Scale hierarchies in particle physics and cosmology

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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)

⇒ 3 very different scales besides $M_{\text{Planck}}$:
Problem of scales

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 ↔ 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

they are independent [8]
Effective scale of gravity: reduced by the number of species

\[ N \text{ particle species } \Rightarrow \text{ lower quantum gravity scale: } M_*^2 = M_p^2/N \]

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

\[ \mathcal{P}_R = \frac{H^2}{8\pi^2 M_*^2 \epsilon} \approx A \times 10^{-10} \quad ; \quad A \approx 22 \]

Power spectrum of primordial tensor anisotropies

\[ \mathcal{P}_t = 2 \frac{H^2}{\pi^2 M_*^2} \]

⇒ tensor to scalar ratio

\[ r = \frac{\mathcal{P}_t}{\mathcal{P}_R} = 16\epsilon \]

measurement of \( A \) and \( r \) ⇒ fix the scale of inflation

\[ H \text{ in terms of } M_* : \quad \frac{H}{M_*} = \left( \frac{\pi^2 A r}{2 \times 10^{10}} \right)^{1/2} \equiv \Upsilon \approx 1.05\sqrt{r} \times 10^{-4} \]
Extra species as Kaluza-Klein states

\[ D = 4 + n \] extra dims of size average size \( R \) ☞

fundamental gravity scale \( M_s^{2+n} R^n = M_{Pl}^2 \)

\[ N = \text{all KK states with mass less than } H \Rightarrow N \sim (HR)^n \]

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

\[ H = M_* \gamma = M_s (M_s/H)^{n/2} \gamma \Rightarrow H = M_s \gamma^{2/(n+2)} \]

\[ \Rightarrow H \sim 1-3 \text{ orders of magnitude less than } M_s \text{ for } 0.001 \lesssim r \lesssim 0.1 \]

as low as near the EW scale \^[4]\]
impose independent scales: *proceed in 2 steps*

1. SUSY breaking at $m_{\text{SUSY}} \sim \text{TeV}$
   
   with an infinitesimal (tunable) 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 $m_{\text{SUSY}}$ \[^{[18]}\]

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**: $B = \frac{m}{nA} \equiv \frac{p}{A}$  \implies \text{moduli stabilization}
  
  $B$: constant magnetic field  \quad m: \text{units of magnetic flux}
  
  $n$: brane wrapping  \quad A: \text{area of the 2-cycle}

- **Spin-dependent mass shifts for charged states**  \implies \text{SUSY breaking}

- **Exact open string description**:  \implies \text{calculability}
  
  $qB \rightarrow \theta = \arctan qB\alpha'$  
  weak field \implies \text{field theory}

- **T-dual representation**: \text{branes at angles}  \implies \text{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

I.A.-Derendinger-Maillard '08

- its form is fixed by the axion shift symmetry
  $\Rightarrow$ break SUSY with tunable vacuum energy [12]

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: $6 \times 5/2 = 15 = 9 + 2 \times 3$

complexification $\Rightarrow \begin{cases} 
\text{Kähler class } & J \\
\text{complex structure } & \tau
\end{cases}$

9 complex moduli for each

classical moduli:

magnetic flux: $6 \times 6$ antisymmetric matrix $F$

complexification $\Rightarrow$

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

$F_{(1,1)}$ on mixed (1,1)-cycles: potential for $J$ FI D-terms
Content (besides $N = 1$ SUGRA): one vector $V$ and one chiral multiplet $S$

with a shift symmetry $S \rightarrow S - ic\omega \leftarrow$ transformation parameter

String theory: compactification modulus or universal dilaton

$$s = \frac{1}{g^2} + ia \leftarrow \text{dual to antisymmetric tensor}$$

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

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

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

$$\int d^2\theta W \text{ invariant} \quad b < 0 \Rightarrow \text{non perturbative}$$
Scalar potential

\[ V_F = a^2 e^{b \frac{1}{l^p - 2}} \left\{ \frac{1}{p} (pl - b)^2 - 3l^2 \right\} \quad l = 1/(s + \bar{s}) \]

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:

\[ V_D = c^2 l (pl - b)^2 \quad \text{for gauge kinetic function } f(S) = S \]

- \( b > 0 \): \( V = V_F + V_D \) SUSY local minimum in AdS space at \( l = b/p \)

- \( b = 0 \): SUSY breaking minimum in AdS \((p < 3)\)

- \( b < 0 \): SUSY breaking minimum with tunable cosmological constant \( \Lambda \)
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 $m_{3/2} \approx e^{\alpha/2}la \leftarrow$ TeV scale
\[ V \]
\[ c = 1 \]
\[ c = 0.7 \]
Properties and generalizations

- Metastability of the ground state: extremely long lived
  
  \[ I \simeq 0.02 \text{ (GUT value } \alpha_{\text{GUT}}/2) \text{ } m_{3/2} \sim \mathcal{O}(\text{TeV}) \Rightarrow \]
  
  decay rate \( \Gamma \sim e^{-B} \) with \( B \approx 10^{300} \)

- Add visible sector (MSSM) preserving the same vacuum
  matter fields \( \phi \) neutral under R-symmetry

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

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

- gaugino masses at the quantum level

  \( \Rightarrow \) suppressed compared to scalar masses and A-terms

  experimental bounds on gluinos \( \Rightarrow \) scalar masses \( \mathcal{O}(10) \text{ TeV} \)
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 [8] [25].
Starobinsky model of inflation

\[ \mathcal{L} = \frac{1}{2} R + \alpha R^2 \]

Lagrange multiplier \( \phi \) \( \Rightarrow \) \( \mathcal{L} = \frac{1}{2} (1 + 2\phi) R - \frac{1}{4\alpha} \phi^2 \)

Weyl rescaling \( \Rightarrow \) equivalent to a scalar field with exponential potential:

\[ \mathcal{L} = \frac{1}{2} R - \frac{1}{2} (\partial \phi)^2 - \frac{M^2}{12} \left( 1 - e^{-\sqrt{\frac{2}{3}}\phi} \right)^2 \quad M^2 = \frac{3}{4\alpha} \]

Note that the two metrics are not the same

supersymmetric extension:

add D-term \( \mathcal{R} \bar{\mathcal{R}} \) because F-term \( \mathcal{R}^2 \) does not contain \( R^2 \)

\( \Rightarrow \) brings two chiral multiplets
Convex

Concave

Tensor-to-scalar ratio \( (r_{0.002}) \)

Primordial tilt \( (n_s) \)

Legend:
- \( \text{Planck+WP+BAO} \)
- \( \text{Planck+WP+highL} \)
- \( \text{Planck+WP} \)
- \( \text{Natural Inflation} \)
- \( \text{Hilltop quartic model} \)
- \( \text{Power law inflation} \)
- \( \text{Low scale SSB SUSY} \)
- \( R^2 \text{ Inflation} \)
- \( V \propto \phi^2 \)
- \( V \propto \phi^{2/3} \)
- \( V \propto \phi \)
- \( V \propto \phi^3 \)
- \( N_* = 50 \)
- \( N_* = 60 \)
SUSY extension of Starobinsky model

\[ K = -3 \ln(T + \bar{T} - C\bar{C}) \; ; \; W = MC(T - \frac{1}{2}) \]

- \( T \) contains the inflaton: \( \text{Re} \, T = e^{\sqrt{\frac{2}{3}} \phi} \)

- \( C \sim R \) is unstable during inflation
  \[ \Rightarrow \text{add higher order terms to stabilize it} \]
  e.g. \( C\bar{C} \rightarrow h(C, \bar{C}) = C\bar{C} - \zeta(C\bar{C})^2 \)  \[ \text{Kallosh-Linde '13} \]

- SUSY is broken during inflation with \( C \) the goldstino superfield \[ [23] \]
Constrained superfields

Rocek-Tseytlin ’78, Lindstrom-Rocek ’79, Komargodski-Seiberg ’09

spontaneous global SUSY: no supercharge but still conserved supercurrent

\[ \Rightarrow \text{superpartners exist in operator space (not as 1-particle states)} \]

\[ \Rightarrow \text{constrained superfields: ‘eliminate’ superpartners} \]

Goldstino: chiral superfield \( X_{NL} \) satisfying \( X_{NL}^2 = 0 \) \( \Rightarrow \)

\[
X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2} \theta \chi + \theta^2 F \quad y^\mu = x^\mu + i \theta \sigma^\mu \bar{\theta}
\]

\[
= F \Theta^2 \quad \Theta = \theta + \frac{\chi}{\sqrt{2F}}
\]

\[
\mathcal{L}_{NL} = \int d^4 \theta X_{NL} \bar{X}_{NL} - \frac{1}{\sqrt{2} \kappa} \left\{ \int d^2 \theta X_{NL} + h.c. \right\} = \mathcal{L}_{\text{Volkov–Akulov}}
\]

\[
F = \frac{1}{\sqrt{2} \kappa} + \ldots
\]
Non-linear SUSY in supergravity

I.A.-Dudas-Ferrara-Sagnotti '14

\[ K = -3 \log(1 - X \bar{X}) \equiv 3X \bar{X} \quad ; \quad W = f X + W_0 \quad X \equiv X_{NL} \]

\[ \Rightarrow V = \frac{1}{3} |f|^2 - 3 |W_0|^2 \quad ; \quad m_{3/2}^2 = |W_0|^2 \]

- \( V \) can have any sign contrary to global NL SUSY
- NL SUSY in flat space \( \Rightarrow f = 3 m_{3/2} M_p \)
- Dual gravitational formulation: \( (\mathcal{R} - 6 W_0)^2 = 0 \)  I.A.-Markou '15

- Minimal SUSY extension of \( R^2 \) gravity [20]

chiral curvature superfield
SUSY extension of Starobinsky model

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  e.g. \( C\bar{C} \to h(C, \bar{C}) = C\bar{C} - \zeta(C\bar{C})^2 \) \text{ Kallosh-Linde '13} \]

- SUSY is broken during inflation with \( C \) the goldstino superfield

Minimal SUSY extension that evades stability problem:

replace \( C \) by the non-linear multiplet \( X \)
Non-linear Starobinsky supergravity

\[ K = -3 \ln(T + \bar{T} - X \bar{X}) ; \quad W = M XT + f X + W_0 \]

\[ \mathcal{L} = \frac{1}{2} R - \frac{1}{2} (\partial \phi)^2 - \frac{M^2}{12} \left( 1 - e^{-\sqrt{\frac{2}{3}} \phi} \right)^2 - \frac{1}{2} e^{-2\sqrt{\frac{2}{3}} \phi} (\partial a)^2 - \frac{M^2}{18} e^{-2\sqrt{\frac{2}{3}} \phi} a^2 \]

- axion a much heavier than \( \phi \) during inflation, decouples:

\[ m_\phi = \frac{M}{3} e^{-\sqrt{\frac{2}{3}} \phi_0} \ll m_a = \frac{M}{3} \]

- inflation scale \( M \) independent from NL-SUSY breaking scale \( f \)

\[ \Rightarrow \text{compatible with low energy SUSY} \]
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