MODULI, ANOMALOUS U(1) AND LHC PHENOMENOLOGY

E. DUDAS[1,2], Y. MAMBRINI[2], S. POKORSKI[3], A. ROMAGNONI[2,1]
[1] *CPhT, Ecole Polytechnique 91128 Palaiseau Cedex, France*
[2] *Laboratoire de Physique Théorique, Université Paris-Sud, F-91405 Orsay, France*
[3] *Institute of Theoretical Physics, Warsaw University, Hoza 69, 00-681 Warsaw, Poland*

In these proceedings we present a phenomenological model of moduli stabilization where the uplift of the cosmological constant to zero is provided by a Fayet-Iliopoulos sector. In the presence of an extra anomalous U(1) gauge symmetry, fields with the same features of the "messengers" in gauge-mediation scenarios are naturally introduced. The original phenomenology induced at low-energy in this kind of mixed gravity-gauge mediation presents a superpartners spectrum efficiently compressed and a good dark matter relic density compatible with WMAP bounds.

1 Introduction

A quite general result concerning the high-energy models in the presence of extra-dimensions, it's that when one reduces to the four dimensional space time, new fields appear in the model, often parametrizing flat directions. This kind of fields are called moduli. For example, in the following, the modulus T will be the superfield representing the fluctuations of the overall internal volume. Since the vev of the moduli are strictly related to physical parameters, it is compelling to find a mechanism to provide them a potential in order to properly define a minimum.
Recently, Kachru et al. [1] (KKLT) proposed a strategy to stabilize the moduli in the context of Type IIB string theory orientifold, following earlier work [2]. The KKLT set-up involves different logical steps to achieve a supersymmetry breaking Minkowski vacuum, while stabilizing all moduli. All steps except the last one (uplifting the vacuum energy through the addition of anti D3-branes) can be understood within the context of an effective supergravity. Other works changed this point by insisting on the possibility of using F-terms or D-terms of matter fields in a decoupled sector to perform the uplift. In this proceedings we will show an alternative way to obtain de Sitter space with a TeV gravitino mass by using a Fayet-Iliopoulos (FI) model as uplift sector [3].

It is important to stress that this kind of approach is not an attempt to solve the problem of the cosmological constant, but instead it is meant to be a pragmatic program: The aim is to look at the low-energy phenomenology starting from a high-energy model, imposing some constraints due to consistency requirements and fixing some basic phenomenological inputs (like $\Lambda_c = 0$ and the value of the mass of the gravitino).
The peculiarity of our model is due to the presence of one extra $U(1)_X$ gauge symmetry in the game. This kind of symmetry appears in a very natural way in many compactification of extra-dimensional models, and in the most general case, all the fields entering in the stabilization and uplifting procedure can be charged under it.
More precisely the $U(1)_X$ transformations for the gauge superfield V_X, the matter chiral superfields Φ_i and the modulus T have the form:

$$\delta V_X \;=\; \Lambda_X + \bar{\Lambda}_X \quad , \quad \delta \Phi_i \;=\; -2 q_i \Phi_i \Lambda_X \;, \qquad \delta T \;=\; \delta_{GS} \Lambda_X \;, \tag{1}$$

where q_i are the charges of the fields Φ_i and δ_{GS} a suitable constant. Gauge invariance forces the Kahler potential for the modulus T to be of the form $K(T + \bar{T} - \delta_{GS} V_X)$ and this leads in turn to the FI term

$$\xi_{FI} \;=\; \frac{3\delta_{GS}}{2} \frac{1}{T + \bar{T}} \quad . \tag{2}$$

The presence of this T-dependent FI term is crucial, because the corresponding non-vanishing D-term, even if it doesn't change directly the cosmological constant, at the same time induces the suitable F-terms performing the uplift and play an important role for the corresponding low-energy phenomenology.

2 Uplifting and Gravity mediation

2.1 The model

The supergravity model we focus on, is defined in terms of the modulus T and two scalar fields $\Phi_\pm$ of opposite charges under $U(1)_X$, by the superpotential:

$$W \;=\; W_0 \; + m \; \phi_+ \phi_- + a \; \phi_-^q \; e^{-bT} \; . \tag{3}$$

In the presence of a charged modulus T, the last term in Eq. 3 is the right gauge invariant version of the KKLT gaugino condensation contribution to the superpotential. The usual negative W_0 constant, the presence of the charged fields $\Phi_\pm$, their mass term and the interaction term between T and Φ_-, are motivated by stringy argument and can be microscopically defined in the type IIB orientifold setup, in terms of fluxes, intersecting branes and stringy instantons effects.

Using a conventional Kahler potential of the form [a] $K = |\phi_+|^2 + |\phi_-|^2 - 3\ln(T + \overline{T})$ and considering a region of the parameters space where

$$\delta_{GS} \;\sim\; 1 \quad , \quad m \ll M_P \quad , \quad W_0 \ll M_P^3 \quad , \quad a \; e^{-bT} \;\ll\; W_0 \;\ll m \tag{4}$$

hold, the minimization of the scalar potential given by standard supergravity formula in terms of the auxiliary fields [b] F_i and D

$$V(\phi_+, \phi_-, T) = F^T F_T + F^- F_- + F^+ F_+ + \frac{g_X^2}{2} D^2 - 3 e^K |W|^2 \tag{5}$$

[a] The Kahler metric of the charged fields $\Phi_\pm$ can be more complicated and can also depend on T. We checked explicitly that with the Kahler potential $K = -3\ln(T + \bar{T} - |\Phi_-|^2 - |\Phi_+|^2)$ we obtain very similar results.

[b] Here we use the definitions $F_i = e^{K/2} D_i W$ and $D = K_+ \Phi_+ - K_- \Phi_- + \xi_{FI}$. As usual, the indices are raised and lowered by using the Kahler metric.

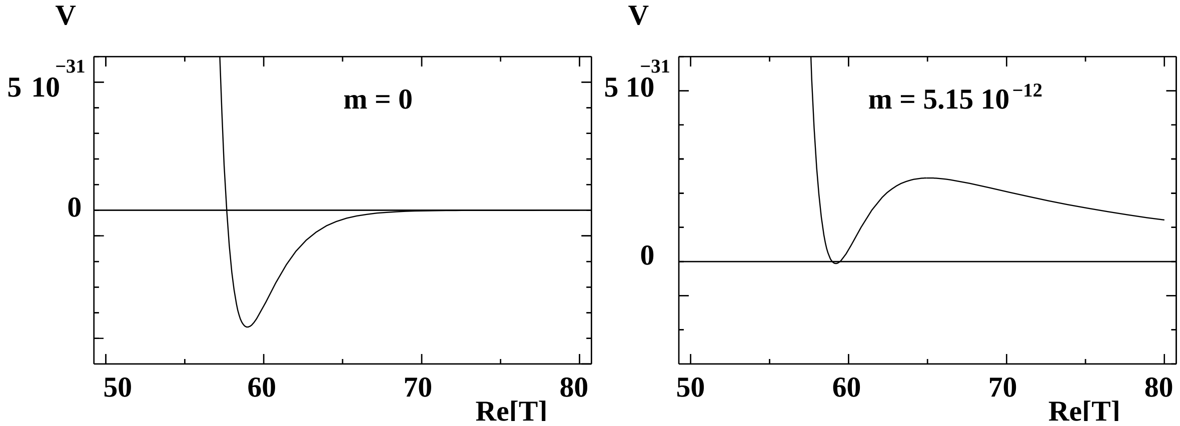

Figure 1: Scalar potential (in M_P units) for $m = 0$ (left) and $m \neq 0$ (right) for a gravitino mass of 3.3 TeV. The other parameters are determined by gauge invariance conditions, minimization of the potential and $\Lambda_c = 0$.

shows that the vacuum of the theory breaks supersymmetry. Moreover it can give a zero cosmological constant Λ_c if the parameters m and W_0 satisfy $|m\phi_-| \simeq \sqrt{3}\,|W_0|$, considering that the vev of Φ_- is fixed proportional to ξ_{FI} by the FI mechanism. In Fig. 1 we show the shape of the scalar potential in the two cases $m = 0$ and m tuned in order to have $\Lambda_c = 0$. In our case the uplift of the AdS to a Minkowski vacuum is mainly provided by F_+, but the crucial point is that this is induced by the non-vanishing D-term. Moreover, since the superpotential for T is not completely decoupled from the supersymmetry breaking sector, due to the interaction term with Φ_-, F_T is bigger than the values obtained in typical sequestered F-term uplifting models, even if the numerical value for T is very close to its supersymmetric solution.

2.2 First phenomenological results

Even if the supersymmetry is broken in a hidden sector, (super)gravity interactions communicate this breaking to the observable sector, that we take for simplicity to be the Minimal Supersymmetric Standard Model (MSSM). In particular, irrespective on the string theory brane configuration giving our model as effective field theory, if magnetic fluxes are turned on, the coupling constants of the MSSM gauge fields contain a T-dependence. This implies that under very general assumptions, a mass for the gaugino fields is directly provided,and it as the form

$$(M_a)_{\text{grav.}} \simeq \frac{F^T}{T} \,. \tag{6}$$

Concerning the scalars soft masses, the relevant quantity for computing the soft terms is the coupling of the matter fields metric $K_{i\bar{j}}$ to the SUSY breaking fields. This can in turn be parameterized as

$$K_{i\bar{j}} = (T+\overline{T})^{n_i}\left[\delta_{i\bar{j}} + (T+\overline{T})^{m_{ij}}|\phi_+|^2 Z'_{i\bar{j}} + (T+\overline{T})^{p_{ij}}|\phi_-|^2 Z''_{i\bar{j}} + (T+\overline{T})^{l_{ij}}(\phi_+\phi_- Z'''_{i\bar{j}} + \text{h.c}) + O(|\phi_i|^4)\right], \tag{7}$$

but the final results is quite simple:

$$(\tilde{m}^2_{0\;i\bar{j}})_{\text{grav.}} = m^2_{3/2}\left[\delta_{i\bar{j}} + (\ldots)\right]. \tag{8}$$

Here $(\ldots)$ represents subleading terms if the weights n_i and m_{ij} satisfy the relation $r_{ij} = m_{ij} + (n_i - n_j)/2 \leq -1$. Actually this relation is strongly motivated from the string theory point of view, and the only dangerous case is $r_{ij} = 0$, where a flavour dependence and FCNC

effects could arise.
The first important result is that in our non completely decoupled model, F^T is greater than the usual KKLT-like models and we obtain a splitting between the scalar and gaugino masses smaller by a factor of two. Nonetheless this implies that the one-loop contributions (AMSB) are less important here compared to the tree-level ones.
Finally, in the presence of gravity mediation, trilinear couplings are produced in a similar way and the μ and B_μ parameters for the Higgs sector can be generated at the TeV scale through a Giudice-Masiero mechanism [4].

3 Anomalies and Mixed mediation

3.1 Anomalies and messengers

As introduced in the previous section, the T-modulus transforms under the extra anomalous $U(1)_X$. Moreover, in a very generic way, it is related to the MSSM gauge coupling via a dependence on T of the gauge kinetic functions. Therefore this implies that under $U(1)_X$ gauge transformation, mixed $U(1)_X$ - G_a^2 anomalous terms are produced (with G_a subgroup of the SM gauge group) and a chiral spectrum is required. More precisely, there should be fields carrying Standard Model quantum numbers charged under the additional $U(1)_X$.
Since quarks and leptons carrying $U(1)_X$ charge should imply various phenomenological problems (related to very large soft masses), the most natural possibility is to keep uncharged under $U(1)_X$ the SM fields and to introduce additional heavy fields with the right quantum numbers. These fields have exactly the features of the "messengers" fields in gauge-mediated scenario [5] (GMSB).
Since the cancelation of the anomaly implies a positive $U(1)_X$ charge for the messengers [c] M and $\tilde{M}$, a natural gauge invariant superpotential is

$$W_{\rm mess} = \lambda \phi_- M \tilde{M} \ , \tag{9}$$

which naturally pushes the messenger scale up to the GUT scale.
In the usual gauge mediated scenario, adding messengers to a supersymmetry breaking sector generates a new supersymmetric vacuum. However, in our case, the vacuum presented in the previous section is preserved by $U(1)_X$.
Nonetheless another very important new point with respect to the standard gauge-mediation concerns the contribution to the scalar masses. Indeed, as pointed out by Poppitz and Trivedi [6], when the supertrace of the messenger mass matrix is non-vanishing, a new UV divergent term appear at the quantum level and play a very crucial role in what follows.
More precisely, in our case the supertrace is proportional to the $U(1)_X$ D-term:

$$(StrM^2)_{\rm mess.} \ = \ 2 \ g_X^2 \ D \ = \ \frac{2m^2}{(T+\bar{T})^3} \ \neq \ 0 \ . \tag{10}$$

While this does not affect the GMSB one-loop contribution for the gaugino masses,

$$M_a^{\rm GMSB} \simeq \frac{m}{(T+\bar{T})^{3/2}} \frac{g_a^2}{16\pi^2} \left(\frac{\phi_+}{\phi_-} \right) \ , \tag{11}$$

it changes significantly the two-loop soft masses for the scalar superpartners

$$(\tilde{m}_0^{\rm GMSB})^2 \simeq \frac{m^2}{(T+\bar{T})^3} \sum_a \frac{g_a^4}{128\pi^4} C_a \left[1 - \log \left(\frac{\Lambda_{\rm UV}}{\lambda \phi_-} \right)^2 + \left(\frac{\phi_+}{\phi_-} \right)^2 \right] \ , \tag{12}$$

[c] The messengers fields are chosen in a complete vector-like SU(5) in order to preserve the perturbative gauge coupling unification.

Table 1: Low energy sample spectra for two different choices of the high-energy parameters, in both the cases of simple gravity and mixed gravity-gauge mediation. All superpartner masses are in GeV, whereas W_0, m and t are in Planck units. The last line correspond to the relic abundance, within WMAP bounds in each case.

	(A) Gravity	**(A) Mixed**	**(B) Gravity**	**(B) Mixed**
W_0	$-7\ 10^{-13}$	$-7\ 10^{-13}$	$-4.3\ 10^{-13}$	$-4.3\ 10^{-13}$
m	$7.3\ 10^{-12}$	$7.3\ 10^{-12}$	$3.1\ 10^{-12}$	$3.1\ 10^{-12}$
a	1	1	1	1
b	0.3	0.3	0.5	0.5
q	1	1	1	1
$\tan\beta$	30	30	15	15
t	97.3	97.3	60.2	60.2
λ	0	$1.7\ 10^{-3}$	0	$1.1\ 10^{-3}$
N_{Mess}	0	6	0	6
μ (GeV)	810	186	1070	216
$B\mu\ (GeV)^2$	$(400)^2$	$(330)^2$	$(870)^2$	$(730)^2$
$m_{\chi_1^0}$	110	120	140	150
$m_{\chi_1^+}$	220	160	290	200
$m_{\tilde{g}}$	760	850	950	1060
m_h	120	120	120	120
m_A	2220	1740	3290	2770
$m_{\tilde{t}_1}$	1380	990	1770	1220
$m_{\tilde{t}_2}$	1920	1280	2610	1710
$m_{\tilde{c}_1},\ m_{\tilde{u}_1}$	2580	1950	3300	2420
$m_{\tilde{b}_1}$	1910	1250	2610	1700
$m_{\tilde{b}_2}$	2310	1930	3230	2690
$m_{\tilde{s}_1},\ m_{\tilde{d}_1}$	2580	1950	3300	2420
$m_{\tilde{\tau}_1}$	2290	2130	3200	2870
$m_{\tilde{\tau}_2}$	2420	2160	3230	2960
$m_{\tilde{\mu}_1},\ m_{\tilde{e}_1}$	2550	2290	3270	2910
Ωh^2	–	0.12	–	0.12

where C_a is the Casimir in the MSSM scalar fields representations. From a low energy - GMSB point of view, the logarithmic divergence shows the scale beyond which "new physics" occurs, since there the scalars can become tachyonic. In our case, we can take Λ_{UV} as the Planck scale, and for suitable values of λ the GMSB contribution is actually negative.

3.2 Phenomenology

Once the messengers are introduced in the model, in the complete framework scalar and gaugino masses get contributions both from gravity and gauge mediation diagrams

$$\begin{aligned}(\tilde{m}_0^2) &= (\tilde{m}_0^2)_{\text{grav.}} + N_{\text{Mess}}(\tilde{m}_0^{\text{GMSB}})^2 \ , \\ M_a &= (M_a)_{\text{grav.}} + N_{\text{Mess}}(M_a^{\text{GMSB}}) \ . \end{aligned} \tag{13}$$

The negative contibution to $\tilde{m}_0^2$ induced by the UV divergence has strong consequences on the mass spectrum and the phenomenology of the model. Indeed, first of all, the spectrum is generically "compressed", since the values of the gaugino masses are increased whereas the

scalars ones decreased. Moreover, since the GMSB negative contributions are proportional to the SM charges of the scalars, the squarks are more sensitive than sleptons to them, whereas the gravitational contribution is universal, as shown above. The result of this interplay is shown in Table 1, where two different point in the space of the high-energy parameters are chosen (together with the value of the coupling λ and the number of messengers $N_{\rm Mess}$) and the comparison between the simple gravity mediated model and the complete one is shown. The low-energy mass spectrum is calculated using the Fortran package `SUSPECT`[7].
In addition, also the nature of the neutralino is considerably altered. Indeed, decreasing the value of m^2_{U3} and m^2_{Q3} affects the RG equation for $m^2_{H_2}$ and consequently one can have a smaller value for μ^2. In this case the lightest neutralino is generally higgsino-like or a mixed bino-higgsino state and a good value for the relic abundance, compatible with WMAP bounds, is obtained, whereas this is not possible in the simple gravity mediated models, as computed using the routines provided by the program `micrOMEGAs2.0`[8].

Acknowledgments

Work partially supported by the CNRS PICS # 2530 and 3059, RTN contracts MRTN-CT-2004-005104 and MRTN-CT-2004-503369, the European Union Excellence Grant, MEXT-CT-2003-509661 and the European contract MTKD-CT-2005-029466. E.D. would like to thanks the financial support via the "Marie Curie Host Fellowship for Transfer of Knowledge" MTKD-CT-2005-029466. The work of Y.M. is sponsored by the PAI program PICASSO under contract PAI–10825VF. He would like to thank the European Network of Theoretical Astroparticle Physics ILIAS/N6 under contract number RII3-CT-2004-506222 and the French ANR project PHYS@COLCOS for financial support. The work of A.R. was partially supported by INFN and by the European Commission Marie Curie Intra-European Fellowships under the contract N 041443.

References

1. S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi, *Phys. Rev.* D **68** (2003) 046005 [arXiv:hep-th/0301240].
2. S. B. Giddings, S. Kachru and J. Polchinski, *Phys. Rev.* D **66** (2002) 106006 [arXiv:hep-th/0105097].
3. E. Dudas, Y. Mambrini, S. Pokorski and A. Romagnoni, *JHEP* **0804** (2008) 015 [arXiv:0711.4934 [hep-th]].
4. G. F. Giudice and A. Masiero, *Phys. Lett.* B **206** (1988) 480.
5. G. F. Giudice and R. Rattazzi, *Phys. Rept.* **322** (1999) 419 [arXiv:hep-ph/9801271].
6. E. Poppitz and S. P. Trivedi, *Phys. Lett.* B **401** (1997) 38 [arXiv:hep-ph/9703246].
7. A. Djouadi, J. L. Kneur and G. Moultaka, *Comput. Phys. Commun.* **176** (2007) 426 [arXiv:hep-ph/0211331].
8. G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *Comput. Phys. Commun.* **176** (2007) 367 [arXiv:hep-ph/0607059] ;
   See also the web page http://wwwlapp.in2p3.fr/lapth/micromegas .