Non-thermal Dark Matter and Moduli/Gravitino Problem in M theory

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Cosmological Moduli and Gravitino Problems

- When moduli decay, they produce radiation and reheat the Universe
- For TeV scale moduli this often leads to a reheating temperature of order MeV
- This spoils the successes of Big Bang Nucleosynthesis
- For heavier moduli this problem naively goes away
- BUT, such moduli can decay into gravitinos which also spoil BBN
- Furthermore, moduli decays could easily produce too much Dark Matter
- G. Coughlan, W. Fischler, E. Kolb, S. Raby,G. Ross (1983). J. Ellis, D. Nanopoulos and M. Quiros,(1986). M. Endo, K. Hamaguchi and F. Takahashi, [arXiv:hep-ph/0602061]. S. Nakamura and M. Yamaguchi, [arXiv:hep-ph/0602081].

- In a series of papers we have shown that that strong dynamics in the hidden sector both stabilises all the moduli of M theory and generates a small scale of susy breaking
- B. S. A, K. Bobkov, G. Kane, P. Kumar and D. Vaman, *An M theory solution to the hierarchy problem,* Phys. Rev. Lett. 97, 191601 (2006) [arXiv:hep-th/0606262].
- B. S. A, K. Bobkov, G. Kane, P. Kumar and J. Shao, *Explaining the electroweak scale and stabilizing moduli in M theory,* Phys. Rev. D 76, 126010 (2007) [arXiv:hep-th/0701034].
- B. S. A, K. Bobkov, G. Kane, J. Shao and P. Kumar, *The G2-MSSM - An M Theory motivated model of Particle Physics* arXiv:0801.0478
- Todays talk is based on B. S. A, K. Bobkov, G. Kane, P. Kumar, J.Shao, S.Watson, *Non-thermal Dark Matter and the Moduli Problem in String Frameworks* JHEP 0806:064,2008 arXiv:0804.0863

$$
\begin{aligned}
K/m_p^2 &= -3\ln(4\pi^{1/3}V_7) + \bar{\phi}\phi, \quad V_7 = \prod_{i=1}^{N} s_i^{a_i} \\
W &= m_p^3 \left(C_1\, P\, \phi^{-(2/P)}\, e^{ib_1 f_1} + C_2\, Q\, e^{ib_2 f_2} \right);\ b_1 = \frac{2\pi}{P},\ b_2 = \frac{2\pi}{Q} \\
f_1 &= f_2 \equiv f_{\rm hid} = \sum_{i=1}^{N} N_i\, z_i;\ z_i = t_i + i s_i. \qquad (1) \\
s_i|_{vac} &= \frac{a_i}{N_i}\frac{3}{14\pi}\frac{P_{eff}\, Q}{Q-P} + \mathcal{O}(P_{eff}^{-1}), \qquad (2) \\
|\phi|^2|_{vac} &= 1 - \frac{2}{Q-P} + \sqrt{1 - \frac{2}{Q-P}} + \mathcal{O}(P_{eff}^{-1}), \qquad (3)
\end{aligned}
$$

where $P_{eff} \equiv P\ln(C_1/C_2)$.

G_2-MSSM Spectrum

- MSSM matter content plus $N+1$ scalars - N G_2 Moduli X_i plus a "Meson" ϕ.
- N is roughly $\mathcal{O}(50)$ - $\mathcal{O}(100)$
- Gauginos are the lightest BSM particles $M_a \sim \kappa m_{3/2}$. ($\kappa \sim 0.01$) – ϕ dominates susy breaking, at leading order gauge couplings independent of ϕ
- MSSM scalars and Higgsinos have masses of order $m_{3/2}$
- $N-1$ light moduli X_i and ϕ have masses $\leq 2m_{3/2}$
- Heavy modulus X_N has mass order $600m_{3/2}$
- *Wino is typically the LSP.*
- Experimental bound on lightest neutralino 46 GeV $\longrightarrow m_{3/2} > 5TeV$
- We typically take $m_{3/2} \sim \mathcal{O}(10-100)$TeV.
- *Note that thermal production of Winos gives too little Dark Matter*
- T. Moroi and L. Randall, *Wino cold dark matter from AMSB,* [arXiv:hep-ph/9906527] considered similar models with important differences eg we have a hierarchy of moduli masses and decay widths.

Moduli Decays and DM: Basic Idea

- In the early Universe, moduli start to oscillate when Hubble, $H \sim m_X$
- Then when $H \sim \Gamma_X$, the decay width, the moduli decay
- They decay into Standard Model and supersymmetric particles
- Since the LSP is stable, the wino's produced in this process are still present today
- This is not the usual "Thermal Relic Density" idea
- Thermal production of Wino's gives too little Dark Matter

Moduli Decays

- Decays paramaterized by width $\Gamma_X = \frac{d_X m_X^3}{m_p^2}$
- Explicit calculation reveals that d_X order one for X_i but order 700 for ϕ.

Modulus	Mass ($m_{3/2} = 50 \quad$ TeV)	Oscillation Time (s)
X_N	$m_{X_N} = 600\ m_{3/2}$	$t_{osc}^{X_N} = 2 \times 10^{-32}$
X_ϕ	$m_\phi \lesssim 2\ m_{3/2}$	$t_{osc}^{\phi} = 7 \times 10^{-30}$
X_i	$m_{X_i} \lesssim 2\ m_{3/2}$	$t_{osc}^{X_i} = 7 \times 10^{-30}$

- Note that decays of the light moduli and meson into gravitinos is supressed!

Moduli Decays

- Reheat temperature when the moduli decay is $T_r \sim (\Gamma_X^2 m_p^2)^{1/4}$

Modulus	Decay constant	Decay Time (seconds)
X_N	$d_{X_N} = 2$	$\tau_{X_N} = 9 \times 10^{-11}$
X_ϕ	$d_\phi = 710$	$\tau_\phi = 6 \times 10^{-6}$
X_i	$d_{X_i} = 4.00$	$\tau_{X_i} = 10 \times 10^{-4}$

- First X_N decays and reheats the Universe to about 40 GeV and increases entropy by 10^{10}
- Then ϕ decays and reheats the Universe to about 100 MeV and increases entropy by 100
- Finally X_i decays and reheats the Universe to about 30 MeV and increases entropy by 100
- The high reheat temperature, the supressed decay into gravitinos and the large entropy dilution *avoid the Moduli and Gravitino problems*

Dark Matter Abundance

- Initial LSP number density at *final decay stage* is large enough for the winos to self-annihilate.
- $n_{LSP}^{initial} > \frac{3H}{<\sigma v>}|_{T_r}$, with σv typical Weak x-section $\sim 10^{-7}\text{GeV}^{-2}$
- They will therefore continue to self-annihilate until $n_{LSP} = \frac{3H}{<\sigma v>}|_{T_r}$
- $n_{LSP} \sim 10^{12}\text{eV}^3$ or $\rho_{LSP} \sim 10^{23}\text{eV}^4$
- Entropy density at reheat time $s \sim 10T_r^3 \sim 10.(30\text{MeV})^3 \sim 10^{23}\text{eV}^3$
- Therefore $\frac{\rho}{s} \sim \mathcal{O}(1)\text{eV}$
- Observed value today is 3.6 h^2eV , where $h = 0.71$
- Thus, non-thermally produced Wino's are excellent DM candidates
- Important to emphasise that it is the *last modulus to decay* which dominates the DM abundance but the *hierarchy of moduli masses and widths* are important for diluting gravitino abundance

- The HEAT and AMS-01 collaborations have some evidence for a positron excess - $\sim 5 - 10$GeV
- The PAMELA satellite is in operation and may be able to confirm/deny this
- Dark matter self-annihilations could be a source of these positrons
- Seems to require Wino or Higgsino LSP
- Binos dont annihilate efficiently enough.

- Assume tree level unification of M_1, M_2, M_3 at M_{GUT} and that the dominant correction is from AMSB terms *ie other thresholds less important*:
- $M_a = M_{1/2} + \Delta M_a(AMSB)$
- Then *either* A: $\Delta M_a(AMSB) >> M_{1/2}$ ie pure AMSB
- *or* G: $M_{1/2} \sim \Delta M_a(AMSB)$ such that $M_2 < 2M_1$.
- The G2-MSSM is an example of case G.

Conclusions

- Non-thermal production of Dark matter seems inevitable in string theory because of the moduli and gravitino problems
- We have addressed this in a detailed model of moduli masses, decays and soft susy breaking terms
- Gives a rather tight, consistent picture with a Wino LSP relic density of about the right amount