Aspects of string phenomenology and Scale hierarchies in particle physics and cosmology

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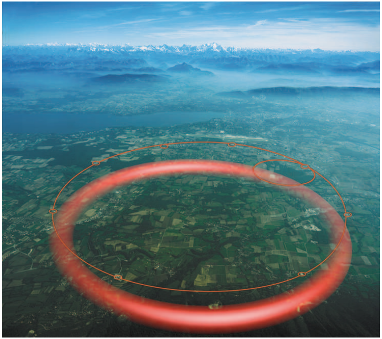
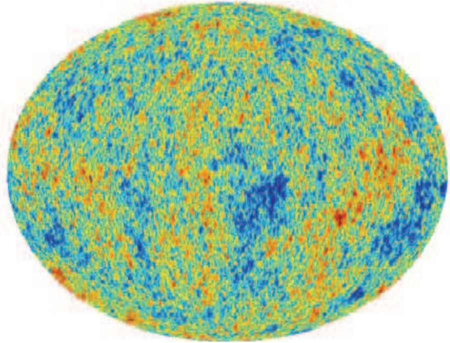
String theory

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- If theory of Nature can it describe both particle physics and cosmology?





Problem of scales

- describe high energy SUSY extension of the Standard Model

  unification of all fundamental interactions

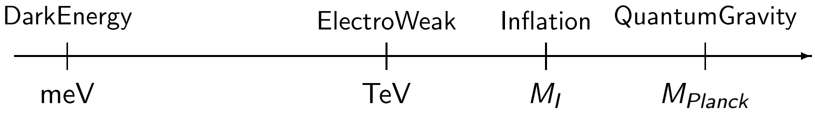
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

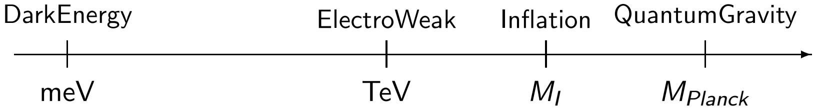
- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

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



Problem of scales



1. possible connections
   - M_I could be near the EW scale, such as in Higgs inflation

     but large non minimal coupling to explain
   - M_{Planck} could be emergent from the EW scale

     in models of low-scale gravity and TeV strings

     2 extra dims at submm $\leftrightarrow$ meV: interesting coincidence with DE scale

     $M_I \sim TeV$ is also allowed by the data since cosmological observables are dimensionless in units of the effective gravity scale

     I.A.-Patil '14 and '15
2. they are independent [9]

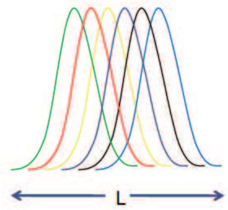
Effective scale of gravity: reduced by the number of species

N particle species $\Rightarrow$ lower quantum gravity scale : $M_*^2 = M_p^2/N$

Dvali '07, Dvali, Redi, Brustein, Veneziano, Gomez, Lüst '07-'10

derivation from: black hole evaporation or quantum information storage

Pixel of size L containing N species storing information:



localization energy $E \gtrsim N/L \rightarrow$

Schwarzschild radius $R_s = N/(LM_p^2)$

no collapse to a black hole : $L \gtrsim R_s \Rightarrow L \gtrsim \sqrt{N}/M_p = 1/M_*$

Cosmological observables

Power spectrum of temperature anisotropies

(adiabatic curvature perturbations $\mathcal{R}$)

$$\mathcal{P}_{\mathcal{R}} = \frac{H^2}{8\pi^2 M_*^2 \epsilon} \simeq \mathcal{A} \times 10^{-10} \quad ; \quad \mathcal{A} \approx 22$$

$-\dot{H}/H^2$

Power spectrum of primordial tensor anisotropies $\quad \mathcal{P}_t = 2\frac{H^2}{\pi^2 M_*^2}$

$\Rightarrow$ tensor to scalar ratio $r = \mathcal{P}_t/\mathcal{P}_{\mathcal{R}} = 16\epsilon$

measurement of $\mathcal{A}$ and $r \Rightarrow$ fix the scale of inflation

$$H \text{ in terms of } M_* \quad : \quad \frac{H}{M_*} = \left(\frac{\pi^2 \mathcal{A}\, r}{2 \times 10^{10}}\right)^{1/2} \equiv \Upsilon \approx 1.05\sqrt{r} \times 10^{-4}$$

Extra species as Kaluza-Klein states

$D = 4 + n$ extra dims of size average size $R \Rightarrow$

fundamental gravity scale $M_s^{2+n} R^n = M_{Pl}^2$

$N =$ all KK states with mass less than $H \Rightarrow N \simeq (HR)^n$

$M_* = M_{Pl}/\sqrt{N} = M_s (M_s R)^{n/2} / (HR)^{n/2} = M_s (M_s/H)^{n/2}$

$H = M_* \Upsilon = M_s (M_s/H)^{n/2} \Upsilon \quad \Rightarrow \quad H = M_s \Upsilon^{2/(n+2)}$

$\Rightarrow H \sim$ 1-3 orders of magnitude less than M_s for $0.001 \lesssim r \lesssim 0.1$

as low as near the EW scale

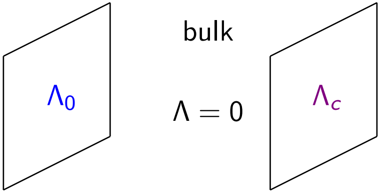
A brane-world model

5D brane-world realisation: empty bulk with two boundary dS branes

$$ds^2 = \frac{(1 + H|y|)^2}{H^2\tau^2}\left(-d\tau^2 + dx_1^2 + dx_2^2 + dx_3^2\right) + dy^2$$

dS brane

$H = -\kappa_5^2\Lambda_0/6$



$y = 0$ $\qquad$ $y = y_c$

dS brane

$|y_c| = \frac{6(\Lambda_0+\Lambda_c)}{\kappa_5^2\Lambda_0\Lambda_c}$

$\Rightarrow$ keeping H fixed one can make y_c large, so that $H^2 \gg 1/y_c^2$ [4]

impose independent scales: proceed in 2 steps

1. SUSY breaking at $m_{SUSY} \sim$ TeV

   with an infinitesimal (tuneable) positive cosmological constant

   Villadoro-Zwirner '05

   I.A.-Knoops, I.A.-Ghilencea-Knoops '14, I.A.-Knoops '15

2. Inflation in supergravity at a scale different than m_{SUSY}

impose independent scales: proceed in 2 steps

1. SUSY breaking at $m_{SUSY} \sim$ TeV
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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: $B = \frac{m}{nA} \equiv \frac{p}{A}$ [14] $\Rightarrow$ 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 explicit examples: e.g. T^6 toroidal compactification

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

- all geometric moduli can be stabilized in a supersymmetric way

  need 9 magnetized $U(1)$s (branes)

- however tadpole (anomaly) cancellation requires an extra $U(1)$ brane

  $\Rightarrow$ dilaton potential [15] I.A.-Derendinger-Maillard '08

  its form is fixed by the axion shift symmetry

  $\Rightarrow$ break SUSY with tuneable vacuum energy

  I.A.-Knoops '14, '15

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 $U(1)$

   $$\tau^{\mathrm{T}} p_{xx} \tau - (\tau^{\mathrm{T}} p_{xy} + p_{yx}\tau) + p_{yy} = 0$$ [11]

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

   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: $\quad \xi \sim F \wedge F \wedge F - J \wedge J \wedge F$

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

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

3. Tadpole cancellation conditions : introduce an extra brane(s) [12]

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

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

Dilaton fixing

add a 'non-critical' dilaton potential

$\Rightarrow$ AdS vacuum with tunable string coupling

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

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

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

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

I.A.-Knoops '14, '15

Toy model for SUSY breaking

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

with a shift symmetry $S \to S - ic\omega \leftarrow$ transformation 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 $W = ae^{bS}$

$\int d^2\theta W$ invariant

$b < 0 \Rightarrow$ 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 tuneable cosmological constant Λ

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

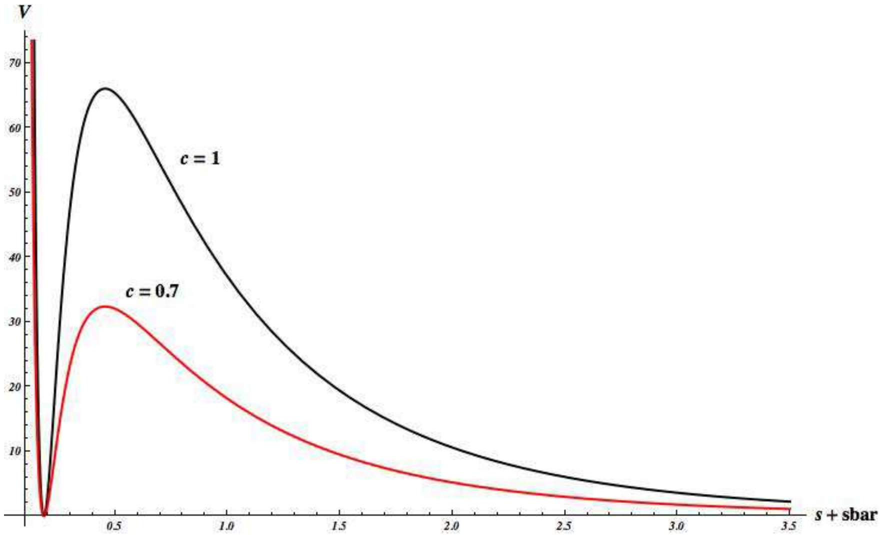
$b/l = \alpha \approx -0.183268$

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

physical spectrum:

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

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

- Toy model classically equivalent to

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

Properties and generalizations

- 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

  $\Rightarrow$ one extra parameter

- alternatively: add 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

- distinct features from other models of SUSY breaking and mediation
- gaugino masses at the quantum level

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

A realistic 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!

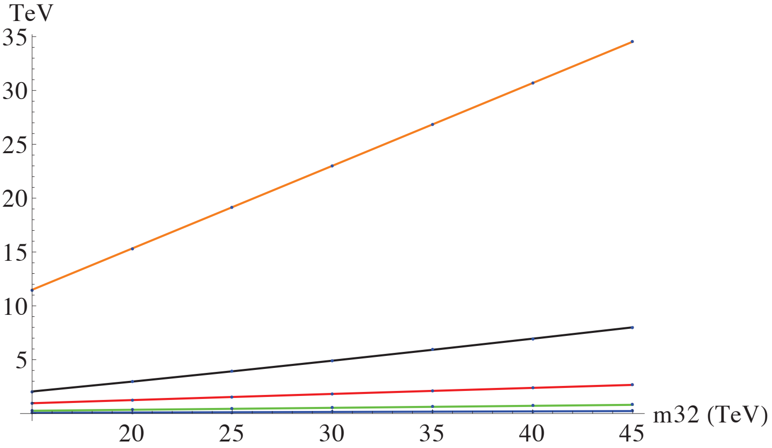
resolution of the puzzle: 'anomaly' mediation contribution

due to super-Weyl-Kähler and σ-model anomalies   Bagger-Moroi-Poppitz '00

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

difference in K_S is accounted by difference in f

Typical spectrum



The masses of sbottom squark (yellow), stop (black), gluino (red), lightest chargino (green) and lightest neutralino (blue) as a function of the gravitino mass. The mass of the lightest neutralino varies between $\sim$ 40 and 150 GeV

Identify the dilaton shift with a global SM symmetry

I.A.-Knoops '15

A combination of Baryon and Lepton number

containing the matter parity $(-)^{B-L}$

- $B-L$: anomaly free in the presence of 3 R-handed neutrinos
- $3B-L$: forbids all dim-4 and dim-5 operators violating B or L

  anomalies cancel by a Green-Schwarz mechanism

  S-dependant gauge kinetic functions
- one extra parameter: the unit of charge for SM fields

  or equivalently the $U(1)$ gauge coupling
- similar phenomenology with lighter stop quark $\gtrsim 1.5$ GeV

Conclusions

String phenomenology:

Consistent framework for particle phenomenology and cosmology

at least 3 very different scales (besides M_{Planck})

electroweak, dark energy, inflation

their origins may be connected or independent

- $\not{S}$USY with infinitesimal (tuneable) $+$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