The Cosmological Moduli Solution(s)

ExDIP workshop, KEK, Japan 09.Nov.2010
Based on work done with G. Kane, K. Bobkov, P. Kumar, J. Shao, S. Watson, Eric Kuflik, Ran Lu

Bobby Samir Acharya

International Center for Theoretical Physics, Trieste

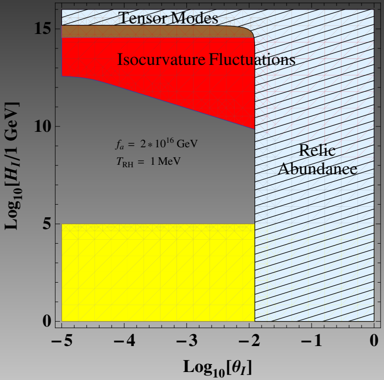
Introduction

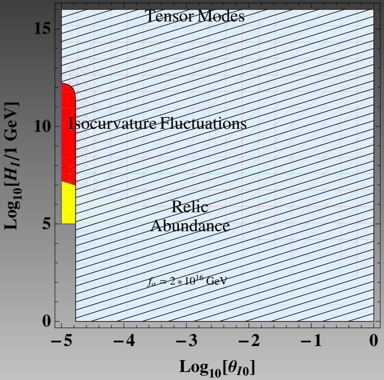
- One general feature of string/M theory which could distinguish it from QFT is the existence of moduli fields
- A simple question one can ask is: what is the mass of the lightest modulus field?
- Related to moduli stabilization mechanisms.
- In all known cases where all moduli can be stabilized, $m_\varphi \leq O(m_{3/2})$
- Studies of the geometry of string/M theory moduli spaces support this (Scrucca, Louis et al)
- A "generic feature" which could emerge from string/M theory is that the pre-BBN Universe is dominated by oscillating moduli
- Studies of string/M theory phenomenology with moduli stabilised suggest The Cosmological Moduli Solution(s)

Main Points

- The cosmological moduli solution(s) are based on the following
- Non-thermal, moduli dominated, pre BBN cosmology is very plausibly "a generic" outcome of string/M theory
- A Non-Thermal WIMP 'miracle' occurs for wino-like Dark Matter particles produced when the moduli decay before BBN.
- Wino Dark Matter consistent with Indirect DM Detection data (PAMELA, Fermi)
- Axion physics becomes non-anthropic in a non-thermal moduli dominated cosmology with GUT scale decay constants
- All of this has a simple origin in one of the best understood classes of examples: M theory on a G_2-manifold

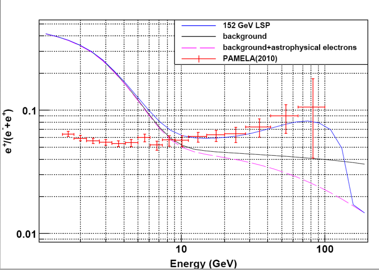
Non-anthropic Axion Physics

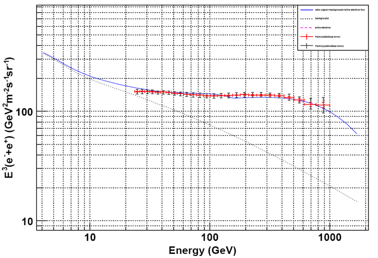




Non-thermal is the case on the Left.

Wino DM and PAMELA Data





Left: $e^+/(e^+ + e^-)$ Right: Energy Spectrum of $e^+ + e^-$

Moduli Stabilization in M theory

- Basic (old, but great) idea that strong dynamics in the hidden sector:
  1. Generates the hierarchy between m_{pl} and M_W
  2. That supersymmetry breaking will also stabilize the moduli
- Realised for the first time in string/M theory by considering M theory on G_2-manifolds
- In fact, strong hidden sector dynamics generates the hierarchy, the moduli potential and supersymmetry breaking *simultaneously*!
- There are two INTEGER parameters P, Q which determine $\alpha_{GUT}, M_{GUT}, M_{pl}, m_{3/2}$ all *consistently*.

Moduli Stabilzation in M theory

- Moduli vevs $s_i \sim 3Q/N = \frac{1}{N\alpha_{GUT}}$
- So Q=6,7,8,9
- $m_{pl}^2 = Vol(X) M_{11}^2 \sim \frac{1}{\alpha_{GUT}^{7/3}} M_{11}^2$
- $M_{GUT} = M_{11}\alpha_{GUT}^{1/3}$
- $m_{3/2} = m_{pl} \frac{\alpha_{GUT}^{7/2}}{\sqrt{\pi}} \frac{|Q-P|}{Q} e^{-\frac{P_{eff}}{Q-P}}$
- $P_{eff} = \frac{14(3(Q-P)-2)}{3(3(Q-P)-2\sqrt{6(Q-P)})} \sim 60$ when $Q-P=3$
- So, $m_{3/2} \sim O(50)$ TeV
- So, moduli can decay before BBN.
- There are two INTEGER parameters P, Q which determine $\alpha_{GUT}, M_{GUT}, M_{pl}, m_{3/2}$ all *consistently*.

Moduli Masses in Supergravity

- Supergravity potential $V \sim F^i F_i - 3|W|^2$
- In vacuum this is $V_o \sim < F^i F_i > -3m_{3/2}^2 m_{pl}^2$
- Therefore $m_{3/2} \sim \frac{F}{m_{pl}}$ where F dominates susy breaking.
- *Generically* F/m_{pl} sets the mass scale of *ALL SCALARS* in the theory
- This not only includes the moduli, but also charged scalars: Higgses and Squarks and Sleptons
- eg $V \sim \cdots + K^i K_i |W|^2 + ... \sim \phi^i \phi_i |W|^2 ... \sim m_{3/2}^2 \phi_i^2$
- Therefore $m_\phi \sim m_{3/2}$
- The G2 M theory model has $m_\phi \sim m_{3/2}$.

The Spectrum

- Already observed: *generically* Supersymmetry breaking must be gravity mediates and all scalars have masses of order $m_{3/2} \geq 10\text{TeV}$
- What about the Higgsino and Gaugino masses ?
- For Higgsinos, Giudice-Masiero guarantees $\mu \geq m_{3/2}$
- But, $m_f \leq m_{3/2}$ for gauginos
- Why? Because *there is no reason why the field which has the largest F-term is the field whose vev is the gauge coupling*.
- These arguments suggest a spectrum in which
- All scalar particles and vector like fermions have masses of order $m_{3/2} \geq 10\text{TeV}$
- Gauginos ie gluinos, Winos and Binos have $m_{1/2} \leq m_{3/2}$
- This all comes from simple cosmological constraints plus EFT
- Fine tuning?

The Spectrum in String/M theory

- In string/M theory in the classical limit a positive cosmological constant is not possible.
- 'Pure moduli dynamics has an anti de Sitter vacuum'
- Therefore, the field which dominates supersymmetry breaking is not a modulus
- e.g. a matter field
- In M theory this is a hidden sector matter field
- $F_{moduli} \sim \alpha_{GUT} m_{3/2} m_{pl}$
- Leads to a Wino LSP
- Note: this is NOT pure AMSB in the gaugino sector, but similar to it.

Non-thermal Dark Matter

- Energy density of Universe when moduli decay is
- $\rho_{decay} \sim {\Gamma_\phi}^2 m_{pl}^2 = \frac{m_\phi^6}{m_{pl}^2}$
- The number density of DM particles is thus
- $n_\chi^i \sim \frac{Br_{\phi\to\chi}\rho_d}{m_\chi} \sim 10^{-10}\mathrm{GeV}^3 Br_{\phi\to\chi}(\frac{100\mathrm{GeV}}{m_\chi})(\frac{m_\phi}{100\mathrm{TeV}})^6$
- We can compare this with $\frac{H}{\sigma v}$ to evaluate if n_χ^i is large enough to allow χ particles to annihilate
- $\frac{H}{\sigma v} \sim \frac{\Gamma_\phi}{\sigma v} \sim 10^{-16}\mathrm{GeV}^3(\frac{m_\phi}{100\mathrm{TeV}})^3\frac{\sigma_o}{\sigma v}$
  where $\sigma_o = 10^{-7}\mathrm{GeV}^{-2}$
- Unless $\mathrm{Br}_{\phi\to\chi}$ is small, χ particles will annihilate until $n_\chi \sim \frac{H}{\sigma v}$
- The Branching ratio is large since 'χ is a gaugino' and moduli couple like gravitons.

Miracles can be Non-thermal!

- Reheat temperature
  $T_{rh} \sim (\Gamma_\phi m_{pl})^{1/2} \sim \frac{m_\phi^{3/2}}{m_{pl}^{1/2}} \sim 10\text{MeV}(\frac{m_\phi}{50\text{TeV}})^{3/2}$
- So BBN can occur after the moduli have decayed!
- Entropy at decay time $s_{decay} \sim s_{rh} \sim g_* \frac{m_\phi^{9/2}}{m_{pl}^{3/2}}$
- Non-thermal relic abundance is therefore predicted to be
- $\frac{\rho}{s}|_{today} = \frac{m_\chi H}{s \ \sigma v}|_{decay} \sim \mathcal{O}(\text{eV}) \ \frac{m_\chi}{100\text{GeV}} \frac{10.75}{g_*} \frac{\sigma_o}{\sigma v} \ (\frac{100\text{TeV}}{m_\phi})^{3/2}$
- **This is the Non-thermal WIMP 'Miracle'**
- First realised by Moroi-Randall that this happens in AMSB + heavy scalars ten years ago.
- In M theory, because $M_\chi \sim c\frac{\alpha_{GUT}}{4\pi} m_{3/2}$, $\rho/s \sim m_{3/2}^{3/2}$ so upper limit $m_{3/2} \leq 250\text{TeV}$.

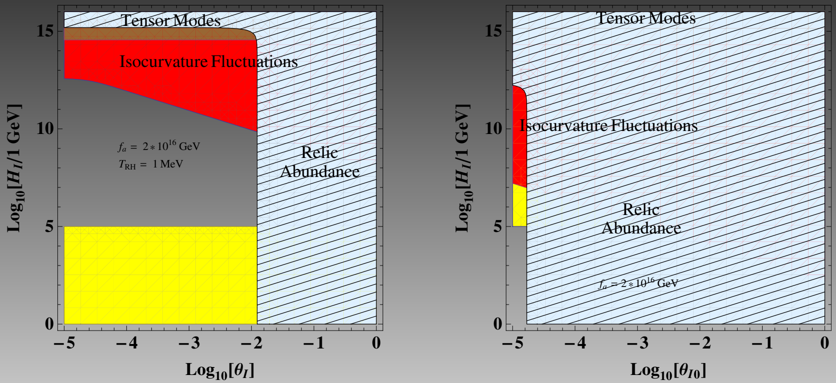
Non-anthropic Axion Physics

- Coherent Axion oscillations produced during non-thermal moduli domination have (cf Fox, Pierce, Thomas '04).

$$\Omega_{a_k} h^2 = \mathcal{O}(10) \left(\frac{\hat{f}_{a_k}}{2 \times 10^{16} \mathrm{GeV}} \right)^2 \left(\frac{T_{RH}^{X_0}}{1\,\mathrm{MeV}} \right) \langle \theta_{I_k}^2 \rangle$$

- Due to large amount of entropy dilution from the moduli decay
- Independent of axion mass
- Much less tuning required (10^{-2})

Non-anthropic Axion Physics with GUT scale decay constants



Non-thermal is the case on the Left.

Planck experiment: Isocurvature perturbations? YES.

Tensor Modes: NO.

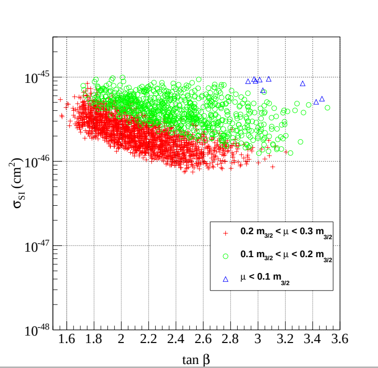
Caveats

- A late period of pre-BBN inflation with $H < m_{3/2}$ can inflate away the energy density of the moduli and their decay products.
- Is this possible in string/M theory?
- Is it "generic" in the same sense that a non-thermal history is "generic"?
- Note: In gauge mediated supersymmetry breaking $m_{3/2} <<$TeV
- So late inflation is *required* in gauge mediation because the moduli lifetimes are too long and $\rho/s \sim (m_{3/2} m_{pl})^{1/2}$

Lots of testable predictions!

- LHC: events with up to four top quarks plus missing energy
- LHC: short track stubs from the $SU(2)$ partners of the Wino
- Isocurvature perturbations but no tensor modes
- PAMELA/Fermi already consistent
- No signals at existing Axion search experiments
- Xenon 100: Calculation of μ in M theory leads to no signal, but observable at a Xenon 1000 detector. (work with Gordy Kane, Eric Kuflik and Ran Lu, to appear)

Direct Detection of DM



The G2 models are out of reach of Xenon 100.

Xenon 1000 or equivalent will be sensitive to this signal though.

Conclusions

If our Universe is in a string/M theory vacuum ....

- Moduli must be stabilized
- A Non-thermal history seems to be a "generic" outcome
- Moduli decays will wash out any previous thermal relics
- Dark Matter is a mixture of axions and wino-like particles
- Forthcoming data will *really* test the consequences of a Non-thermal string/M theory cosmological history.

THANK YOU

BACK UP

Mapping the Axiverse

- In M theory we have a framework for calculating the full low energy effective action
- Up to now we have focussed on the moduli fields and a few of the axions
- Here, we will describe what happens when all axions are included.
- ADDKM only considered low scale inflation, $H \leq 0.1$ GeV, because they are worried about the moduli problem
- But, in the G_2-based M theory models, the moduli are sufficiently massive (50 TeV o so) that the moduli problem is solved. So, we also extend the picture to include high scale inflation as well.
- Basic formula: $m_t \sim \frac{M_{pl}}{M_{GUT}}(m_{3/2}M_{pl})^{1/2}e^{-bV}$.
- In the course of this work we could "see in practice" how the strong CP problem is solved!

Basic Calculation

- Consider the dynamics which stabilises the moduli "plus exponentially small corrections which generate the axion potential". $V = V_0(s) + V(t)$.
- Superpotential $W = W_0 + W_t = W_0 + \sum_k D_k e^{ib_k z_k}$ $z_k = t_k + is_k$.
- $m_{3/2} \sim W_0 \longrightarrow V(t) \sim m_{3/2} M_{pl}^3 \sum_k D_k e^{-b_k V_k} cos(t_1 - t_k)$
- where t_1 is the axion field which appears in W_0. It's mass is order $m_{3/2}$
- $m_{t_k} \sim \frac{M_{pl}}{f}(m_{3/2}M_{pl})^{1/2}e^{-b_k V_k} \sim \frac{M_{pl}}{M_{GUT}}(m_{3/2}M_{pl})^{1/2}e^{-b_k V_k}$

Range of Axion Masses

- Scales in M theory. Generalisation to other limits straightforward.
- $M_{pl}^2 \sim M_{11}^2 V_X$. $M_{11} \sim 10^{17}$GeV.
- $V_X \sim \frac{1}{\alpha_{GUT}}^{7/3}$. Ranges from 500 to 3000.
- If V_k ranges from about 15 to 35.
- 1eV $\leq m_{t_i} \leq 10^{-29}$ eV
- A GUT instanton gives $m_t \sim 10^{-15} eV$, which is just about light enough to not interfere with the CP problem.
- Smaller axion masses are also possible in general since the dependence of V_X on a given V_k is not just a simple scaling.

Explicit Toy Model

$$
\begin{aligned}
K &= -3\ln 4\pi^{1/3} V_X + \frac{\bar{\phi}_1\phi_1}{V_X}; \quad V_X = s_1^{\frac{7}{6}} s_2^{\frac{7}{6}}\,, \\
W &= A_1 \phi_1^{-2/P_1} e^{i\frac{2\pi}{P_1} f^1} + A_2 e^{i\frac{2\pi}{P_2} f^2} + A_3 e^{i\frac{2\pi}{P_3} f^3} \\
&+ A_4 e^{i\frac{2\pi}{P_4} f^4}, \\
f^1 &= f^2 = z_1 + 2z_2;\ f^3 = f^4 = 2z_1 + z_2.
\end{aligned}
$$

$$
\begin{aligned}
&A_1 = 28.83\,,\ \ A_2 = 2.28\,,\ \ A_3 = 3\,,\ \ A_4 = 5\,, \\
&P_1 = 27\,,\ \ P_2 = 30\,,\ \ P_3 = 4\,,\ \ P_5 = 3\,,
\end{aligned}
$$

we obtain

$$
\begin{aligned}
s_1 &\approx 48.82\,,\ s_2 \approx 24.41\,,\ \phi_1^0 \approx 53.81\,, \\
t_1 &\approx 5\,,\ t_2 \approx -10\,,\ \theta_1 \approx -15\pi\,. \qquad (1)
\end{aligned}
$$

Toy Model

The geometric moduli s_1, s_2 and the meson ϕ_1^0 form three mass eigenstates with masses

$$m_1 \approx 284.9\, m_{3/2}\,,\;\; m_2 \approx 2.0\, m_{3/2}, m_3 \approx 1.1\, m_{3/2}. \qquad (2)$$

Diagonalize axion kinetic terms with:

$$U \approx \begin{pmatrix} 1.00 & -10^{-4} & 0.01 \\ 10^{-4} & 1.00 & 0.02 \\ -0.01 & -0.02 & 1.00 \end{pmatrix}. \qquad (3)$$

$$\frac{f}{M_{pl}} \approx (3.03 \times 10^{-2}\,,\;\; 6.05 \times 10^{-2}\,,\;\; 1.22)\,. \qquad (4)$$

Toy Model

Diagonalize axion mass matrix with:

$$\mathcal{U} \approx \begin{pmatrix} 0.706 & 0.708 & -0.019 \\ 0.706 & -0.702 & 0.093 \\ -0.053 & 0.079 & 0.995 \end{pmatrix}. \tag{5}$$

Masses *without* QCD effects:

$$\hat{m}_{\psi_1} \approx 286\, m_{3/2}\,, \quad \hat{m}_{\psi_2} \approx 6.3 \times 10^{-35}\, m_{3/2}\,, \tag{6}$$
$$\hat{m}_{\psi_3} \approx 4.0 \times 10^{-51}\, m_{3/2}.$$

Next... include QCD

Axion masses in Toy Model

$$\begin{aligned} \hat{m}_{\tilde{\psi}_1} &\approx 286 m_{3/2}\,, \;\; \hat{m}_{\tilde{\psi}_2} \approx 10^{-36} m_{3/2}\,, \\ \hat{m}_{\tilde{\psi}_3} &\approx 10^{-23} m_{3/2}\,. \end{aligned} \tag{7}$$

$$\begin{aligned} \theta_{QCD} &= 2\pi (N_1^{\rm vis} t_1 + N_2^{\rm vis} t_2) = 2\pi (t_1 + t_2) \\ &\approx 219.8\,\tilde{\psi}_1 + 5.5 \times 10^{-28} \tilde{\psi}_2 - 74.3\,\tilde{\psi}_3. \end{aligned} \tag{8}$$

- Note that $\tilde{\psi}_1$ has a very similar mass , but that $\tilde{\psi}_3$ now has a larger mass, of order $\Lambda^2_{QCD}/f \sim m_t^{QCD}$.
- Generally, the other axions (here $\tilde{\psi}_2$) which are very light compared to Λ^2_{QCD}/f will couple to $F\tilde{F}$ with supressed couplings $(m_{\tilde{\psi}_2}/m_t^{QCD})^2$.
- This implies that (essentially due to unification) the CMB polarization and the axion decays to photons (except the QCD axion) are suppressed by this factor.

Scanning the Axion Decay Constants

We scanned 200 randomly generated G_2 Kahler potentials:
Peaks at M_{GUT}.

Two Cosmologies

- Low scale inflation: $H_I \leq m_{3/2}$
  1. Assumed by ADDKM to avoid moduli problem
  2. Presumably requires fine tuning to explain density perturbations.
  3. Requires (Anthropic) fine-tuning to reduce the axion relic densities.
- High Scale Inflation: $H_I \geq m_{3/2}$
  1. $m_{3/2} \geq 50$ TeV
  2. Moduli dominate Universe up to BBN
  3. Decay of the moduli reduces axion relic density for axions which begin oscillations before the moduli decay $m_t \geq \Gamma_s \sim 10^{-14}$eV
- Also considered Isocurvature perturbations and Tensor modes (gravity wave contributions).

High Scale Inflation

- Axions with $m_t \leq 10^{-14}$eV are produced in a radiation dominated era and
-

$$\Omega_{a_k} h^2 = 0.17 \left(\frac{\hat{f}_{a_k}^2 \, m_{a_k}^{1/2}}{M_{pl}^{3/2} \, (1 \mathrm{eV})} \right) \langle \theta_{I_k}^2 \rangle \, \chi \tag{9}$$

- So between 10^{-20} eV and 10^{-14} eV, the initial misalignment angle must be tuned.
- Lighter axions are consistent without finetuning.

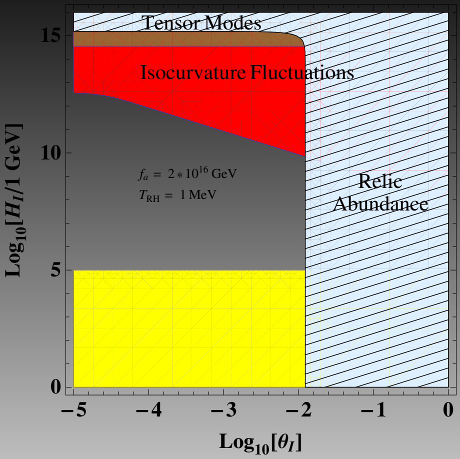
During Moduli Domination

- Axions produced during moduli domination have (cf Fox, Pierce, Thomas '04).

$$\begin{aligned} \Omega_{a_k} h^2 &= \mathcal{O}(1) \left(\frac{T_{RH}^{X_0} \hat{f}_{a_k}^2}{M_{pl}^2 \, (3.6 \, \mathrm{eV})} \right) \langle \theta_{I_k}^2 \rangle \, \chi \\ &= \mathcal{O}(10) \left(\frac{\hat{f}_{a_k}}{2 \times 10^{16} \mathrm{GeV}} \right)^2 \left(\frac{T_{RH}^{X_0}}{1 \, \mathrm{MeV}} \right) \langle \theta_{I_k}^2 \rangle \, \chi \end{aligned} \tag{10}$$

- Independent of axion mass
- Much less tuning required (10^{-2})

Constraints in High Scale Inflation case

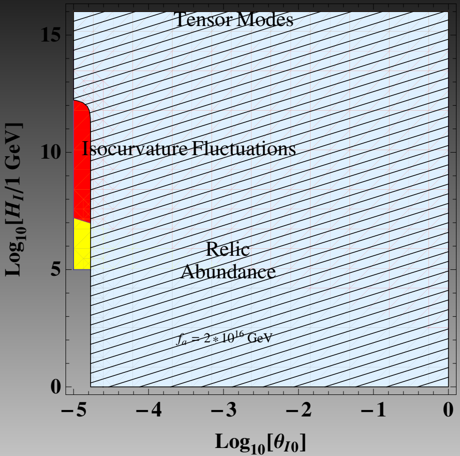


Current Isocurvature bound is $\alpha_a \leq 0.072$.

This generalizes Fox et. al and gives stronger constraints.

Observing Tensor modes in the near future rules out the axiverse **completely**.

Compare to Low scale case



Gives Isocurvature of order 10^{-7}.

So, observing Isocurvature soon rules out Low scale inflation + Axiverse model!