Unification and gauge mediation

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- Introduction
- Combining gauge mediation with unification
- Examples of spectra: light neutralino / light gluino
- Conclusion

<u>based on:</u> E. Dudas, S.L., J. Parmentier, Nucl. Phys. B808 (2009) 237
E. Dudas, S.L., J. Parmentier, in progress

GDR Terascale, ITP Heidelberg, October 14, 2009

Introduction

Most phenomenological studies of SUSY assume gaugino mass unification

$$\frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}$$

This is the case in mSUGRA as well as in minimal gauge mediation (GMSB), although their squark and slepton spectra differ

Not the case in more general schemes though, and it is useful to study alternative theory-motivated relations:

- different signatures at colliders
- new possibilities for dark matter (very constrained in mSUGRA)
- fine-tuning of the MSSM can be improved (e.g. if gluino lighter)

Example: gaugino masses from non-GUT-singlet F-term [e.g. Martin]

$$\frac{\langle F^{ab}\rangle}{M_P}\,\lambda^a\lambda^b \;+\; \text{h.c.}$$

a, b = gauge indices

e.g. SU(5): $(24\otimes 24)_{\rm s} \;=\; 1\oplus 24\oplus 75\oplus 200$

⇒ non-trivial gaugino mass relations:

$SU(5)$	$M_1 \,:\, M_2 \,:\, M_3$
1	$1 : 1 : 1$
24	$-\frac{1}{2} : -\frac{3}{2} : 1$
75	$-5 : 3 : 1$
200	$10 : 2 : 1$

Here we will combine GMSB with unification ⇒ departure from gaugino mass universality leading to non-standard SUSY spectra (e.g. light neutralino or gluino)

Quick review of gauge mediation

Supersymmetry breaking is parametrized by a spurion field X with

$$\langle X \rangle = M + F\theta^2$$

X couples to messenger fields in vector-like representations of the SM gauge group [often complete GUT representations, e.g. $(\mathbf{5}, \bar{\mathbf{5}})$ of SU(5), in order to preserve gauge coupling unification]:

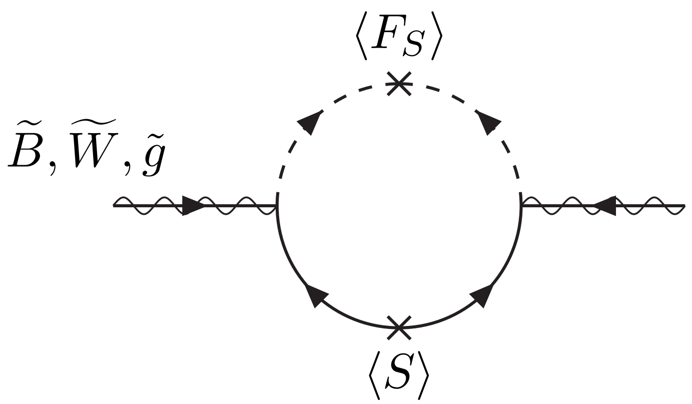
$$W_{mess} = \lambda_X X \Phi \tilde{\Phi}$$

This gives a supersymmetric mass M as well as a supersymmetry breaking mass term $F \phi \tilde{\phi} + \mathrm{h.c.}$ for the scalar messengers:

$$\begin{pmatrix} \phi^* & \tilde{\phi} \end{pmatrix} \begin{pmatrix} M^2 & -F^* \\ -F & M^2 \end{pmatrix} \begin{pmatrix} \phi \\ \tilde{\phi}^* \end{pmatrix} \Rightarrow \text{ scalar masses } M^2 \pm |F|$$

This supersymmetry-breaking mass splitting gives rise to soft terms in the observable sector via gauge loops

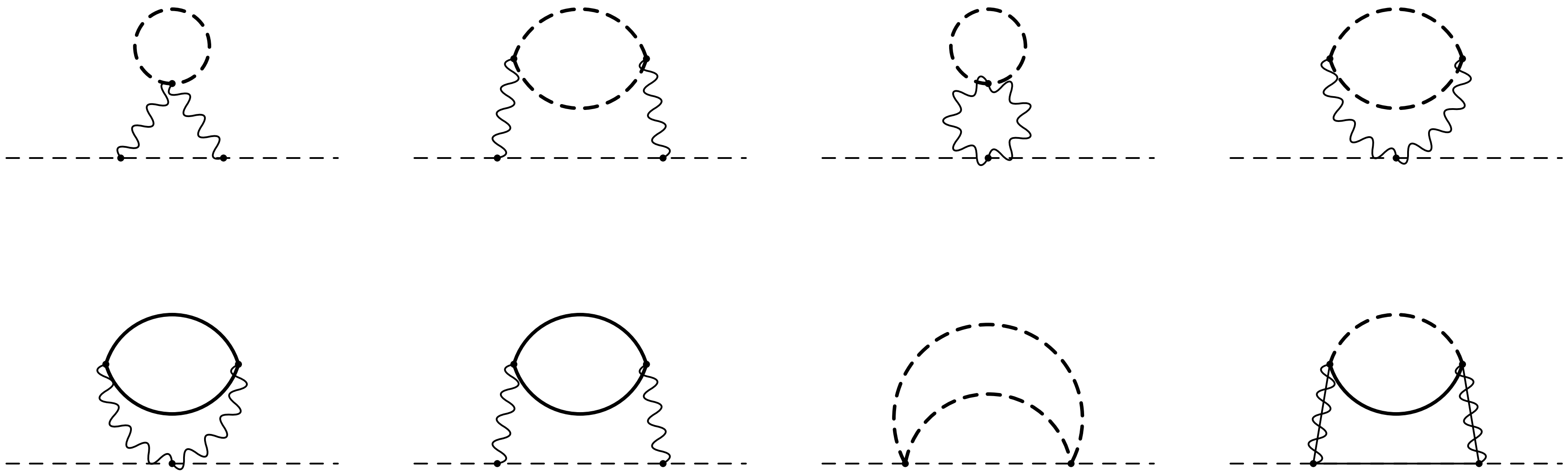
Gaugino masses arise at one loop:



$$M_a(\mu) \;=\; \frac{\alpha_a(\mu)}{4\pi}\, N_m \sum_i 2T_a(R_i)\, \frac{F}{M}$$

R_i = messenger representation, $T_a(R_i)$ = Dynkin index, N_m = number of messengers

Scalar masses arise at two loops:



$$m_\chi^2 \;=\; 2\, N_m \sum_a C_\chi^a \left(\frac{\alpha_a}{4\pi}\right)^2 \sum_i 2T_a(R_i) \left|\frac{F}{M}\right|^2$$

C_χ^a = second Casimir coefficient for the superfield χ

Note: $M_a \sim m_\chi \sim M_{GM} \equiv \dfrac{\alpha}{4\pi}\dfrac{F}{M} \quad \Longrightarrow \quad \dfrac{F}{M} \sim (10 - 100)\ \mathrm{TeV}$

The A-terms and B-term are zero at the messenger scale, and are generated by the renormalization group equations

Main advantage of GMSB: since gauge interactions are flavour blind, the induced soft terms do not violate flavour

⇒ solves the SUSY flavour problem

Dark matter: the LSP is the gravitino (unless $M > \alpha M_P / 4\pi$):

$$m_{3/2} = \frac{F}{\sqrt{3} M_P} \ll M_{GM} \equiv \frac{\alpha}{4\pi} \frac{F}{M}$$

(even for messengers as heavy as 10^{13} GeV, one still has $m_{3/2} < 1$ GeV)

If $m_{3/2} >> 100$ keV, the gravitino behaves as cold dark matter (CDM).
Its abundance is proportional to the reheating temperature after inflation; it can constitute the dark matter, but contrary to the lightest neutralino, Ω_{DM} depends on parameters that cannot be measured at colliders

Combining gauge mediation with unification

Let us take seriously the fact that gauge couplings unify at $2 \times 10^{16}\,\mathrm{GeV}$

Since $(\Phi, \tilde{\Phi})$ are in a vector-like representation of G_{GUT}, they can couple to the adjoint Higgs field Σ involved in gauge symmetry breaking:

$$R \otimes \bar{R} \;=\; 1 \oplus \mathrm{Adj.} \oplus \cdots$$

Writing $$W_{\mathrm{mess}} \;=\; \lambda_X X \Phi \tilde{\Phi} + \lambda_\Sigma \Sigma \Phi \tilde{\Phi}$$

and assuming $\lambda_X \langle X \rangle \ll \lambda_\Sigma \langle \Sigma \rangle$, one obtains a GUT-induced mass splitting inside the messenger multiplets

⇒ non-minimal gauge mediation

Not legitimate to omit $\Sigma\, \Phi\tilde{\Phi}$: generally X neutral under all symmetries but an R-symmetry that is broken by the messenger couplings [cf. ISS, O'Raighfeartaigh...], hence $\Phi\tilde{\Phi}$ neutral too

⇒ $\Sigma^n \Phi \tilde{\Phi}$ always allowed for some n≤3 [assume n=1 in the following]

A first example: G = SU(5), Σ = 24

$$W_{\rm mess} \;=\; \lambda_X X \Phi\tilde{\Phi} \;+\; \lambda_\Sigma \Sigma \Phi\tilde{\Phi} \qquad\qquad \langle X\rangle = X_0 + F_X\theta^2$$

$\langle\Sigma\rangle$ breaks SU(5) down to the SM gauge group:

$$\langle\Sigma\rangle \;=\; V \;\mathrm{Diag}\,(2,2,2,-3,-3) \qquad V \approx 10^{16}\,\mathrm{GeV}$$

Assuming $\lambda_X X_0 \ll \lambda_\Sigma\langle\Sigma\rangle$, this gives a mass splitting inside messenger multiplets:

$$\begin{aligned} \Phi(\bar{5}) \;&=\; \left\{\phi_{\bar{3},1,1/3}\,,\;\phi_{1,2,-1/2}\right\}, & M \;&=\; \{2\lambda_\Sigma v\,,\;-3\lambda_\Sigma v\}\,,\\ \Phi(10) \;&=\; \left\{\phi_{3,2,1/6}\,,\;\phi_{\bar{3},1,-2/3}\,,\;\phi_{1,1,1}\right\}, & M \;&=\; \{\lambda_\Sigma v\,,\;-4\lambda_\Sigma v\,,\;6\lambda_\Sigma v\}\,,\end{aligned}$$

for messengers in $(\mathbf{5},\bar{\mathbf{5}})$ and $(\mathbf{10},\overline{\mathbf{10}})$ representations, and more generally

$$M_i = 6\lambda_\Sigma V Y_i$$

Gaugino masses: $M_a(\mu) \;=\; \frac{\alpha_a(\mu)}{4\pi} \sum_i 2T_a(R_i)\, \frac{\lambda_X F_X}{M_i} \qquad M_i = 6\lambda_\Sigma V Y_i$

⇒ bino mass: $M_1 \;=\; \frac{\alpha_1}{4\pi} \sum_i 2\, \frac{3}{5}\, Y_i^2\, \frac{\lambda_X F_X}{6\lambda_\Sigma V Y_i} \;\propto\; \sum_i Y_i$

Since Y is the generator of a simple gauge group, this gives:

$$M_1 \;=\; 0$$

(up to corrections due to supergravity and to $\langle X \rangle \neq 0$)

The messengers are heavy ⇒ supergravity contributions to soft terms cannot be completely neglected

$$\frac{m_{3/2}}{M_{GM}} \sim \frac{\lambda_\Sigma V}{(\alpha/4\pi)\lambda_X M_P} \sim 10^{-2} \quad \text{for} \quad \lambda_\Sigma \sim \frac{\alpha}{4\pi}\lambda_X$$

We therefore have $M_1 \sim m_{3/2} \ll (M_2, \mu) \sim M_{GM}$

implying that <u>the LSP is a mostly bino light neutralino</u>

(RGE effects give $M_1 \sim 0.5 m_{3/2}$ at low energy)

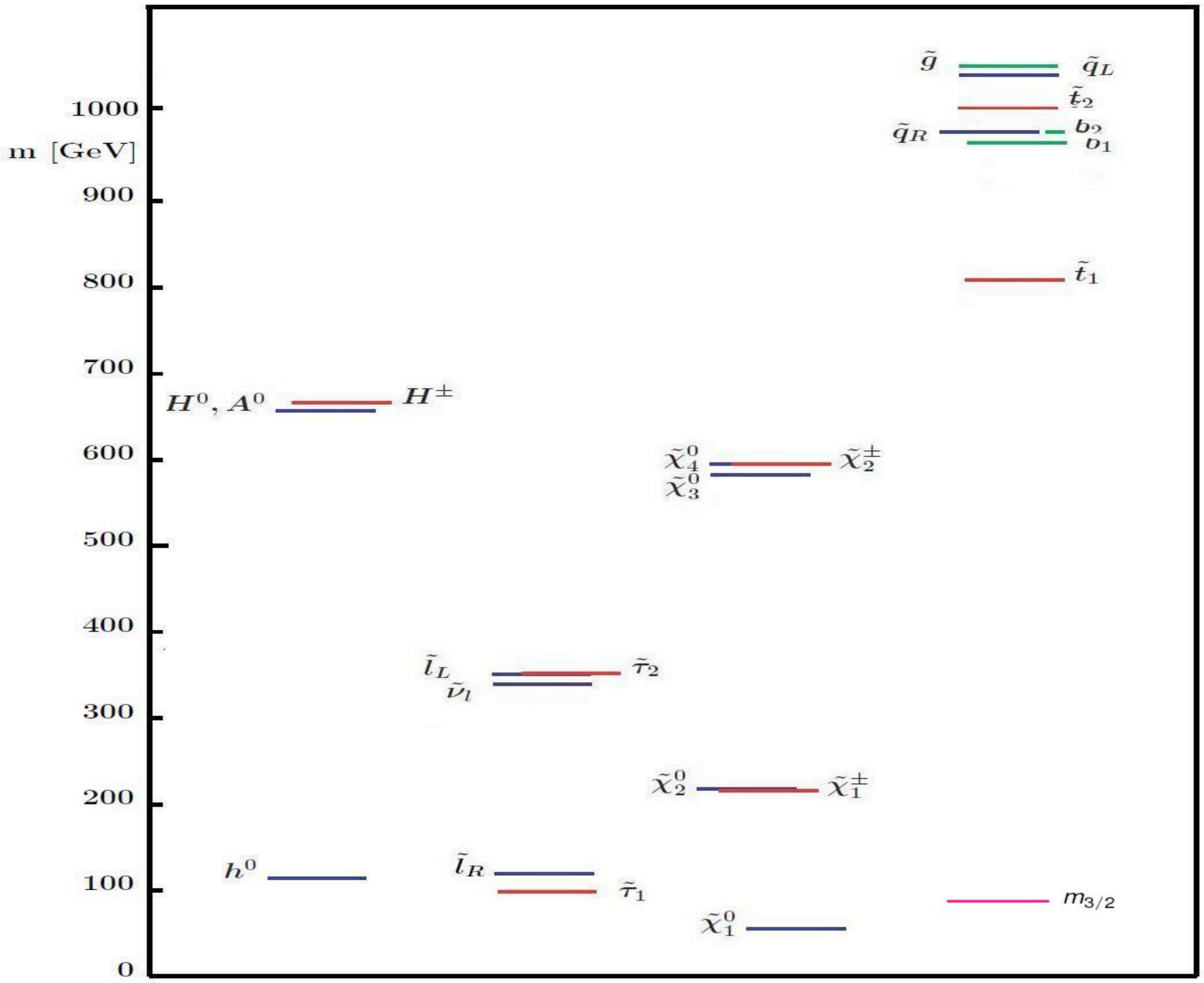
Superpartner spectrum: while M1 = 0 is independent of the messenger representation, this is not the case for the ratios of the other superpartner masses, e.g.

$$(5,\bar{5}) : \qquad \left|\frac{M_3}{M_2}\right| = \frac{3\alpha_3}{2\alpha_2} \qquad (\approx 4 \text{ at } \mu = 1\,\mathrm{TeV})$$

$$(10,\overline{10}) : \qquad \left|\frac{M_3}{M_2}\right| = \frac{7\alpha_3}{12\alpha_2} \qquad (\approx 1.5 \text{ at } \mu = 1\,\mathrm{TeV})$$

→ very different from minimal gauge mediation with SU(5)-symmetric messenger masses, in which the ratio of gaugino masses are independent of the representation (namely $M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$, like in mSUGRA), as well as the ratios of the different scalar masses

Model 6



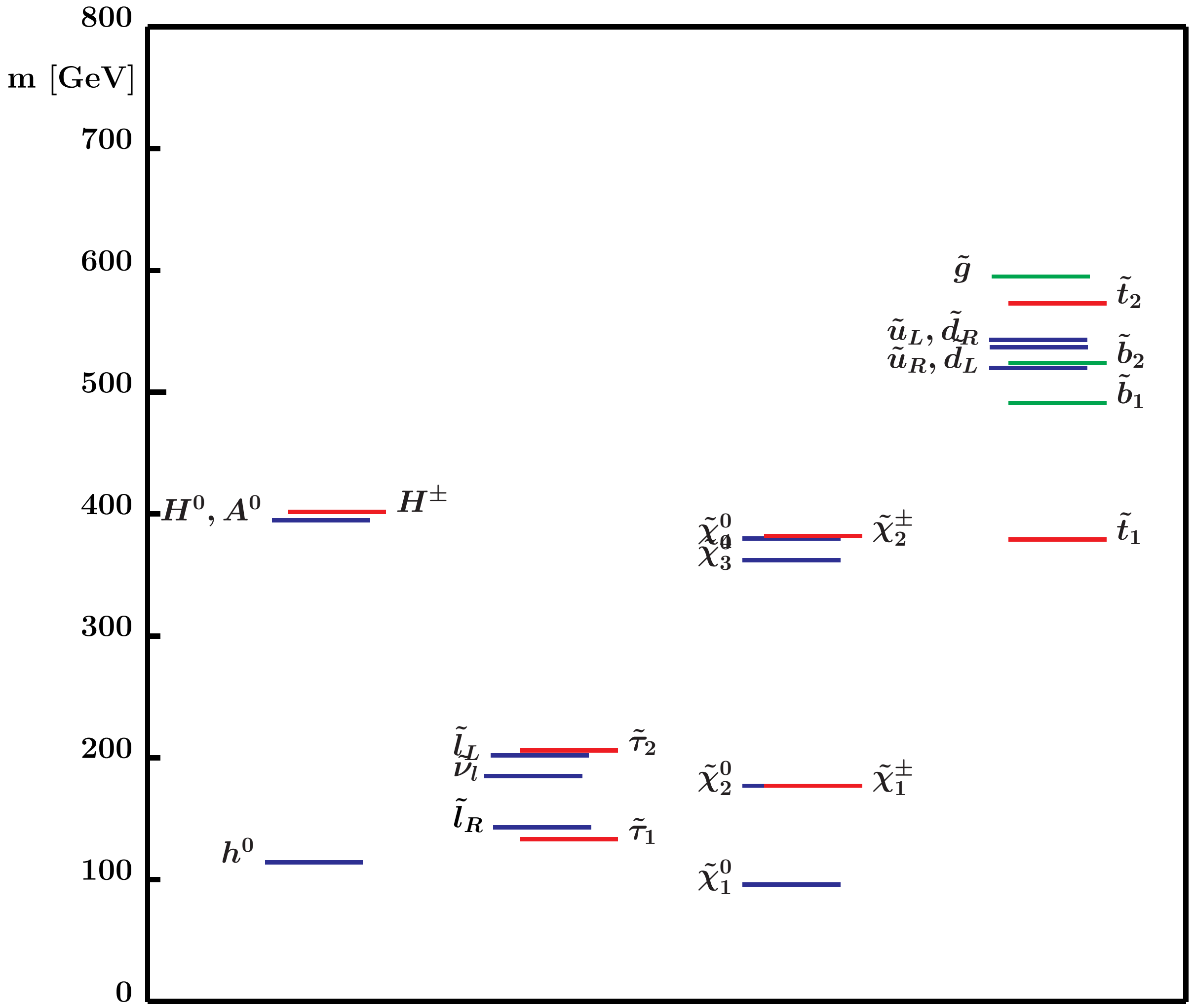
Hybrid Mediation

(courtesy of
Jeanne Parmentier)

$$M_{GM} = 160\,\mathrm{GeV},\ \ M_1 = m_{3/2} = 85\,\mathrm{GeV},$$

$$N_5 = 3,\ \ N_{10} = 1,\ \ \tan\beta = 15,\ \ \mu > 0$$

SPS 1a

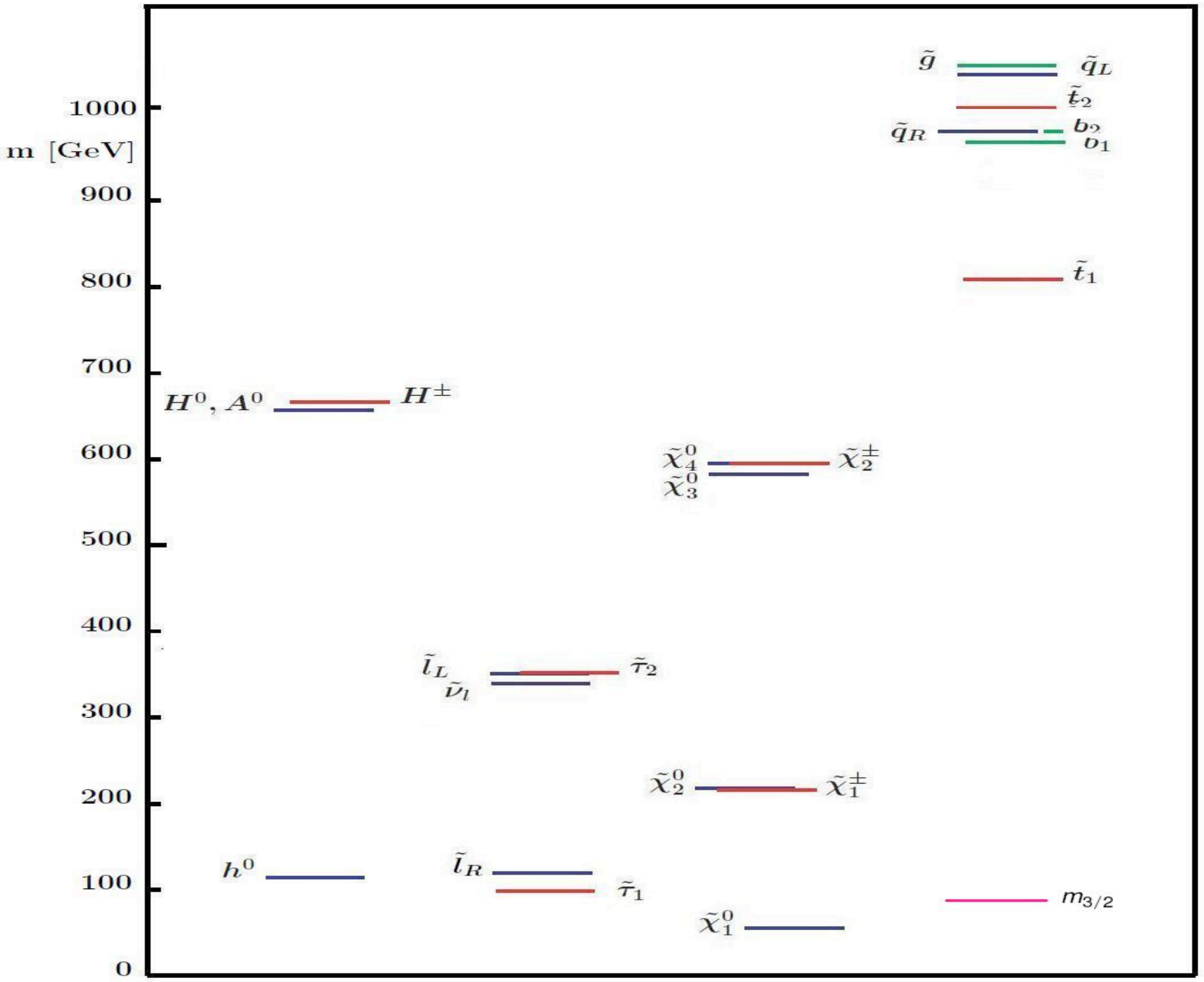


Allanach et al., hep-ph/0202233

$$m_0 = 100\,\mathrm{GeV},\ M_{1/2} = 250\,\mathrm{GeV},$$
$$A_0 = -100\,\mathrm{GeV},\ \tan\beta = 10,\ \mu > 0$$

(typical mSUGRA spectrum)

Model 6



Hybrid Mediation

$$M_{GM} = 160\,\mathrm{GeV},\ M_1 = m_{3/2} = 85\,\mathrm{GeV},$$
$$N_5 = 3,\ N_{10} = 1,\ \tan\beta = 15,\ \mu > 0$$

Spectrum depends on

$$M_{GM} \equiv \frac{\alpha_3(M_{mess})}{4\pi}\,\frac{\lambda_X F_X}{\lambda_\Sigma V},$$

$$M_{mess},\; M_1,\; N_5,\; N_{10},\; \tan\beta$$

$$M_{mess} = 10^{13}\,\mathrm{GeV}$$

model	1	2	3	3 bis	4	5	6
$N_{(5,\bar{5})}$	1	6	0	0	0	1	3
$N_{(10,\overline{10})}$	0	0	1	1	4	1	1
M_{GM}	1000	200	300	300	110	220	160
M_1	50	50	50	85	80	85	85
$\tan\beta$	30	24	15	15	9	15	15
sign(μ)	+	+	+	+	+	+	+
h	114.7	115.0	115.2	115.2	116.5	114.6	114.8
A	779.2	645.4	892.2	892.4	1015	735.8	662.7
H^0	779.2	645.5	892.4	892.6	1015	735.9	662.8
$H^\pm$	783.3	650.3	895.7	895.9	1018	740.1	667.5
$\tilde{\chi}_1^\pm$	259.4	305.0	560.2	560.3	676.7	408.0	223.9
$\tilde{\chi}_2^\pm$	747.8	636.8	693.9	694.0	970.4	590.4	597.5
$\tilde{\chi}_1^0$	24.5	23.5	23.2	42.9	38.1	43.0	42.9
$\tilde{\chi}_2^0$	259.4	305.0	560.1	560.3	677.1	408.0	223.9
$\tilde{\chi}_3^0$	743.3	629.8	596.9	597.1	691.0	570.8	589.2
$\tilde{\chi}_4^0$	745.7	634.7	693.8	693.9	970.4	590.4	596.3
$\lvert Z_{11}\rvert$	0.9982	0.9975	0.9971	0.9971	0.9978	0.9968	0.9969
$\lvert Z_{13}\rvert$	0.0599	0.0708	0.0750	0.0755	0.0648	0.0792	0.0772
$\tilde{g}$	1064	1207	1097	1097	1527	1028	1063
$\tilde{t}_1$	984.6	927.3	861.7	861.6	1080	795.7	809.5
$\tilde{t}_2$	1156	1074	1240	1240	1468	1058	1002
$\tilde{u}_1, \tilde{c}_1$	1195	1087	1135	1135	1361	1006	987.9
$\tilde{u}_2, \tilde{c}_2$	1240	1115	1327	1327	1555	1118	1043
$\tilde{b}_1$	1128	1040	1123	1123	1356	995.4	966.2
$\tilde{b}_2$	1169	1079	1224	1224	1451	1038	987.1
$\tilde{d}_1, \tilde{s}_1$	1184	1085	1134	1134	1360	1005	987.1
$\tilde{d}_2, \tilde{s}_2$	1243	1117	1329	1329	1557	1121	1046
$\tilde{\tau}_1$	242.2	99.0	86.3	89.3	87.0	96.7	95.2
$\tilde{\tau}_2$	420.3	289.4	696.2	696.3	753.1	498.6	349.8
$\tilde{e}_1, \tilde{\mu}_1$	294.4	150.6	131.5	133.6	105.4	123.6	117.4
$\tilde{e}_2, \tilde{\mu}_2$	413.4	275.1	699.1	699.2	754.1	500.1	348.5
$\tilde{\nu}_\tau$	396.6	260.5	691.4	691.5	749.0	491.4	337.6
$\tilde{\nu}_e, \tilde{\nu}_\mu$	405.8	263.6	694.8	694.9	750.1	493.9	339.5
$\Omega_{\tilde{\chi}_1^0} h^2$	6.40	0.428	0.279	0.122	0.124	0.118	0.116

Phenomenology of the light neutralino scenario

Main distinctive features:

- light neutralino LSP
- non-universal gaugino masses
- light singlet sleptons, especially for $(\mathbf{10}, \overline{\mathbf{10}})$

A neutralino lighter than 50 GeV does not contradict the LEP bound, since the latter assumes gaugino mass unification

The late decays of the gravitino into $\tilde{\chi}_1^0 \gamma$ will spoil the successful predictions of Big Bang nucleosynthesis, unless its abundance is suppressed by a low reheating temperature after inflation ($T_R \lesssim (10^5 - 10^6)\,\mathrm{GeV}$). Such a constraints strongly disfavours baryogenesis at very high temperatures, like (non-resonant) thermal leptogenesis

A neutralino lighter than 50 GeV will generally overclose the Universe, unless the CP-odd Higgs boson A or sleptons are very light. A light $\tilde{\tau}_1$ is easily obtained with messengers in $(\mathbf{10}, \overline{\mathbf{10}})$, but the relic density tends to exceed the WMAP value ($\Omega_{DM} h^2 = 0.1099 \pm 0.0062$) if $M_{\tilde{\chi}_1^0} \lesssim 40\,\mathrm{GeV}$

Still a very light neutralino (few GeV) can be made consistent with WMAP if R-parity violation is assumed

Since $m_{3/2}/M_{GM} \sim 10^{-2}$, the SUSY flavour problem is alleviated, but not eliminated in the lepton sector (strong constraints from e.g. μ→eγ)

Hadron collider signatures of a light neutralino: not very different from the usual neutralino of e.g. SPS1a (97 GeV) – larger phase space, in general slightly increased cross sections (e.g. for $p\bar{p}/pp \longrightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + \text{ jet }$), but no distinctive signature [Dreiner et al., arXiv:0905.2051 – also thanks to D. Zerwas and L. Duflot for a useful discussion]

Another SU(5) example: $\Sigma = 75$

The 75 contains a SM singlet and can be used to break SU(5)

It can couple to $(\mathbf{10}, \overline{\mathbf{10}})$ messengers and split the masses of their components in the following way:

$$4\,\Phi_{(\bar{\mathbf{3}},\mathbf{1},-\mathbf{2}/\mathbf{3})}\bar{\Phi}_{(\mathbf{3},\mathbf{1},\mathbf{2}/\mathbf{3})} - 4\,\Phi_{(\mathbf{3},\mathbf{2},\mathbf{1}/\mathbf{6})}\bar{\Phi}_{(\bar{\mathbf{3}},\mathbf{2},-\mathbf{1}/\mathbf{6})} + 12\,\Phi_{(\mathbf{1},\mathbf{1},\mathbf{1})}\bar{\Phi}_{(\mathbf{1},\mathbf{1},-\mathbf{1})}$$

yielding the following gaugino mass ratios:

$$\left(\frac{M_1}{\alpha_1}, \frac{M_2}{\alpha_2}, \frac{M_3}{\alpha_3}\right) = \left(\frac{9}{5}, -3, -1\right)$$

G = SO(10), messengers in $\mathbf{10}$

$$10 \otimes 10 \;=\; 1_s \oplus 45_a \oplus 54_s$$

Both a 45 and a 54 can be used to break SO(10) [often in combination]. The case Σ = 54 is the simplest, since

$$\langle 54 \rangle \;=\; V \begin{pmatrix} 2\, I_{6\times 6} & 0_{6\times 4} \\ 0_{4\times 6} & -3\, I_{4\times 4} \end{pmatrix}$$

Since $10 = 5 \oplus \bar{5}$ under SU(5), this is equivalent to a pair of $(\mathbf{5}, \bar{\mathbf{5}})$ of SU(5) coupled to a 24 and gives the same SUSY spectrum

The 45 has two SM singlet vevs, in the B-L and T3R directions respectively. The first one is often used to break SO(10) and for the doublet-triplet splitting (missing vev mechanism). Both can be used for obtaining realistic fermion masses.

Viable spectra are difficult to obtain from 45_{B-L} (tachyons)

Messenger superpotential:

$$W_{\rm mess} \;=\; \lambda_X X 10\, 10' + \lambda_{45} 10\, 45\, 10'$$

Two 10's are necessary, since $45 = (10 \otimes 10)_a$

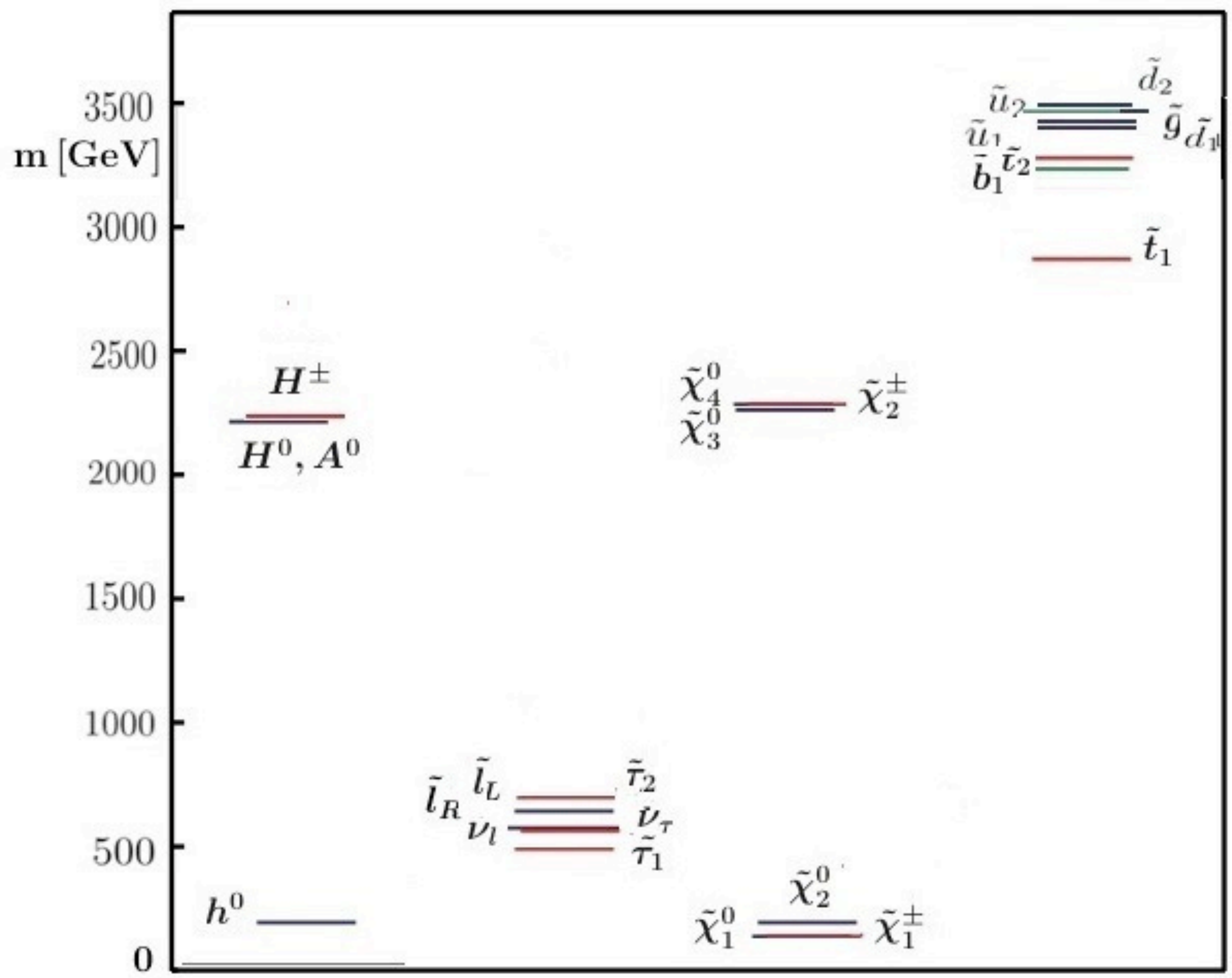
The vev $\langle 45 \rangle = V_R\, T_{3_R}$ does not contribute to the masses of the colour triplets/anti-triplets in 10 and 10', thus suppressing the wino mass with respect to the bino and gluino masses (in the limit $\lambda_X X_0 \ll \lambda_{45} V_R$):

$$M_2 \;\propto\; \frac{F_X}{X_0} \left(\frac{\lambda_X X_0}{\lambda_{54} V_R} \right)^2 \qquad\qquad M_1,\, M_3 \;\propto\; \frac{F_X}{X_0}$$

$\Rightarrow$ wino NLSP (gravitino LSP)

Since $\tilde{\chi}^0_1 \to \gamma\, \tilde{G}$, potentially serious problems with BBN

10 - 45 (T3R) - 10’



(courtesy of Jeanne Parmentier)

$$M_{GM} = 775\,\mathrm{GeV},\ \ V_R = 6X_0,\ \ \tan\beta = 20,\ \ \mu > 0$$

G = SO(10), messengers in $(\mathbf{16}, \overline{\mathbf{16}})$, Σ = 45

Most interesting case: $\langle 45 \rangle = V_{B-L}\, T_{B-L}$

The mass of each component of the 16 is fixed by its B-L charge. As a result, a cancellation occurs in the formula for the gluino mass:

$$M_a(\mu) \;=\; \frac{\alpha_a(\mu)}{4\pi} \sum_i 2T_a(R_i)\, \frac{\lambda_X F_X}{M_i} \qquad\qquad M_i = (B-L)_i\, \lambda_{45} V_{B-L}$$

$$M_3 \;=\; \frac{\alpha_3}{4\pi}\, \frac{\lambda_X F_X}{\lambda_{45} V_{B-L}} \left(2 \times \frac{1}{1/3} + \frac{1}{-1/3} + \frac{1}{-1/3} \right) \;=\; 0$$

A nonzero gluino mass arises from SUGRA (and possibly from $X_0 \neq 0$)

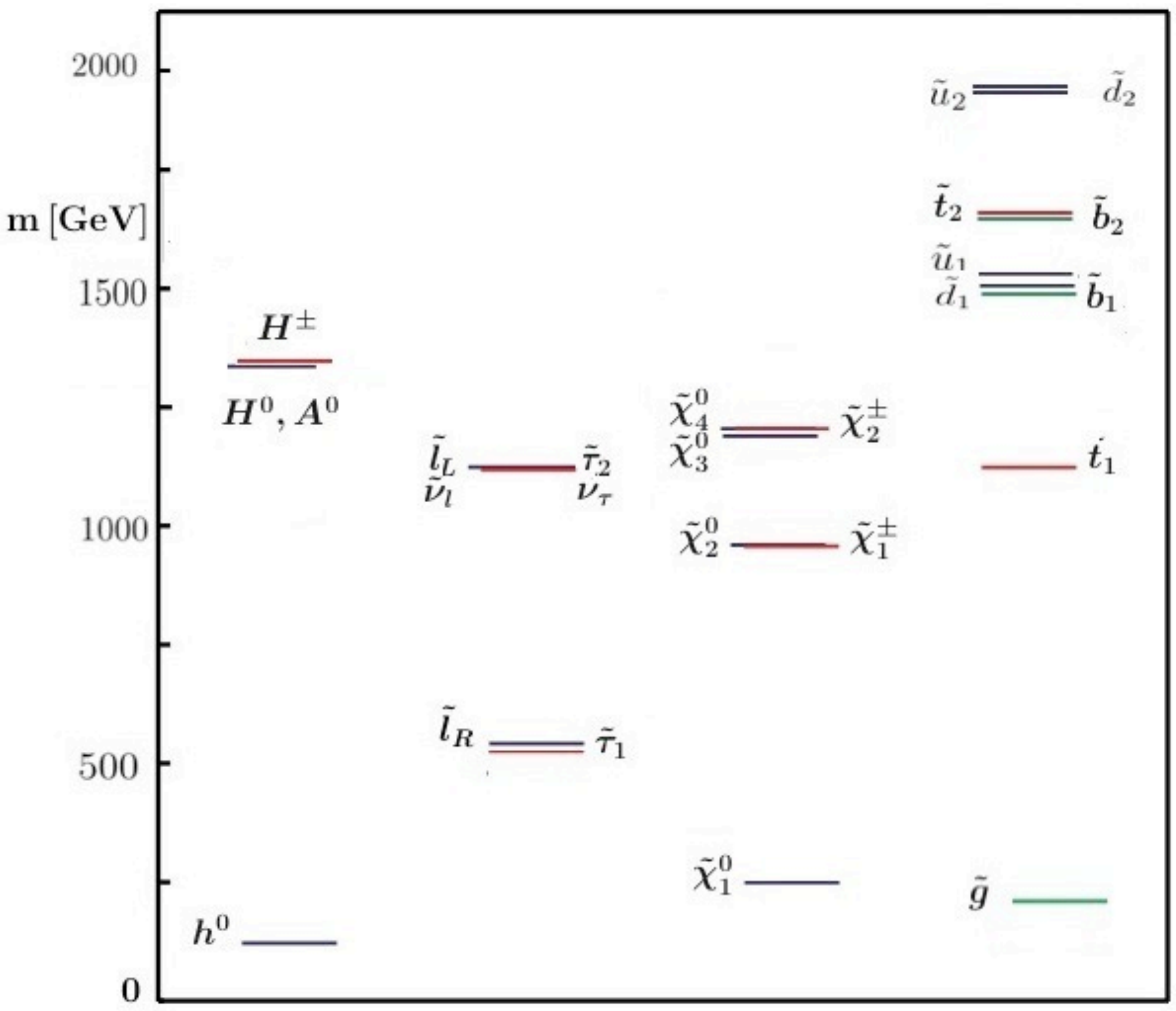
⇒ <u>gluino NLSP</u> (gravitino LSP)

Since the gluino decays gravitationally ($\tilde{g} \to g\, \tilde{G}$), it is very long lived

$$1/\tau_{\tilde{g}} \;\approx\; \frac{m_{\tilde{g}}^5}{48\pi (m_{3/2} M_P)^2} \qquad \Longrightarrow \qquad \tau_{\tilde{g}} \sim 10^7\,\mathrm{s} \quad \mathrm{for} \quad m_{\tilde{g}} \sim 250\,\mathrm{GeV}$$

$$(M_3 = m_{3/2})$$

16* - 45 (B-L) - 16



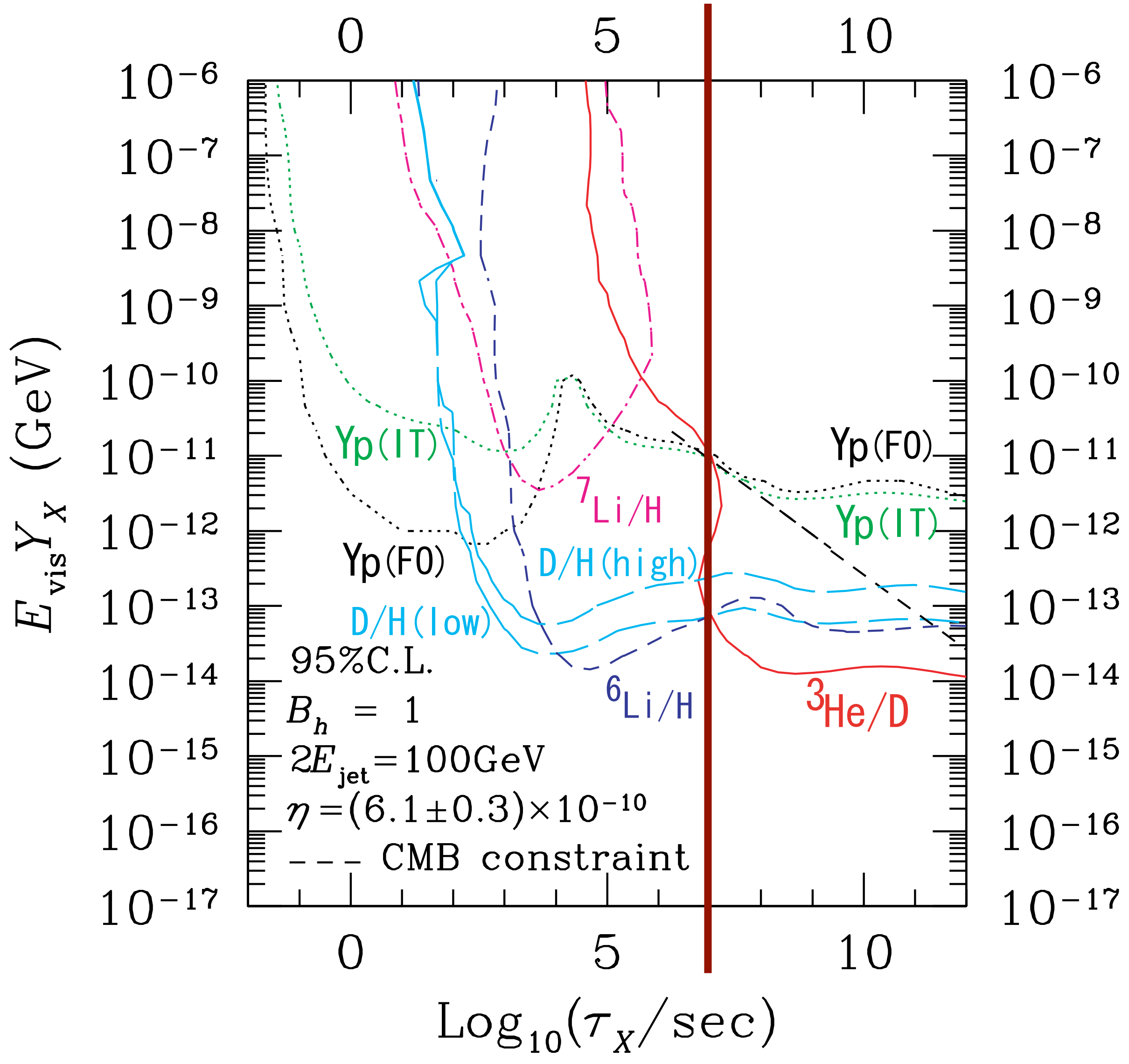
(courtesy of Jeanne Parmentier)

$$M_{GM} = 150\,\mathrm{GeV},\;\; M_3 = m_{3/2} = 60\,\mathrm{GeV},\;\; \tan\beta = 20,\;\; \mu > 0$$

BBN constraints

A long-lived relic decaying hadronically can spoil BBN

Kawasaki, Kohri, Moroi,
astro-ph/0408426



$$Y_X m_X \lesssim 10^{-14}\,\mathrm{GeV}$$

$$\text{for } \tau_X \sim 10^7\,\mathrm{s}$$

Figure 38: Upper bounds on $m_X Y_X$ at 95% C.L. for $B_h = 1$ and $m_X = 100$ GeV. The horizontal axis is the lifetime of X. Here, the lines with "D/H (low)" and "D/H (high)" are for the constraints (2.1) and (2.2), respectively. The straight dashed line is the upper bound by the deviation from the Planck distribution of the CMB.

Arvanitaki et al., hep-ph/0504210

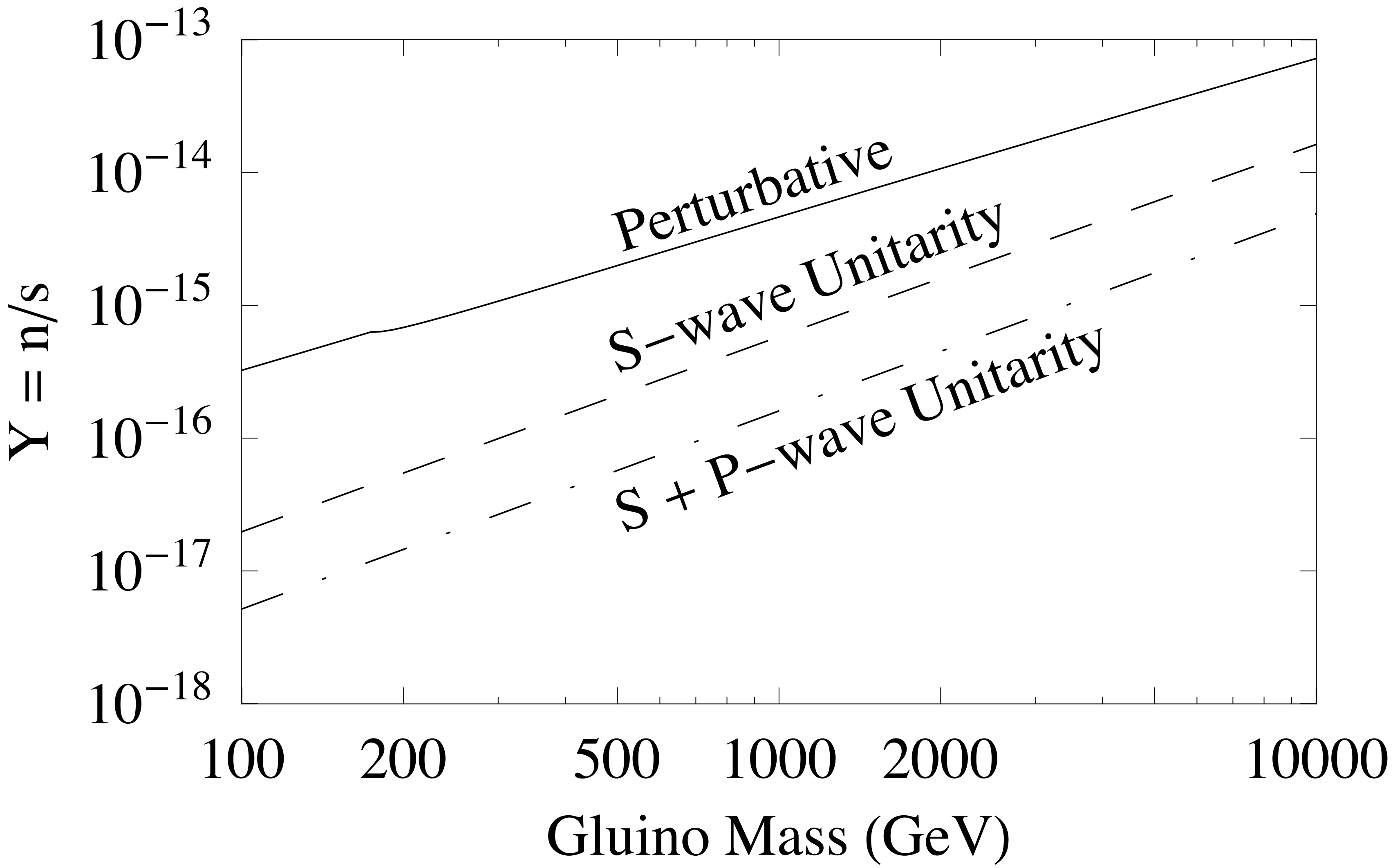


Figure 1: Gluino abundance per co-moving volume as a function of mass. Three curves are shown. In the first (solid), the annihilation cross section is assumed to be simply given by the perturbative cross section of Eqn. 3. The other curves correspond to a cross section that saturates s-wave (dashed) and s-wave plus p-wave unitarity (dot-dashed).

For $m_{\tilde{g}} \sim 250\,\mathrm{GeV}$, the condition $Y_{\tilde{g}}\, m_{\tilde{g}} \lesssim 10^{-14}\,\mathrm{GeV}$ is satisfied even without a strong enhancement of the annihilation cross section due to bound state effects

Collider signatures?

Being very long-lived (even worse than split SUSY), the gluino will not decay but hadronize and form R-hadrons

If the lightest R-hadron is neutral, it will escape the detector leaving only a small fraction of the event energy

The corresponding signature is monojet + missing energy (from gluino pair production in association with a high p_T jet). This allows to set a lower bound from Tevatron Run II data:

$$m_{\tilde{g}} \; > \; 210\,\mathrm{GeV}$$

LHC should probe masses up to 1.1 TeV [Hewett et al., hep-ph/0408248, Kilian et al., hep-ph/0408088]

Any hope from associated neutralino-gluino production?

Input from experts very much welcome!

Conclusions

In gauge-mediated scenarios with an underlying GUT structure, the messengers fields can in principle couple to Higgs fields with GUT-scale vevs (no obvious symmetry to forbid such couplings)

This leads to a hybrid gauge-gravity mediation of supersymmetry breaking in which supergravity contributions are subdominant, thus alleviating the supersymmetric flavour problem

The resulting spectrum is a non-minimal GMSB spectrum which is mainly determined by the choice of the unified gauge group and of the messenger representations

Some of these spectra exhibit striking features such as a light neutralino or a gluino NLSP with a gravitino LSP