The Cosmological Moduli Solution(s)

Non-Thermal Cosmological Histories Workshop, MCTP, UofM 18.Oct.2010

Based on work done with G. Kane, K. Bobkov, P. Kumar, J. Shao, S. Watson, Eric Kuflik, Ran Lu

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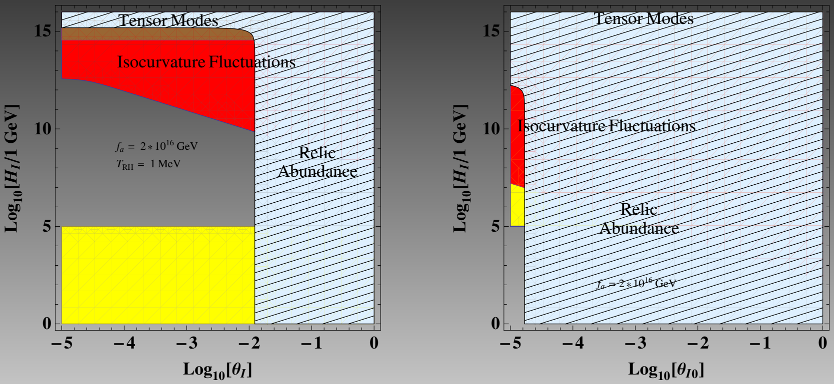
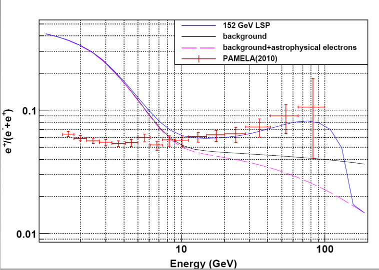
- Axion physics becomes non-anthropic in a non-thermal moduli dominated cosmology with GUT scale decay constants
- All of this has a simple origin in one of the best understood classes of examples: M theory on a G_2-manifold

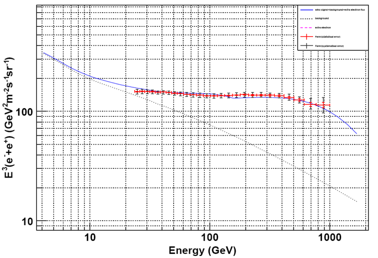
Non-anthropic Axion Physics



Non-thermal is the case on the Left.

Wino DM and PAMELA Data





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

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- 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*.

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- The G2 M theory model has $m_\phi \sim m_{3/2}$.

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- Fine tuning?

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- 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

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- First realised by Moroi-Randall that this happens in AMSB + heavy scalars ten years ago.

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- $\frac{\rho}{s}|_{today} = \frac{m_\chi H}{s \ \ \sigma v}|_{decay} \sim \mathcal{O}(\text{eV}) \ \frac{m_\chi}{100\text{GeV}} \frac{10.75}{g_*} \frac{\sigma_o}{\sigma v} \ (\frac{100\text{TeV}}{m_\phi})^{3/2}$
- **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).

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

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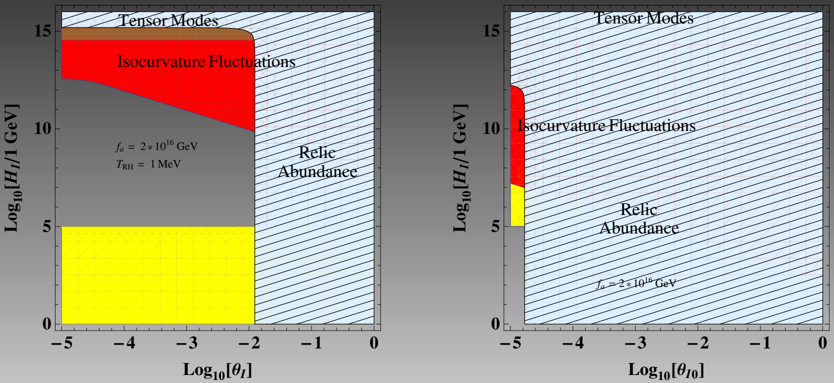
- Much less tuning required $(10^{-2}\ )$

Non-anthropic Axion Physics with GUT scale decay constants



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Planck experiment:

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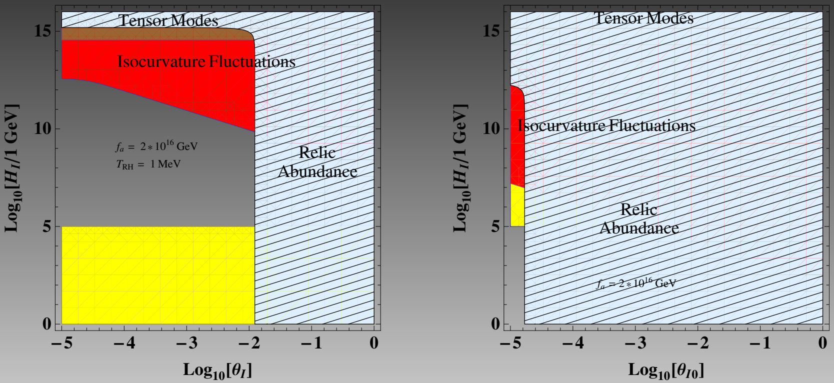

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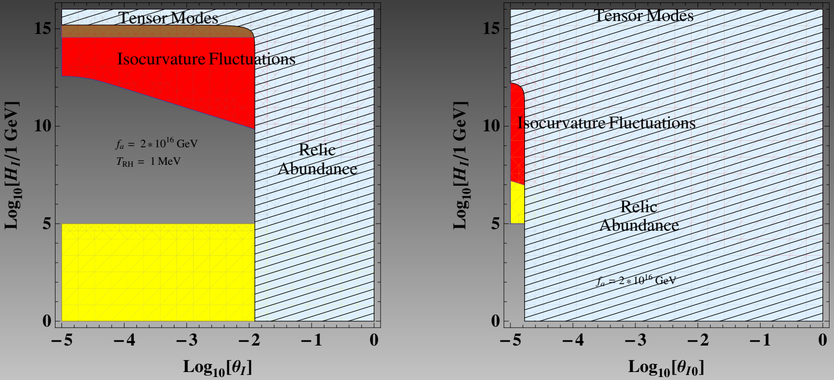

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Planck experiment:Isocurvature perturbations? YES. Tensor Modes: NO.

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- 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 $\rho/s \sim (m_{3/2} m_{pl})^{1/2}$

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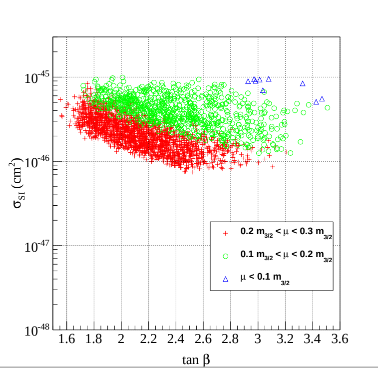
- Xenon 100: Calculation of μ in M theory leads to no signal, but observable at a Xenon 1000 detector. (work with Gordy, Eric Kuflik and Ran Lu)

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.

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- Forthcoming data will *really* test the consequences of a Non-thermal string/M theory cosmological history.

THANK YOU

BACK UP

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- In the course of this work we could "see in practice" how the strong CP problem is solved!

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- 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

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

$$
A_1 = 28.83\,,\ \ A_2 = 2.28\,,\ \ A_3 = 3\,,\ \ A_4 = 5\,,
$$
$$
P_1 = 27\,,\ \ P_2 = 30\,,\ \ P_3 = 4\,,\ \ P_5 = 3\,,
$$

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

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

Diagonalize axion kinetic terms with:

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

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

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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:

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

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Next... include QCD

Axion masses in Toy Model

$$\hat{m}_{\tilde{\psi}_1} \approx 286 m_{3/2}\,, \;\; \hat{m}_{\tilde{\psi}_2} \approx 10^{-36} m_{3/2}\,,$$
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$$\theta_{QCD} = 2\pi(N_1^{\rm vis} t_1 + N_2^{\rm vis} t_2) = 2\pi(t_1 + t_2) \tag{8}$$
$$\approx 219.8\,\tilde{\psi}_1 + 5.5 \times 10^{-28}\tilde{\psi}_2 - 74.3\,\tilde{\psi}_3.$$

- 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 $(m_{\tilde{\psi}_2}/m_t^{QCD})^2$.

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- 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}.

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- Also considered Isocurvature perturbations and Tensor modes (gravity wave contributions).

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- Lighter axions are consistent without finetuning.

During Moduli Domination

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

$$\Omega_{a_k} h^2 = \mathcal{O}(1) \left(\frac{T_{RH}^{X_0} \hat{f}_{a_k}^2}{M_{pl}^2 \, (3.6\,\mathrm{eV})} \right) \langle \theta_{I_k}^2 \rangle \, \chi \qquad (10)$$

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

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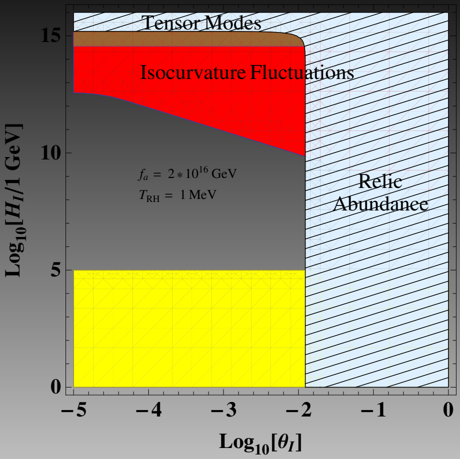
- Axions produced during moduli domination have (cf Fox, Pierce, Thomas '04).

$$\Omega_{a_k} h^2 = \mathcal{O}(1) \left(\frac{T_{RH}^{X_0} \hat{f}_{a_k}^2}{M_{pl}^2 \, (3.6 \, \mathrm{eV})} \right) \langle \theta_{I_k}^2 \rangle \, \chi \qquad (10)$$

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

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

Constraints in High Scale Inflation case

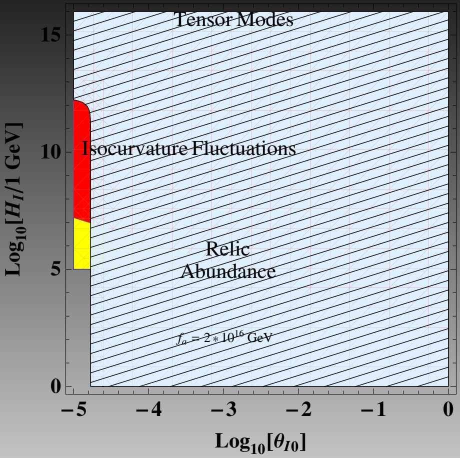


Current Isocurvature bound is $\alpha_a \leq 0.072$.

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!