Aspects of string phenomenology and scale hierarchies

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Main predictions \(\rightarrow\) inspirations for BSM physics

- Spacetime supersymmetry \(\text{but arbitrary breaking scale}\)
- Extra dimensions of space \(\text{six or seven in M-theory}\)
- Brane-world description of our Universe
  - matter and gauge interactions may be localised in less dimensions
- Landscape of vacua
- \(\ldots\)
Connect string theory to the real world

- 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)

\[ \Rightarrow 3 \text{ very different scales besides } M_{\text{Planck}}: \]

<table>
<thead>
<tr>
<th>DarkEnergy</th>
<th>ElectroWeak</th>
<th>Inflation</th>
<th>QuantumGravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>meV</td>
<td>TeV</td>
<td>( M_I )</td>
<td>( M_{\text{Planck}} )</td>
</tr>
</tbody>
</table>
Problem of scales

1. they are independent
2. 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

What about $M_I$? can it be at the TeV scale?
Can we infer $M_I$ from cosmological data?

I.A.-Patil ’14 and ’15

connect inflation and SUSY breaking scales
impose independent scales: proceed in 2 steps

1. SUSY breaking at $m_{SUSY} \sim \text{TeV}$
   with an infinitesimal (tuneable) positive cosmological constant
   Villadoro-Zwirner '05
   I.A.-Knoops, I.A.-Ghilencea-Knoops '14, I.A.-Knoops '15

2. Inflation connected or independent? [15] [23]
Toy model for SUSY breaking

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

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

String theory: compactification modulus or universal dilaton

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

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

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

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

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

$$\int d^2 \theta W \text{ invariant}$$

$b < 0 \Rightarrow$ non perturbative

can also be described by a generalized linear multiplet [11]
Scalar potential

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

Planck units

- \( b > 0 \) \( \Rightarrow \) SUSY local minimum in AdS space with \( l = b/p \)
- \( b \leq 0 \) \( \Rightarrow \) no minimum 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:
    \[ V_D = c^2 l(pl - b)^2 \]  for gauge kinetic function \( f(S) = S \)
- \( b > 0 \): \( V = V_F + V_D \) SUSY AdS minimum remains
- \( b = 0 \): SUSY breaking minimum in AdS \((p < 3)\)
- \( b < 0 \): SUSY breaking minimum with tuneable cosmological constant \( \Lambda \)
Minimisation of the potential: $V' = 0$, $V = \Lambda$

In the limit $\Lambda \approx 0$ ($\rho = 2$) \(\Rightarrow [17]\)

\[
b/l = \rho \approx -0.183268 \Rightarrow \langle l \rangle = b/\rho
\]

\[
\frac{a^2}{bc^2} = 2 \frac{e^{-\rho}}{\rho} \frac{(2-\rho)^2}{2+4\rho-\rho^2} + \mathcal{O}(\Lambda) \approx -50.6602 \Rightarrow c \propto a
\]

Physical spectrum:

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

All masses of order $m_{3/2} \approx e^{\rho/2} l a \leftarrow \text{TeV scale}$
\( V \) vs. \( s + s_{\text{bar}} \)

- \( c = 1 \)
- \( c = 0.7 \)

[15]
Properties and generalizations

- Metastability of the ground state: extremely long lived

\[ l \approx 0.02 \text{ (GUT value } \alpha_{GUT}/2) \quad m_{3/2} \sim O(\text{TeV}) \Rightarrow \]

\[ \text{decay rate } \Gamma \sim e^{-B} \text{ with } B \approx 10^{300} \]

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

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

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

- Toy model classically equivalent to \([7]\)

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

- Dilaton shift can be identified with \( B - L \supset \text{matter parity } (-)^{B-L} \)
Properties and generalizations

- R-charged fields needed for anomaly cancellation
- A simple (anomaly free) variation: \( f = 1 \) and \( p = 1 \)
  - tuning still possible but scalar masses of neutral matter tachyonic
  - possible solution: add a new field \( Z \) in the ‘hidden’ SUSY sector
    \( \Rightarrow \) one extra parameter

- alternatively: add an \( S \)-dependent factor in Matter kinetic terms
  \[
  K = - \ln(S + \bar{S}) + (S + \bar{S})^{-\nu} \sum \Phi \bar{\Phi} \quad \text{for} \quad \nu \gtrsim 2.5
  \]
  \( \Rightarrow \) 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
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.
### ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

#### Preliminary

<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>Mass limit</th>
<th>Reference</th>
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<tr>
<td><strong>Inclusive Searches</strong></td>
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<td>20.3</td>
<td>635 GeV</td>
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<tr>
<td>$\tilde{g}$, $\tilde{g}$, $\tilde{q}$, $\tilde{d}$</td>
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<td><strong>Preproduction</strong></td>
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<td>1.58 TeV</td>
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<td><strong>Long-lived particles</strong></td>
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<td>0-4 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.0 TeV</td>
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<td>Scalar charm, $\tilde{c}$</td>
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<td>2 c</td>
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<td>20.3</td>
<td>510 GeV</td>
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</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.*

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I. Antoniadis (HEP2017-Ioannina)
Can the dilaton be the inflaton in the simple model of SUSY breaking based on a gauged shift symmetry? 

the only physical scalar left over, partner (partly) of the goldstino partly because of a D-term auxiliary component 

Same potential cannot satisfy the slow roll condition $|\eta| = |V''/V| << 1$ with the dilaton rolling towards the Standard Model minimum

$\Rightarrow$ need to create an appropriate plateau around the maximum of $V$ \[10\]

without destroying the properties of the SM minimum

$\Rightarrow$ study possible corrections to the Kähler potential

only possibility compatible with the gauged shift symmetry
Extensions of the SUSY breaking model

Parametrize the general \textit{correction} to the Kähler potential:

\[
K = -p\kappa^{-2} \log \left( s + \bar{s} + \frac{\xi}{b} F(s + \bar{s}) \right) + \kappa^{-2} b(s + \bar{s})
\]

\[
W = \kappa^{-3} a, \quad f(s) = \gamma + \beta s
\]

\[
\mathcal{P} = \kappa^{-2} c \left( b - p \frac{1 + \frac{\xi}{b} F'}{s + \bar{s} + \frac{\xi}{b} F} \right)
\]

Three types of possible corrections:

- \textbf{perturbative: } \( F \sim (s + \bar{s})^{-n}, \quad n \geq 0 \)
- \textbf{non-perturbative D-brane instantons: } \( F \sim e^{-\delta(s+\bar{s})}, \quad \delta > 0 \)
- \textbf{non-perturbative NS5-brane instantons: } \( F \sim e^{-\delta(s+\bar{s})^2}, \quad \delta > 0 \)

Only the last can lead to slow-roll conditions with sufficient inflation
Slow-roll inflation

\[ F = \xi e^{\alpha b^2 \phi^2} \text{ with } \phi = s + \bar{s} = 1/l \Rightarrow \text{two extra parameters } \alpha < 0, \xi \]

they control the shape of the potential

slow-roll conditions: \( \epsilon = 1/2(V'/V)^2 \ll 1, |\eta| = |V''/V| \ll 1 \)

\Rightarrow \text{allowed regions of the parameter space with } |\xi| \text{ small}

additional independent parameters: \( a, c, b \)

SM minimum with tuneable cosmological constant \( \Lambda \): \( V' = 0, V = \Lambda \approx 0 \)

\[ \xi = 0 \Rightarrow b\phi_{min} = \rho_0, \frac{a^2}{bc^2} = \lambda_0 \text{ with } \rho_0, \lambda_0 \text{ calculable constants} \]

\( b \) controls \( \phi_{min} \sim 1/g_s \) choose it of order 10

tuning determines \( a \) in terms of \( c \) overall scale of the potential

\[ \xi \neq 0 \Rightarrow \rho_0, \lambda_0 \text{ become functions } l(\xi, \alpha), \lambda(\xi, \alpha) \]

numerical analysis \( \Rightarrow \) mild dependence
$\xi = 0.025$, $\alpha = -4.8$, $p = 2$, $b = -0.018$
inflation starts with an initial condition for $\phi = \phi_*$ near the maximum and ends when $|\eta| = 1$

$\Rightarrow$ number of e-folds $N = \int_{\text{start}}^{\text{end}} \frac{V}{V'}$

Predictions for the power spectrum of perturbations in CMB:

amplitude of density perturbations $A_s = \frac{\kappa^4 V_*}{24\pi^2 \epsilon_*}$

spectral index $n_s = 1 + 2\eta_* - 6\epsilon_*$

tensor – to – scalar ratio $r = 16\epsilon_*$

Numerical analysis: fit Planck ’15 data and keep the SM minimum with an infinitesimal cosmological constant

$\Rightarrow$ fine tuning of the parameters of the model
Fit Planck '15 data and predictions

$p = 2, \phi_* = 27.32, \xi = 0.025, \alpha = -4.8, b = -0.018, c = 0.61 \times 10^{-13}$

<table>
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<tr>
<th>$N$</th>
<th>$n_s$</th>
<th>$r$</th>
<th>$A_s$</th>
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<td>1075</td>
<td>0.965</td>
<td>$3 \times 10^{-23}$</td>
<td>$2.259 \times 10^{-9}$</td>
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</table>
\[
\alpha \approx -4.84112 \\
\xi \approx 0.02535 \\
b = -0.01820 \\
c = 0.61 \times 10^{-13}
\]
$p = 1$: similar analysis $\Rightarrow$

$\phi_\ast = 64.53, \xi = 0.30, \alpha = -0.78, b = -0.023, c = 10^{-13}$

<table>
<thead>
<tr>
<th>N</th>
<th>$n_s$</th>
<th>$r$</th>
<th>$A_s$</th>
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<tbody>
<tr>
<td>889</td>
<td>0.959</td>
<td>$4 \times 10^{-22}$</td>
<td>$2.205 \times 10^{-9}$</td>
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</table>

SM minimum: $\langle \phi \rangle \approx 21.53, \langle m_{3/2} \rangle = 18.36$ TeV, $\langle M_{A_\mu} \rangle = 36.18$ TeV

During inflation:

$H_\ast = \kappa \sqrt{V_\ast/3} = 5.09$ TeV, $m_{3/2}^* = 4.72$ TeV, $M_{A_\mu}^* = 6.78$ TeV

Low energy spectrum essentially the same with $\xi = 0$:

$m_0^2 = m_{3/2}^2 [-2 + C], \quad A_0 = m_{3/2} C, \quad B_0 = A_0 - m_{3/2}$

$C = 1.53$ vs at $\xi = 0$: $C_0 = 1.52, m_{3/2}^0 = 17.27$, although $\langle \phi \rangle_0 \approx 9.96$ [6] [28]
Non-linear supersymmetry $\Rightarrow$ goldstino mode $\chi$

Volkov-Akulov '73

Effective field theory of SUSY breaking at low energies

Analog of non-linear $\sigma$-model $\Rightarrow$ constraint superfields

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

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

$$X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2}\theta \chi + \theta^2 F$$

$$y^\mu = x^\mu + i\theta \sigma^\mu \bar{\theta}$$

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

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

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

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

\[ X \equiv X_{NL} \]

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

- \( V \) can have any sign contrary to global NL SUSY
- NL SUSY in flat space \( \Rightarrow f = 3 \frac{m_{3/2}}{M_p} \)
- \( R \)-symmetry is broken by \( W_0 \)
- Dual gravitational formulation: \( (\mathcal{R} - 6W_0)^2 = 0 \)

I.A.-Markou '15

chiral curvature superfield

- Minimal SUSY extension of \( R^2 \) gravity
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:

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

\[ M^2 = \frac{3}{4\alpha} \]

Note that the two metrics are not the same

supersymmetric extension:

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

\( \Rightarrow \) brings two chiral multiplets
SUSY extension of Starobinsky model

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

- \( T \) contains the inflaton: \( \text{Re} \ T = e^{\sqrt{\frac{2}{3}}\phi} \)
- \( C \sim R \) is unstable during inflation
  \( \Rightarrow \) add higher order terms to stabilize it
  e.g. \( C\bar{C} \rightarrow h(C, \bar{C}) = C\bar{C} - \zeta(C\bar{C})^2 \quad \text{Kallosh-Linde '13} \)

- SUSY is broken during inflation with \( C \) the goldstino superfield
  \( \rightarrow \) model independent treatment in the decoupling sgoldstino limit
  \( \Rightarrow \) minimal SUSY extension that evades stability problem
Non-linear Starobinsky supergravity

\[ K = -3 \ln (T + \tilde{T} - X \tilde{X}) \; ; \; \; \; W = MXT + f X + W_0 \Rightarrow \]

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

- 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 \( f \)

\( \Rightarrow \) compatible with low energy SUSY

- however inflaton different from goldstino superpartner

- also initial conditions require trans-planckian values for \( \phi \) (\( \phi > 1 \))
Conclusions

String phenomenology:
Consistent framework for particle physics and cosmology

**Challenge of scales:** at least three very different (besides $M_{\text{Planck}}$)
electroweak, dark energy, inflation, SUSY?

their origins may be connected or independent

SUSY with infinitesimal (tuneable) +ve cosmological constant

- interesting framework for model building incorporating dark energy
- identify inflaton with goldstino superpartner
  inflation at the SUSY breaking scale (TeV?)