Phenomenology of strong moduli stabilization

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Strong moduli stabilization and uplift

In KKLT models of moduli stabilization,

$$W_{\rm KKLT} = W_0 + Ae^{-a\rho}$$

the mass of the modulus is ($\sigma = Re\ \rho$)

$$m_\sigma \simeq 2a\ \sigma_0\ m_{3/2}$$

In order to have low (TeV) gravitino mass,

$a\ \sigma\ \sim\ 30$ so $m_\sigma \simeq 60\ m_{3/2}$

KKLT models of moduli stabilization have therefore a decompactification problem during inflation, when $H \geq m_{3/2}$

The simplest way to avoid this is to strongly stabilize the vacuum by making $m_\sigma \gg m_{3/2}$

This was achieved in the KL (Kallosh-Linde, 2004) scenario, where

$$W_{\rm KL} = W_0 + Ae^{-a\rho} - Be^{-b\rho}$$

For the fine-tuned value

$$W_0 = -A(\frac{aA}{bB})^{\frac{a}{b-a}} + B(\frac{aA}{bB})^{\frac{b}{b-a}}$$

there is a SUSY Minkowski minimum

$$W_{\rm KL}(\sigma_0) = 0 \ , \ D_\rho W_{\rm KL}(\sigma_0) = 0 \ , \ V(\sigma_0) = 0$$

One can now detune slightly ➡ add $\delta W_{\rm KL} = \Delta$

This will shift the minimum to an AdS one with

$$V_{AdS} = -3m_{3/2}^2 \text{ , where } m_{3/2}^2 = \frac{\Delta^2}{8\sigma^3} \ll 1$$

The mass of the modulus is

$$m_\sigma^2 = \frac{2}{9} W^2_{\rho,\rho}\sigma_0 = \frac{2}{9} a\, A\, b\, B\, (a-b) \left(\frac{aA}{bB}\right)^{-\frac{a+b}{a-b}} \ln\left(\frac{aA}{bB}\right)$$

and is typically very heavy $\quad m_\sigma \gg m_{3/2}$

The uplift essentially does not change the potential/mass. As a result, modulus contribution to SUSY breaking is very small

$$D_\rho W \sim \frac{m_{3/2}}{m_\sigma} m_{3/2}$$

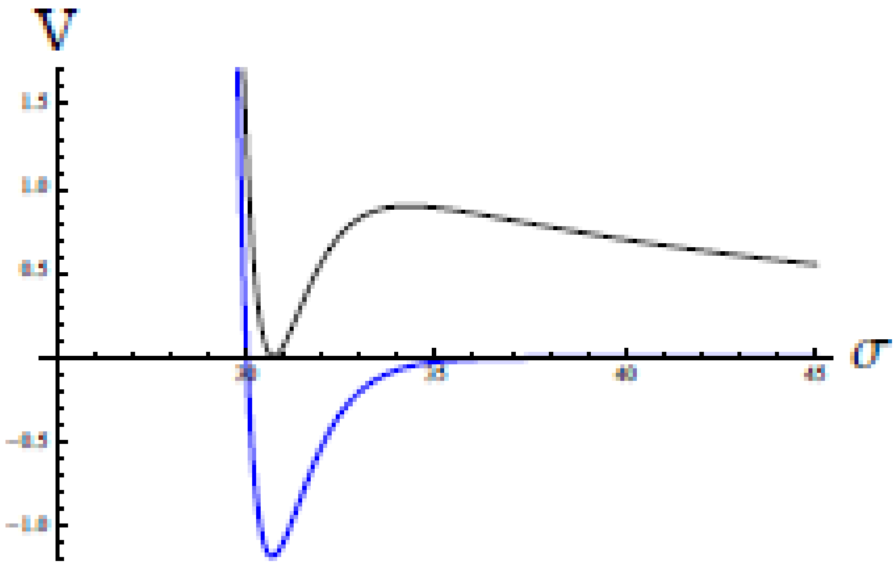

FIG. 1. Scalar potential of the KKLT model for the values of the parameters $A = 1$, $a = 1$ and $W_0 = 10^{-12}$ before and after uplifting. The potential has been multiplied by a factor of 10^{29} for clarity.

Figures taken from
Linde,Mambrini,Olive,
arXiv:1111.1465[hep-th]

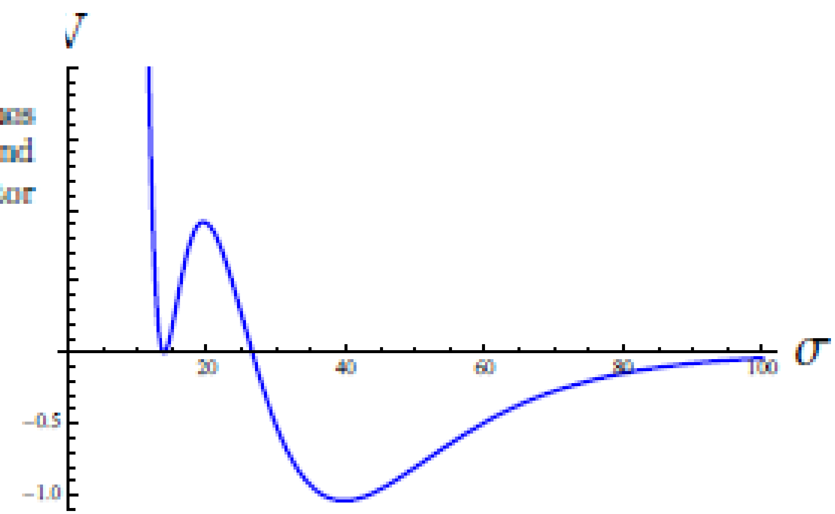

FIG. 2. Scalar potential of the KL model for the values of the parameters $A = B = 1$, $a = 0.1$, $b = 0.05$. The potential has been multiplied by a factor of 10^7 for clarity. The effect of uplifting is so small as compared to the height of the barrier in this model that one cannot distinguish an uplifted and non-uplifted potential on the scale of this figure.

Simplest uplift picture:

- F-term by a DSB or O'R sector, fields S, with a dynamical scale M
- The uplift sector breaks SUSY in the rigid limit
- it is coupled only by gravity to KL and MSSM sectors

$$
\begin{aligned}
W &= W_{\rm KL}(\rho) + W_F(S) + W_{MSSM}(\rho, \Phi^i) \\
K &= -3 \ln(\rho + \bar{\rho}) + K(S, \bar{S}) + K_{MSSM}(\rho, \bar{\rho}, \Phi^i, \bar{\Phi}^i)
\end{aligned}
$$

Provided KL modulus mass and uplift sector masses >> $m_{3/2}$, SUGRA interactions change the original KL and uplift sector dynamics in a very tiny way

(large literature starting with KKLT models: Lebedev, Nilles,Ratz; E.D.,Papineau,Pokorski; Koyabashi et al...)

Simplest examples of uplifts: O'KL and ISS.

Ex: O'KL

$$W_F(S) = M^2 S$$
$$K(S,\bar{S}) = S\bar{S} - \frac{(S\bar{S})^2}{\Lambda^2}$$

M=dynamical scale; Λ is an effective scale from integrating out heavy states.

In this case we get :

$$M^4 == 3\Delta^2 = 24\sigma_0^3 m_{3/2}^2 \quad , \quad \langle S \rangle = \frac{\sqrt{3}\Lambda^2}{6} \qquad << 1$$

$$m_S^2 = \frac{3\Delta^2}{2\sigma_0^3\Lambda^2} = \frac{12 m_{3/2}^2}{\Lambda^2} \gg m_{3/2}^2 \qquad \text{and}$$

$$D_S W \sim \sigma_0^{3/2}\, m_{3/2}$$

- Since both moduli and uplift fields are very heavy

$$m_\sigma \;,\; m_S \;\gg\; m_{3/2}$$

there are no cosmological (Polony) moduli problems.

- Cosmological gravitino problem is also solved for

$m_{3/2} \;\geq\; 30\; TeV$

Soft terms for matter fields

Soft terms for MSSM fields are given in general (for F-breaking) by

$$m^2_{i\bar{j}} = m^2_{3/2}\left(G_{i\bar{j}} - R_{i\bar{j}\alpha\bar{\beta}}G^\alpha G^{\bar{\beta}}\right) ,$$

$$(B\ \mu)_{ij} = m^2_{3/2}\left(2\nabla_i G_j + G^\alpha \nabla_i \nabla_j G_\alpha\right) ,$$

$$(A\ y)_{ijk} = m^2_{3/2}\left(3\nabla_i \nabla_j G_k + G^\alpha \nabla_i \nabla_j \nabla_k G_\alpha\right)$$

$$\mu_{ij} = m_{3/2}\ \nabla_i G_j\ ,$$

$$m^a_{1/2} = \frac{1}{2}(Re\ h_A)^{-1} m_{3/2}\ \partial_\alpha h_A\ G^\alpha\ ,$$

In our models with :

- strong moduli stabilization
- decoupling between uplift and matter fields

we find to a high accuracy $m_0^2 = m^2_{3/2}$, which fixes the universal scalar masses.

SUGRA contributions to A-terms and gaugino masses are very small, since $D_\rho W \ll m_{3/2}$, $\langle S \rangle \ll 1$

$$A \sim max\,(m_{3/2}\Lambda^2, \frac{m_{3/2}^2}{m_\sigma})$$

$$m_{1/2} \sim \frac{m_{3/2}^2}{m_\sigma}$$

The main contributions come from anomaly mediation:

$$m_{1/2}^a = \frac{b_a g_a^2}{16\pi^2}\frac{F^C}{C_0} \quad , \quad A_{ijk} = -\frac{\gamma_i + \gamma_j + \gamma_k}{16\pi^2}\frac{F^C}{C_0} \ .$$

where $$\frac{F^C}{C_0} = -\frac{1}{3}e^{K/2}K^{\alpha\bar{\beta}}K_\alpha \bar{D}_{\bar{\beta}}\bar{W} + m_{3/2} \simeq m_{3/2}$$

For the Higgs sector, we get

$$\mu = \mu_0 + m_{3/2} K_{12} \quad , \quad B\mu = (A_0 - m_{3/2})\mu_0 + 2m_{3/2}^2 K_{12}$$

where $\mu_0 = e^{K/2} W_{12}$ is the usual mu-term

and $m_{3/2} K_{12}$ is a Giudice-Masiero contribution

Soft Higgs masses are $m_1^2 = m_2^2 = m_{3/2}^2$ with our decoupling hypothesis. However, usually in string theory Higgses have a different origin compared to quarks/leptons. They could couple directly to the uplift field S, leading to non-universal Higgs masses.

- The spectrum is different compared to KKLT case (mixed modulus/anomaly: Choi,Falkowski,Nilles,Olechowski,2005), similar to « pure gravity mediation » : Ibe,Yanagida,2011.

Low-energy phenomenology

Radiative EWSB is problematic unless, either :

- we start the running of parameters at a scale

$M_{in} > M_{GUT}$ or

- start with non-universal Higgs masses at M_{GUT} .

In the paper we explore the first option (we expect similar results for the second option), for a minimal ex.

$$W_5 = \mu_\Sigma \,\mathrm{Tr}\,\hat{\Sigma}^2 + \frac{1}{6}\lambda' \,\mathrm{Tr}\,\hat{\Sigma}^3 + \mu_H \hat{\mathcal{H}}_1 \hat{\mathcal{H}}_2 + \lambda \hat{\mathcal{H}}_1 \hat{\Sigma} \hat{\mathcal{H}}_2$$
$$+ (\mathbf{h_{10}})_{ij} \hat{\psi}_i \hat{\psi}_j \hat{\mathcal{H}}_2 + (\mathbf{h_{\overline{5}}})_{ij} \hat{\psi}_i \hat{\phi}_j \hat{\mathcal{H}}_1 \,, \qquad (48)$$

where $\hat{\phi}_i$ ($\hat{\psi}_i$) correspond to the $\overline{\mathbf{5}}$ ($\mathbf{10}$) representations of superfields, $\hat{\Sigma}(\mathbf{24})$, $\hat{\mathcal{H}}_1(\overline{\mathbf{5}})$ and $\hat{\mathcal{H}}_2(\mathbf{5})$ represent the Higgs adjoint and five-plets. Here $i, j = 1..3$ are generation indices and we suppress the SU(5) index structure for brevity.

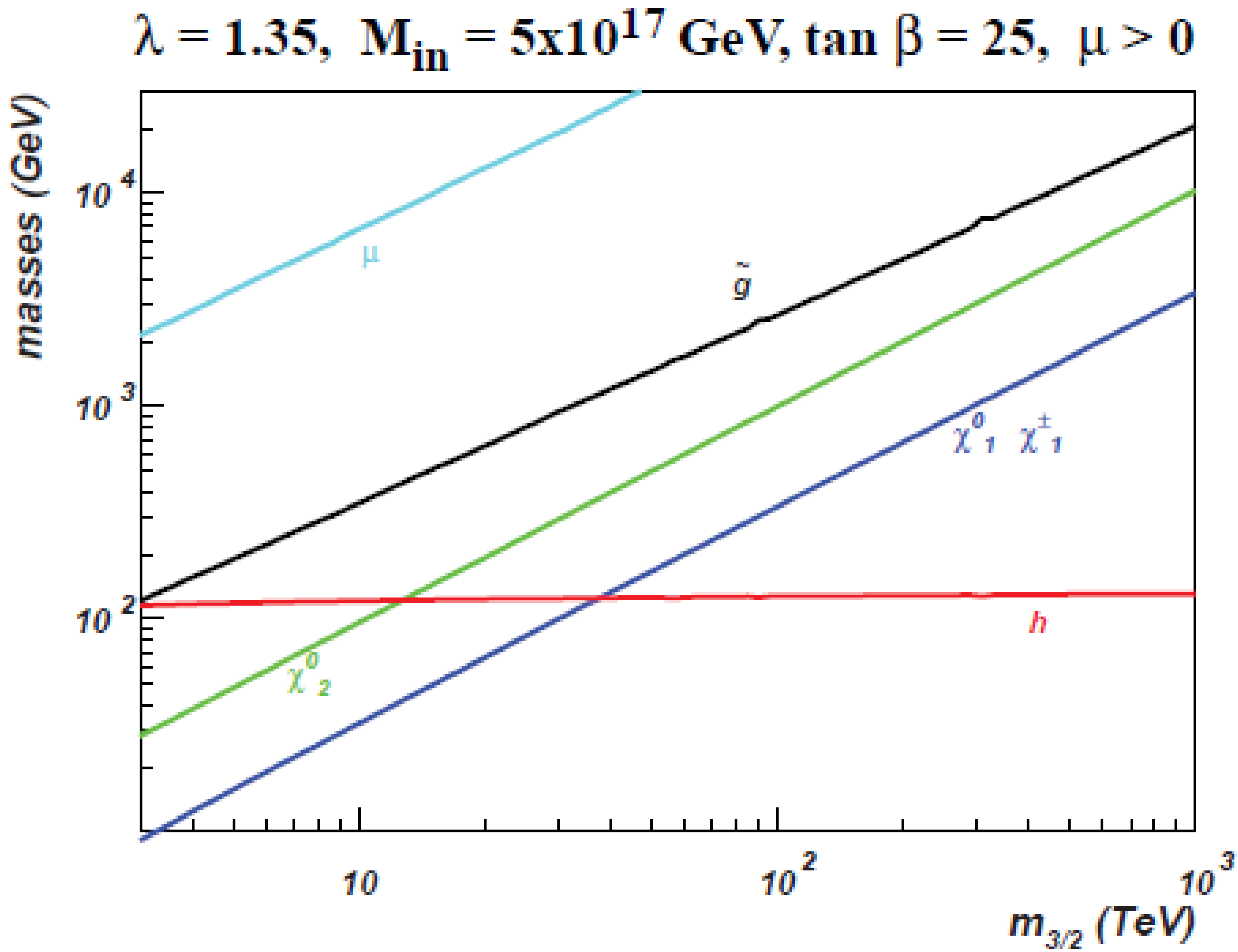

Fig. 1. *The gaugino and chargino masses and the μ-term as a function of the gravitino mass, $m_{3/2}$. Here we have chosen,* $\tan\beta = 25$, $M_{in} = 5 \times 10^{17}\ GeV$, $\lambda = 1.35$.

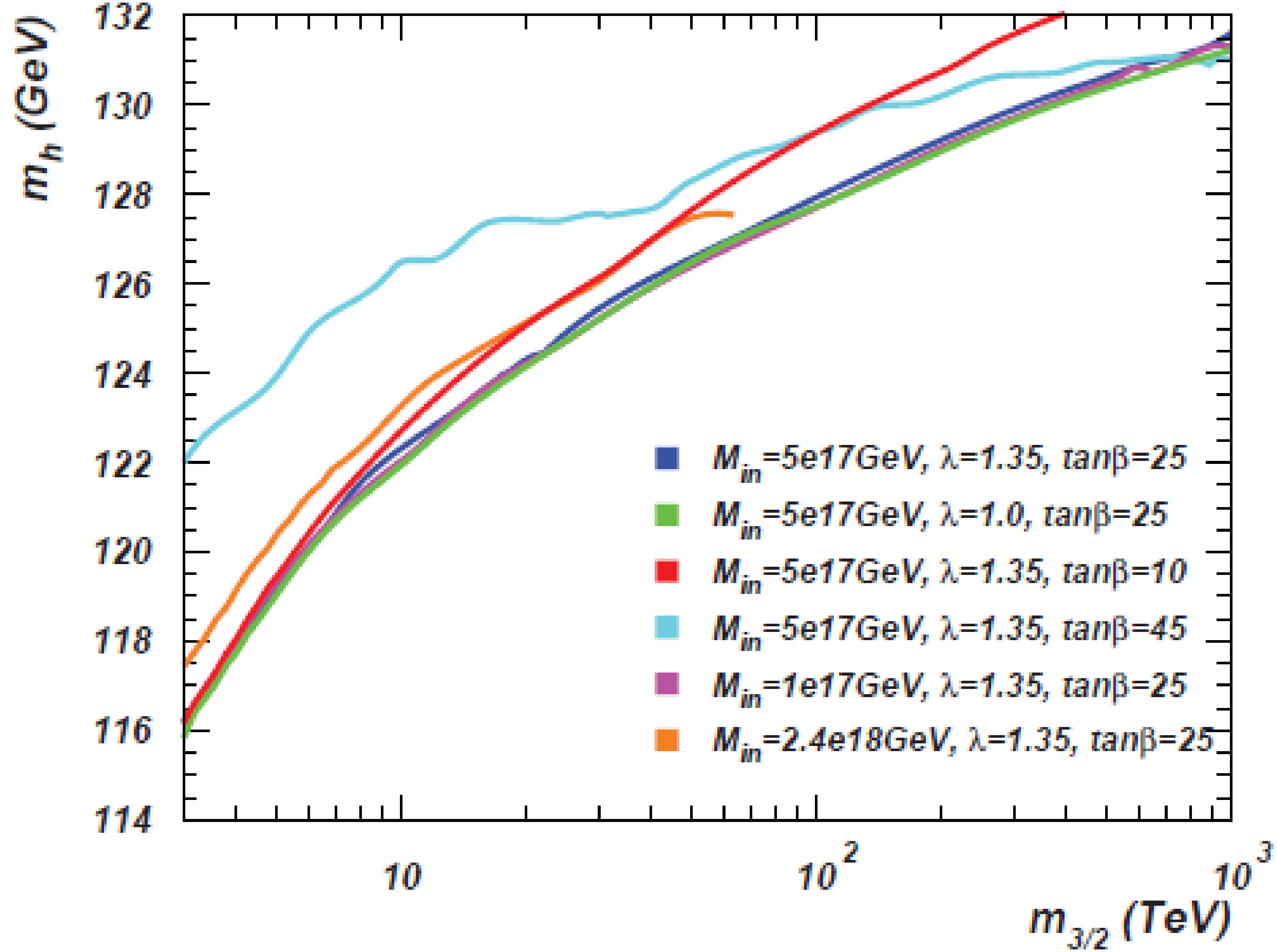

Fig. 2. *The Higgs mass as a function of the gravitino mass, $m_{3/2}$. Here we have chosen, several combinations of* $\tan\beta$*, M_{in}, and λ as indicated on the figure.*

- LEP chargino mass limit $m_{\chi^+} > 104\ GeV$

  implies $m_{3/2} \geq 31\ TeV$

- The Higgs mass at this value of $m_{3/2}$ is 125.3 GeV (slight dependence on $\tan\beta$).

- For $30\ TeV \leq m_{3/2} \leq 10^3\ TeV$ and reasonable values of the other parameters we find

$$125\ GeV \leq m_h \leq 130\ GeV$$

-Only light superpartners are: gauginos , bino and gluinos.

- The LSP is the neutral wino (anomaly-mediation)

parameter	1	2	3	4	5
$m_{3/2}$ [TeV]	32	50	100	500	1000
$m_{\tilde{g}}$ [TeV]	1.0	1.5	2.7	11.1	20.8
$m_{\tilde{\chi}_1}$ [GeV]	107	168	338	1705	3423
$m_{\tilde{\chi}_2}$ [GeV]	314	495	1000	5130	10400
$m_{\tilde{\chi}_3}$ [TeV]	22.0	34.9	70.7	367	745
$m_{\tilde{\chi}_4}$ [TeV]	22.0	34.9	70.7	367	745
$m_{\chi_1^+}$ [GeV]	107	168	338	1705	3420
$m_{\chi_2^+}$ [TeV]	22.0	34.9	70.7	367	745
$m_{\tilde{t}_1}$ [TeV]	24.2	38.0	77.2	397	803
$m_{\tilde{t}_2}$ [TeV]	26.8	42.1	84.6	428	860
$m_{\tilde{b}_1}$ [TeV]	26.9	42.1	84.7	428	860
$m_{\tilde{b}_2}$ [TeV]	30.6	47.9	96.0	483	969
$m_{\tilde{q}_L}$ [TeV]	31.4	49.2	98.5	494	990
$m_{\tilde{u}_R}$ [TeV]	31.5	49.3	98.7	495	990
$m_{\tilde{d}_R}$ [TeV]	31.6	49.4	98.9	496	992
$m_{\tilde{\tau}_1}$ [TeV]	29.6	46.2	92.3	459	917
$m_{\tilde{\tau}_2}$ [TeV]	31.2	48.7	97.5	488	978
$m_{\tilde{\nu}_\tau}$ [TeV]	31.2	48.7	97.5	488	978
$m_{\tilde{e}_L}$ [TeV]	31.9	49.8	99.6	498	996
$m_{\tilde{e}_R}$ [TeV]	32.0	50.0	100	500	1000
$m_{\tilde{\nu}_L}$ [TeV]	31.9	49.8	99.6	498	996
m_h [GeV]	125	127	128	131	132
μ [TeV]	20.4	32.3	65.0	333	673
m_A [TeV]	19.5	30.6	58.4	262	494
$\Omega_{\tilde{\chi}} h^2$	0.0003	0.0008	0.0030	0.067	0.26
$\sigma^{SI}(\chi_1 p) \times 10^{14}$ [pb]	4.74	1.81	0.44	0.02	0.003
$\sigma^{SD}(\chi_1 p) \times 10^{12}$ [pb]	6.78	0.94	0.04	0.0008	0.001

Table 1. Input parameters and resulting masses and rates for benchmark points with $M_{in} = 5 \times 10^{17}$ GeV, $\lambda = 1.35$, λ
$c_\Sigma = -0.85$, $\tan\beta = 25$, $\mu > 0$ and $m_t = 173.1$ GeV.

Dark matter relic density is generically too small. We presented three standard possibilities:

i) Non-thermal LSP's creation via gravitino decays. Thermal density comes out to be

$$\Omega_\chi h^2 = \frac{m_\chi}{m_{3/2}} \Omega_{3/2} h^2 = 0.4 (\frac{m_\chi}{\text{TeV}})(\frac{T_R}{10^{10}\text{GeV}}) .$$

Ex. that saturates WMAP

$$m_\chi \sim 100\ GeV\ ,\ T_R \sim 3 \times 10^{10}\ GeV$$

ii) Increase gravitino mass. Ex:

$$m_{3/2} \simeq 650\ TeV\ \Rightarrow\ \Omega_\chi h^2 \simeq 0.11$$

In this case higgs mass is 128.5 GeV, still possible.

iii) Dark matter is something else (axion ?)

Conclusions

Strong moduli stabilization addresses cosmological questions:

- destabilization of internal space during inflation
- Polony moduli and gravitino cosmological problems

- Our main hypothesis is decoupling of uplift sector

- LEP constraints on chargino mass and DM relic density ⟹ $30\ TeV \leq m_{3/2} \leq 650\ TeV$,

implying $125\ GeV \leq m_h \leq 128.5\ GeV$

- Low-energy spectrum: particular version of mini-split SUSY: gaugino masses and A-terms given by anomaly mediation, heavy higgsinos

- LHC signatures of strong moduli stabilization are difficult :

- no sizeable displaced vertices from gluinos decays
- small mass difference between chargino and LSP wino leads to very soft pions in the decay

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}^0 + \pi^+$$

which were argued to lead to observable charged track stubs.

Backup:

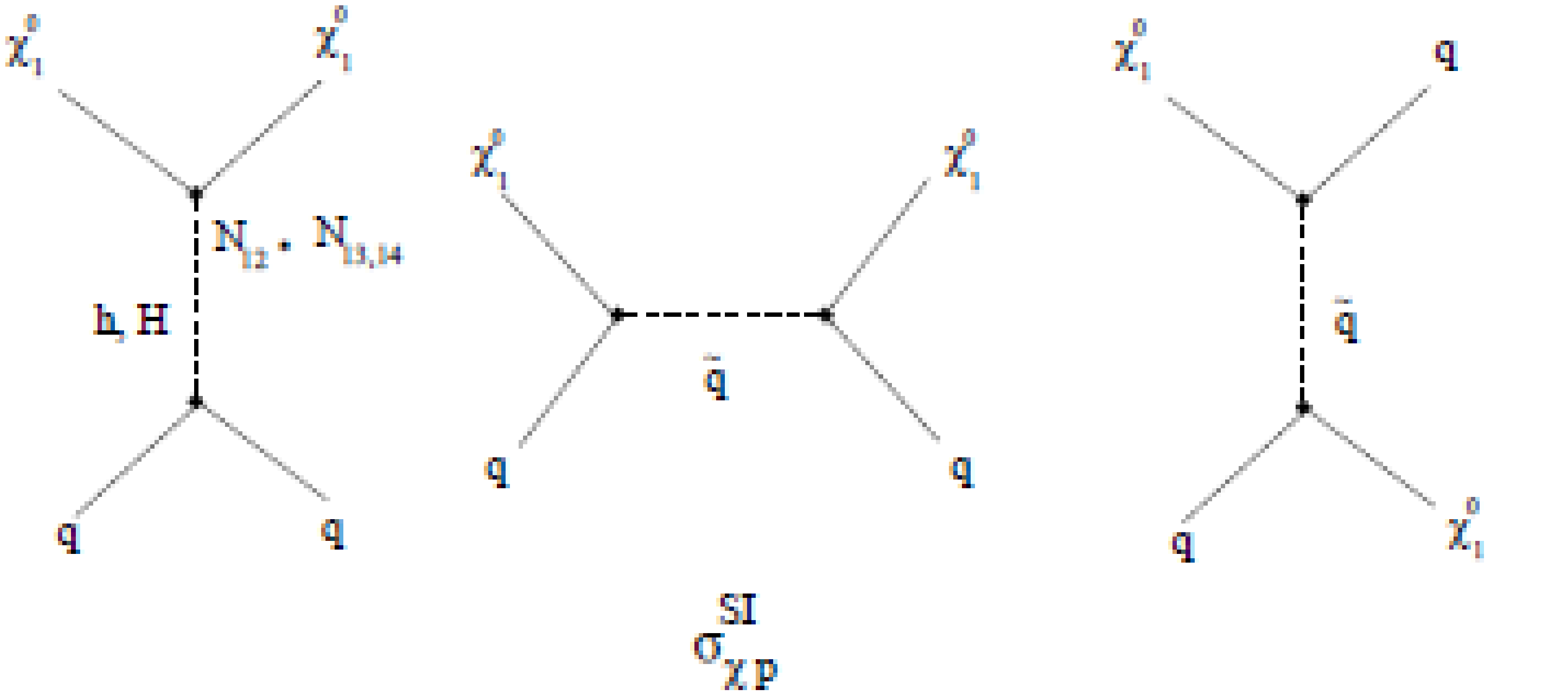

Fig. 5. *Direct detection processes for the neutralino-nucleon elastic scattering.*

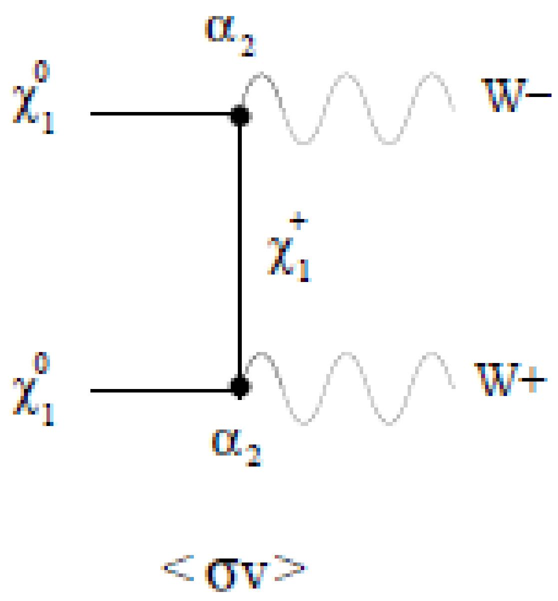

Fig. 6. *Main neutralino annihilation channel for indirect detection constraint imposed by FERMI.*

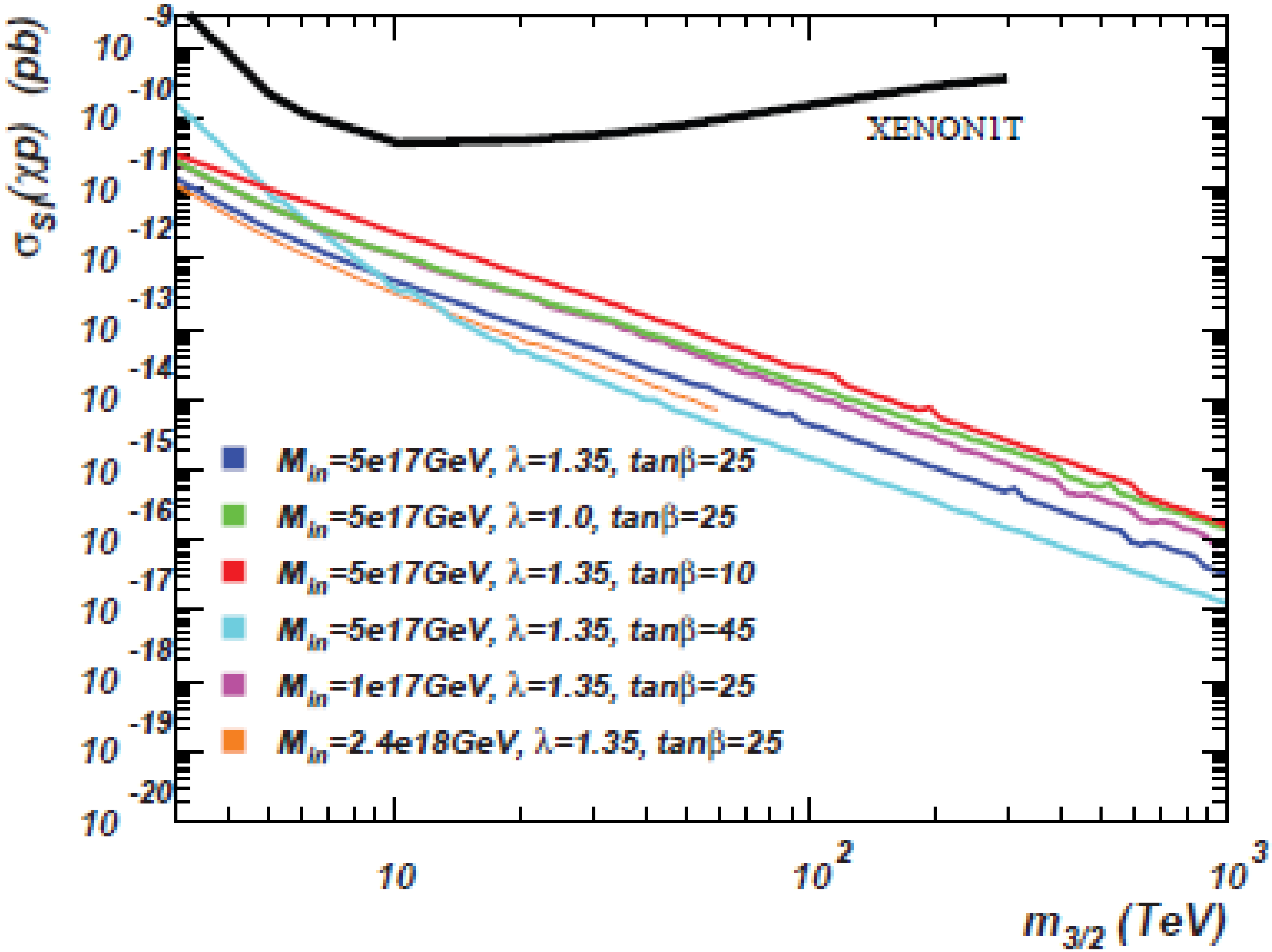

Fig. 7. *The spin independent elastic cross section, $\sigma_{\chi p}$, as a function of the gravitino mass, $m_{3/2}$. Also shown is the projected limit for a XENON-1 ton detector [78].*