Solution to the Strong and Weak CP Problems & Constraints on the Axiverse

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May 5th , 2010

Strings Vacuum Project Meeting 2010

KITP, Santa Barbara

Acharya, Bobkov,PK ;1004.5138[hep-th]

Braun, Bobkov,PK, Raby; 1003.1982 [hep-th]

Kane,PK,Shao; 0905.2986 [hep-ph]

Outline

- Introduction & Motivation

- Results for classes of M-theory and IIB compactifications

- Some Phenomenological Consequences very similar.

  Example:

  -- Realization of the String “Axiverse”

  -- Dynamical solution to the Strong CP Problem.

- Detailed Pheno. Consequences can be different. Example

  -- Mediation of SUSY Breaking & particle pheno.

Introduction & Motivation

One of the Central Goals of String Phenomenology

- Explain values of low energy physics parameters - α_{em}, Y_{elec}, etc.
- Tied to *vevs* of Moduli - classically massless.

So, Moduli Stabilization crucially important for connecting to Real World

- Explaining low energy parameters.
- Supersymmetry Breaking and Mediation
- Cosmological history and Observables.

Lot of work done in Moduli Stabilization in various corners of String Theory

-- Type IIB, Type IIA, Heterotic, M Theory

many many papers,….

- Consider in particular classes of compactifications in

M theory *Acharya, Bobkov, Kane, PK, Vaman PRL 97, (2006)*

Acharya, Bobkov, Kane, PK, Shao PRD 76, (2007)

Acharya, Bobkov 0810.3285 [hep-th]

Type IIB *Bobkov, Braun, PK, Raby 1003.1982 [hep-th]*

- Limit to compactifications with low energy SUSY

Results for Moduli Stabilization

see Konstantin's talk for details

- **M-theory**: Stabilize all moduli with entirely non-perturbative W arising from strong gauge dynamics (no fluxes turned on).

Only one linear combination of moduli appear in W.

All but one Axions NOT stabilized at this level.

- *Minimal Framework*: Two hidden sectors – at least one of which has charged matter ($N_f < N_c$)
- Then, by **discrete** choice of ranks (dual coxeter #s) of Gauge groups :

-- Naturally obtain metastable dS vacua with spontaneous $\cancel{\text{SUSY}}$.

-- $M_{3/2} = O(10)$ TeV.

Type IIB - Many features of the M-theory stabilization mechanism can be realized in classes of Type IIB

Braun, Bobkov,PK, Raby; 1003.1982 [hep-th]

- Dilaton and C.S. Moduli stabilized by Fluxes at a high scale.
- Kahler moduli stabilized typically by non-pert. effects.

-- Naively, require h_{11}^+ Non. Pert. Terms to stabilize h_{11}^+ moduli.

-- Quite difficult for large $h_{11}^+ \sim O(100)$.

-- In particular, Modulus determining visible gauge coupling cannot be stabilized by pure non-pert. effects. *Blumenhagen et al JHEP 01 (2008)*

- Possible to stabilize ALL *Kahler* moduli by few (one) instantons in the SUGRA regime if:

-- The four-cycle (Divisor) supporting the instanton is "ample".

-- The Divisor has $\chi_+ - \chi_- = 1$.

Phenomenological Consequences

- Applications for Cosmology & Phenomenology

some depend primarily on the moduli stabilization mechanism & are qualitatively same for IIB & M Theory compactifications considered above.

Eg. -- Solution to the Strong-CP Problem & Dynamical Realization of the Axiverse.

First considered in *Arvanitaki et al 0905.4720 [hep-th]* from a pheno. point of view.

Topic of Discussion Now

- **Focus on M theory** for concreteness

But, All Qualitative results below applicable to

the particular class of Type IIB compactifications

Bobkov, Braun, PK, Raby: 1003.1982 [hep-th]

& perhaps other compactifications with these features

Axions

- Until now, considered only moduli stabilization (& one axion) What about other axions?

  Problem? Or Virtue? --- The Latter !

- Naturally occur in String Theory – Zero Modes from KK reduction of p-form gauge fields. Quite Plentiful - O(100-1000)!

$$C_p = \sum_i t_i(x) \wedge \phi_i(y) \ , \ \phi_i$$

Harmonic p-forms

- Axions (arising from PQ symmetry) – probably the most elegant solution to the Strong-CP Problem *(Peccei-Quinn; Weinberg; Wilczek).*

--- Can also provide significant fraction of Dark Matter

--- Typically very light, so could have important consequences for astrophysics & cosmology.

- Long cherished Dream in String Phenomenology – Use one of the many axions to solve the Strong-CP problem.

  -- Solving Strong CP requires that the QCD axion dominantly gets a mass from QCD instantons.

$$\boxed{\mathbf{M_{QCD} \sim \Lambda_{QCD}{}^2/f_a \sim 10^{-10}\ eV}}$$

1) Many moduli stabilization mechanisms also give masses to axions.

Flux compactifications – Fluxes explicitly break PQ of axion partners of Complx. Str. & Dilaton moduli.

Eg. KKLT-like mechanisms, Large Volume Compactifications (Conlon,Quevedo) , others

In the above, Axionic partners of Kahler moduli in Type IIB stabilized at

$$\mathbf{O\ (m_{3/2}) \sim TeV \ \ >>> \ \ M_{QCD}}$$ *(Conlon JHEP 0605 (2006))*

- 2) Axion Decay Constant $f_a \sim M_{GUT}$ for High $M_{string} >\sim M_{GUT}$

“Standard” Cosmology → Too many axions!

For $\langle\theta_I\rangle = O(1)$, Relic Abundance Overcloses the Universe . So,

a) Make $M_{string} << M_{GUT}$, but $Vol(Vis)/L_{string}^{3} \sim \alpha_{GUT}^{-1} \sim 25\text{-}26$

b) $M_{string} >\sim M_{GUT}$ → $\langle\theta_I\rangle << O(1)$ is required.

c) Third option → Have different cosmological History before BBN

Axion Stabilization

Acharya, Bobkov, PK 1004.5138 [hep-th]

- Moduli Stabilization

All Moduli stabilized with just one linear combination

- All but one axions NOT stabilized

Fixed by other (subdominant) terms in W.

$$W = A_1 \phi_1^a \, e^{i b_1 V_1} + A_2 \, e^{i b_2 V_1} + \sum_{k=3}^{\infty} A_k \, e^{i b_k V_k}$$

in Planck units

(N+1 axions)

- $b_{1,2} = 2\pi / P_{1,2}$ condensates
- $b_k = 2\pi I$ instantons
- $V_k = \sum N_k^i s_i$; $z_i = t_i + i s_i$

Generically sufficient number of independent terms expected to be present if # of susy 3-cycles large enough

Also required for

- $W_1 \sim W_2 \gg W_k$; $k=3,4,\ldots, N+2$ self-consistency

Details

- From first two terms W_1 and W_2, find $\cos(\chi_1 - \chi_2) = -1$

$$\chi_i = b_i \vec{N}.\vec{t} + a\,\theta\,\delta_{i1}$$

- This fixes one combination of Axions with mass ~ $M_{3/2}$, where

$$M_{3/2} = O(1)\, e^{-b1\ V1}\, m_p \sim W_1 / m_p^2$$

- The next largest (N) terms stabilize the remaining (N) axions (Cross terms between the dominant term and subdominant ones)

$$V \supset (W_1 \overline{W_K} + \text{h.c.}) + \ldots.; \qquad k = 3,4\ldots$$

$$
\begin{aligned}
V_{eff} &\approx V_0 - m_{3/2} m_p^3 \, e^{K/2} \sum_{k=3}^{N+2} D_k \, e^{-b_k V_k} \cos(\chi_1 - \chi_k) \\
\forall k: &\quad b_k V_k < b_{k+1} V_{k+1} \qquad (5)
\end{aligned}
$$

- Will fix the remaining axions cos $(\chi_1-\chi_k) = \mp 1$.

  This fixes cos $(\chi_k-\chi_m)$ as well since $\chi_k-\chi_m = -(\chi_1-\chi_k) + (\chi_1-\chi_m)$

- → Phases in the superpotential dynamically align

  (up to a minus sign)

- Also important for Weak CP phases and EDMs as will see later.

Axion Spectrum

– $M_{ak}^2 \sim M_{3/2}\, m_p^3/f_a^2\ \mathrm{Exp}\,[-b_k V_k]$ with $b_k V_k > b_1 V_1\,,\ b_2 V_1$

- fa $\sim M_{GUT} \sim M_{KK} < M_{11} < m_p$
- M_{ak} *exponentially* suppressed relative to $M_{3/2}$
- V_k expected to differ by O(1) for different k=3,4,..,N+2. Can be determined in terms of V_1 (corresponding to W_1, W_2)

Many (N) Axions → Exponential Hierarchy in Axion Masses

- Axion Spectrum distributed roughly linearly on a Log. Scale.

Realization of the String Axiverse

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell : 0905.4720[hep-th]

The QCD Axion

- Until now, Not taken into account QCD instanton effects.
- QCD axion → Axion Partner of Visible 3-cycle

→ Linear combination of all geometric axions.

- Since Kahler metric non-diagonal and non-normalized

$$\theta_{QCD} = \sum \alpha_i \psi_i / f_i \approx \sum \alpha_i \psi_i / M_{GUT}; \quad \psi_i = \text{Mass eigenstates}$$

- Ψ_i exponential hierarchy → QCD effects cannot affect masses of Ψ_i heavier than M_{QCD}, only which are (much) lighter than M_{QCD}.

- As long as there exists ***AT LEAST ONE*** eigenstate with

$$\boxed{M_{ak} < 10^{-5}\, M_{QCD} \sim 10^{-15}\ \text{eV}\ ; \quad \text{then} \quad \theta_{QCD} < 10^{-10}}$$

- Thus, choosing O(1) numbers for microscopic parameters, can naturally satisfy above requirement.

- Interestingly, success of Gauge Unification in the MSSM suggests

$\alpha_{GUT}^{-1} \approx 25\text{-}26$ At least one $V_k \approx 25\text{-}26$

Corresponding $M_a \approx 10^{(-15)}$ eV , quite close

Solution to the Strong CP-Problem with Moduli Stabilization

An Explicit (Toy) Example

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

For the following choice of parameters:

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

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

$$
\begin{aligned}
&\hat{m}^2_{\psi_1} \approx 1.1\times 10^{-27}\, m_p^2\,,\ \ \hat{m}^2_{\psi_2} \approx 5.2\times 10^{-101}\, m_p^2\,, \\
&\hat{m}^2_{\psi_3} \approx 2.1\times 10^{-133}\, m_p^2\,, \qquad \text{(B9)}
\end{aligned}
$$

$$
\begin{aligned}
t_1 &= 23.3\psi_1 + 23.4\psi_2 - 0.6\psi_3\,, \\
t_2 &= 11.7\psi_1 - 11.6\psi_2 + 1.6\psi_3\,, \\
\theta_1 &= -0.6\psi_1 + 6.3\times 10^{-2}\psi_2 + 0.8\psi_3\,.
\end{aligned}
$$

$$
\begin{aligned}
\theta_{QCD} &= 2\pi(N_1^{\text{vis}}t_1 + N_2^{\text{vis}}t_2) = 2\pi(t_1+t_2) \quad \text{(B14)} \\
&\approx 219.8\,\tilde{\psi}_1 + 5.5\times 10^{-28}\,\tilde{\psi}_2 - 74.3\,\tilde{\psi}_3.
\end{aligned}
$$

$M_{\Psi 1} \sim M_{3/2} \sim$ TeV

$M_{\Psi 2}{}^2$, $M_{\Psi 3}{}^2 << M_{QCD}{}^2$

$\sim\Psi_3$ – QCD axion for practical purposes

Constraints on the Axiverse

$$\Omega_a h^2 \equiv \sum_{k=1}^{N} \Omega_{a_k} h^2 \leq 0.11 \qquad (29)$$

$$\alpha_a \equiv \sum_{k=1}^{N} \frac{8}{25} \left(\frac{(\Omega_{a_k}/\Omega_m)^2}{\langle(\delta T/T)^2_{tot}\rangle}\right) \sigma^2_{\theta_k} \left(2\theta^2_{I_k} + \sigma^2_{\theta_k}\right) \leq 0.072$$

$$Q_t \equiv \frac{H_I}{5\pi\, m_p} \leq 9.3 \times 10^{-6}$$

– Relic Abundance

Isocurvature Fluctuations

Tensor Modes

- Bounds depend on Cosmological History. Arvanitaki et al only considered very low scale inflation H_{Inf} <~ 0.1 GeV.

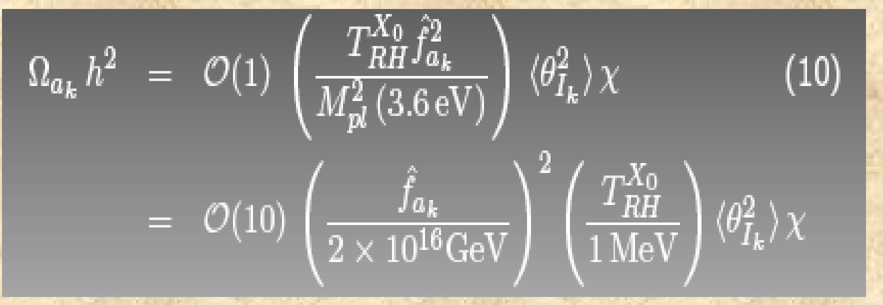
- We consider both a) H_{inf} <~ M_{moduli} -- "Thermal" Cosmology

  b) H_{inf} >~ M_{moduli} -- "Non-thermal" Cosmology

(presumably more generic from top-down point of view,
See Gordy's Talk)

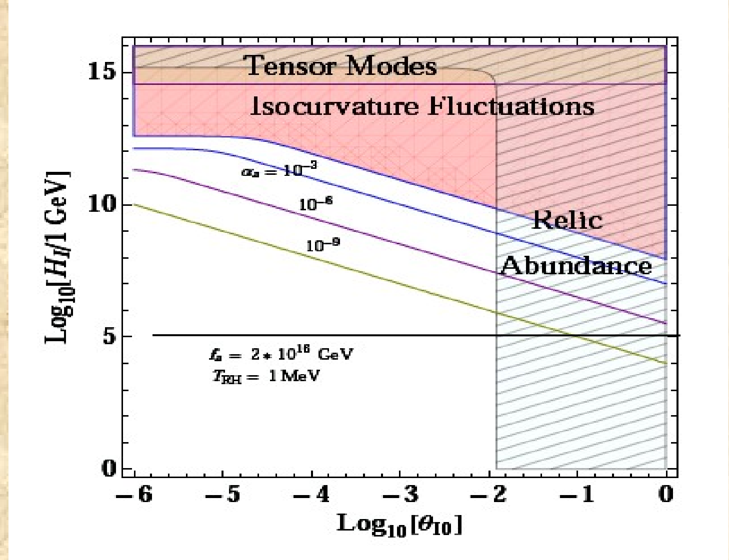
For $H_{inf} > M_{moduli}$

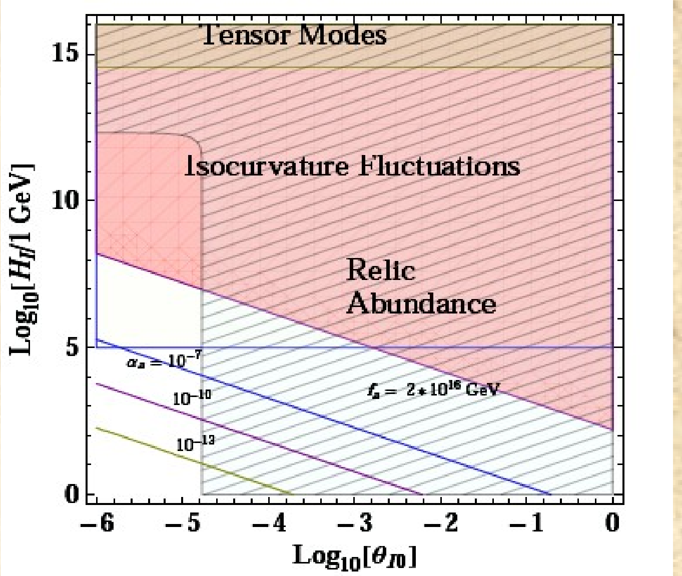
- – "Standard" Computation of Axion Relic Abundance Modified.
- – Parametric Dependence of Ωh^2 on M_{ak} different for axions with $M_{ak} > \sim 10^{-14}$ eV (including the QCD axion).



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

- Independent of mass of axions! Helps in significantly reducing fine-tuning.





- A) Non-thermal Cosmology B) Standard Cosmology

One Axion in each e-folding between ~10^{-33} eV to ~ 1 eV
(H_0)

- Clearly see that tuning in $\langle\theta_I\rangle$ for (A) (percent level) much smaller than that for (B). *generalization of old results for the entire Axiverse*
- Isocurvature Fluctuations can easily distinguish between the TWO cases.

Falsifiable Predictions

- Observation of Tensor Modes in near Future

→ **Rule out Entire Approach** (The Axiverse)

generalization of results in Fox, Pierce, Thomas [hep-th/0409059]

- Expect O(1) Fraction of Dark Matter in the form of Axions. For non-thermal cosmology, in M theory also expect wino DM. So, two sources of DM.

- If observe isocurvature in near future, can *rule out* "thermal" cosmology within approach.

Other Observables

Arvanitaki et al 0905.4720 [hep-th]

- For 10^{-33} <~ M_a <~ 10^{-28} eV, axions which couple to E. B can give rise to polarization of CMB.

  However, within standard GUTs there are no such axions, since coupling ~ $(m_a / m_{QCD})^2$

  - For 10^{-28} <~ M_a <~ 10^{-18} eV, suppression of Matter Power Spectrum should be probed by BOSS
  - For 10^{-18} <~ M_a <~ 10^{-10} eV (QCD axion), could have interesting effects on Rapidly Rotating Black Holes (Axion-BH bound states)

Arvanitaki, Dubovsky 1004.3558[hep-th]

Detailed Predictions for Particle Physics

M Theory

- Two Three-cycles generically do not intersect in a 7D manifold. No warping

Gravity Mediation

Phenomenology studied in *Acharya, Bobkov, Kane, PK, Shao* PRD78, 2008
Acharya, Grajek, Kane, Kuflik, Wang 0901.3367*[hep-ph]*

Type IIB

- Warping present -- Depending on the location of visible and hidden sector, can have :

Gravity Mediation -*Blumenhagen et al, Conlon et al, Choi et al, Ibanez et al, Kachru et al, Nilles et al.. ....*
Gauge Mediation--*Buican et al,Cvetic et al, Diaconescu et al,Heckman et al,Marsano etal...*
Gaugino Mediation -- *Benini et al, Mcguirk et al* ....

Weak $\cancel{CP}$ Phases

- Will briefly discuss Weak CP phases in M theory framework.

  -- only focus on Flavor-diagonal sector. Give rise to EDMs

  Kane, PK, Shao, 0905.2686 [hep-ph]

  some earlier papers -- *Abel, Khalil -ph/0112260; Conlon:th/0710.0873*

  Choi -ph/0804.4283

- From earlier – All phases in W dynamically aligned.

  Since overall phase of W not physical, *can treat W as real*. Then, from:

$$F^I = K^{IJ}\bar{F}_J = K^{IJ}(\partial_J \bar{W} + \partial_J K \bar{W})$$

we see that all F^I are real & aligned with W

→ **(Not true in general)**

Crucial for soft terms

$$\mathcal{L}_{soft} = \frac{1}{2}(M_a\lambda\lambda + h.c.) - m^2_{\bar\alpha\beta}\hat{C}^{\bar\alpha\dagger}\hat{C}^{\beta} - \frac{1}{6}\hat{A}_{\alpha\beta\gamma}\hat{C}^{\alpha}\hat{C}^{\beta}\hat{C}^{\gamma} + \frac{1}{2}\left(B_{\alpha\beta}\hat{C}^{\alpha}\hat{C}^{\beta} + h.c.\right) \quad (6)$$

Yukawas factored out

$$M_a^{\text{tree}}(\mu) = \frac{g_a^2(\mu)}{8\pi}\left(\sum_I e^{\hat{K}/2}F^I\partial_I\, f_a^{vis}\right) \qquad A_{\alpha\beta\gamma} = e^{\hat{K}/2}F^I\partial_I\left[\ln\left(e^{\hat{K}}Y'_{\alpha\beta\gamma}/\tilde{K}_\alpha\tilde{K}_\beta\tilde{K}_\gamma\right)\right]$$

- All combinations : $F^I\,\partial_I f_a^{vis}$; $F^I\,\partial_I K$; $F^I\,\partial_I \ln(Y')$ are real

  $I = \{z_i, \phi\}$

- Negligible CP violating phases from SUSY breaking. Quite important.
  In general, with many comparable terms in W and many F^I,

  F^I not aligned with each other and with W -- SUSY (weak) CP problem

  Solve this problem in the above framework.

Have we completely gotten rid of CP phases ?

- Not quite ! Full A terms (Ǟ = A. Y) not aligned with Y.

  Since yukawas have O(1) CP phases ⇨ going to the CKM basis

  in which Y_{CKM} is real introduces O(1) phases in $\bar{\ddot{A}}_{CKM}$.

- Gives rise to contributions to EDMs for ***Hg, n, Tl***, etc.

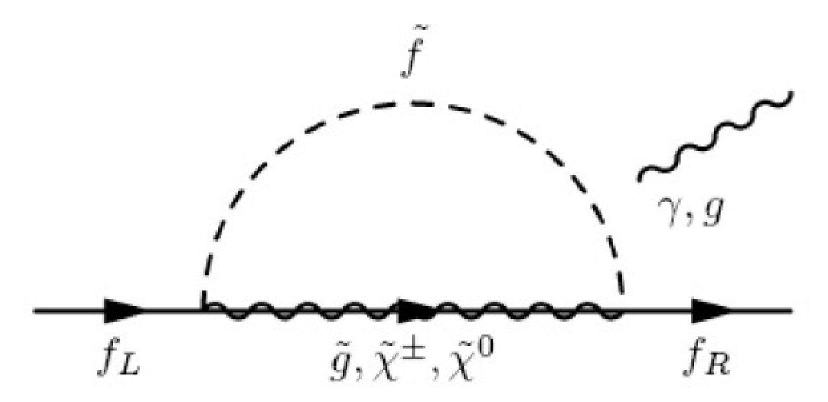
- Will estimate sizes of these EDMs in the framework. Utilize :

  a) $(M^{sq}_{CKM})^2$, $\bar{\ddot{A}}_{CKM} \sim M_{3/2}$ >~ 10 TeV *Acharya et al PRD78 (2008)*

  b) Hierarchical Yukawa texture (Assumption, not derived)

EDMs

$$\begin{aligned}\delta\mathcal{L} = \quad & -\sum_{q=u,d,s} m_q\bar{q}(1+i\theta_q\gamma_5)q+\theta_G\frac{\alpha_s}{8\pi}G\tilde{G}\\ & -\frac{i}{2}\sum_{f=u,d,s}\left(d_q^E\,\bar{q}F_{\mu\nu}\sigma_{\mu\nu}\gamma_5 q+\tilde{d}_q^C\,\bar{q}g_s t^a G^a_{\mu\nu}\sigma_{\mu\nu}\gamma_5 q\right)\\ & -\frac{1}{6}d_q^G f_{\alpha\beta\gamma}G_{\alpha\mu\rho}G^{\rho}_{\beta\nu}G_{\gamma\lambda\sigma}\epsilon^{\mu\nu\lambda\sigma}, \qquad (24)\end{aligned}$$



- $d_q^C \sim 10^{-28}$ (m_{gluino}/600 GeV) (20 TeV/m_{sq})^3 e cm

- Gives rise to :

$|d_n| \sim 3*10^{-28}$ e cm $(m_{gluino}/600 \text{ GeV}) (20 \text{ TeV}/m_{sq})^3$

$|d_{Hg}| \sim 10^{-30}$ e cm $(m_{gluino}/600 \text{ GeV}) (20 \text{ TeV}/m_{sq})^3$

| $d_e^E| \sim 10^{-31}$ e cm $(m_{gluino}/600 \text{ GeV}) (20 \text{ TeV}/m_{sq})^3$

A few orders of magnitude smaller than current bounds :

$| d_n | < 3 * 10^{-26}$ e cm ; $|d_{Hg}| < 10^{-28} - 10^{-29}$ e cm

$| d_e^E| < 2*10^{-27}$ e cm

Could be probed in the near future ! Crucial to have heavy squarks and trilinears >~ 10 TeV.

- In the Type IIB case, ($\bar{A}$ = A. Y) aligned with Yukawas if superpotential Yukawas only depend on moduli which do not break susy.

Hence, expect negligible contribution to EDMs for Type IIB models considered in *Bobkov et al 1003.1982*

gravity mediation

Summary & Conclusions

- Studied particular class of effective theories arising in classes of M theory & Type IIB compactifications with interesting features which allow to connect to observable physics

  -- An explicit realization of the Axiverse.
  -- Solution to the Strong CP Problem.
  -- Solution to the Weak CP Problem (Flavor Diagonal Sector)
  -- Many falsifiable predictions.

- Try to look for more such broad features of realistic compactifications which allow us to connect to data, so that data can reveal insights about nature of underlying theory.

Backup Slides

Moduli Stabilization Details

$$s_i = \frac{\tilde{a}_i}{N_i}\frac{3}{7}V_Q\,.$$

$$V_Q \approx \frac{QP_{eff}}{2\pi(Q-P)}\,,$$

$$P_{eff} = \frac{14(3(Q-P)-2)}{3(3(Q-P)-2\sqrt{6(Q-P)})}\,.$$

$$m_{3/2} = m_{pl}\frac{e^{\frac{\phi_0^2}{2V_X}}}{8\sqrt{\pi}V_X^{3/2}}|P-Q|\frac{A_2}{Q}e^{-\frac{P_{eff}}{Q-P}}\,.$$

1) Modified Cosmological History

- Cosmological history of the Universe – depends crucially on the moduli spectrum vis-a-vis the Hubble Parameter during Inflation.
- Within the framework – can compute moduli spectrum and $M_{3/2}$ in terms of microscopic parameters.
  - $M_{3/2} = e^{K/2} W / m_p^{\,2} = F^i F_i / m_p$ (after tuning CC. in N=1 SUGRA)

Since entire W generated non-perturbatively, $M_{3/2}$ naturally small relative to Planck scale.

With a Generic Super- and Kahler- potential,

$$V \supset K_i K^i |W|^2/m_p^2 \sim M_{3/2}^2 X_i^2$$

X_i stand for all scalar fields (moduli, charged matter, Higgs)

X_i are light, typically of $O(m_{3/2})$.

Thus, $M_{3/2}$ ~ TeV → Light Moduli exist in the spectrum

Also True in Type IIB compactifications – Kahler moduli light

- What about the Hubble parameter during Inflation (H_{inf})? Although not measured yet, have some idea.

- Measured amplitude of density perturbations

$$\delta\rho/\rho \sim 10^{-5} \Longrightarrow \varepsilon \sim 10^{10} \, (H_{inf}^{\,2}/\, m_p^{\,2})$$

ε = slow-roll parameter $\leq 10^{-2}$ required for Inflation.

- So, any $H_{inf} <\sim 10^{-6}\, m_p$ requires further fine-tuning not necessary for Inflation.
- Suggests that H_{inf} is as large as allowed. Expect:

$$\mathbf{H_{inf} \gg M_{3/2}}$$

- Light Moduli generically displaced during Inflation.

Start Oscillating later → Dominate the energy density of the Universe

- If decay late, can spoil the successes of BBN.

MODULI PROBLEM (An OLD Problem)

Coughlan, Fischler, Kob, Raby, Ross, PLB, 131 (59) 1983; Banks, Berkooz,Moore,Shenker,Steinhardt; th/9503114; Banks, Kaplan, Nelson, ph/9308292; etc.

Generic Problem in String Compactifications with Moduli Stabilization & Low energy SUSY

- Standard Picture of a Radiation dominated Universe from end of Inflation to beginning of BBN drastically modified.

- Important effects on the origin and abundance of Dark Matter.
- Late Decay of Moduli will also generically vastly dilutes the Baryon Asymmetry produced by known mechanisms.

Non-thermal WIMP "Miracle"

Acharya,Kane,PK,Watson;0908.2430 [astro-ph.CO]

Gravity Mediation → $M_{3/2}$ ~ TeV typically → Moduli and Gravitino problems.

Our Framework -- $M_{3/2}$ naturally >~ 10 TeV → Decay before BBN.

Acharya, Bobkov, Kane, PK, Shao:PRD76:126010; Acharya, Bobkov; 0810.3285[hep-th]

Superpartner spectrum – Superpartner scalars ~ $M_{3/2}$ = O(10) TeV

But gauginos can be light (sub-TeV) due to approx. R-symmetry in gauge sector. ($F_{X0} << F_{dominant}$)

μ, $B\mu$ ~ $M_{3/2}$ (Giudice-Masiero)

Acharya, Bobkov, Kane, PK, Shao; Phys.Rev.D78:065038,2008

Lightest Modulus X_0 decays last. Since M_{X0} >~ 10 TeV,

$X_0 \longrightarrow$ superpartners $\longrightarrow$ LSP.

- For weak scale masses and cross-sections, typically BR to DM such that

$\mathbf{n}_\chi$ **>** $$n_\chi^{(c)} = \frac{3H}{\langle \sigma_\chi v \rangle}\Big|_{T_R^{X_{lightest}}}$$, the critical density at temp T_R^{X0}

Relic Abundance fixed at $\mathbf{n}_\chi^{(c)}$

Non-thermal freezeout – similar to thermal freezeout, but at T= T_R^{X0} instead of T= T_{freeze}^{LSP}

- $$\boxed{\Omega h^2 = \Omega h^2_{thermal} \left(T_{freeze}^{LSP}/T_R^{X0}\right)}$$

For M_{moduli} = O(10) TeV (T_R^{X0} = O(MeV)), weak scale mass and cross-section of WIMP, get correct abundance.

  - **Nonthermal WIMP miracle !** Requires σv ~ 100-1000 $\sigma v_{thermal}$, since T_{freeze}^{LSP} =100-1000 T_R^{X0}
  - **Wino or Higgsino-like WIMPs quite natural**

Simple solution to the Moduli Problem & Correct WIMP DM Abundance

Possible Applications/Tests

- WIMP with $\sigma v \sim 100\text{-}1000\ \sigma v_{\text{thermal}}$ may help explain cosmic-ray anomalies by PAMELA, etc. in this setup.

  Grajek, Kane, Phalen, Pierce, Watson; PRD79:043506;0807.1508 [hep-ph]

  Goh, Hall, PK ; JHEP 0905:097,2009; 0902.0814 [hep-ph]

- Non-thermal DM from decay in general has different Phase Space distribution.

  -- In principle, could have effects on Structure Formation & Cosmic Microwave Background.

Detailed Study Required.