Moduli stabilization, de Sitter vacua and supersymmetry breaking

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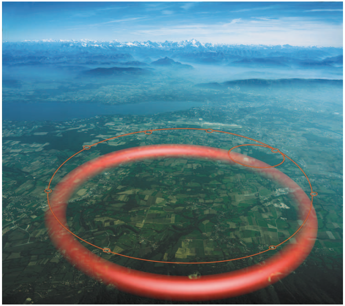
String phenomenology

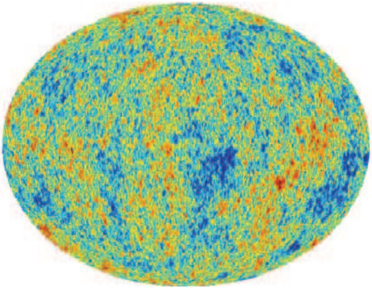
- Is string theory a tool for strong coupling dynamics

  or a theory of fundamental forces?

- If theory of Nature can string theory describe

  both particle physics and cosmology?





Problem of scales

- describe high energy SUSY extension of the Standard Model

  unification of all fundamental interactions

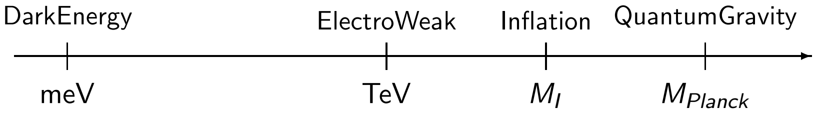
- incorporate Dark Energy

  simplest case: infinitesimal (tunable) +ve cosmological constant

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

$\Rightarrow$ 3 very different scales besides M_{Planck} :



impose independent scales: proceed in 2 steps

1. SUSY breaking at $m_{SUSY} \sim$ TeV
   with an infinitesimal (tunable) positive cosmological constant

   Villadoro-Zwirner '05

   I.A.-Knoops, I.A.-Ghilencea-Knoops '14, I.A.-Knoops in preparation
2. Inflation in supergravity at a scale different than m_{SUSY}

1st step: Maximal predictive power if there is common framework for :

- moduli stabilization
- model building (spectrum and couplings)
- SUSY breaking (calculable soft terms)
- computable radiative corrections (crucial for comparing models)

Possible candidate of such a framework: **magnetized branes**

Type I string theory with magnetic fluxes B_{ij} on 2-cycles of the compactification manifold

- Dirac quantization: $B = \frac{m}{nA} \equiv \frac{p}{A}$ [8] $\Rightarrow$ moduli stabilization

  B: constant magnetic field m: units of magnetic flux

  n: brane wrapping A: area of the 2-cycle

- Spin-dependent mass shifts for charged states $\Rightarrow$ SUSY breaking

- Exact open string description: $\Rightarrow$ calculability

  $qB \to \theta = \arctan qB\alpha'$ weak field $\Rightarrow$ field theory

- T-dual representation: branes at angles $\Rightarrow$ model building

  (m, n): wrapping numbers around the 2-cycle directions

Magnetic fluxes can be used to stabilize moduli

I.A.-Maillard '04, I.A.-Kumar-Maillard '05, '06, Bianchi-Trevigne '05

e.g. T^6: 36 moduli (geometric deformations)

internal metric: $6 \times 7/2 = 21 = 9 + 2 \times 6$

type IIB RR 2-form: $6 \times 5/2 = 15 = 9 + 2 \times 3$

$$\text{complexification} \Rightarrow \begin{cases} \text{Kähler class} & J \\ \text{complex structure} & \tau \end{cases} \quad \text{9 complex moduli for each}$$

magnetic flux: 6×6 antisymmetric matrix F complexification $\Rightarrow$

$F_{(2,0)}$ on holomorphic 2-cycles: potential for τ superpotential

$F_{(1,1)}$ on mixed (1,1)-cycles: potential for J FI D-terms

$N=1$ SUSY conditions $\Rightarrow$ moduli stabilization

1. $F_{(2,0)} = 0 \;\; \Rightarrow \tau$ matrix equation for every magnetized $U(1)$

   need 'oblique' (non-commuting) magnetic fields to fix off-diagonal components of the metric $\leftarrow$ but can be made diagonal

2. $J \wedge J \wedge F_{(1,1)} = F_{(1,1)} \wedge F_{(1,1)} \wedge F_{(1,1)} \;\; \Rightarrow J$

   vanishing of a Fayet-Iliopoulos term: $\xi \sim F \wedge F \wedge F - J \wedge J \wedge F$

   magnetized $U(1) \to$ massive absorbs RR axion

   one condition $\Rightarrow$ need at least 9 brane stacks

3. Tadpole cancellation conditions : introduce an extra brane(s)

   $\Rightarrow$ dilaton potential from the FI D-term $\to$ two possibilities:

   - keep SUSY by turning on charged scalar VEVs
   - break SUSY in a dS or AdS vacuum $d = \xi / \sqrt{1+\xi^2}$ [9]

I.A.-Derendinger-Maillard '08

$F_{(2,0)} = 0 \Rrightarrow \quad \tau^{\mathrm{T}} p_{xx} \tau - (\tau^{\mathrm{T}} p_{xy} + p_{yx} \tau) + p_{yy} = 0$ [5]

T^6 parametrization: $(x^i, y^i) \quad i = 1, 2, 3 \qquad z^i = x^i + \tau^{ij} y^i$

Non-trivial VEVs v for charged brane scalars $\Rrightarrow$

D-term condition is modified to:

$$q\, v^2 \,(J \wedge J \wedge J - J \wedge F \wedge F) = -(F \wedge F \wedge F - F \wedge J \wedge J)$$

charge

break SUSY in a dS or AdS vacuum

I.A.-Derendinger-Maillard '08

$N = 2$ non-linear supersymmetry $\Rightarrow$

General form of the localized dilaton potential:

$$V(\phi, d) = \frac{e^{-\phi}}{g^2} \left\{ \left(\sqrt{1 - d^2} - 1 \right) + \xi d + \delta T \right\}$$

DBI action FI-term

d: D-auxiliary in $2\pi\alpha'$-units

δT: tension leftover RR tadpole cancellation $\Rightarrow \delta T = 1 - \sqrt{1 - \xi^2}$

d elimination $\Rightarrow$ $d = \frac{\xi}{\sqrt{1+\xi^2}}$

$$V_{\min} = \delta \bar{T} e^{-\phi} \quad ; \quad \delta \bar{T} = \sqrt{1 + \xi^2} - \sqrt{1 - \xi^2}$$

Dilaton fixing:

1) by 3-form fluxes in a SUSY way $\Rightarrow$ dS vacuum with positive energy

D-term uplifting possible from flat space

2) add a 'non-critical' (bulk) dilaton potential

$\Rightarrow$ AdS vacuum with tunable string coupling

$V_{\rm non-crit} = \delta c\, e^{-2\phi}$ δc: central charge deficit

minimization of $V = V_{\rm non-crit} + V_{\rm min} \Rightarrow \delta c < 0$

$e^{\phi_0} = -\frac{2\delta c}{3\delta\bar{T}}$ $V_0 = \frac{\delta c^3}{3\delta\bar{T}^2}$ $R_0 = -\delta\bar{T}e^{3\phi_0}$

curvature in Einstein frame

e.g. replace a free coordinate by a CFT minimal model of central charge $1 + \delta c$

$\rightarrow$ generalize: add a dilaton potential preserving the axion shift symmetry

$\Rightarrow$ break SUSY with tunable vacuum energy

Toy model for SUSY breaking

Content (besides $N = 1$ SUGRA): one vector V and one chiral multiplet S

with a shift symmetry $S \to S - ic\omega \leftarrow$ transfomration parameter

String theory: compactification modulus or universal dilaton

$s = 1/g^2 + ia \leftarrow$ dual to antisymmetric tensor

Kähler potential K: function of $S + \bar{S}$

string theory: $K = -p \ln(S + \bar{S})$

Superpotential: constant or single exponential if R-symmetry $W = ae^{bS}$

$b < 0 \Rightarrow$ non perturbative

can also be described by a generalized linear multiplet

Scalar potential

$$\mathcal{V}_F = a^2 e^{\frac{b}{l}} l^{p-2} \left\{ \frac{1}{p}(pl - b)^2 - 3l^2 \right\} \qquad l = 1/(s + \bar{s})$$

Planck units

no minimum for $b < 0$ with $l > 0$ $(p \leq 3)$

but interesting metastable SUSY breaking vacuum

when R-symmetry is gauged by V allowing a Fayet-Iliopoulos (FI) term:

$$\mathcal{V}_D = c^2 l(pl - b)^2 \qquad \text{for gauge kinetic function } f(S) = S$$

- $b > 0$: $\mathcal{V} = \mathcal{V}_F + \mathcal{V}_D$ SUSY local minimum in AdS space at $l = b/p$
- $b = 0$: SUSY breaking minimum in AdS $(p < 3)$ $\delta c = -a^2$
- $b < 0$: SUSY breaking minimum with tunable cosmological constant Λ

In the limit $\Lambda \approx 0$ $(p = 2) \Rightarrow$

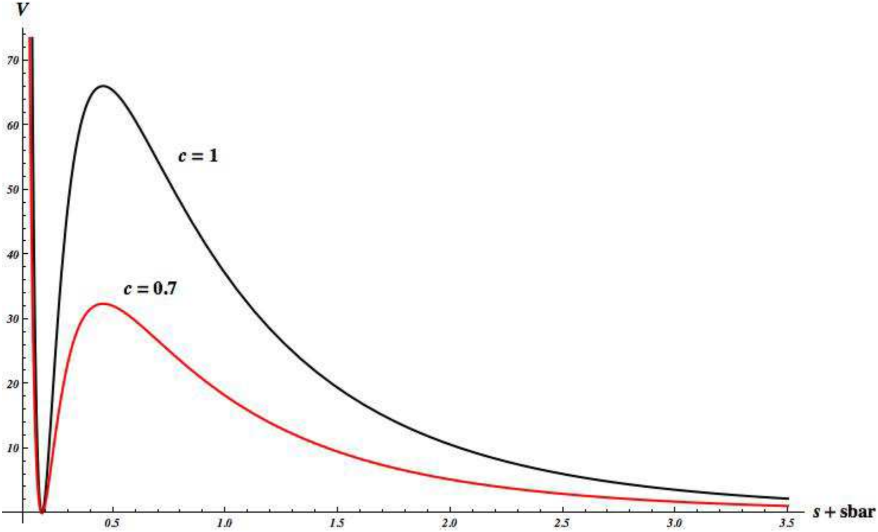
$b/l = \alpha \approx -0.183268$

$\frac{a^2}{bc^2} = 2\frac{e^{-\alpha}}{\alpha}\frac{(2-\alpha)^2}{2+4\alpha-\alpha^2} + \mathcal{O}(\Lambda) \approx -50.6602$

physical spectrum:

massive dilaton, $U(1)$ gauge field, Majorana fermion, gravitino

All masses of order $m_{3/2} \approx e^{\alpha/2} l a \leftarrow$ TeV scale


V
70
60
50
40
30
20
10
c = 1
c = 0.7
0.5
1.0
1.5
2.0
2.5
3.0
3.5
s + sbar

Properties and generalizations

- Metastability of the ground state: extremely long lived

  $l \simeq 0.02$ (GUT value $\alpha_{GUT}/2$) $m_{3/2} \sim \mathcal{O}(TeV) \Rightarrow$

  decay rate $\Gamma \sim e^{-\mathcal{B}}$ with $B \approx 10^{300}$

- Add visible sector (MSSM) preserving the same vacuum

  matter fields ϕ neutral under R-symmetry

  $$K = -2\ln(S+\bar{S}) + \phi^\dagger\phi \quad ; \quad W = (a + W_{MSSM})e^{bS}$$

  $\Rightarrow$ soft scalar masses non-tachyonic of order $m_{3/2}$ (gravity mediation)

- R-charged fields can be added in the hidden sector

  needed for anomaly cancellation (important constraint)

Properties and generalizations

- Interesting phenomenology: work in progress
- Toy model classically equivalent to

  $K = -p\ln(S+\bar{S}) + b(S+\bar{S}) \quad ; \quad W = a$ with V ordinary $U(1)$

- string origin of b ? allows flat space solution

  unphysical in the absence of a

- Consider a simple (anomaly free) variation of the model with

  the above K and W, gauge kinetic function $f = 1$ and $p = 1$

  $\Rightarrow$ tuning still possible but scalar masses of neutral matter tachyonic

  possible solution: add a new field Z in the 'hidden' SU̸SY sector

An alternative model

$$K = -\ln(S+\bar{S}) + b(S+\bar{S}) + Z\bar{Z} + \sum \Phi\bar{\Phi}$$

$$W = a(1+\gamma Z) + W_{MSSM}(\Phi)$$

$$f = 1 \quad , \quad f_A = 1/g_A^2$$

Existence of tunable dS vacuum + non-tachyonic soft scalar masses

$\Rightarrow 0.5 \leq \gamma \lesssim 1.7$

- main properties remain with $\mathrm{Re}z, F_z \neq 0$
- soft scalar masses: $m_0 \approx B_0 \sim \mathcal{O}(m_{3/2})$
- trilinear scalar couplings: $A_0 = B_0 + m_{3/2}$

gaugino masses appear to vanish since f_A are constants

however in the gauged R-symmetry representation they don't

Kähler transformation and gaugino masses

$$K = -\ln(S+\bar{S}) + Z\bar{Z} + \sum \Phi\bar{\Phi}$$

$$W = [a(1+\gamma Z) + W_{MSSM}(\Phi)]\, e^{bS}$$

$$f_A = 1/g_A^2 + \beta_A S \quad ; \quad \beta_A = \frac{b}{8\pi^2}(T_{R_A} - T_{G_A})$$

S-dependent contribution: needed to cancel the $U(1)_R$ anomalies

$\Rightarrow$ generate non-vanishing gaugino masses!

resolution of the puzzle: 'anomaly' mediation contribution

due to super-Weyl-Kähler and sigma-model anomalies

$$m_{1/2} = -\frac{g^2}{16\pi^2}[(3T_G - T_R)m_{3/2} + (T_G - T_R)K_\alpha F^\alpha + 2\frac{T_R}{d_R}(\log\det \underset{\underset{0}{\parallel}}{K|''_R})_{,\alpha} F^\alpha]$$

difference in K_S is accounted by difference in f

Phenomenology

- distinct features

  different from other models of SUSY breaking and mediation

- gaugino masses at the quantum level

  $\Rightarrow$ suppressed compared to scalar masses and A-terms

  experimental bounds on gluinos $\Rightarrow$ scalar masses $\mathcal{O}(10)$ TeV

- μ-term as in SUGRA: e.g. add in the Kähler potential $zh\bar{h}$

- Z-field can be avoided (non tachyonic scalar masses)

  by adding an S-dependent factor in Matter kinetic terms

  $K = -\ln(S+\bar{S}) + (S+\bar{S})^{-\nu}\sum\Phi\bar{\Phi}$ for $\nu \gtrsim 2.5$

  $\Rightarrow$ similar phenomenology

Conclusions

String phenomenology:

Consistent framework for particle phenomenology and cosmology

possible 3 very different scales (besides M_{Planck})

electroweak, dark energy, inflation

Maximal predictive power if common frame for:

moduli stabilization, model building, SUSY breaking and calculability

e.g. magnetized branes

- SUSY breaking with infinitesimal (tunable) $+$ve cosmological constant

  interesting framework for model building incorporating dark energy

- Inflation models at a hierarchically different third scale

  Sgoldstino-less supergravity models of inflation