

Non-standard SUSY spectra in gauge mediation

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- Introduction
- Quick review of gauge mediation
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- Conclusions

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

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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 (e.g. if gluino lighter)

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

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

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

⇒ 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

[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]:

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

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

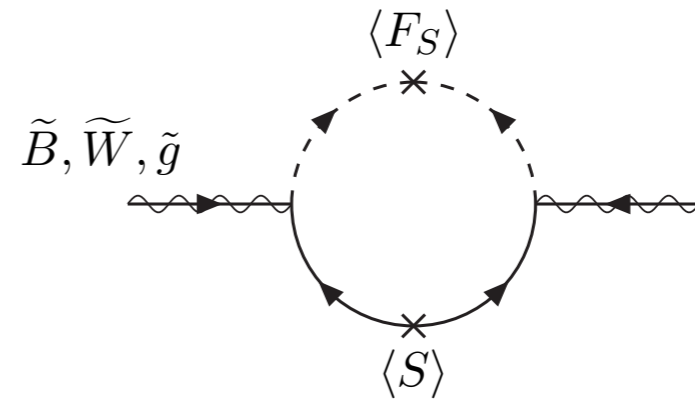
$$\begin{pmatrix} \phi^* & \tilde{\phi} \end{pmatrix} \begin{pmatrix} M^2 & -F^* \\ -F & M^2 \end{pmatrix} \begin{pmatrix} \phi \\ \tilde{\phi}^* \end{pmatrix} \Rightarrow \text{scalar masses } M^2 \pm |F|$$

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

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

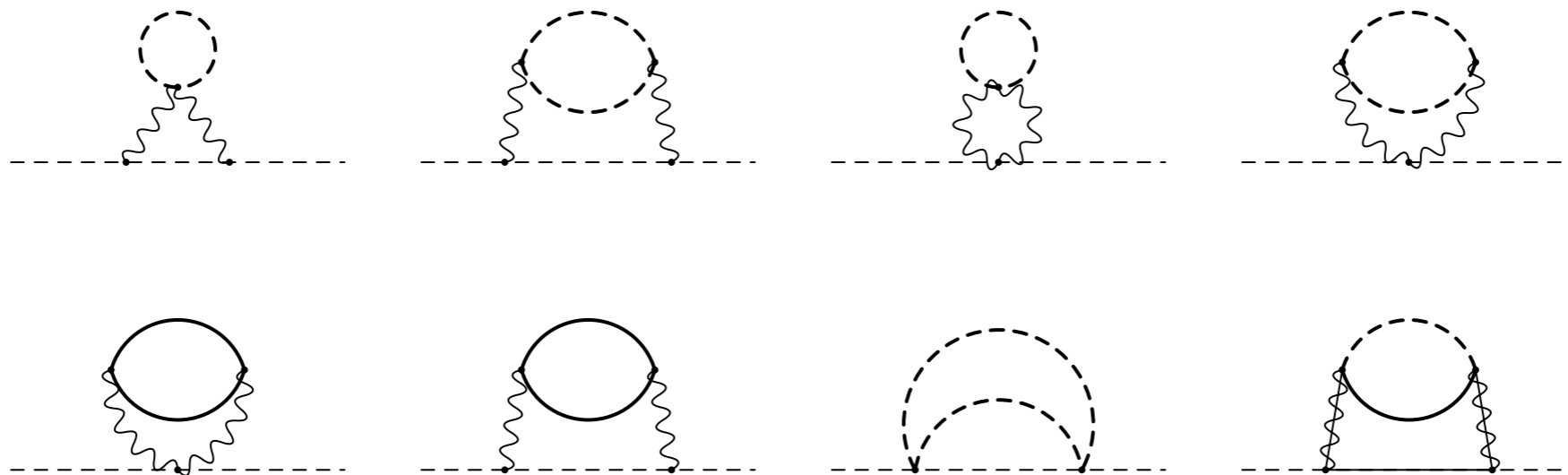
Gaugino masses arise at one loop:

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



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

(these expressions are the first term in an expansion in powers of F/M^2)

Note: $M_a \sim m_\chi \sim M_{GM} \equiv \frac{\alpha}{4\pi} \frac{F}{M} \implies \frac{F}{M} \sim (10 - 100) \text{ TeV}$

with $F < M^2 \implies M > (10 - 100) \text{ TeV} \implies F > (10 - 100 \text{ TeV})^2$

In the absence of additional messenger interactions, the A-terms and Bmu are zero at the messenger scale, and are generated by the RGEs

Minimal gauge mediation: a single spurion X

since messengers belong to a GUT representation, $\sum_i 2T_a(R_i)$ is independent of Ga \implies fixed superpartner spectrum (up to M_a/m_χ and to an overall scale) before RG running

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

\implies superpartner spectrum depends on 3 complex + 3 real parameters

[Meade, Seiberg, Shih]

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 a cold relic. 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

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

EWSB: proper EWSB requires $B\mu \sim \mu^2$, while gauge mediation typically gives $B\mu \sim 16\pi^2 \mu^2 \Rightarrow \mu/B\mu$ problem of gauge mediation

Combining gauge mediation with unification

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

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

$$R \otimes \bar{R} = 1 \oplus \text{Adj.} \oplus \dots$$

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

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

\Rightarrow non-minimal gauge mediation

Not legitimate to omit $\Sigma \Phi \tilde{\Phi}$: generally X neutral under all global symmetries (except for an R-symmetry which eventually must be broken), hence $\Phi \tilde{\Phi}$ neutral too

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

A first example: $G = \text{SU}(5)$, $\Sigma = 24$

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

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

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

Assuming $\lambda_\Sigma \langle \Sigma \rangle$ gives the dominant contribution to M , this induces a mass splitting inside messenger multiplets:

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

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

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

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

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

Since Y is a $SU(5)$ generator, this gives:

$$M_1 = 0$$

(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

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

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

implying that the LSP is a mostly bino light neutralino

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

Superpartner spectrum: while $M_1 = 0$ is independent of the messenger representation, this is not the case for the ratios of the other superpartner masses, e.g.

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

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

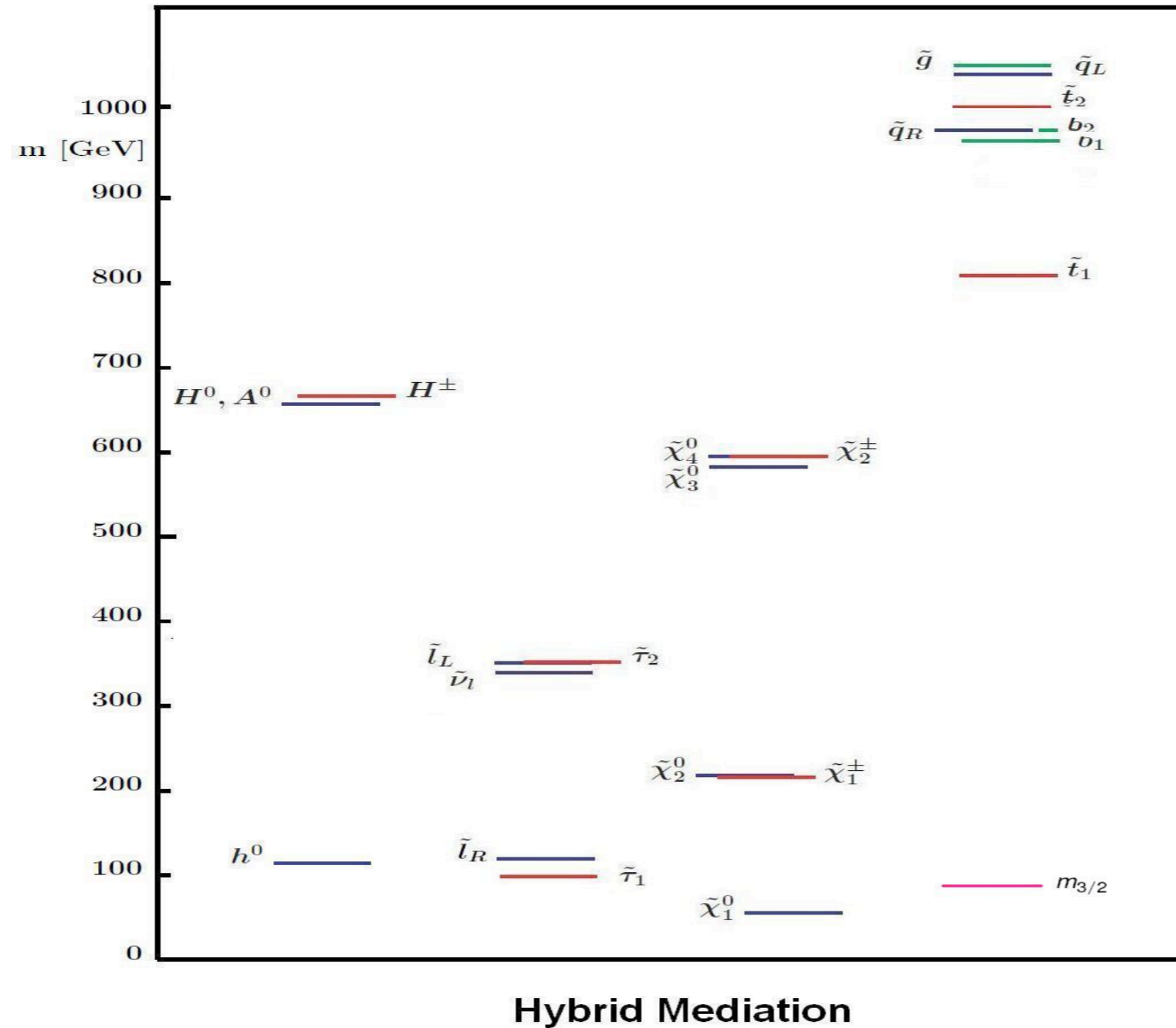
$$(5, \bar{5}) : \quad m_Q^2 : m_{U^c}^2 : m_{D^c}^2 : m_L^2 : m_{E^c}^2 \approx 0.79 : 0.70 : 0.68 : 0.14 : 0.08$$

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

(before RG running)

→ very different from minimal gauge mediation with SU(5)-symmetric messenger masses

Model 6



$$M_{\tilde{\chi}^0_1} = 42.9 \text{ GeV}$$

$$m_{3/2} = 85 \text{ GeV}$$

$$m_{\tilde{\tau}_1} = 95.2 \text{ GeV}$$

$$m_{\tilde{e}_R, \tilde{\mu}_R} = 117.4 \text{ GeV}$$

$$\Omega_{\tilde{\chi}^0_1} h^2 = 0.116$$

(1 σ from WMAP)

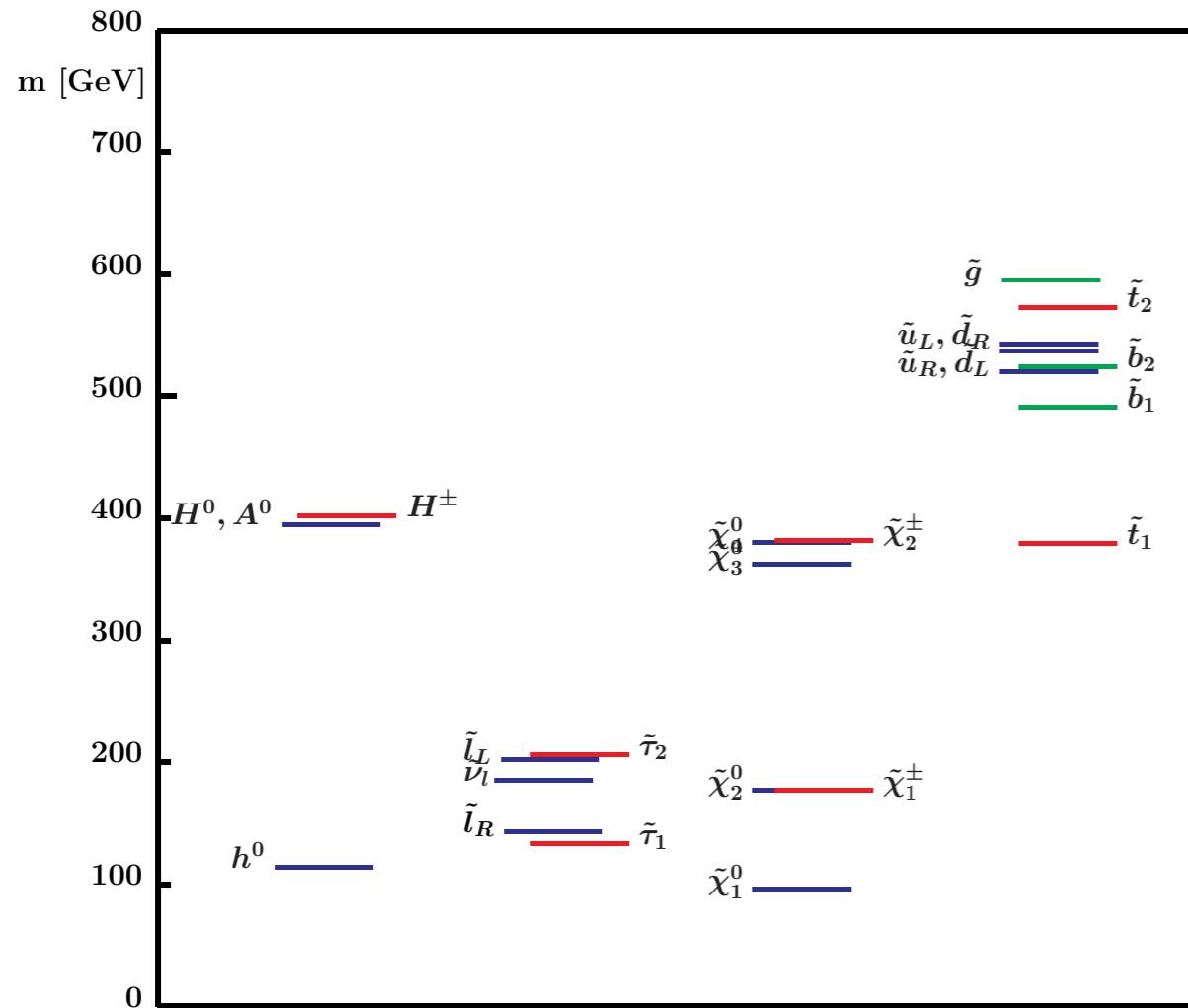
$$\Delta a_\mu = 20.6 \times 10^{-10}$$

(2.6 σ from exp.)

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

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

SPS Ia

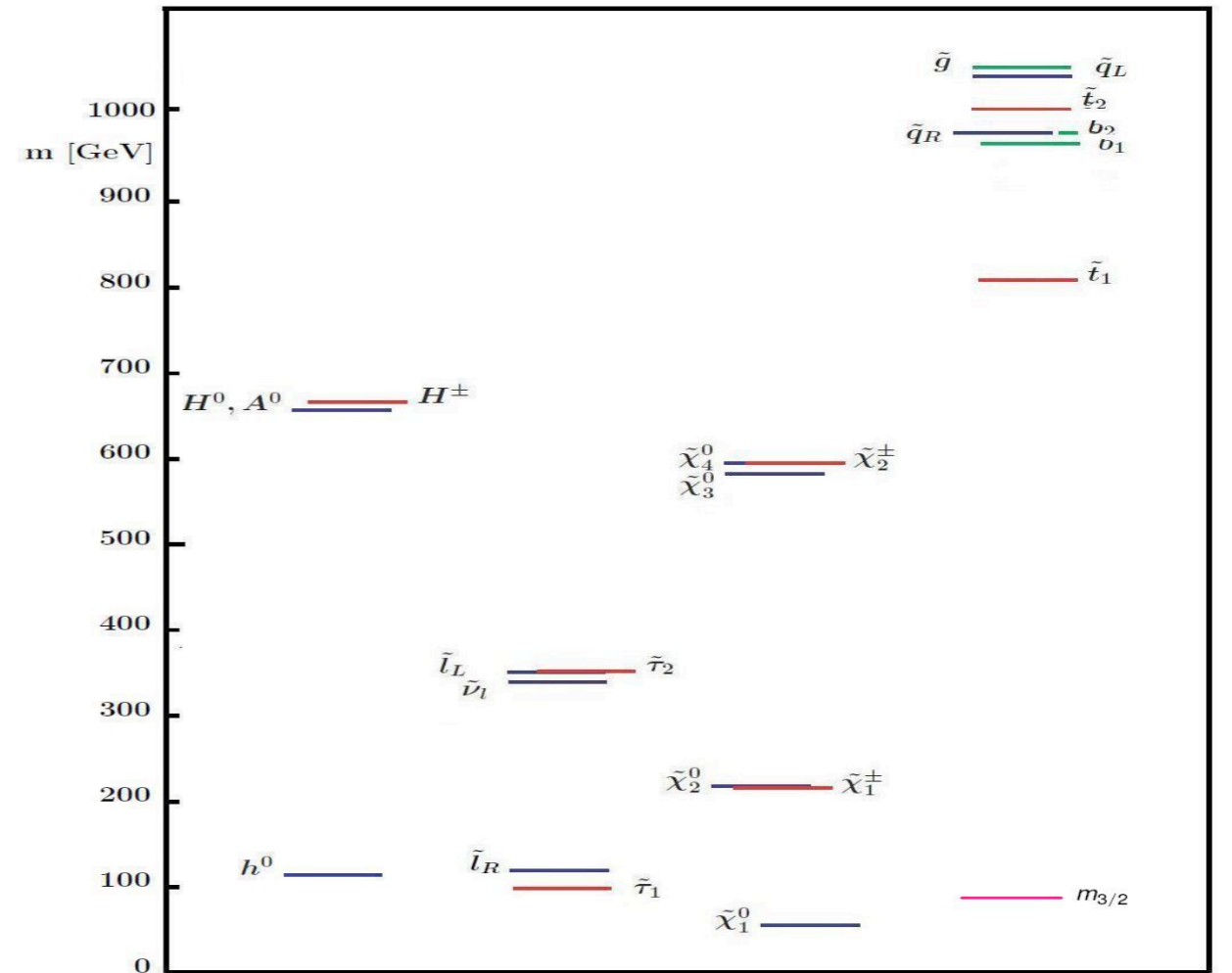


Allanach et al., hep-ph/0202233

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

(typical mSUGRA spectrum)

Model 6



Hybrid Mediation

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

Phenomenology of the light neutralino scenario

Main distinctive features:

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

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 $\Rightarrow T_R \lesssim (10^5 - 10^6) \text{ GeV}$ required. 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 $(10, \overline{10})$, but the relic density tends to exceed the WMAP value if $M_{\tilde{\chi}_1^0} \lesssim 40 \text{ GeV}$

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. $\mu \rightarrow e\gamma$)

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 $p\bar{p}/pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + \text{jet}$, $\sigma_{\text{SPS1a}} = 270 \text{ fb}$), 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]

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

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

yielding less hierarchical gaugino masses than in minimal gauge mediation (with a wino mass rather close to the gluino mass at the EW scale):

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

The LSP is the gravitino as in conventional gauge mediation

$G = SO(10)$, messengers in 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 $\Sigma = 54$ 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 $(5, \bar{5})$ 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 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 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', thus suppressing the wino mass with respect to the bino and gluino masses (in the limit $\lambda_X X_0 \ll \lambda_{45} V_R$):

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

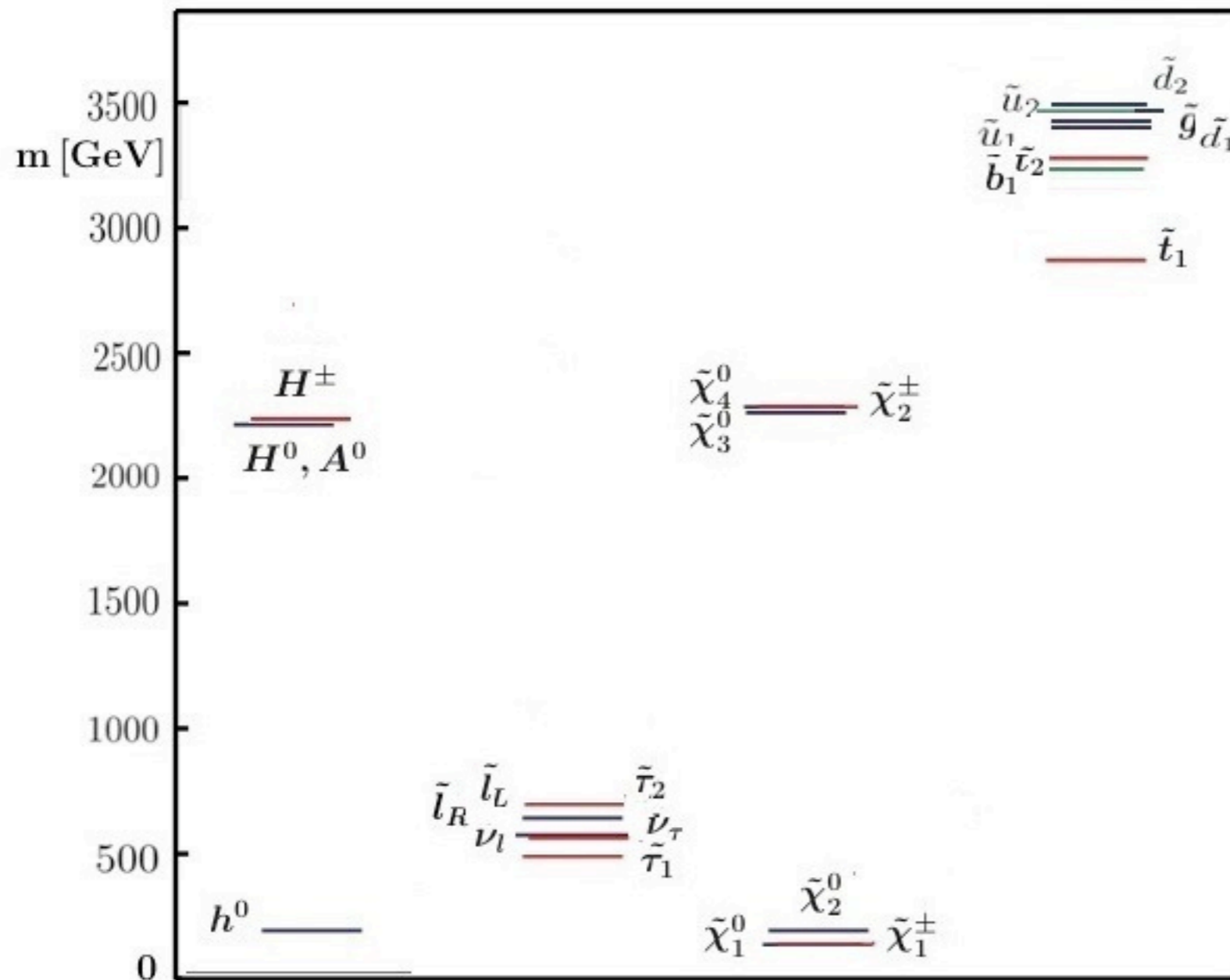
\Rightarrow wino NLSP (gravitino LSP)

Annihilations via gauge interactions very efficient \Rightarrow small relic density:

$$\Omega_{\tilde{W}} h^2 \approx 5 \times 10^{-4} \left(\frac{M_2}{100 \text{ GeV}} \right)^2$$

BBN constraints more easily satisfied (may still require $m_{3/2} < 1 \text{ GeV}$)

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



$$m_{3/2} \lesssim 60 \text{ GeV}$$

$$M_{\tilde{\chi}_1^0} = 105.7 \text{ GeV}$$

$$M_{\tilde{\chi}_2^0} = 127.6 \text{ GeV}$$

$$M_{GM} = 775 \text{ GeV}, \quad \lambda_{45} V_R = 6\lambda_X X_0,$$

$$\tan \beta = 20, \quad \mu > 0$$

Collider signatures?

I-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 $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$ leads to displaced vertices [Gherghetta et al., hep-ph/9904378]

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

$$1/\tau_{\tilde{\chi}_1^0} \approx \frac{m_{\tilde{\chi}_1^0}^5}{48\pi(m_{3/2}M_P)^2} \quad \Rightarrow \quad \tau_{\tilde{\chi}_1^0} \sim 10^6 \text{s for } m_{3/2} \sim 10 \text{ GeV}$$

(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

(also $\tilde{\chi}_2^0 \tilde{\chi}_1^+$ production followed by $\tilde{\chi}_2^0 \rightarrow l^+ l^- \tilde{\chi}_1^0$ or $\bar{\nu} l^- \tilde{\chi}_1^+$)

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

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:

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

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

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

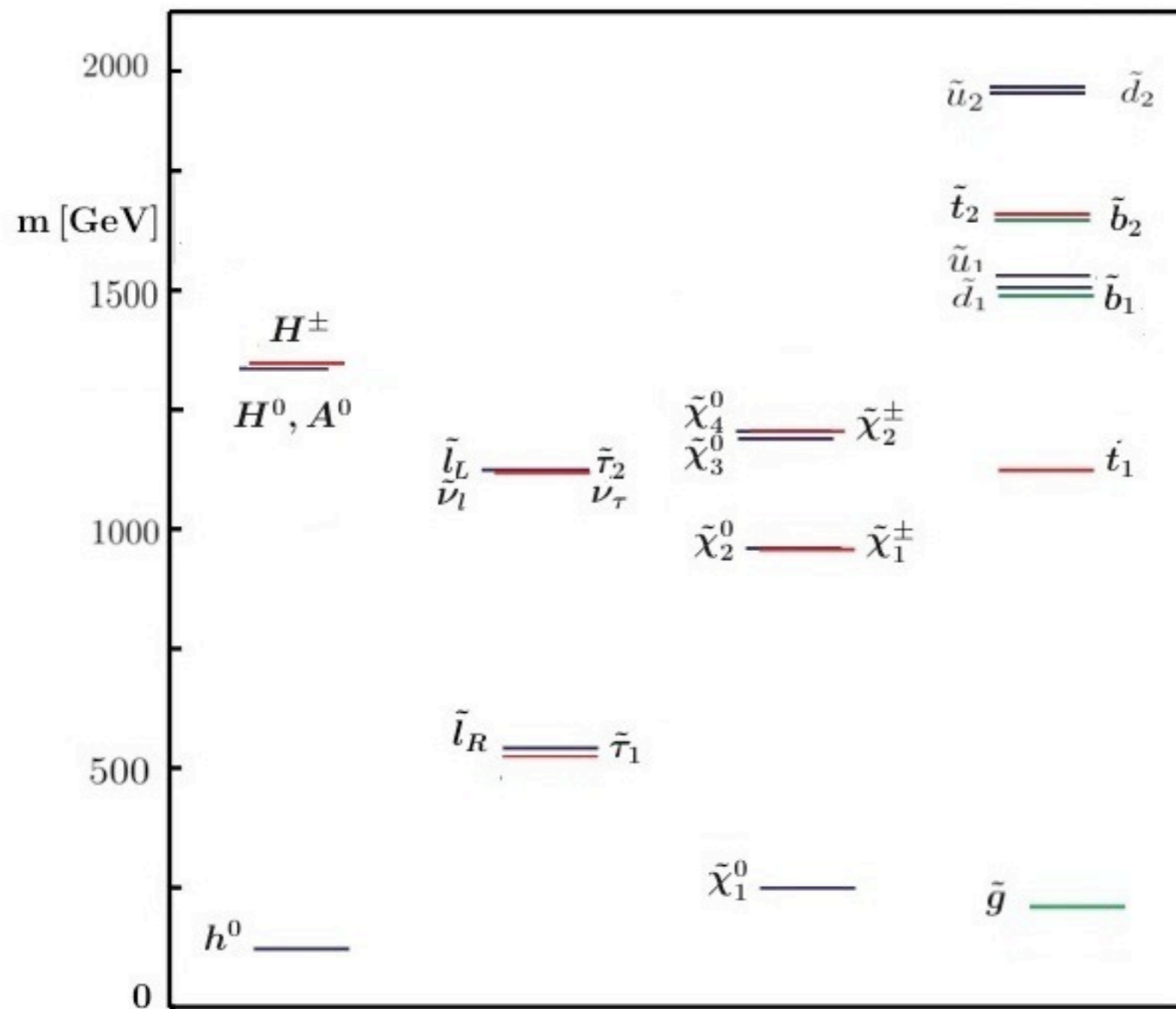
\Rightarrow gluino NLSP (gravitino LSP)

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

$$1/\tau_{\tilde{g}} \approx \frac{m_{\tilde{g}}^5}{48\pi(m_{3/2}M_P)^2} \Rightarrow \tau_{\tilde{g}} \sim 10^7 \text{ s for } m_{\tilde{g}} \sim 250 \text{ GeV} \quad [M_3 = m_{3/2}]$$

Remiscent of split SUSY (except that gluino NLSP)

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



$$m_{3/2} = 60 \text{ GeV}$$

$$m_{\tilde{g}} = 213.3 \text{ GeV}$$

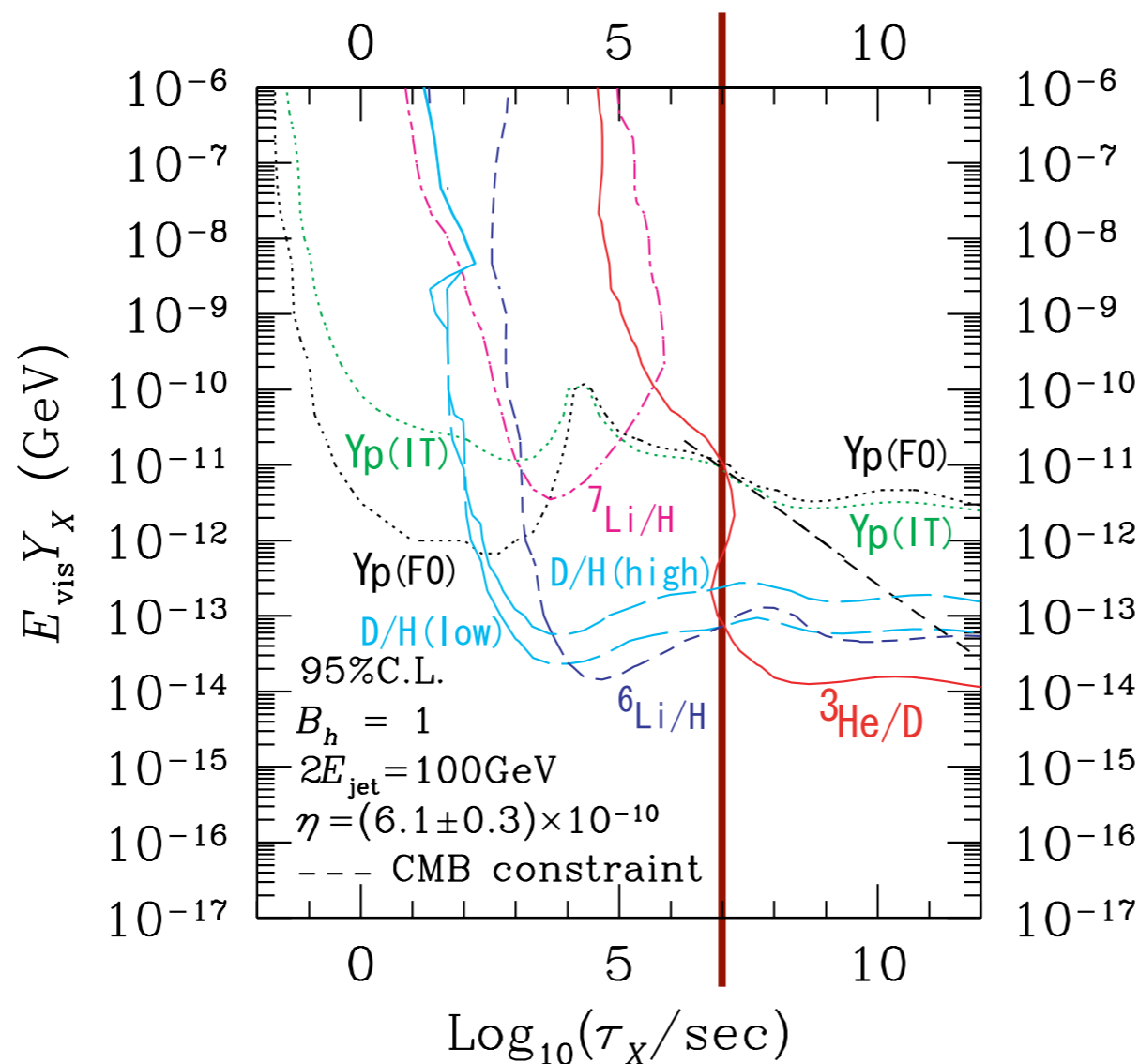
$$M_{\tilde{\chi}_1^0} = 230.5 \text{ GeV}$$

$$M_{GM} = 150 \text{ GeV}, \ M_3 = m_{3/2} = 60 \text{ GeV},$$

$$\tan \beta = 20, \ \mu > 0$$

BBN constraints

A long-lived relic decaying hadronically can spoil BBN



Kawasaki, Kohri, Moroi,
astro-ph/0408426

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

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

Figure 38: Upper bounds on $m_X Y_X$ at 95% C.L. for $B_h = 1$ and $m_X = 100 \text{ GeV}$. 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.

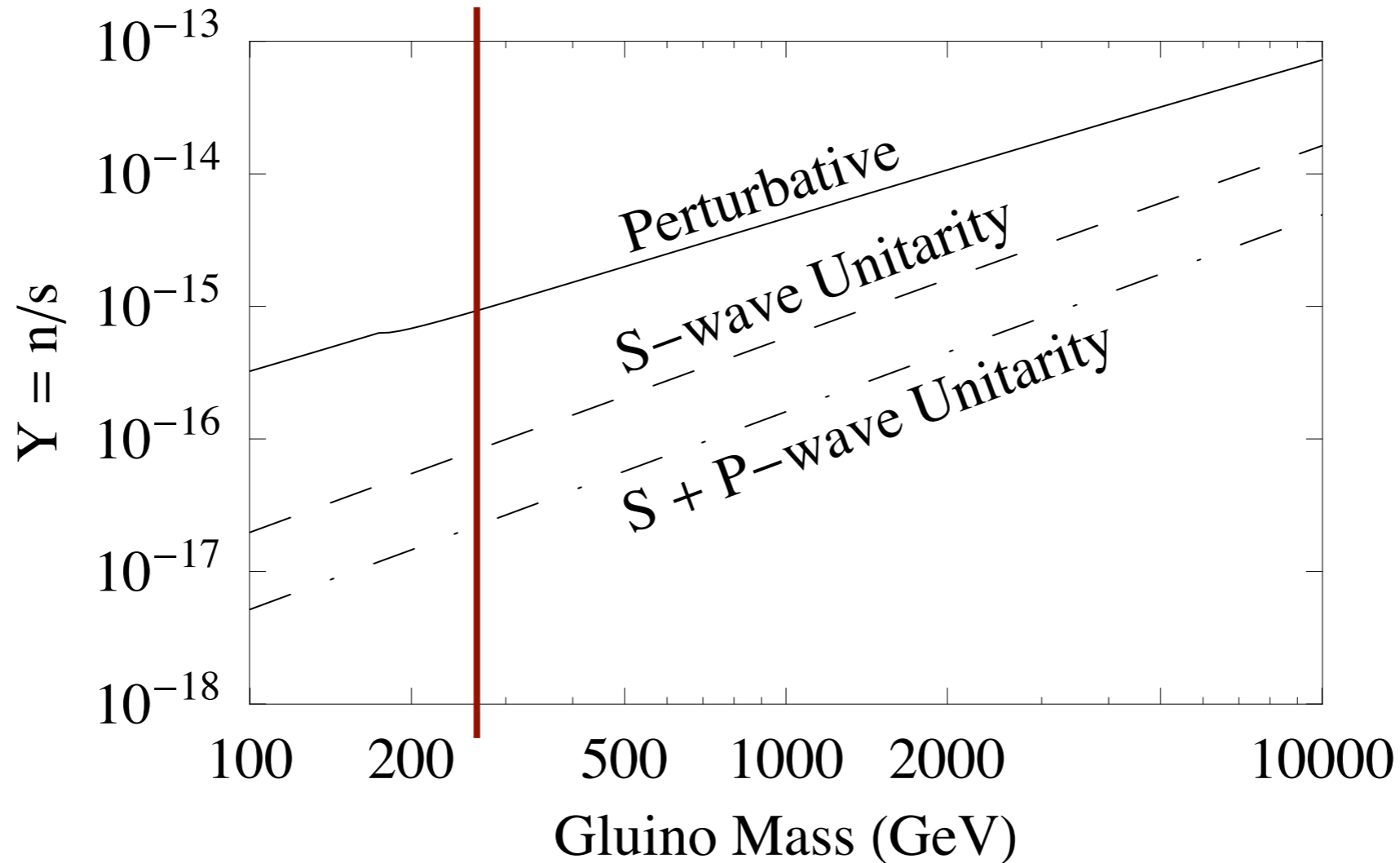


Figure 1: Gluino abundance per co-moving volume as a function of mass. Three curves are shown. In the first (solid), the annihilation cross section is assumed to be simply given by the perturbative cross section of Eqn. 3. The other curves correspond to a cross section that saturates s -wave (dashed)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

For $m_{\tilde{g}} \sim 250$ GeV, the condition $Y_{\tilde{g}} m_{\tilde{g}} \lesssim \text{few } 10^{-14}$ GeV is satisfied thanks to the enhancement of the annihilation cross section due to bound state effects (assumed to saturate S-wave unitarity)

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

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:

$$m_{\tilde{g}} > 210 \text{ GeV}$$

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]: $m_{\tilde{g}} < 270 \text{ GeV}$ for $\tau_{\tilde{g}} < 3 \text{ h}$
(assumes a neutral-to-charged hadron conversion cross section of 3 mb)

Conclusions

In gauge-mediated scenarios with an underlying GUT structure, the dominant contribution to messenger masses may come from the coupling between the GUT and messenger sectors

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

BACK-UP SLIDES

light neutralino scenario

$$M_{mess} = 10^{13} \text{ GeV}$$

Spectrum depends on

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

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

WMAP constraint:

$$\Omega_{DM} h^2 = 0.1099 \pm 0.0062 \, (1\sigma)$$

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
$\text{sign}(\mu)$	+	+	+	+	+	+	+
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
$ Z_{11} $	0.9982	0.9975	0.9971	0.9971	0.9978	0.9968	0.9969
$ Z_{13} $	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

An explicit model

An explicit realization of the light neutralino scenario requires specifying the supersymmetry breaking sector. Here we consider the ISS (Intriligator, Seiberg, Shih) model, in which supersymmetry is broken in a long-lived metastable vacuum, and we identify X with the meson fields of ISS

The theory considered by ISS is $N=1$ SQCD with N_f quark flavours and gauge group $SU(N_c)$ in the regime $N_c < N_f < 3N_c/2$. In the IR, it is strongly coupled and can be described by a dual, IR-free “magnetic” theory

- gauge group $SU(N_f - N_c)$
 - N_f flavours of quarks q_a^i and antiquarks \tilde{q}_i^a
 - meson fields X_i^j
- $$i, j = 1 \cdots N_f$$
- $$a = 1 \cdots N \equiv N_f - N_c$$

The superpotential of the magnetic theory

$$W_{ISS} = h q_a^i X_i^j \tilde{q}_j^a - h f^2 \text{Tr} X$$

leads to supersymmetry breaking à la O’Raifeartaigh, since the auxiliary fields $(-F_X^\star)_j^i = h q_a^i \tilde{q}_j^a - h f^2 \delta_j^i$ cannot all be set to zero

The supersymmetry-breaking ISS vacuum is:

$$\langle X \rangle = 0, \quad \langle q_a^i \rangle = f \delta_a^i, \quad \langle \tilde{q}_i^a \rangle = f \delta_i^a$$

This vacuum is metastable, since the theory possesses N_c supersymmetric vacua, which can be obtained by going away from $\langle X \rangle = 0$ and integrating out the magnetic quarks (which get masses $h \langle X \rangle$)

The lifetime of the metastable vacuum is given by the formula

$$\tau_{ISS} \sim e^S \quad S \sim \frac{(\Delta X)^4}{\Delta V} \quad \text{Duncan, Jensen}$$

One finds $S \rightarrow \infty$ for $\epsilon \equiv f/\Lambda_m \rightarrow 0$, where Λ_m is the scale above which the magnetic theory is strongly coupled

We now couple the meson fields of the ISS sector to the messengers:

$$W_{mess} = (\lambda_X)_j^i X_i^j \Phi \tilde{\Phi} + \lambda_\Sigma \Sigma \Phi \tilde{\Phi}$$

where the indices i, j run from 1 to N_f

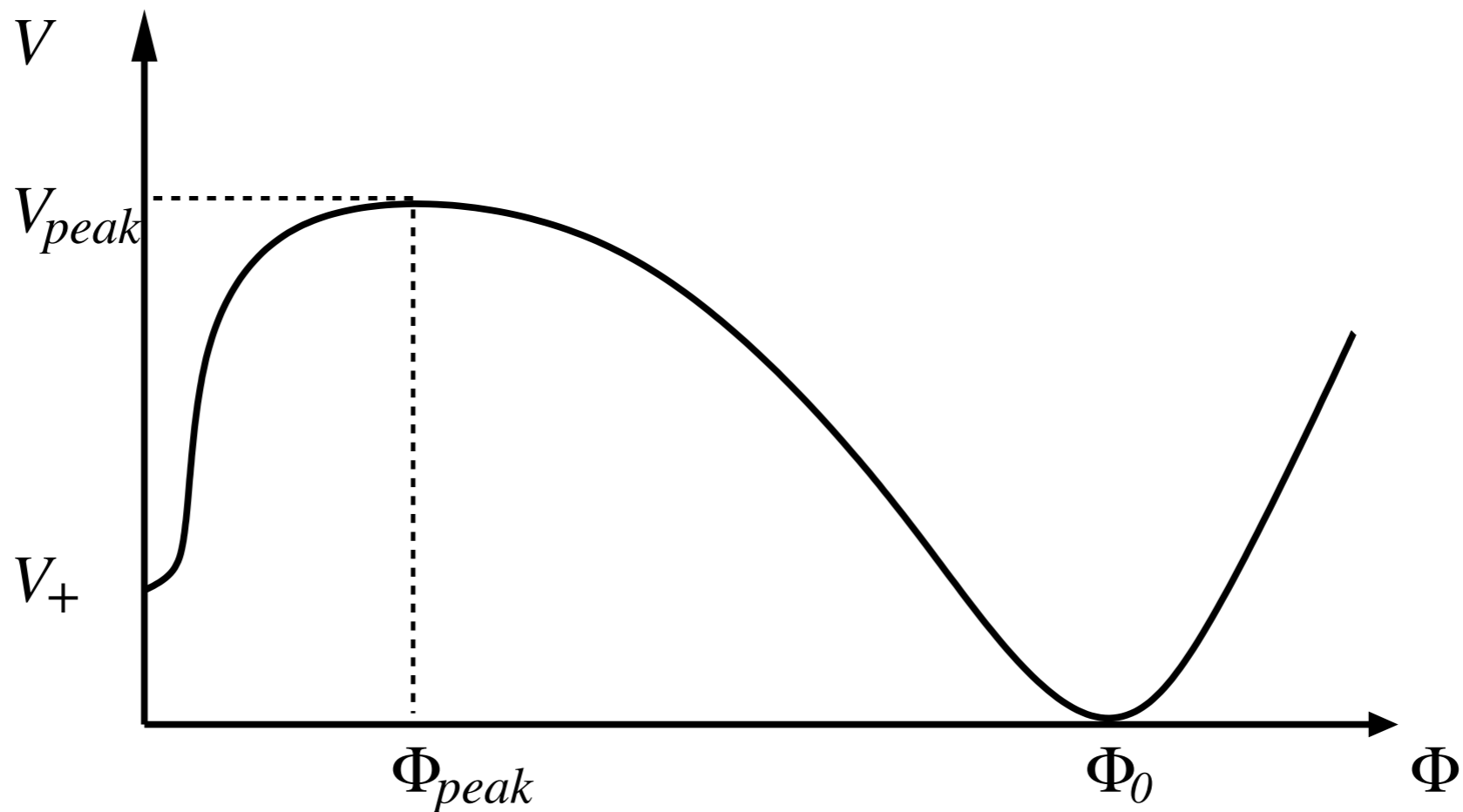


Figure 1: The potential along the bounce trajectory. The peak is at $\Phi_{peak} \sim \mu$ and the supersymmetric minimum with vanishing potential is at large field $\Phi_0 \sim \mu/\epsilon^{(N_f-3N)/(N_f-N)} \gg \mu$. The values of the potential at the local minimum V_+ and at the peak V_{peak} are of order μ^4 .

(Meta)stability of the ISS vacuum

One must check that the coupling of the messenger fields does not spoil the viability of the ISS vacuum by introducing new supersymmetric vacua to which it would quickly decay, or by triggering messenger vev's that would break the SM gauge symmetries

At tree-level, we find the following vacua:

- the ISS vacuum with no messenger vev's and energy

$$V(\phi\tilde{\phi} = 0) = (N_f - N)h^2 f^4$$

- lower (supersymmetry breaking) minima with nonzero messenger vev's

$$\phi\tilde{\phi} = - \sum_{i=N+1}^{N_f} \lambda_{X,i}^i h f^2 \bigg/ \sum_{(i,j) \notin \{i=j=1\dots N\}} |\lambda_{X,j}^i|^2$$

We can estimate the transition probability to the lower minima:

$$\frac{\Delta V}{(\Delta\phi)^4} = \sum_{(i,j) \notin \{i=j=1\dots N\}} |\lambda_{X,j}^i|^2 \equiv \overline{\lambda^2} \implies \tau_{ISS} \sim e^{1/\overline{\lambda^2}}$$

To ensure that the ISS vacuum is sufficiently long lived, it is enough to take

$$\overline{\lambda^2} \lesssim 10^{-3}$$

One must also check the stability of the ISS vacuum against quantum corrections. The contributions of the ISS sector itself to the effective one-loop potential have been computed by ISS:

$$V_{ISS}^{(1)} = \frac{1}{64\pi^2} 8 h^4 f^2 (\ln 4 - 1) N (N_f - N) |X_0|^2$$

in the parametrization

$$X = \begin{pmatrix} \tilde{Y} & \delta Z^\dagger \\ \delta \tilde{Z} & \tilde{X} \end{pmatrix} \quad \tilde{Y} = Y_0 \mathbf{I}_N, \quad \tilde{X} = X_0 \mathbf{I}_{N_f - N}$$

Including the tree-level potential and the contributions of the messenger sector to the one-loop potential, one obtains:

$$V_{1\text{-loop}}(X_0, Y_0) = 2N h^2 f^2 |Y_0|^2 + \frac{1}{64\pi^2} \left\{ 8h^4 f^2 (\ln 4 - 1) N (N_f - N) |X_0|^2 \right. \\ \left. + \frac{10N_m h^2 f^4 |\text{Tr}' \lambda|^2}{3\lambda_\Sigma v} \left[(\text{Tr}' \lambda) X_0 + (\text{Tr}'' \lambda) Y_0 + \text{h.c.} \right] \right\},$$

where $\text{Tr}' \lambda \equiv \sum_{i=N+1}^{N_f} \lambda_{X,i}^i, \quad \text{Tr}'' \lambda \equiv \sum_{i=1}^N \lambda_{X,i}^i$

Minimizing $V_{\text{1-loop}}$, one finds a small shift of the meson vev's with respect to the original ISS vacuum:

$$\langle X_0 \rangle \simeq - \frac{5N_m |\text{Tr}' \lambda|^2 (\text{Tr}' \lambda)^*}{12(\ln 4 - 1)h^2 N(N_f - N)} \frac{f^2}{\lambda_\Sigma v} ,$$

$$\langle Y_0 \rangle \simeq - \frac{5N_m |\text{Tr}' \lambda|^2 (\text{Tr}'' \lambda)^*}{192\pi^2 N} \frac{f^2}{\lambda_\Sigma v} .$$

These vev's help solving the $\mu/B\mu$ problem, if the following non-renormalizable superpotential operators are present:

$$(i) \quad \lambda_1 \frac{q\tilde{q}}{M_P} H_u H_d , \qquad (ii) \quad \lambda_2 \frac{XX}{M_P} H_u H_d$$

(i) yields $\mu = \frac{\lambda_1}{h} \frac{N}{\sqrt{N_c}} \sqrt{3} m_{3/2}$ (which can give $\mu \sim 1$ TeV for $m_{3/2} \sim (10-100)$ GeV by taking h small),

but its contribution to $B\mu$ is suppressed

(ii) gives a negligible μ , but a $B\mu$ of the appropriate size