LIGHT HIGGSINOS AS HERALDS OF HIGHER DIMENSIONAL UNIFICATION

Wilfried Buchmüller
DESY

with Felix Brümmer, arXiv:1105.0802,
Sergei Bobrovskyi and Jan Hajer, in preparation

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Is the GUT scale related to extra dimensions?

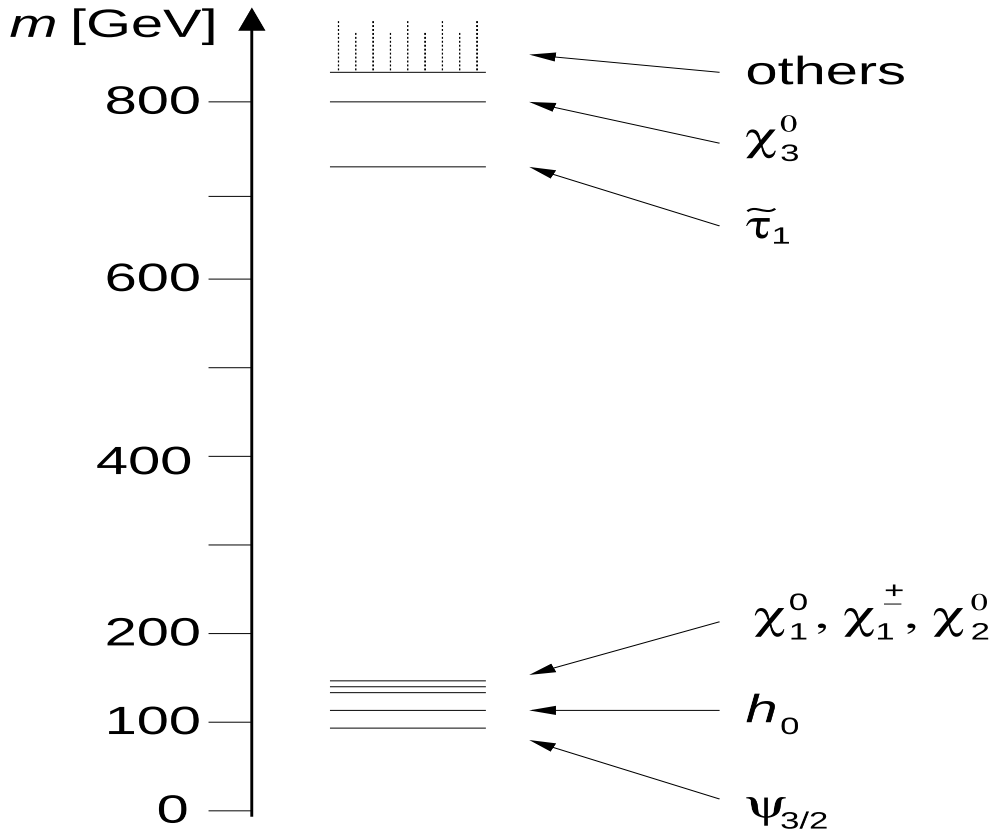
- Strong motivation for SUSY GUTs: symmetries of SM, gauge coupling unification, neutrino physics,...

- GUTs in more than 4D more attractive than GUTs in 4D

- Even more interesting: string compactifications with $\mathrm{E}_8(\times \mathrm{E}_8)$, as in compactifications of the heterotic string, F-theory GUTs, ...

- Possible signature: unusual spectrum of superparticle masses, due to large number of 'split multiplets' with GUT-scale masses

Example: spectrum in heterotic orbifold string model



Superparticle mass spectrum from hybrid mediation: gauge mediation terms rouphly (large) integer multiples of gravity mediation terms

(1) Soft terms from hybrid gauge-gravity mediation

Gauge-mediated supersymmetry breaking (see review Giudice & Rattazzi): background chiral superfield X and messenger fields in vector-like pairs Σ_i, $\widetilde{\Sigma}_i$, with superpotential

$$W = \sum_i \lambda_i X \Sigma_i \widetilde{\Sigma}_i \ .$$

Mass generation and SUSY breaking,

$$\langle X \rangle = M_{\rm m} + F\theta^2 \ , \quad M_{\rm m} \sim \Lambda_{\rm GUT} \ , \quad F \ll M_{\rm m}^2 \ ,$$

yields contribution to gaugino masses at the messenger scale,

$$M_a = \frac{g_a^2}{16\pi^2} n_a(r_i) \frac{F}{M_{\rm m}} \ ,$$

$a = 1, 2, 3$: SM gauge factors; $n_a(r_i)$: Dynkin index for rep $r_i(\Sigma_i)$.

In general, X-dependent gauge kinetic functions

$$\mathcal{L} = \frac{1}{4}\sum_a \int d^2\theta \left(\frac{1}{g_a^2} + \kappa_a \frac{X}{M_{\rm P}}\right) W^{a\alpha} W^a_\alpha + \text{h.c.} \ ,$$

yields gravity-mediated contribution to gaugino masses,

$$M_a = \frac{1}{2} g_a^2 \kappa_a \frac{F}{M_{\rm P}} \ ,$$

with Planck mass $M_{\rm P} = 2.4 \cdot 10^{18}$ GeV; contribution of messenger pair comparable with gravity-mediated term since $(16\pi^2) M_{\rm m} \simeq M_{\rm P}$!.

Gauge-mediated soft scalar masses at 2-loop level,

$$m_\Phi^2 = \frac{2}{(16\pi^2)^2} \left(\sum_{ai} g_a^4 C_a n_a(r_i)\right) \left|\frac{F}{M_{\rm m}}\right|^2 \ ,$$

with quadratic Casimirs for rep of $C_a(\Phi)$. In addition gravity-mediated piece,

$$\mathcal{L} = \int d^4\theta \left(\frac{X^\dagger}{M_{\rm P}} + {\rm h.c.} - \frac{1}{2}\frac{X^\dagger X}{M_{\rm P}^2} \right) \Phi^\dagger \Phi \ ,$$

which gives

$$m_\Phi^2 = \frac{1}{2}\left|\frac{F}{M_{\rm P}}\right|^2 \ .$$

Gravity mediation also generates μ and B_μ terms,

$$\mathcal{L} = \int d^4\theta \, \frac{X^\dagger}{M_{\rm P}} H_u H_d + \int d^4\theta \, \frac{X^\dagger X}{M_{\rm P}^2} H_u H_d + {\rm h.c.} \ ,$$

with $\mu = \overline{F}/M_{\rm P}$ and $B_\mu = |F/M_{\rm P}|^2$, cubic terms $a \sim F/M_{\rm P}$ and a gravitino mass

$$m_{3/2} = \frac{F}{\sqrt{3} M_{\mathrm{P}}}$$

of the order of the gravity-mediated soft masses.

Electroweak symmetry breaking requires

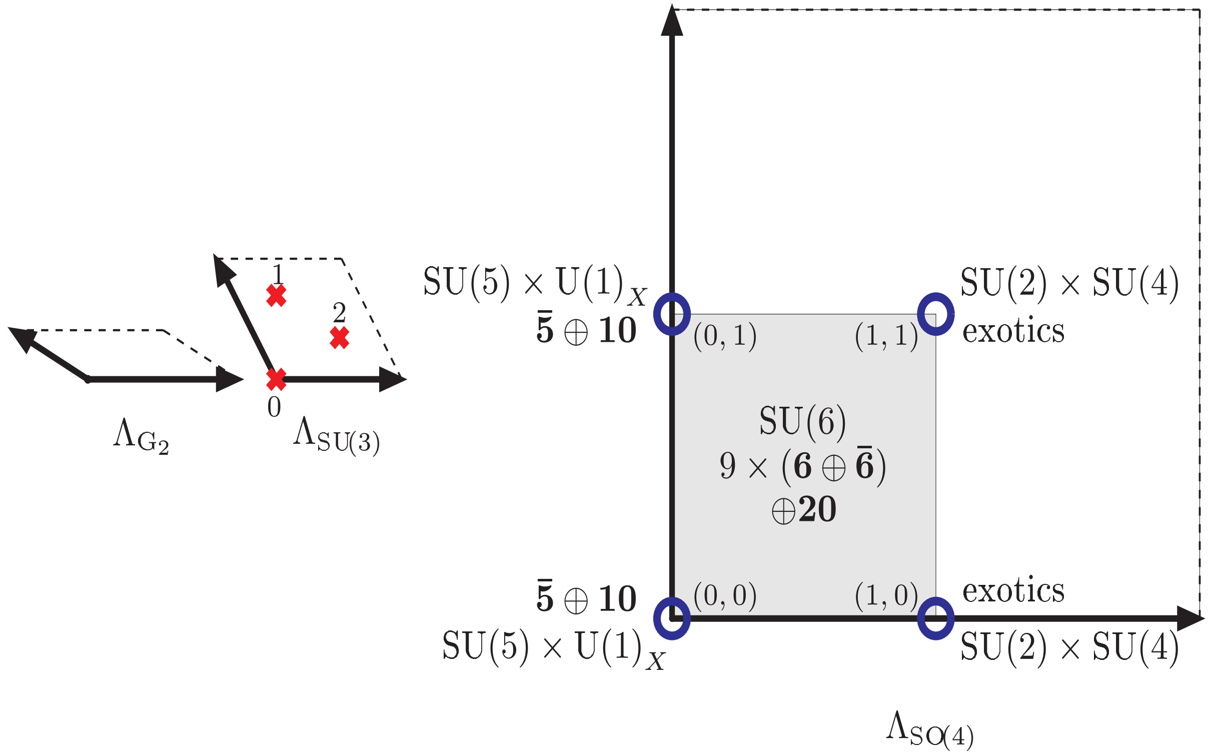
$$-\frac{M_Z^2}{2} \simeq |\mu|^2 + m_{H_u}^2 \ ,$$

$$\tan\beta \simeq \frac{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2}{2\,B_\mu} \ ;$$

hence for $\mu \sim 100$ GeV also $|m_{H_u}^2| \sim (100$ GeV$)^2$; but $|m_{H_d}^2| \gg (100$ GeV$)^2$ for $N_{\mathrm{mess}} \gg 1$, and therefore $\tan\beta \gg 1$; less fine tuning?

(2) A heterotic orbifold model

Example: heterotic string on $\mathbb{Z}_{6-\mathrm{II}} = \mathbb{Z}_3 \times \mathbb{Z}_2$ orbifold (Kobayashi, Raby, Zhang '04; WB,Hamaguchi, Lebedev, Ratz '05,06; Lebedev et al '06,'07; WB, Lüdeling,Schmidt '07,08;...)
3 SM generations, 1 pair of Higgs doublets, $\mathcal{O}(100)$ SM singlets, part of 'mini-landscape'.



Mass generation for vector-like exotics Σ_i:

field	representation	multiplicity	6D origin
d	$(\mathbf{3},\mathbf{1})_{-1/3}$	4	bulk
$\tilde{d}$	$(\overline{\mathbf{3}},\mathbf{1})_{1/3}$	4	bulk
ℓ	$(\mathbf{1},\mathbf{2})_{1/2}$	4	bulk
$\tilde{\ell}$	$(\mathbf{1},\mathbf{2})_{-1/2}$	4	bulk
m	$(\mathbf{1},\mathbf{2})_{0}$	8	brane
s^+	$(\mathbf{1},\mathbf{1})_{1/2}$	16	brane
s^-	$(\mathbf{1},\mathbf{1})_{-1/2}$	16	brane

Selection rules for couplings require at least two SUSY-breaking background superfields X_1 and X_2,

$$W = X_1\, d\tilde{d} + X_1 \ell\tilde{\ell} + X_2 mm + X_2 s^+ s^- \ .$$

Huge vacuum degeneracy; SUSY breaking not yet fully explored, conceptual problem: moduli stabilization! Example: assume expectation values of SM singlets ($M_{\mathrm{m}} \sim \Lambda_{\mathrm{GUT}}$, $F_i \ll M_{\mathrm{m}}^2$),

$$\langle X_1 \rangle = M_{\mathrm{m}} + F_1\, \theta^2, \qquad \langle X_2 \rangle = M_{\mathrm{m}} + F_2\, \theta^2\ ,$$

with goldstino mixing angle ϕ,

$$F_1 = F \cos\phi\ , \quad F_2 = F \sin\phi\ , \quad \frac{F}{\sqrt{3} M_{\mathrm{P}}} = m_{3/2}\ .$$

Gauge-mediated gaugino masses at the scale M_{m}:

$$M_1 = \frac{g^2}{16\pi^2} \frac{F}{M_{\mathrm{m}}} \left(4 \cos\phi + \frac{24}{5} \sin\phi \right)\ ,$$

$$M_2 = \frac{g^2}{16\pi^2} \frac{F}{M_{\mathrm{m}}} \left(4 \cos\phi + 4 \sin\phi \right)\ ,$$

$$M_3 = \frac{g^2}{16\pi^2} \frac{F}{M_{\mathrm{m}}}\, 4 \cos\phi\ .$$

Gauge-mediated scalar soft masses:

$$m_Q^2 = 2\left(\frac{g^2}{16\pi^2}\right)^2 \left(\frac{F}{M_{\rm m}}\right)^2 \left(\frac{287}{50} + \frac{133}{50}\cos 2\phi\right) \ ,$$

$$m_U^2 = 2\left(\frac{g^2}{16\pi^2}\right)^2 \left(\frac{F}{M_{\rm m}}\right)^2 \left(\frac{96}{25} + \frac{64}{25}\cos 2\phi\right) \ ,$$

$$m_D^2 = 2\left(\frac{g^2}{16\pi^2}\right)^2 \left(\frac{F}{M_{\rm m}}\right)^2 \left(\frac{74}{25} + \frac{66}{25}\cos 2\phi\right) \ ,$$

$$m_L^2 = m_{H_u}^2 = m_{H_d}^2 = 2\left(\frac{g^2}{16\pi^2}\right)^2 \left(\frac{F}{M_{\rm m}}\right)^2 \left(\frac{183}{50} - \frac{3}{50}\cos 2\phi\right) \ ,$$

$$m_E^2 = 2\left(\frac{g^2}{16\pi^2}\right)^2 \left(\frac{F}{M_{\rm m}}\right)^2 \left(\frac{66}{25} - \frac{6}{25}\cos 2\phi\right) \ .$$

NOTE: different mass for each SM representation!

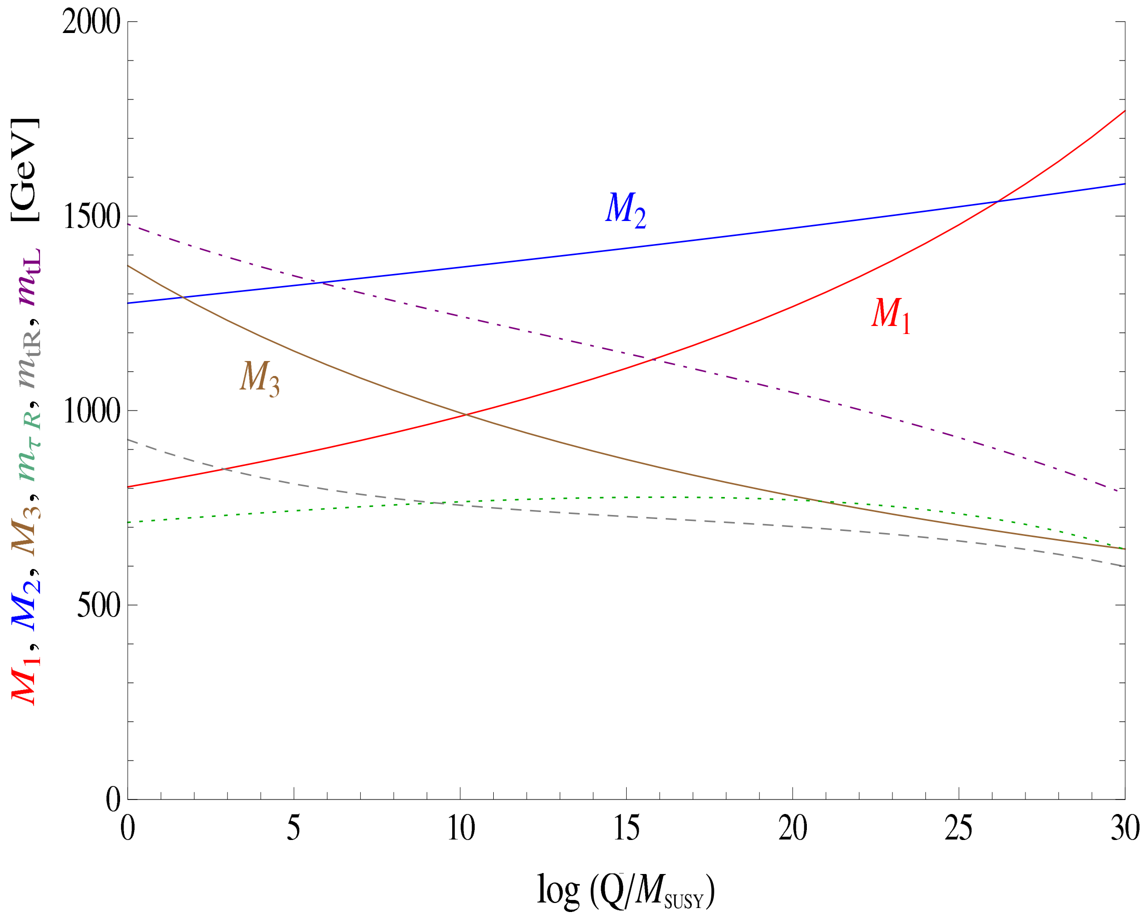
Specific choice of parameters: $M_{\rm m} = 5 \cdot 10^{15}$ GeV, $F = (2 \cdot 10^{10}$ GeV$)^2$; supergravity contributions: $m_0 = m_{1/2} = 150$ GeV $= 0.9\ F/M_{\rm P}$, $m_{3/2} = 100$ GeV, $\tan\phi = 1.9$, $\mu = m_0 = a_0$, $B_\mu = (1.6\, m_0)^2 = (240\ {\rm GeV})^2$; GUT-scale mass parameters listed in Table; $\tan\beta = 41$

mass parameter	value [GeV]
M_1	1771
M_2	1583
M_3	644
m_Q	786
m_U	599
m_D	478
$m_L = m_{H_u} = m_{H_d}$	736
m_E	643

Note: small value of M_3, less than m_{H_u}, crucial for electroweak symmetry breaking!

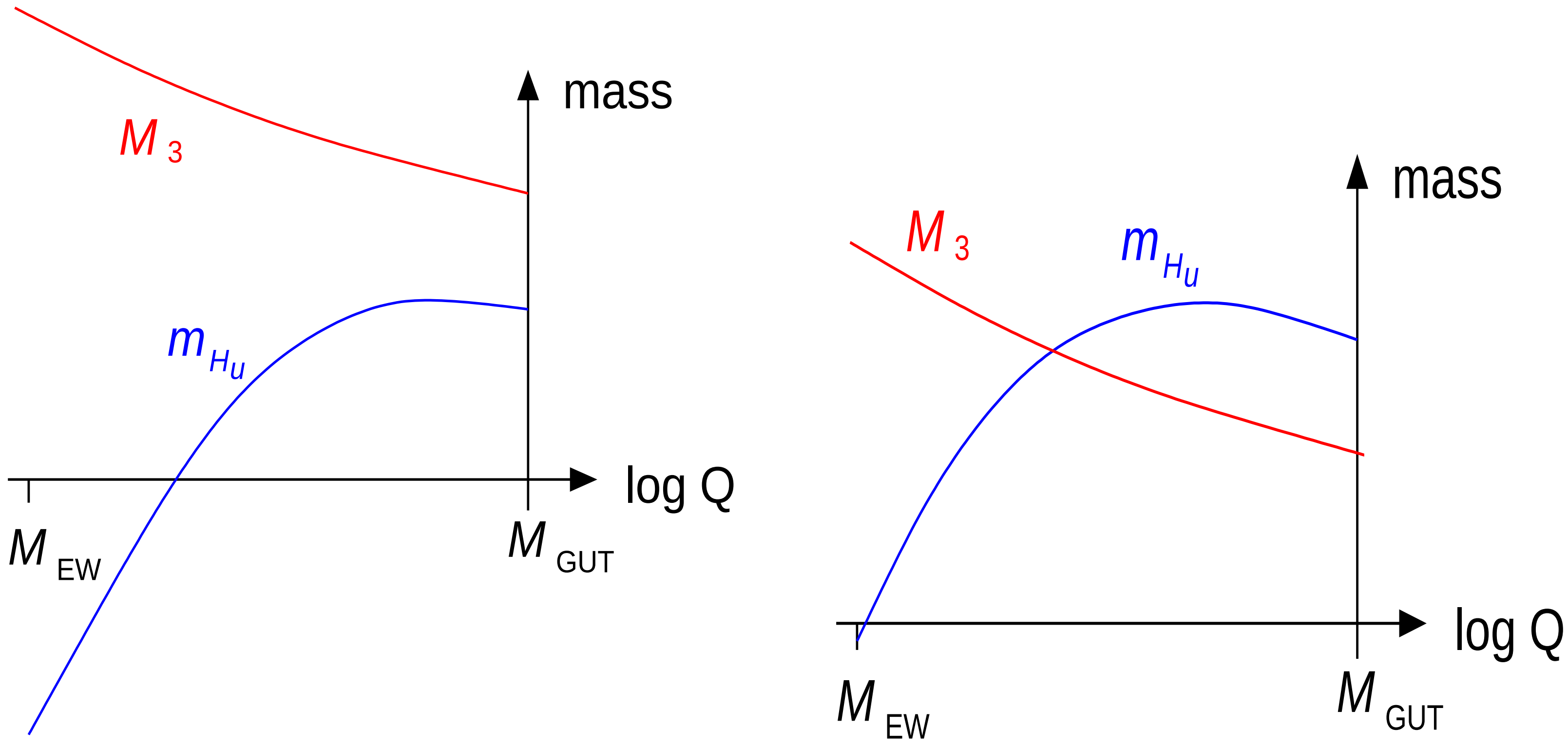
particle	mass [GeV]
h_0	117
χ_1^0	137
$\chi_1^\pm$	140
χ_2^0	144
χ_3^0	799
χ_4^0	1296
$\chi_2^\pm$	1296
H_0	856
A_0	857
$H^\pm$	861
$\tilde{g}$	1453
$\tilde{\tau}_1$	713
other sleptons	$910 - 1290$
squarks	$950 - 1750$

Peculiar low energy spectrum: light Higgs/higgsinos, all the rest heavy!

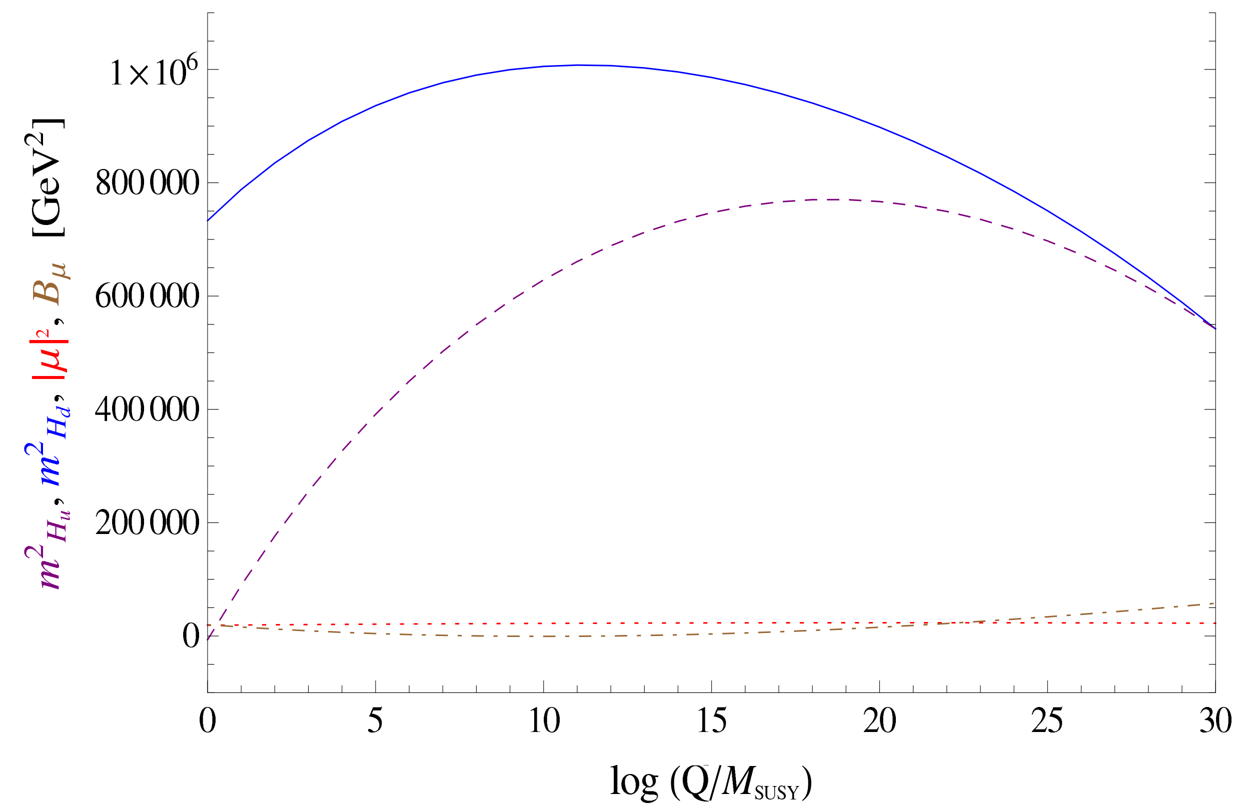


Renormalization group running for gauginos, scalar τ ($\tilde{\tau}_R$), and scalar tops ($\tilde{t}_R$, $\tilde{t}_L$); strong increase of gluino mass at electroweak scale

Radiative electroweak symmetry breaking: large top-Yukawa coupling drives $m_{H_u}^2$ negative



For 'large' gluino mass, $M_3^2 > m_{H_u}^2$, Higgs vev too large; only for 'small' gluino mass, $M_3^2 < m_{H_u}^2$, realistic Higgs vev possible!



Renormalisation group evolution of Higgs mass parameters: $m^2_{H_d}$, $m^2_{H_u}$, $|\mu|^2$, and B_μ. Fine tuning improved? Variation of big gauge-mediation terms in discrete steps of small gravity-mediation term? Only $m^2_{H_u}$ needs to be tuned ...

(3) Cosmology and phenomenology

Gravitino LSP with mass $\mathcal{O}(100)$ GeV is interesting dark matter candidate; for high reheating temperatures, required by thermal leptogenesis, thermal production of gravitinos can yield observed dark matter abundance for typical gluino masses. Potential problem: BBN constraints on late decays of NLSP.

Proposal: consistent cosmology with leptogenesis, gravitino dark matter and BBN with higgsino as NLSP (Bolz, WB, Plümacher '98). Old BBN constraints: $\Omega_{\tilde{h}} h^2 \lesssim 8 \cdot 10^{-3}$ for lifetimes $\tau_{\tilde{h}} \lesssim 2 \cdot 10^6$ s (Ellis et al '90); crucial analysis of WIMP abundances showed 'higgsino hole': BBN bound satisfied for higgsino masses $80 \text{ GeV} < m_{\tilde{h}} < 300 \text{ GeV}$ (Edsjo, Gondolo '97); lifetime constraint yields upper bound on gravitino mass.

Present BBN bounds on NLSP abundances and lifetimes are much more stringent; for dominant hadronic NLSP decays and lifetimes $\tau_{\rm NLSP} \gtrsim$

10^8 s (Kawasaki et al:04,Jedamzik:06):

$$\Omega_{\rm NLSP} h^2 \lesssim 1 \cdot 10^{-4} \quad \text{from} \quad {}^2\text{H} \ ,$$
$$\Omega_{\rm NLSP} h^2 \lesssim 3 \cdot 10^{-5} \quad \text{from} \quad {}^3\text{He} \ .$$

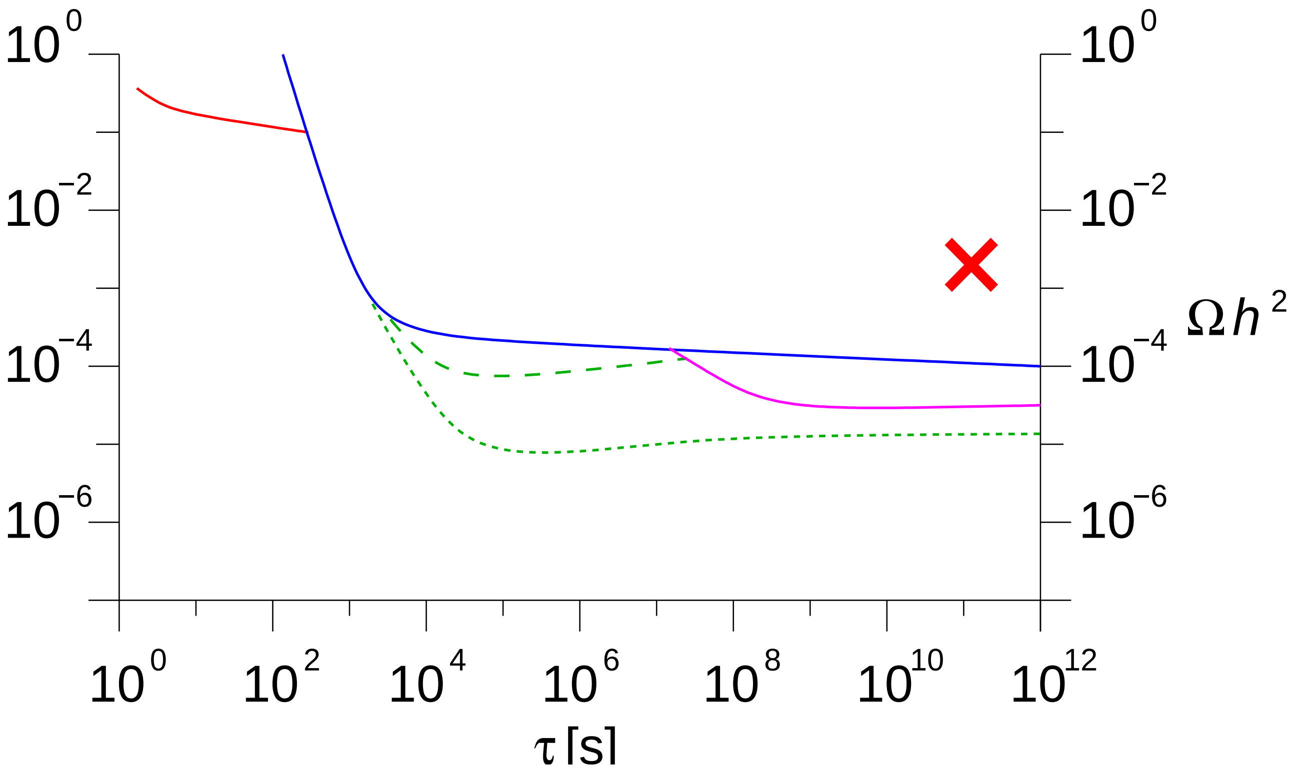
Difficult to satisfy for general neutralino NLSP (Covi et al:'09), requires NLSP masses above $2\ \text{TeV}$.

Our model: higgsino decays mostly hadronic; due to small mass degeneray 3-body decays dominate, yields long lifetime; small relic abundance from coannihilations with chargino:

$$\tau(\chi_1^0) \simeq 2 \cdot 10^{11}\ \text{s} \ , \quad \Omega_{\chi_1^0} h^2 = 3.2 \cdot 10^{-3} \ ;$$

present BBN bounds violated. Possible ways out: (How accurate are the BBN calculations?); small entropy production before BBN, small violation of R-parity, ...

Higgsino abundance is about four orders of magnitude smaller than typical bino-NLSP abundance:



LHC phenomenology: model difficult to test, since coloured states very heavy (consistent with present data!)

Closely related: arXiv:1107.5581, Baer, Barger & Huang, "Hidden SUSY at the LHC: the light higgsino-world scenario and the role of a lepton collider" (gravity mediation, even heavier squarks and gluino)

In principle possible: Drell-Yan production of higgsino pairs $\chi^0_{1,2}\chi^\pm_1$, $\chi^0_1\chi^0_2$, with subsequent 3-body decays, $\chi^\pm_1 \rightarrow l^\pm\nu\chi^0_1, q\bar{q}\chi^0_1$; $\chi^0_2 \rightarrow l^+l^-\chi^0_1, \nu\bar{\nu}\chi^0_1, q\bar{q}\chi^0_1$; problem: low p_T of final state particles.

Baer et al: very difficult at LHC because of QCD background, hope for ILC! We are more optimistic: focus on particular final states where background is suppressed, work in progress.

Also interesting: due to intermediate mass of χ^0_3 ('heavy bino'), 'medium' jet energies favoured in standard jets + MET searches.

OUTLOOK

- Supersymmetric GUTs in more than 4D attractive extrapolation of Standard Model

- Possible signatures: light scalar particles in connection with stabilization of GUT scale? Non-WIMP dark matter candidates? ...

- Further possibility: peculiar pattern of superparticle mass spectrum due to large number of split multiplets

- Hope: new results from the LHC!