Unification and gauge mediation

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- Introduction
- Quick review of gauge mediation
- Combining gauge mediation with unification
- Examples of spectra: light neutralino / wino / gluino
- Conclusions

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

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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 (cf. Ross' talk)

Example: gaugino masses from non-GUT-singlet F-term

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

a, b = gauge indices

e.g. SU(5): $(24 \otimes 24)_s = 1 \oplus 24 \oplus 75 \oplus 200$

$\Rightarrow$ non-trivial gaugino mass relations:

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

[Anderson et al. '96]

Here we will combine GMSB with unification $\Rightarrow$ departure from gaugino mass universality leading to non-standard SUSY spectra

Quick review of gauge mediation

[see e.g. Giudice, Rattazzi, Phys. Rept 332 (1999) 419]

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]:

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

$\Rightarrow$ supersymmetric messenger mass M + supersymmetry breaking mass term $F\phi\tilde{\phi} + \mathrm{h.c.}$ for the scalar messengers:

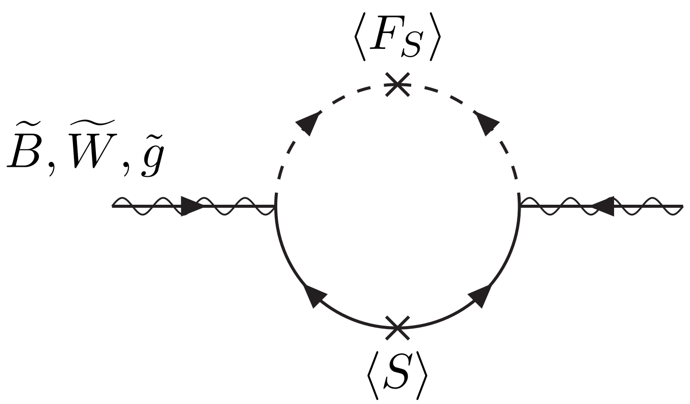
$$\begin{pmatrix} \phi^* & \tilde{\phi} \end{pmatrix} \begin{pmatrix} M^2 & -F^* \\ -F & M^2 \end{pmatrix} \begin{pmatrix} \phi \\ \tilde{\phi}^* \end{pmatrix} \quad \Rightarrow \text{ scalar masses } M^2 \pm |F|$$

$|F| \ll M^2$ required (no tachyon among scalar messenger)

$\Rightarrow$ soft terms in the observable sector via gauge loops

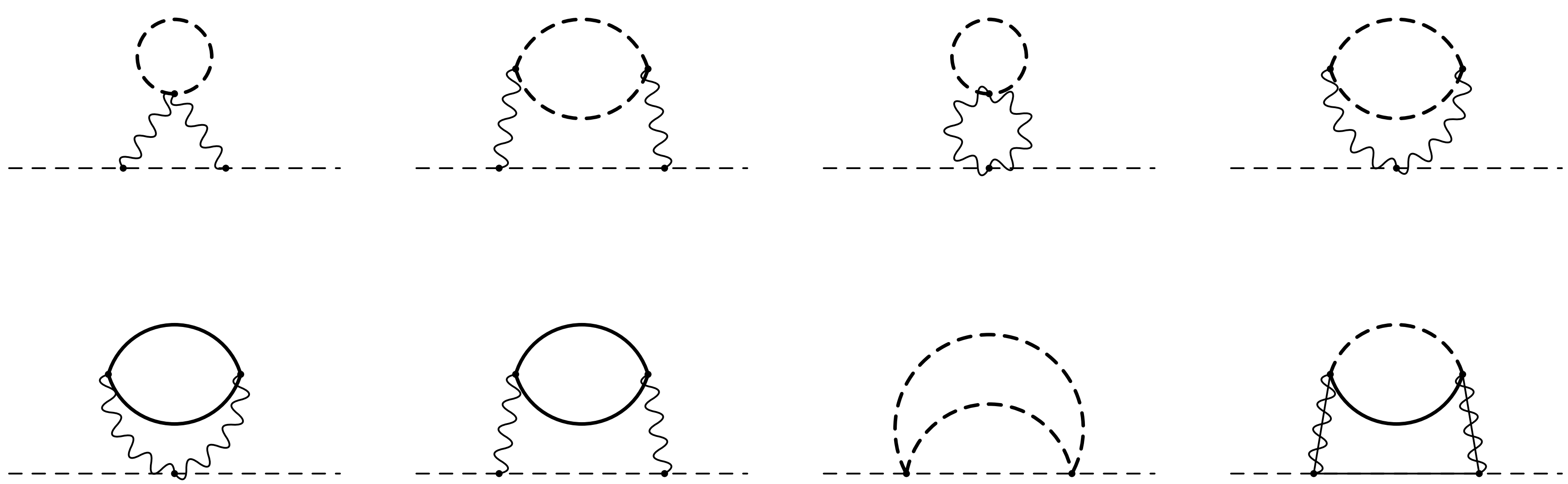
Gaugino masses arise at one loop:

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



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

Minimal gauge mediation: a single spurion X

messengers belong to a GUT representation $\Rightarrow \sum_i 2T_a(R_i)$ independent of Ga $\Rightarrow$ fixed superpartner spectrum (up to M_a/m_χ and an overall scale)

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

General gauge mediation: several spurions Xj

in practice amounts to assign different Fi / Mi to each Ri
$\Rightarrow$ superpartner spectrum depends on 3 complex + 3 real parameters

[Meade, Seiberg, Shih '08]

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 $M > \alpha M_P / 4\pi$):

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

If $m_{3/2} > 100$ keV, the gravitino behaves as a cold relic and can constitute the dark matter; but its relic density depends on parameters that cannot be measured at colliders ($\Omega_{3/2} \propto T_R$) ≠ lightest neutralino

Furthermore, the late NLSP decays can destroy the successful predictions of Big Bang Nucleosynthesis (depends on the NLSP and on $m_{3/2}$)

Combining gauge mediation with unification

In the MSSM, gauge couplings unify at $2 \times 10^{16}\,\mathrm{GeV}$ $\Rightarrow$ GUT?

$(\Phi, \tilde{\Phi})$ in a vector-like representation of G_{GUT} $\Rightarrow$ can couple to the adjoint Higgs field Σ involved in GUT 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 $\lambda_X X_0 \ll \lambda_\Sigma \langle \Sigma \rangle$, one obtains a GUT-induced mass splitting inside the messenger multiplets

$\Rightarrow$ non-minimal gauge mediation

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 $\lambda_\Sigma\langle\Sigma\rangle$ gives the dominant contribution to M:

$$M_i \;\propto\; \lambda_\Sigma V Y_i$$

E.g. for messengers in $(\mathbf{5},\bar{\mathbf{5}})$ and $(\mathbf{10},\overline{\mathbf{10}})$ representations:

$$\Phi(\bar{5}) \;=\; \left\{\phi_{\bar{3},1,1/3}\,,\, \phi_{1,2,-1/2}\right\}, \qquad\qquad M \;=\; \{2\lambda_\Sigma V\,,\, -3\lambda_\Sigma V\}\,,$$

$$\Phi(10) \;=\; \left\{\phi_{3,2,1/6}\,,\, \phi_{\bar{3},1,-2/3}\,,\, \phi_{1,1,1}\right\}, \quad M \;=\; \{\lambda_\Sigma V\,,\, -4\lambda_\Sigma V\,,\, 6\lambda_\Sigma V\}\,,$$

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

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

$$\Rightarrow \quad M_1 = 0$$

(up to corrections due to supergravity and to $X_0 \neq 0$)

The messengers are heavy $\Rightarrow$ supergravity contributions to soft terms cannot be completely neglected

$$\frac{m_{3/2}}{M_{GM}} \sim \frac{\text{coupling}}{\text{loop factor}} \times \frac{M_{GUT}}{M_P} \sim (10^{-2} - 10^{-1})$$

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

$\Rightarrow$ <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: $M_1 = 0$ is independent of the messenger representation, but not the ratios of the other superpartner masses

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

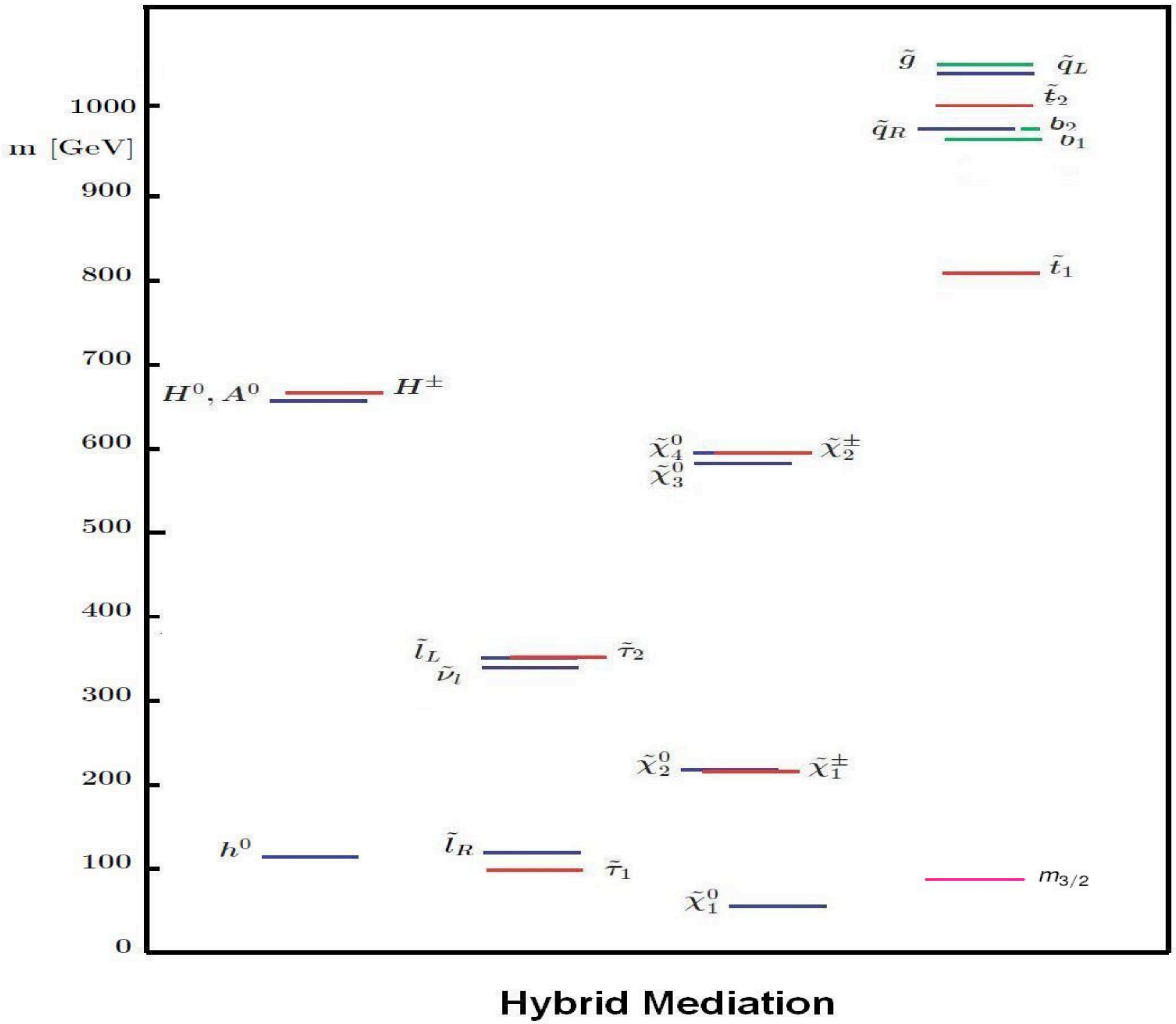
$$(10,\overline{10}): \qquad \left|\frac{M_3}{M_2}\right| = \frac{7\alpha_3}{12\alpha_2} \quad (\approx 1.5 \text{ at } \mu = 1\,\text{TeV})$$

$$(5,\bar{5}): \quad m_Q^2 : m_{U^c}^2 : m_{D^c}^2 : m_L^2 : m_{E^c}^2 \;\approx\; 0.79 : 0.70 : 0.68 : 0.14 : 0.08$$

$$(10,\overline{10}): \quad m_Q^2 : m_{U^c}^2 : m_{D^c}^2 : m_L^2 : m_{E^c}^2 \;\approx\; 8.8 : 5.6 : 5.5 : 3.3 : 0.17$$

→ very different from minimal gauge mediation with SU(5)-symmetric messenger masses, in which the ratios of gaugino/scalar masses are independent of the representation

Model 6



$$M_{\tilde{\chi}_1^0} = 42.9\,\mathrm{GeV}$$
$$m_{3/2} = 85\,\mathrm{GeV}$$
$$m_{\tilde{\tau}_1} = 95.2\,\mathrm{GeV}$$
$$m_{\tilde{e}_R,\tilde{\mu}_R} = 117.4\,\mathrm{GeV}$$

$$\Omega_{\tilde{\chi}_1^0} h^2 = 0.116$$
(1σ from WMAP)

$$\Delta a_\mu = 20.6 \times 10^{-10}$$
(2.6 σ from exp.)

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

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

Late decays of the gravitino into $\tilde{\chi}_1^0 \gamma$ / $\tilde{\chi}_1^0 q \bar{q}$ should not spoil the successful predictions of Big Bang Nucleosynthesis $\Rightarrow T_R \lesssim (10^5 - 10^6)\,\mathrm{GeV}$ required. 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 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

Direct detection: 1 or 2 orders of magnitude below present experimental limits (cannot account for the two CDMS events)

Since $m_{3/2}/M_{GM} \sim 0.1$, the SUSY flavour problem is alleviated, but not eliminated in the lepton sector (strong constraints from e.g. $\mu \to e\gamma$)

Hadron collider signatures of a light neutralino: not very different from the mostly-bino neutralino of e.g. SPS1a (97 GeV) – larger phase space, in general slightly increased cross sections (e.g. for $p\bar{p}/pp \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 + \mathrm{jet}$, $\sigma_{\mathrm{SPS1a}} = 270\,\mathrm{fb}$), but no distinctive signature [Dreiner et al., arXiv:0905.2051]

Full model: couple the messengers to a SUSY breaking sector, e.g. ISS = metastable vacuum [Intriligator, Seiberg, Shih], with X = ISS mesons

- ISS vacuum protected from decay to vacua with $\langle \Phi, \tilde{\Phi} \rangle \neq 0$ if $\lambda_X \lesssim 10^{-2}$
- quantum corrections induce a vev $X_0 \neq 0$, which helps in generating the μ and $B\mu$ terms from Planck-suppressed operators

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

The 75 contains an SM singlet and can be used to break SU(5) [advantage: natural doublet-triplet splitting through the missing partner mechanism]

Can couple to $(\mathbf{10}, \overline{\mathbf{10}})$ messengers $\Rightarrow$ splits 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 an inverted wino-gluino mass hierarchy at the EW scale:

$$\left|\frac{M_1}{\alpha_1}\right| : \left|\frac{M_2}{\alpha_2}\right| : \left|\frac{M_3}{\alpha_3}\right| = \frac{9}{20} : \frac{3}{4} : \frac{1}{4}$$

The LSP is the gravitino as in conventional gauge mediation, with a bino (or possibly a stau) NLSP

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:

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

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 T_{3R} directions. The first one is often used to break SO(10) and for the doublet-triplet splitting (missing vev mechanism). Both can be used to obtain realistic fermion masses.

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

Messenger superpotential:

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

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' $\Rightarrow$ wino mass suppressed with respect to the bino and gluino masses (assuming $M_T \ll \lambda_{45} V_R$) :

$$M_2 \propto \frac{\lambda_X F_X}{M_T} \left(\frac{M_T}{\lambda_{45} V_R} \right)^2 \qquad M_1, M_3 \propto \frac{\lambda_X F_X}{M_T}$$

$\Rightarrow$ wino NLSP (gravitino LSP)

Annihilations via gauge interactions + coannihilations inside the wino triplet very efficient $\Rightarrow$ small relic density:

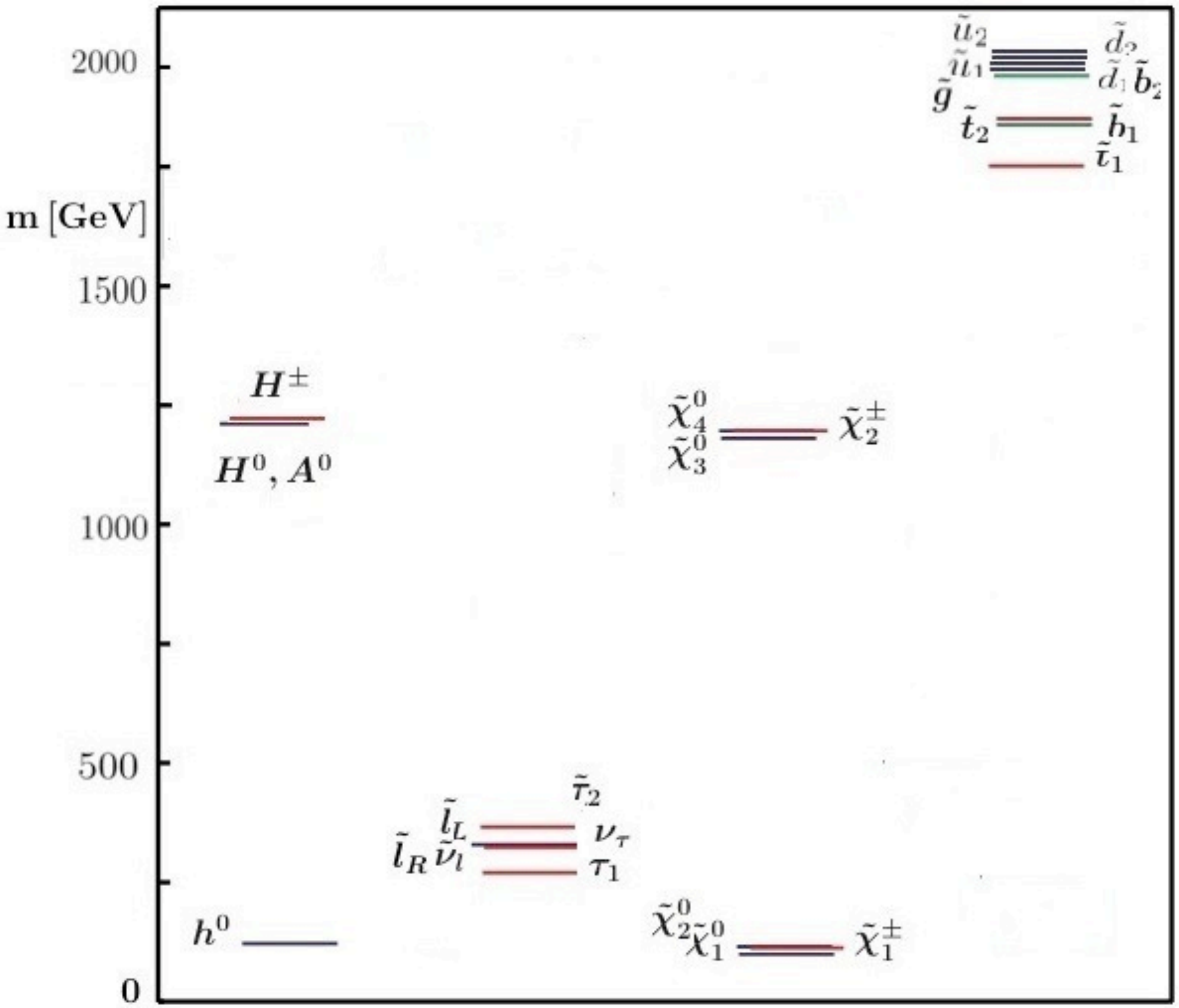
$$\Omega_{\tilde{W}} h^2 \approx 2 \times 10^{-4} \left(\frac{M_2}{100\,\text{GeV}} \right)^2$$

[Arkani-Hamed, Delgado, Giudice '06]

BBN constraints alleviated, but still require $m_{3/2} \lesssim 1\,\text{GeV}$

[Covi, Hasenkamp, Pokorski, Roberts '09]

$\mathbf{10\ 45_{T_{3R}}\ 10'}$



$m_{3/2} \lesssim 1\,\mathrm{GeV}$

$M_{\tilde{\chi}_1^0} = 114.1\,\mathrm{GeV}$

$M_{\tilde{\chi}_2^0} = 117.2\,\mathrm{GeV}$

$M_{GM} = 550\,\mathrm{GeV},\ \lambda_{45} V_R = 6 M_T,$

$\tan\beta = 15,\ \mu > 0$

Collider signatures?

1-loop corrections induce a mass splitting $M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0} > 0$ slightly greater than $m_{\pi^+} \Rightarrow$ neutral wino NLSP, dominant charged wino decay mode $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \pi^+$ leads to displaced vertices [Gherghetta et al., hep-ph/9904378]

The NLSP decays only gravitationally ($\tilde{\chi}_1^0 \to \gamma \tilde{G} / Z \tilde{G}$) $\Rightarrow$ long lived:

$$1/\tau_{\tilde{\chi}_1^0} \simeq \frac{m^5_{\tilde{\chi}_1^0}}{48\pi (m_{3/2} M_P)^2} \quad \Rightarrow \quad \tau_{\tilde{\chi}_1^0} \sim 10^4 \mathrm{s} \ \text{ for } m_{3/2} \sim 1\,\mathrm{GeV}$$

(reminiscent of anomaly-mediated scenario where the wino is the LSP)

Very challenging at the LHC: look for $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production in association with a jet, which leaves two displaced vertices + missing E_T

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
⇒ cancellation in the formula for the gluino mass:

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

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

A nonzero gluino mass arises from SUGRA ⇒ assume $M_3 = m_{3/2}$

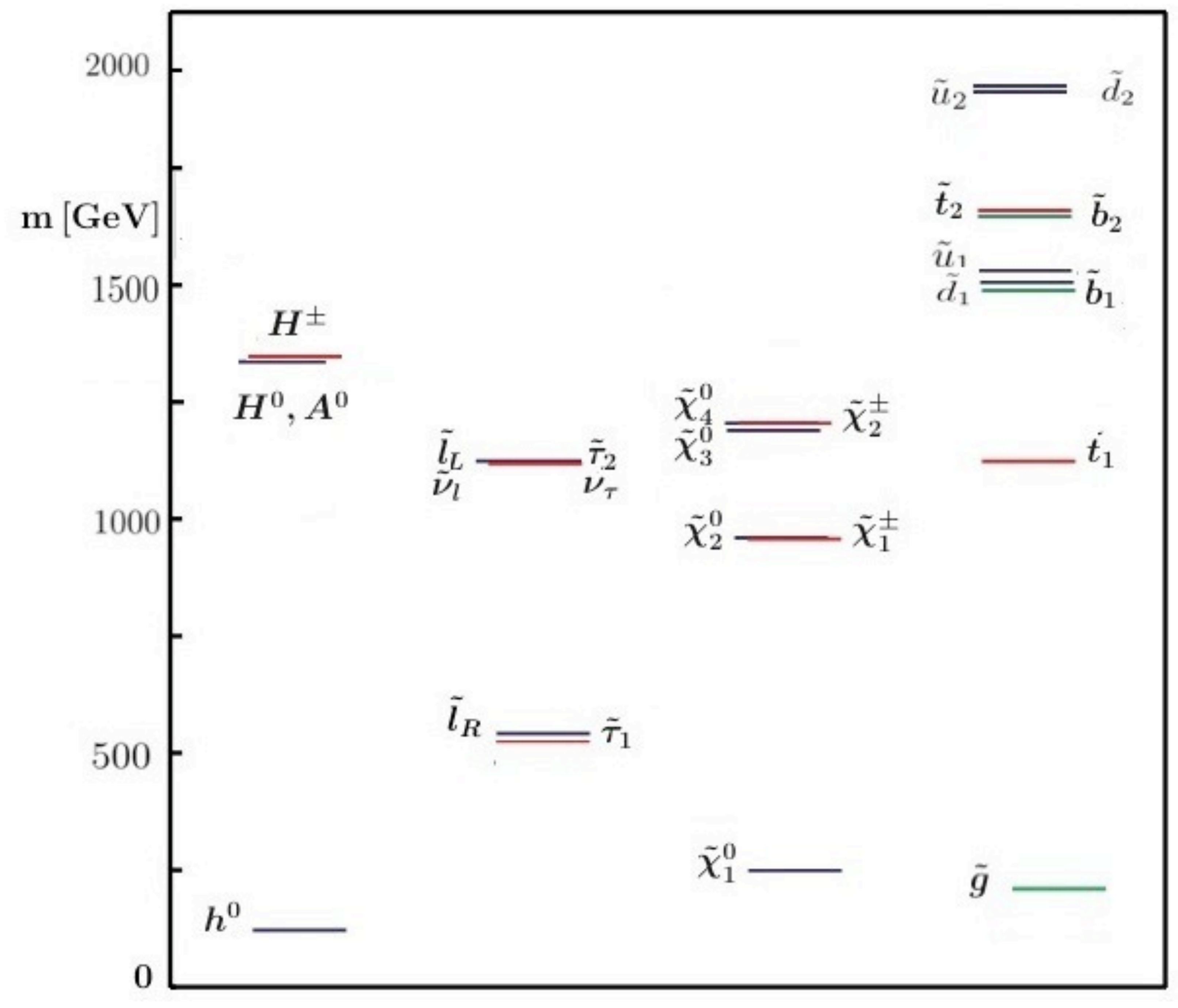
⇒ gluino NLSP (gravitino LSP)

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

$$1/\tau_{\tilde{g}} \simeq \frac{m_{\tilde{g}}^5}{48\pi (m_{3/2} M_P)^2} \quad \Longrightarrow \quad \tau_{\tilde{g}} \sim 10^7 \mathrm{s} \;\; \text{for } m_{\tilde{g}} \sim 250 \, \mathrm{GeV}, \; m_{3/2} \sim 100 \, \mathrm{GeV}$$

Remiscent of split SUSY (except that gluino NLSP)

$\overline{\mathbf{16}}\ \mathbf{45_{B-L}}\ \mathbf{16}$



$$m_{3/2} = 70\,\text{GeV}$$
$$m_{\tilde{g}} = 219.1\,\text{GeV}$$
$$M_{\tilde{\chi}_1^0} = 228.6\,\text{GeV}$$

$$M_{GM} = 150\,\text{GeV},\ \ M_3 = m_{3/2} = 70\,\text{GeV},$$
$$\tan\beta = 15,\ \ \mu > 0$$

Collider signatures

Being long-lived, the gluino will 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

$\Rightarrow$ signature: monojet + missing energy (from gluino pair production in association with a high p_T jet). Lower bound from Tevatron Run II data:

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

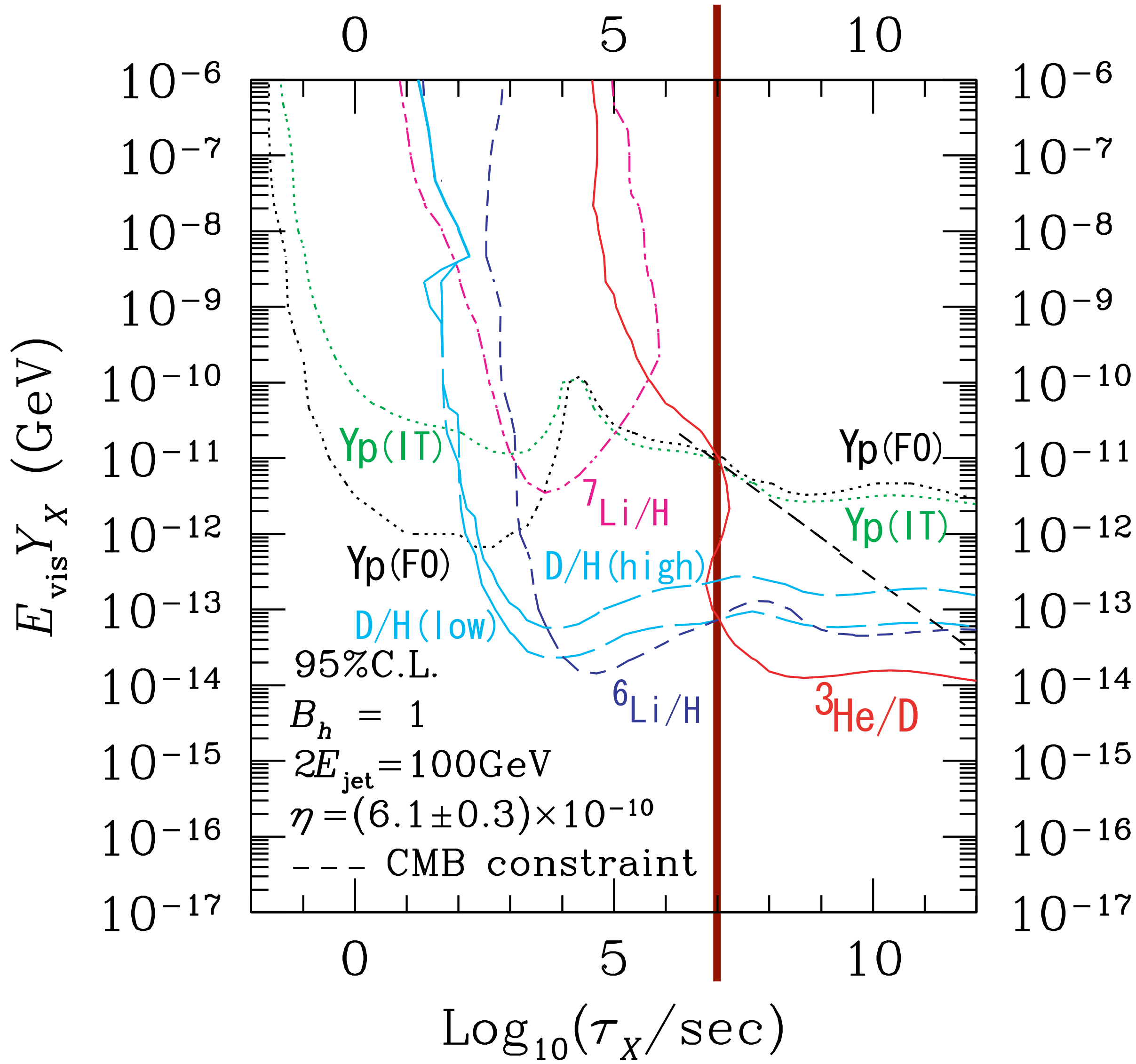
LHC should probe masses up to 1.1 TeV [Hewett et al., hep-ph/0408248, Kilian et al., hep-ph/0408088]

Also possibility of stopped gluinos which decay in the detector not synchronized with a bunch crossing [Arvanitaki et al., hep-ph/0506242]

Bound from D0 [arXiv:0705.0306]: $m_{\tilde{g}} < 270\,\mathrm{GeV}$ for $\tau_{\tilde{g}} < 3\,\mathrm{h}$ (assumes a neutral-to-charged hadron convertion cross section of 3 mb)

BBN constraints

A long-lived relic decaying hadronically can spoil BBN



Kawasaki, Kohri, Moroi, astro-ph/0408426

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

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

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.

The condition $Y_{\tilde{g}} m_{\tilde{g}} \lesssim \text{ few } 10^{-14}\,\mathrm{GeV}$ for $m_{\tilde{g}} \sim 250\,\mathrm{GeV}$ can be satisfied since gluinos annihilate efficiently through strong interactions

However, bound state effects (R-hadrons form bound states with normal nuclei) can affect BBN predictions. Kusakabe, Kajino, Yoshida, Mathews [arXiv:0906.3516] estimate a much stronger constraint: $\tau_X \lesssim 100\,\mathrm{s}$

Way out: lower F_X such that $m_{3/2} \lesssim 1\,\mathrm{GeV}$, with M_3 from subdominant contributions to messenger masses

$\Rightarrow$ similar spectrum with unchanged collider signatures (however the D0 bound $m_{\tilde{g}} < 270\,\mathrm{GeV}$ now applies), but BBN constraints satisfied

Conclusions

If supersymmetry breaking is mediated by gauge interactions and there is an underlying GUT, the dominant contribution to messenger masses may come from the coupling between the GUT and messenger sectors

This leads to a non-minimal GMSB spectrum which is mainly determined by the unified gauge group and by the messenger representations

Some of these spectra exhibit striking features such as a light neutralino LSP, or a gluino NLSP with a gravitino LSP. BBN constraints favour the neutralino LSP scenario