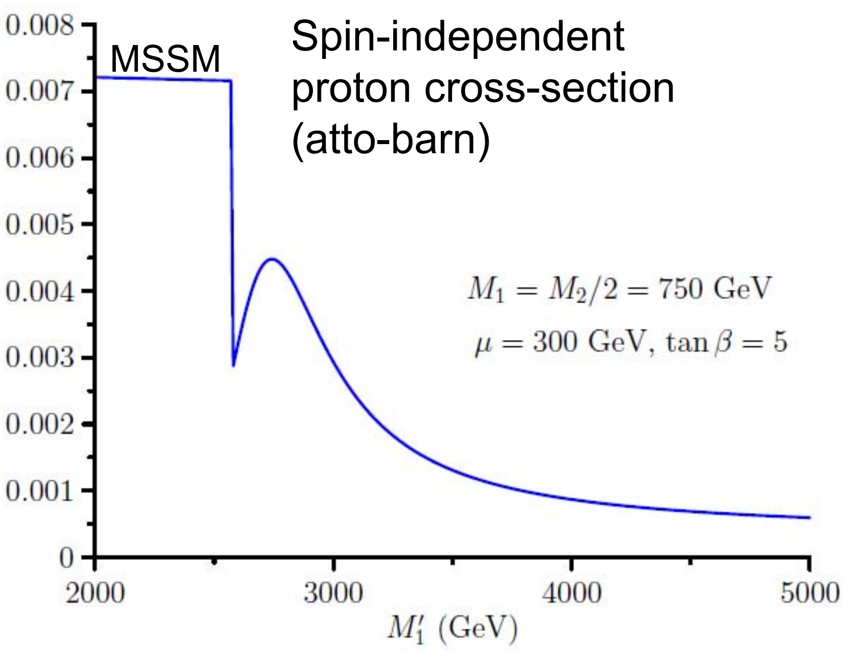


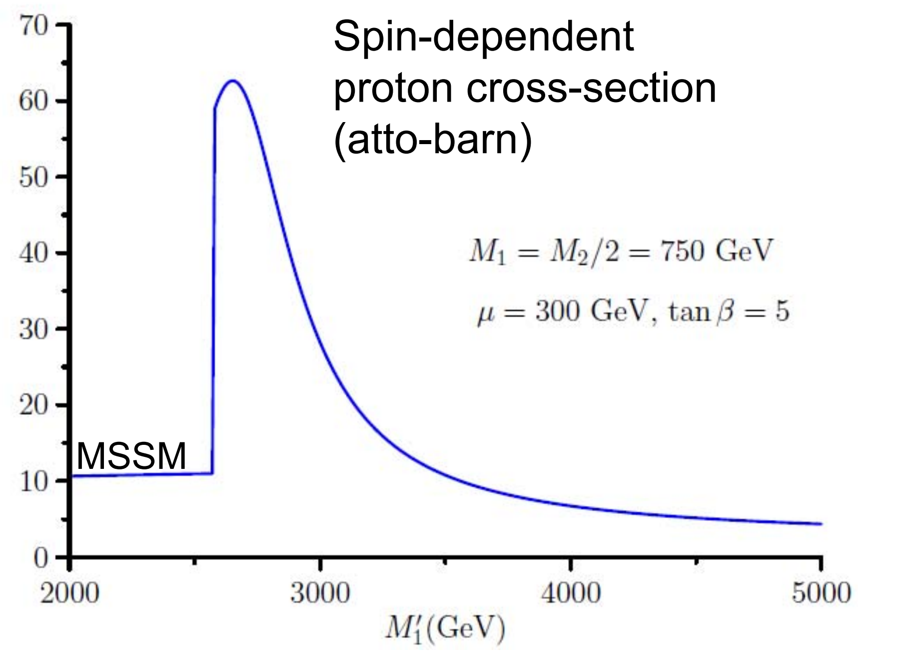


Scenario A: $M_1' \neq M_1$



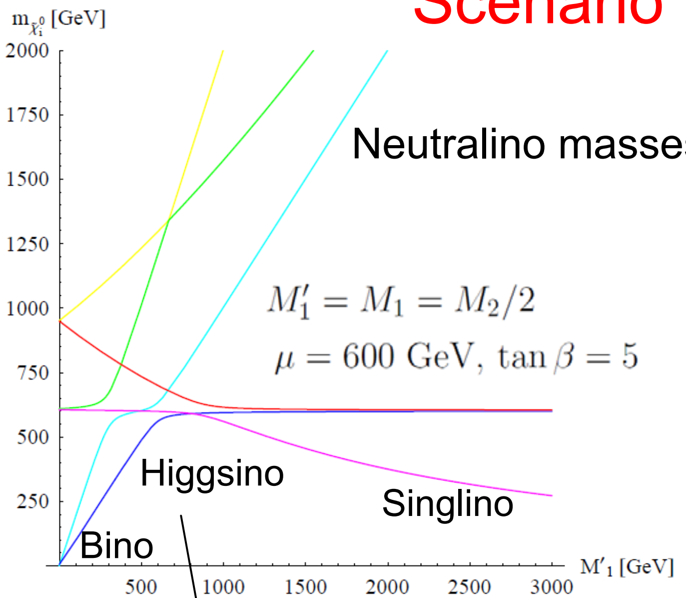


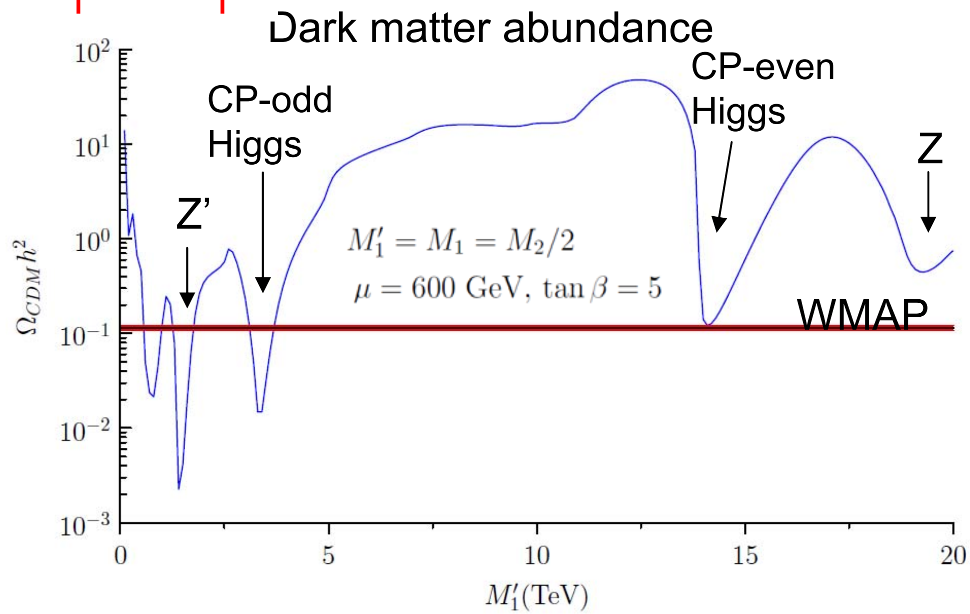


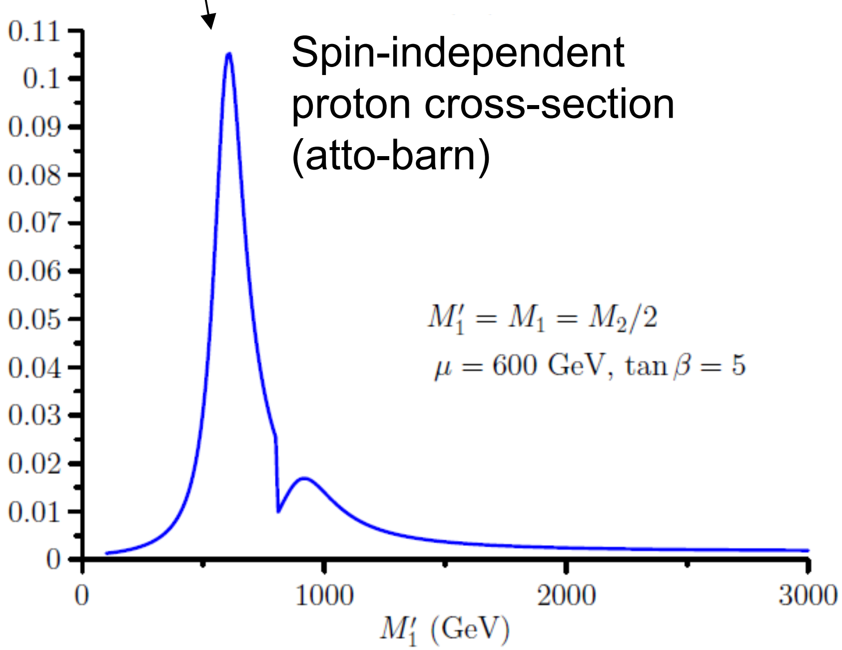


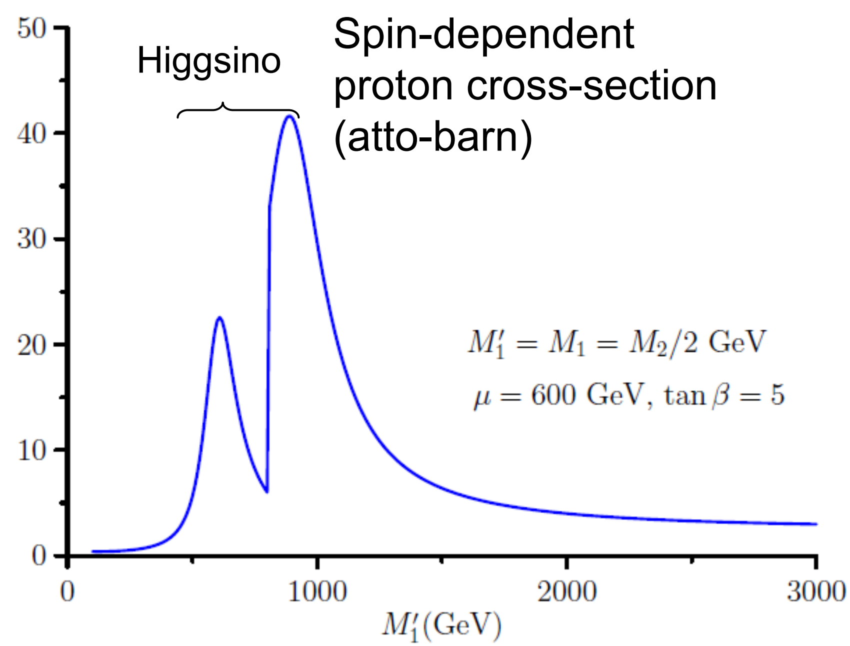
Kalinowski, SFK, Roberts

Scenario B: $M_1' = M_1$









E_6SSM

SFK, Moretti, Nevzorov

$$E_6 \to SO(10) \times U(1)_\psi \qquad SO(10) \to SU(5) \times U(1)_\chi$$

E_6 broken via SU(5) chain

Right handed neutrinos are neutral under: $U(1)_N = \frac{\sqrt{15}}{4} U(1)_\psi + \frac{1}{4} U(1)_\chi \longrightarrow Z'(N)$

M_{GUT} — $E_6 \to SU(5)\times U(1)_N \to SM \times U(1)_N$

$$27_i \to (10,1)_i + (5^*,2)_i + (5^*,-3)_i + (5,-2)_i + (1,5)_i + (1,0)_i \qquad 27', \overline{27}'$$

- $(10,1)_i + (5^*,2)_i$: Quarks, leptons
- $(5^*,-3)_i + (5,-2)_i$: Triplets and Higgs
- $(1,5)_i + (1,0)_i$: Singlets and RHν s
- $27', \overline{27}'$: H',H'-bar

RH ν masses: M_3, M_2, M_1

To achieve GUT scale unification we add non-Higgs

TeV — $U(1)_N$ broken, Z'(N) & triplets get mass, μ term generated

M_W — $SU(2)_L\times U(1)_Y$ broken

Matter content of E_6SSM at TeV

Quarks and Leptons

EXOTIC D,D-bar

$$27_i \rightarrow 3\left[(Q_i,\, u_i^c,\, d_i^c,\, L_i,\, e_i^c)\right] + 3(D_i,\, \overline{D}_i) + 3(H_{2i}) + 3(H_{1i}) + 3(S_i) + 3(N_i^c) + H' + \overline{H}'.$$

Three families of Higgs
= one active family
+ 2 inert families (no VEV)

Singlets

Right-handed neutrinos (superheavy)

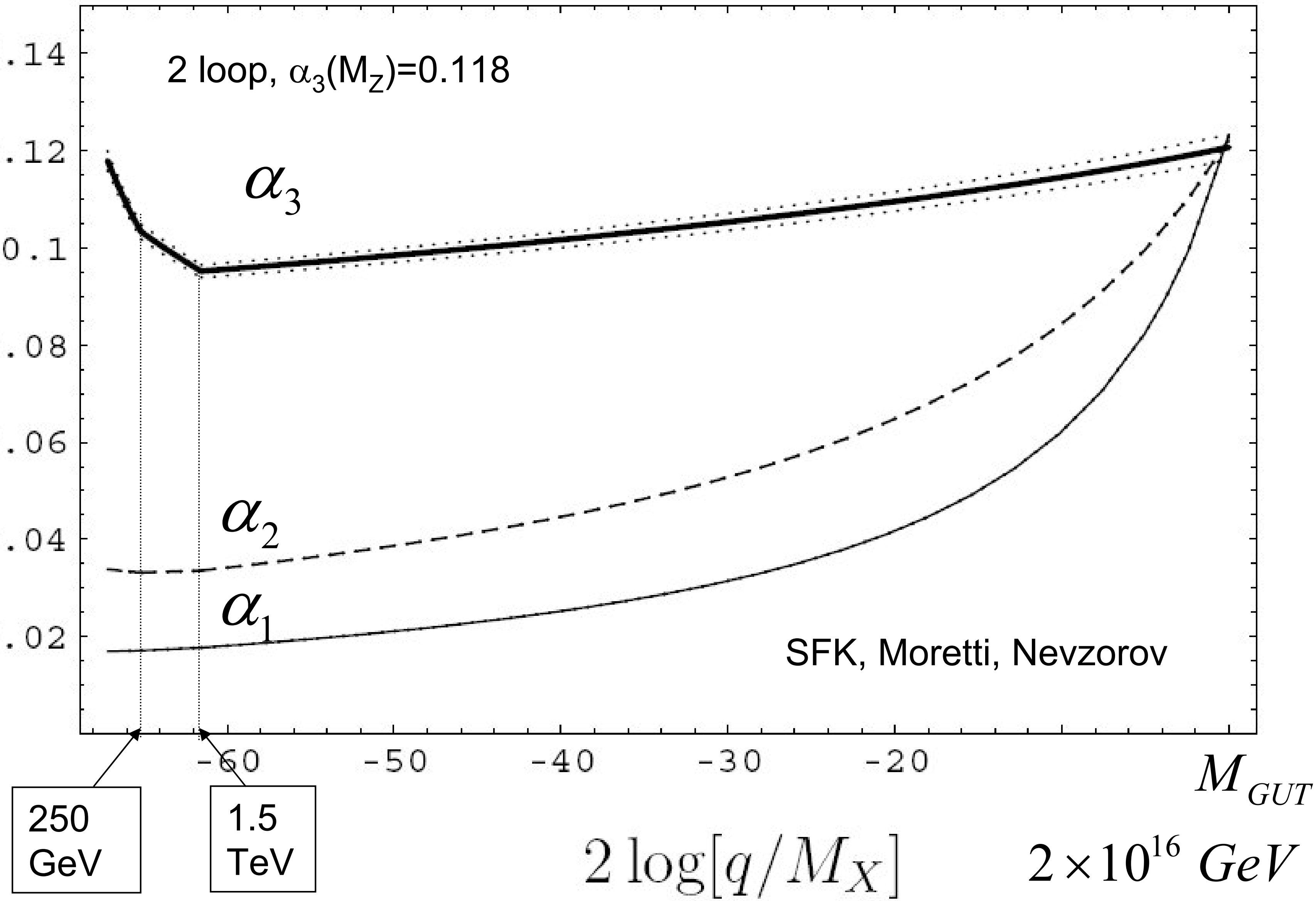
EXOTIC Vector leptons

Plus a TeV scale Z'(N)

Plus all their SUSY superpartners

Message: E_6SSM predicts SUSY+ 3(5+5*+1) + Z' at LHC

Unification in E_6SSM



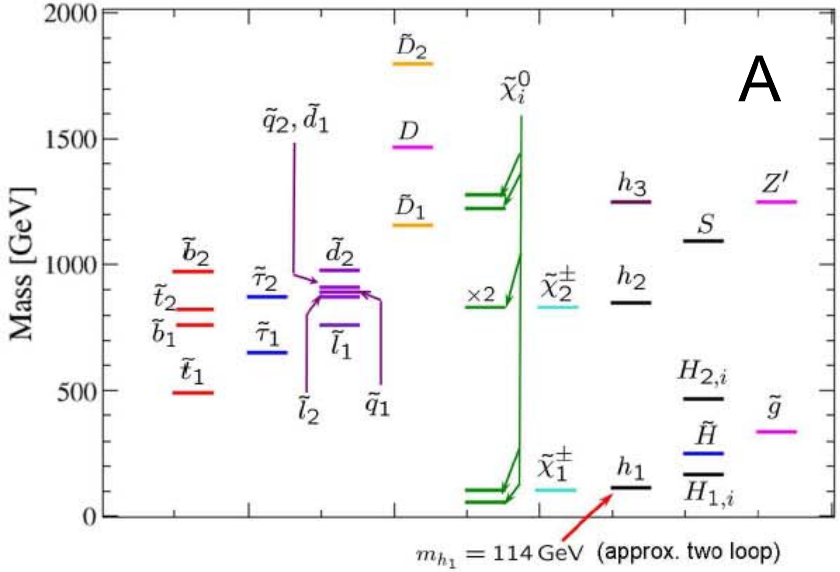
Athron, SFK, Miller, Moretti, Nevzorov

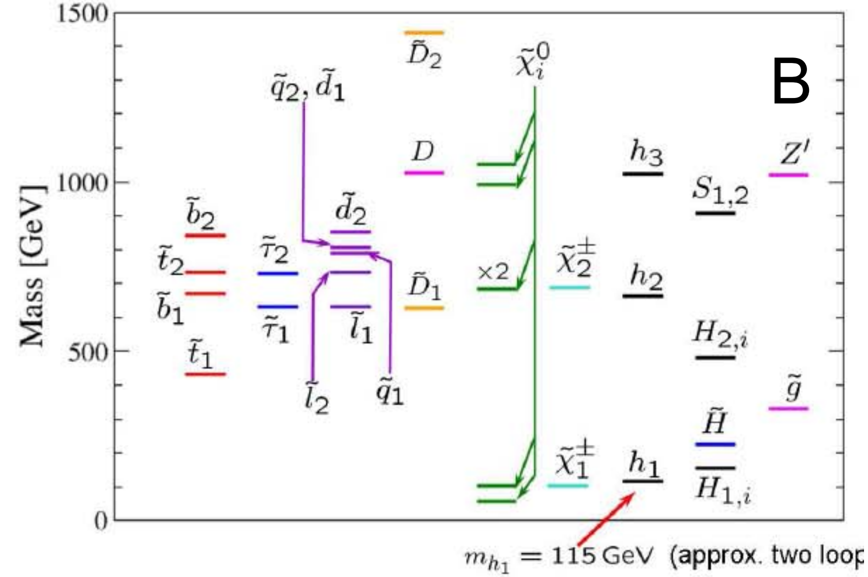
The Constrained E_6SSM

$$W \approx \lambda_i S H_{u,i} H_{d,i} + \kappa_i S D_i \bar{D}_i$$

EWSB, LEP, 2-loop RGE

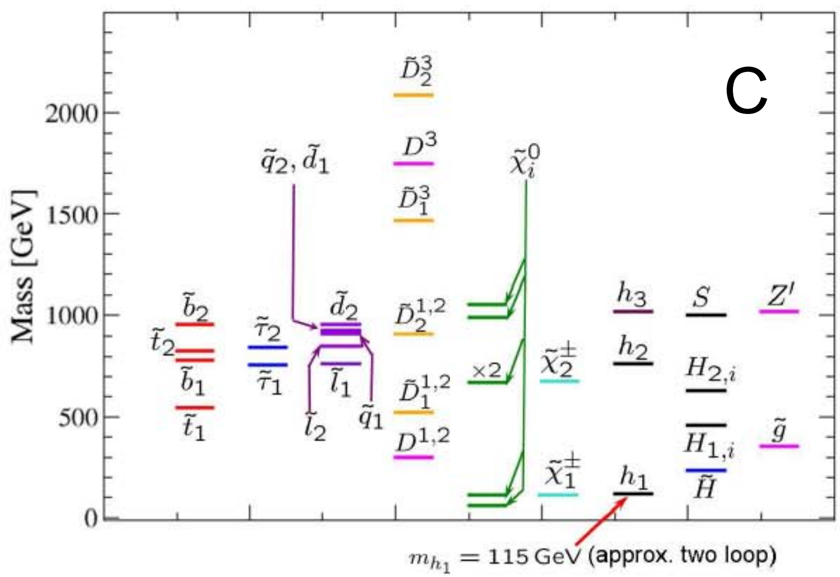
Low Mass Benchmark Points	A	B	C	D
$\tan\beta$	3	10	10	10
$\lambda_3(M_X)$	-0.465	-0.37	-0.378	-0.395
$\lambda_{1,2}(M_X)$	0.1	0.1	0.1	0.1
$\kappa_3(M_X)$	0.3	0.2	0.42	0.43
$\kappa_{1,2}(M_X)$	0.3	0.2	0.06	0.08
s[TeV]	3.3	2.7	2.7	2.7
$M_{1/2}$[GeV]	365	363	388	358
m_0 [GeV]	640	537	681	623
A_0[GeV]	798	711	645	757

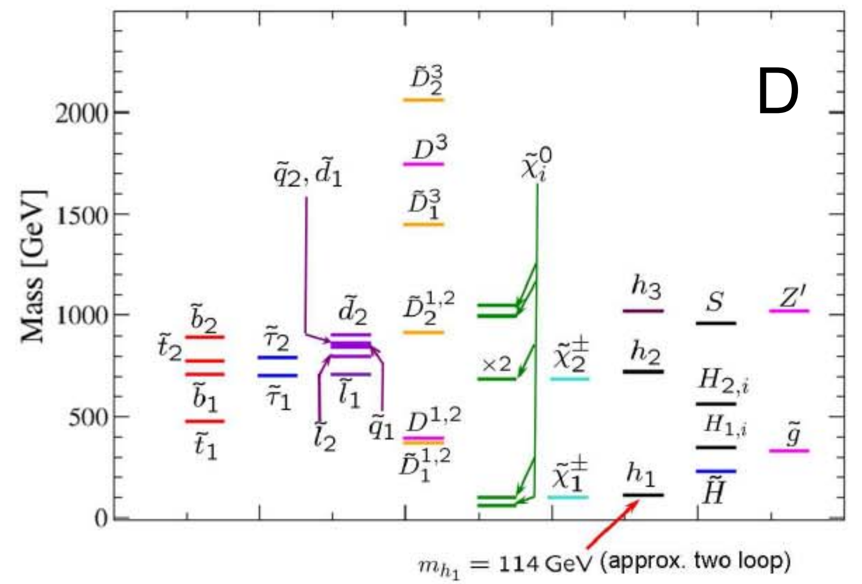




CE_6SSM Low Mass Benchmarks

Athron, SFK, Miller, Moretti, Nevzorov





CE_6SSM predicts light gauginos @ LC

$M_3 \sim 0.7\, M_{1/2}$ ——— $\tilde{g}$ Gluino

$M_2 \sim 0.25 M_{1/2}$ ——— $\chi_2^0, \chi_1^\pm$ ~ Wino

$M_1 \sim 0.15 M_{1/2}$ ——— χ_1^0 ~ Bino → LSP?

What about inert Higgsinos and singlinos?

Since $M_i = \frac{\alpha_i}{\alpha_{GUT}} M_{1/2}$ with $\alpha_3 \sim 0.7\, \alpha_{GUT}$ in E_6SSM

c.f. MSSM $M_3 \sim 2.7 M_{1/2},\ M_2 \sim 0.8 M_{1/2},\ M_1 \sim 0.4 M_{1/2}$

SFK, Hall

Dark Matter from Inert Higgsinos/singlinos

3 families of Higgs = 1 MSSM family H_u, H_d + 2 inert families H_{u1}, H_{d1}, H_{u2}, H_{d2}

3 families of Singlets = 1 NMSSM singlet S + 2 inert singlets S_1, S_2

The full neutralino mass matrix

$$\tilde{\chi}^0_{\rm int} = \Big(\underbrace{\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}^0_d \quad \tilde{H}^0_u}_{\rm MSSM} \;\Big|\; \underbrace{\tilde{S} \quad \tilde{B}'}_{\rm USSM} \;\Big|\; \underbrace{\tilde{H}^0_{d2} \quad \tilde{H}^0_{u2} \quad \tilde{S}_2}_{E_6SSM} \;\Big|\; \underbrace{\tilde{H}^0_{d1} \quad \tilde{H}^0_{u1} \quad \tilde{S}_1}_{E_6SSM} \Big)^{\rm T}$$

$$\begin{pmatrix} M^n_{\rm USSM} & B_2 & B_1 \\ B_2^{\rm T} & A_{22} & A_{21} \\ B_1^{\rm T} & A_{21}^{\rm T} & A_{11} \end{pmatrix}$$

Expect couplings of inert - active sector to be small $\sim$ 1%

Expect almost decoupled inert sector

SFK, Hall

Almost decoupled inert sector

$$\tilde{\chi}^0_{\rm int} = \left(\tilde{H}^0_{d1} \quad \tilde{H}^0_{u1} \quad \tilde{S}_1 \right)$$

$$A_{22} = A_{11} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \lambda' s & f v \sin\beta \\ \lambda' s & 0 & f v \cos\beta \\ f v \sin\beta & f v \cos\beta & 0 \end{pmatrix}$$

$$A_{21} = \epsilon A_{22}.$$

$$\rightarrow m_{LSP} \approx \frac{f^2}{\lambda'} \frac{v^2}{s} \sin 2\beta$$

LSP is naturally light $\sim v^2/s$

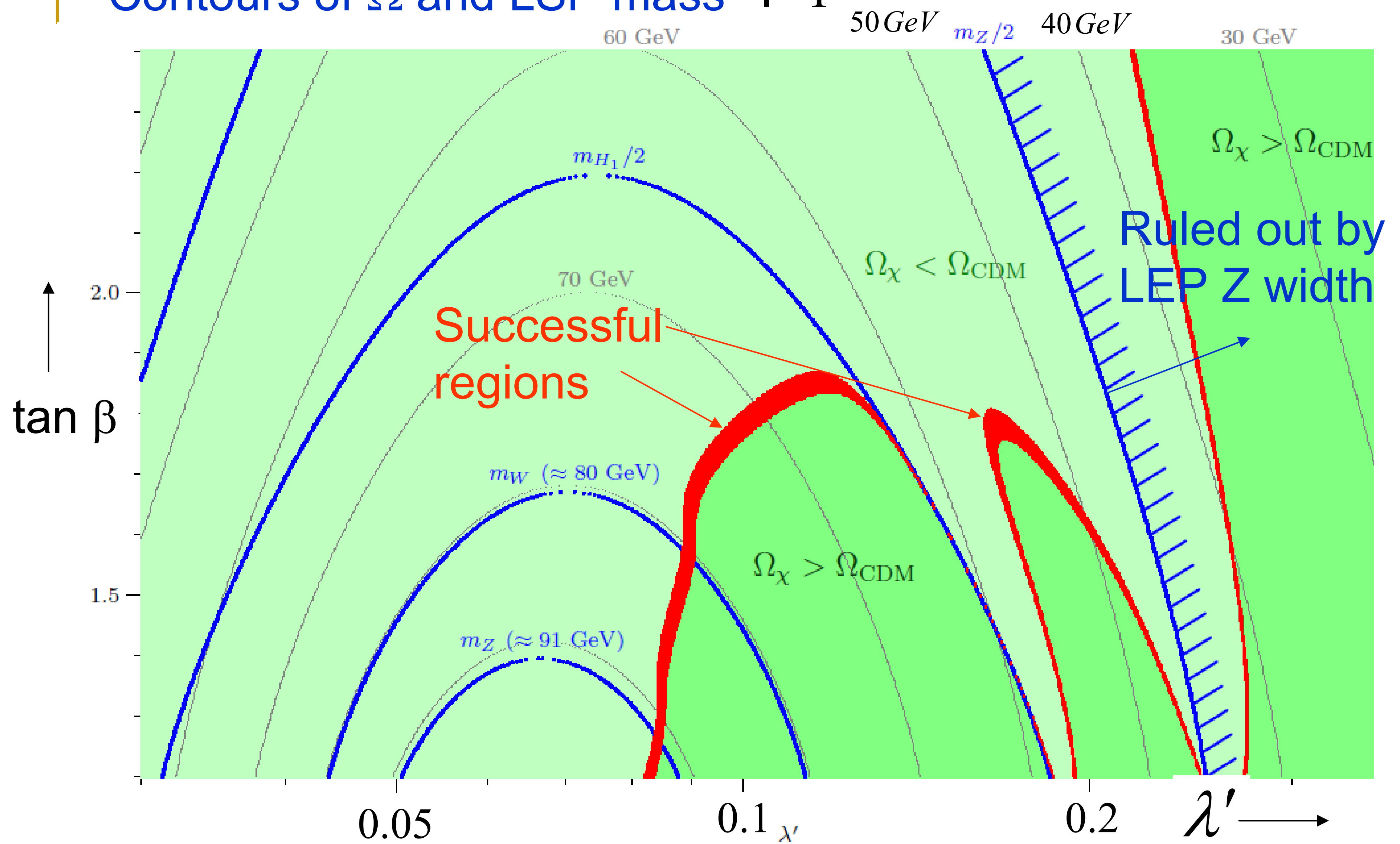
LSP is inert Higgsino/singlino

Following results assume the parameters:

$\varepsilon = 0.1$, $\lambda = 0.2$, s=3000 GeV → $M_{Z'}$=1100 GeV,
$M_1=M_1'=M_2/2$=250 GeV, M_s= 800 GeV, $m_h \sim$ 115 GeV, m_A=500 GeV

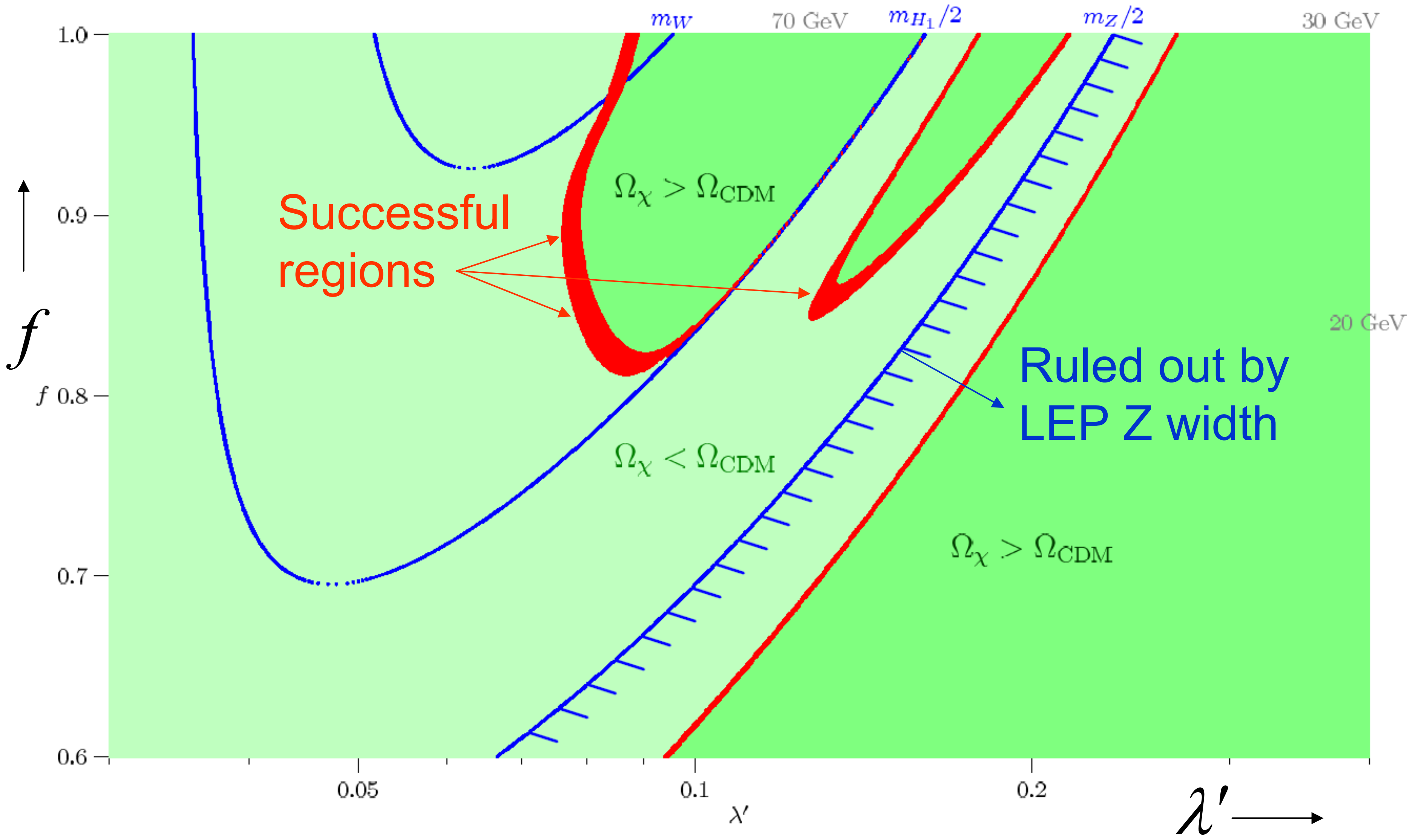
Contours of Ω and LSP mass f=1

SFK, Hall



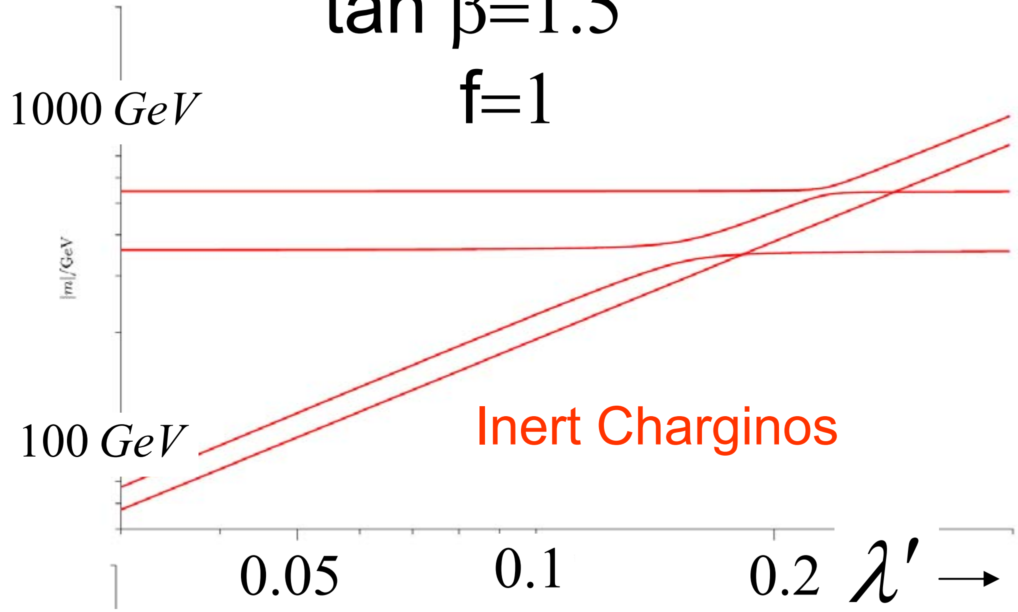
Contours of Ω and LSP mass tan β=1.5

SFK, Hall

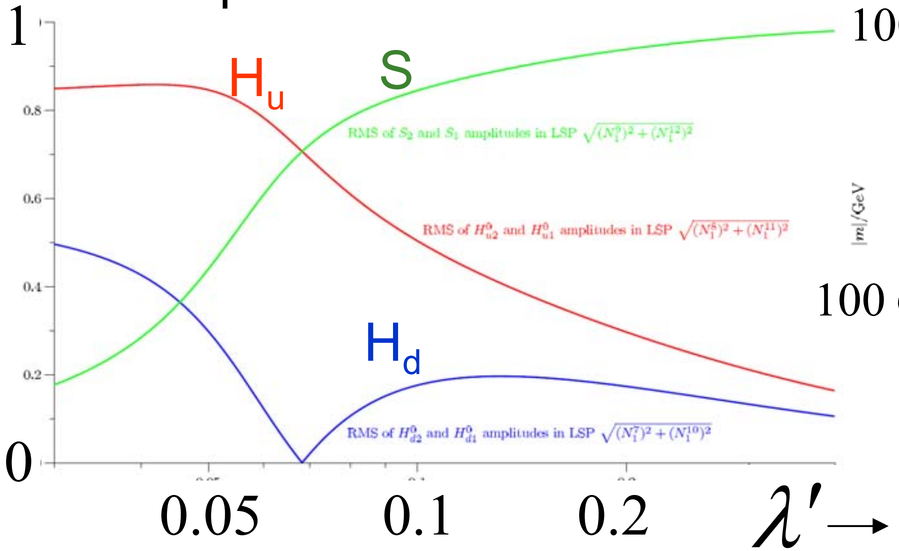


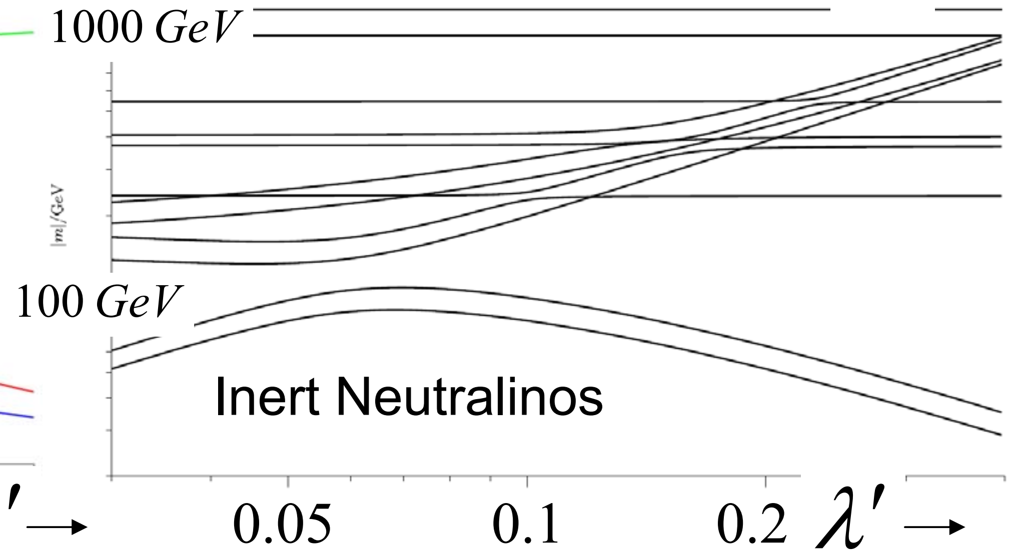
SFK, Hall

Spectrum of Charginos and Neutralinos



Composition of LSP





Conclusion

- **Neutralino Dark Matter in the MSSM is very attractive**
- **However the constrained MSSM is just one special point in a large parameter space of the MSSM**
- **We have considered the MSSM with non-universal Higgs mass, third family scalar mass and gauginos**
- **Non-universal gauginos are possible in SU(5) GUTs and allow “supernatural dark matter” bulk regions not accessible in the CMSSM**
- **We have also considered neutralino dark matter in the USSM containing an extra singlet and Z-prime**
- **In the USSM the neutralino LSP can contain a large singlino component, dramatically affecting the spin independent and spin dependent cross-sections**
- **In E_6SSM the neutralino LSP naturally arises from an almost decoupled inert Higgsino/singlino sector**