Arenas for String Phenomenology

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Possible Arenas for a String Phenomenology

1. Hierarchy problem: LHC scale physics: supersymmetry, RS, large extra dimensions, others? – testing now.
2. Limitations of Standard Model: strong CP (flavor)
3. Known higher energy physics: neutrino masses
4. Known higher energy physics: cosmology – baryogenesis, inflation

I have harangued this conference in the past about the first item and will say a few words about it next week at FERMILAB. I will mention here (2) and concentrate mainly on (3).

Axions and Strong CP

Small θ: No anthropic selection. Conceivably selection of axions as dark matter. But dark matter is typically not a strong enough requirement to yield an axion of sufficient *quality* (i.e. light enough to solve strong CP).

KKLT model problematic; KKLT scenario: a Kahler modulus (including a candidate axion) is fixed by susy preserving dynamics at some scale; the KKLT superpotential is:

$$e^{-\rho/b} + W_0 \qquad (1)$$

Neglecting supersymmetry breaking, all of the elements of ρ obtain equal mass. SUSY breaking is a small perturbation on top of this, so there is no light axion.

This would appear a general phenomenon, if all of the moduli are fixed by supersymmetry-preserving dynamics.

One possibility: only one modulus fixed by such dynamics; others fixed by susy-breaking.

Dimopoulos, Dubovsky, Kaloper, and March-Russell explored the possible consequences of many Kahler moduli (and axions) (“axiverse"). Motivated in part by these ideas, Acharya, Bobkov, Kane, Raby first suggested the possibility that all but one modulus fixed by susy-breaking dynamics. General effective action analysis and structure of such models explored by Festuccia, M.D., Kehayias and Wu.

Generalities about Moduli Fixing and Axions

Consider

$$W = W_0 + e^{-\tau/b} + A_i e^{-\tau_i} + \ldots. \tag{2}$$

where $b \gg 1$. Then τ, some linear combination of moduli, is heavy, while others are light. If the τ_i are the only relevant fields, the theory at low scales is described by a Kahler potential for the light moduli and a constant superpotential. Typically additional fields are needed for supersymmetry breaking and moduli fixing.

Leaves questions:

1. Does such stabilization occur? (In general, not a weak coupling problem)
2. Cosmology: Necessarily moduli with masses of order the susy-breaking scale ($m_{3/2}$). Cosmologically problematic unless their masses are quite large.
3. Cosmology: Axion decay constant is large, but decays of other moduli dilute. Axion itself may be cosmologically acceptable.

Overall, suggests a setting for the axion solution to the strong CP problem.

Axions very hard to observe (speculative ideas for observing such high scale axions: Thomas, Graham, Cabrera)

Note that without some degree of low energy supersymmetry, it is hard to put forward even a scenario which accounts for light axions.

Note also that axions + low energy supersymmetry $\Rightarrow$ at least one modulus (Watson's talk, Kane's talk, Wang's talk). If heavy

String Theory and Cosmology

Cosmology is another arena in which a would-be theory of gravity may confront observation. For string theory, the challenges include:

1. Nature of inflation
2. Cosmological moduli (precise nature of the problem depends on inflation)
3. Dark matter
4. Viability of axions
5. Baryogenesis

Some of these problems may be closely related.

Inflation

We have already remarked on moduli and axions (which might be some or all of the dark matter). Here we ask about inflation (we will have some overlap with other talks at this meeting, e.g. Halter, McAlister, large volume scenarios), though not tied to detailed microscopic picture in string theory, strictly small field, effective field theory).

We distinguish *large field* and *small field* inflation, By *large field*, we will mean field excursions of Planck distance or larger (some authors distinguish “medium" and “large" field. At present, it would seem difficult to characterize large field models in any simply way, and generically they will be difficult to analyze by perturbative (or semiclassical) string methods.

Instead, focus on small field inflation.

Small field inflation, we will see, admits a very general effective lagrangian analysis. Such theories are almost inevitably supersymmetric and hybrid, and their observables can be characterized in terms of a small number of parameters. There is an irreducible level of fine tuning, and a surprisingly low (and mildly model-dependent) upper bound on the energy scale of inflation.

Main ingredients: Degrees of Freedom

Call $V_0 = \mu^4$ the scale of inflation. This scale is necessarily well below M_p. Slow roll inflation requires at least one field with mass (during inflation) $m^2 \ll H_0$. In a conventional, non-supersymmetric field theory, even a field with mass *of order* H_0 is fine-tuned, so we will assume supersymmetry at the scale H_0.

So we require at least one chiral field, S. We can describe the effective theory for S (and possibly other light fields) in terms of a superpotential and Kahler potential.

Ingredients: Effective Action

Because of small field assumption, can expand W:

$$W = W_0 + \mu^2 S + \frac{m}{2} S^2 + \frac{\lambda}{3} S^3 + \ldots . \qquad (3)$$

Because of the small field assumption, W_0 cannot dominate during inflation, so

$$W_0 \ll H_0 M_p^2 . \qquad (4)$$

Then $\mu^2 = H_0 M_p$.

The slow roll conditions then imply

$$W_0 \ll \mu^2 M_p; \quad m \ll \mu \left(\frac{\mu}{M_p}\right); \quad \lambda \ll \frac{\mu^2}{M_p^2}. \tag{5}$$

The smallness of terms W_0, S^2, S^3 is most readily accounted for if the theory possesses an R symmetry; we will assume that the R symmetry is discrete.

Note that the R symmetry assumption means that the origin is a special place; small field excursions now mean small S.

At the end of inflation, supersymmetry must be restored, and the energy vanish; we need additional degrees of freedom coupled to S (will describe an alternative possibility if time). We will suppose that there is one such field, ϕ. Any additional light fields coupled to S are likely to be quite light. So

$$W = S(\kappa\phi^2 - \mu^2) + \text{ non } - \text{renormalizable terms.} \tag{6}$$

This system has a supersymmetric minimum at $\kappa\phi^2 = \mu^2, \; S = 0$. Classically, however, it has a moduli space with

$$|\kappa S|^2 > |\mu^2|. \tag{7}$$

This pseudomoduli space will be lifted both by radiative corrections in κ and the non-renormalizable terms in the superpotential. As we will see, both are necessarily relevant if inflation occurs in the model. Inflation takes place on this pseudomoduli space; ϕ is effective pinned at zero during inflation.

Three points should be noted:

1. The assumption that the symmetry is discrete means couplings like $\frac{S^{N+1}}{M_p^{N-2}}$ are permitted, and, as we will soon see, they significantly constraint inflation.
2. There are additional conditions, as we will shortly enumerate, on the Kahler potential in order that one obtain inflation with adequate number of *e*-foldings. These constitute at least one fine tuning, needed to obtain an inflaton with mass small compared to the Hubble scale.
3. This structure is not unique; the inflaton need not lie in a supermultiplet with the Goldstino. If there are several multiplets with non-zero R charges, it is possible to tune parameters so that the scalar component of one of these other multiplets is light, while the partner of the Goldstino is heavy.
4. We will see that these structures can be embedded in a model of low energy supersymmetry breaking. This is not required, but would seem elegant and economical.

The assumption of a discrete Z_N R-symmetry allows additional terms in the superpotential:

$$W = S(\kappa\phi^2 - \mu^2) + W_R; \quad W_R = \frac{\lambda}{2(N+1)} \frac{S^{N+1}}{M_p^{N-2}} + \mathcal{O}\left(\frac{S^{2N+1}}{M_p^{2N-2}}\right). \quad (8)$$

So a supersymmetric vacuum at

$$S^N = M_p \left(\frac{\mu}{M_p}\right)^2. \quad (9)$$

Has negative c.c. Important that not flow to this point.

First ignore W_R. Now have a theory with an approximate global supersymmetry, spontaneously broken. Fermionic component of S is Goldstino. Low energy effective theory: need Kahler potential for S.

$$K = S^\dagger S + \phi^\dagger \phi - \frac{\alpha}{4M_p^2}(S^\dagger S)^2 + \dots . \tag{10}$$

$$V_{SUGRA} = \alpha \mu^4 \frac{S^\dagger S}{M_p^2}. \tag{11}$$

The slow roll conditions are:

$$\eta = \frac{V''}{V} M_p^2 \ll 1; \quad \epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 M_p^2 \ll 1. \tag{12}$$

Both conditions are satisfied if $\alpha \ll 1$, and if $|S| \ll M_p$; these are minimal conditions for successful inflation in any case.

For large S, we can integrate out the field ϕ. This gives a further contribution to the Kahler potential for S. This contribute dominates over the supergravity contribution for sufficiently small S (but $\kappa|S| \gg \mu$).

$$\delta K_{quant}(S, S^\dagger) = \frac{\kappa^2}{16\pi^2} \log(S^\dagger S). \tag{13}$$

Below S_{quant}, the quantum contribution to the potential dominates over the supergravity contribution:

$$|S^2_{quant}| \equiv \sigma^2_{quant} = \frac{1}{\alpha} \frac{\kappa^2}{16\pi^2} M_p^2. \tag{14}$$

At still lower values of S, one has $V'' \approx H_0$, and inflation ends:

$$|S_f^2| = \frac{\kappa^2}{8\pi^2} M_p^2. \tag{15}$$

Call $\sigma = \sqrt{2}S$. The number of e-foldings in the supergravity regime is:

$$\mathcal{N} = \int_{\sigma_{quant}}^{\sigma_i} d\sigma \frac{V}{V' M_p^2} \tag{16}$$

$$\frac{1}{2\alpha} \log \frac{\sigma_i}{\sigma_{quant}},$$

The total number of e-foldings in the quantum regime is

$$\mathcal{N}_{quant} = \frac{1}{4\alpha}. \tag{17}$$

Significant inflation requires that α is small. Generically, this is a tuning, of order $\frac{1}{\mathcal{N}}$ (possibly modulo a logarithm). *This is irreducible*.

Aside on fine tuning

N. Agarwal, R. Bean, L.McAllister, G. Xu have estimated fine tuning in brane models with six (real) fields. Find $\frac{1}{\mathcal{N}^3}$. We can easily estimate fine tuning in the present case

If multiple Hubble scale fields, requirement that one is light is a constraint on the quartic Kahler potential couplings. With N complex fields, there is one coupling which must be order $1/\mathcal{N}$, and $2N$ (N if CP conserved) which must be of order $1/\sqrt{\mathcal{N}}$. So scaling is

$$\Delta \propto \left(\frac{1}{\mathcal{N}}\right)^{1+(N-1)/2}. \qquad (18)$$

The more Hubble-scale fields (which can mix with the Goldstino) the more fine tuning.

$\frac{\delta\rho}{\rho}$ is determined in terms of μ and κ:

$$V^{3/2}/V' = 5.15 \times 10^{-4} M_p^3. \tag{19}$$

This determines μ in terms of κ (or vice versa):

$$\kappa = 0.17 \times \left(\frac{\mu}{10^{15}\mathrm{GeV}}\right)^2 = 7.1 10^5 \times \left(\frac{\mu}{M_p}\right)^2. \tag{20}$$

If $\alpha \ll 1/15$, we can calculate S_{60}, the value of $|S|$ 60 e-foldings before the end of inflation, and express the slow roll parameters and the spectral index in terms of the parameters of $\mathcal{L}_{eff}$. In this limit, in which supergravity corrections are unimportant, η and n_s are universal, and ϵ is small.

$$\eta = \frac{1}{\mathcal{N}}; \ n_s = 1 - 2\eta. \tag{21}$$

So one expects, quite generally, that $n_s \approx 0.98$.

Constraints from W_R

In the presence of W_R, the system has supersymmetric minima, satisfying

$$S^N = \frac{\mu^2 M_p^{N-2}}{\lambda} \quad \phi = 0. \tag{22}$$

At large S, the potential includes terms

$$\delta V_R = \lambda \mu^2 \frac{S^N}{M_p^{N-2}} + \mathrm{c.c.}. \tag{23}$$

If these terms dominate, the system will be driven towards the supersymmetric minimum. So if we insist that the system is driven to the R symmetric stationary point, we must require that these terms are small, and this in turn places limits on the scale μ (or, through equation 20, the coupling κ), as well as σ_i.

Constraint on the scale of inflation (using κ, μ relation):

$$\left(\frac{\mu}{10^{15} GeV}\right)^{2N-6} \ll \frac{0.34(69)^{N-2}\alpha^{N/2}}{\lambda N(N-1)} \times 10^{-6} \qquad (24)$$

For $N = 4$, this yields $\mu \approx 1.22 \times 10^{13} \alpha \ \mathrm{GeV}$.

Note that we now have three types of constraints/tunings:

1. α must be small, comparable, up to a logarithmic factor, to $1/\mathcal{N}$, one over the number of *e*-foldings.
2. μ and κ must be small, in order that the superpotential corrections not drive *S* to a large field regime.
3. The initial conditions for *S* are constrained. *S* must lie in a range small enough that, at least for a time, the quantum potential is dominant, and large enough that inflation can take place.

Reheating

$$\langle \phi \rangle = \kappa^{-1/2} \mu \tag{25}$$

easily of order grand unified scales. Many hybrid inflation models take ϕ to be, say, in the adjoint representation of some grand unified group. If S is a singlet, this is potentially problematic, since there may be additional light states (in the final vacuum); these can spoil unification and lead to other difficulties. A very simple possibility is to take ϕ to be a gauge singlet, and couple ϕ to some charged fields; schematically

$$\delta W = \lambda \phi \bar{5} 5. \tag{26}$$

In the vacuum, the masses of $\bar{5}$, 5, are of order $m_Q = \lambda\phi$. So the ϕ lifetime is of order

$$\Gamma = \left(\frac{\alpha_s}{\pi}\right)^2 \frac{\lambda^2}{4\pi} \frac{m_\phi^3}{m_Q^2}. \tag{27}$$

Using $\phi = \kappa^{-1/2}\mu$, and the relation between κ and μ:

$$\Gamma = \frac{1}{4\pi} \left(\frac{\alpha_s}{\pi}\right)^2 \kappa^{5/2}\mu \tag{28}$$

$$\approx 3 \times 10^9 \left(\frac{\mu}{10^{15}}\right)^6 \mathrm{GeV}.$$

For $\mu = 10^{12}$ GeV, this corresponds to $\Gamma = 3 \times 10^{-9}$ GeV, or a reheat temperature of order $10^{4.5}$ GeV. Larger μ leads to higher reheat temperatures. Such temperatures are clearly interesting from the point of view of the gravitino problem and other cosmological issues.

Supersymmetry Breaking

The structure of the hybrid inflation superpotential is reminiscent of O'Raifeartaigh models. It is interesting to include additional degrees of freedom so that S is part of a sector responsible for (observed) supersymmetry breaking. For small S, in addition to the field ϕ, we can include another field, X, with R charge two and superpotential:

$$W = S(\kappa\phi^2 - \mu^2) + mX\phi. \tag{29}$$

Assuming that the scale of inflation is large compared to the scale of supersymmetry breaking leads to consideration of the limit $|m|^2 \ll |\kappa\mu^2|$. In this limit, the vacuum state has $\phi \approx \kappa^{-1/2}\mu$, $X = S = 0$, and

$$F_X \approx \kappa^{-1/2} m\mu. \tag{30}$$

By choosing m, we can arrange F_X as we please.

In the model as it stands, the R symmetry is unbroken by loop effects. This can be avoided through additional, "retrofitted" couplings (J. Kehayis, M.D.), or through models like that of Shih.

Challenges for String Theory

There are a number of exciting ideas for a microscopic understanding of inflation in string theory. One might imagine that the problem is inherently one of quantum gravity, and/or that many degrees of freedom may play a role simultaneously (colliding branes, bouncing cosmologies...). But it is also possible that only a small number of field-theoretic degrees of freedom are active, and we have seen here that even small field inflation, if it emerges from string theory, is challenging enough. The identification of the correct degrees of freedom, computation of the quartic terms in the Kahler potential, are critical and challenging.

Of course, how often the low energy theory has suitable degrees of freedom, vs. how often more complicated microscopic dynamics is important, is a question to which we would dearly like to know the answer.