Scale hierarchies in particle physics and cosmology

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4th International Conference on New Frontieres in Physics

OAC, Kolymbari, Crete, Greece 23-30 August 2015

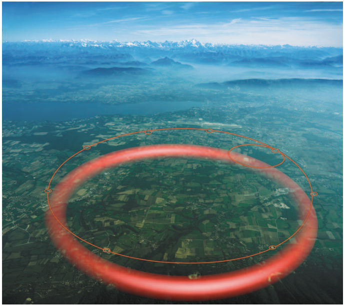
String phenomenology

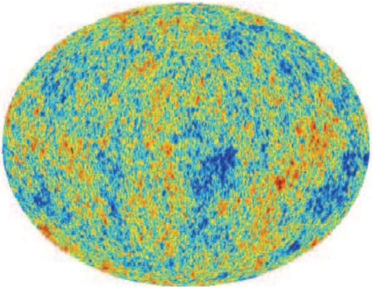
- Is string theory a tool for strong coupling dynamics

  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

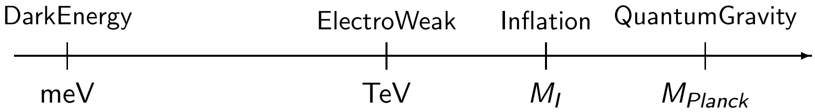
- incorporate Dark Energy

  simplest case: infinitesimal (tunable) +ve cosmological constant

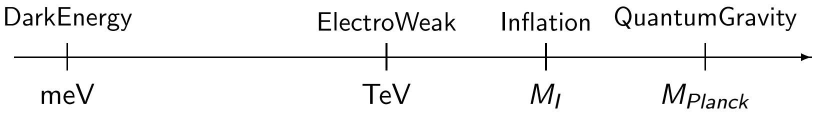
- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

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



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
2. they are independent [8]

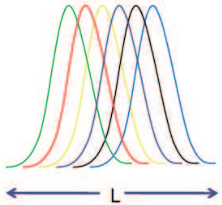
Effective scale of gravity: reduced by the number of species

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 $\mathcal{R}$)

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

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

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

$\Rightarrow$ 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 [4]

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 '15

2. Inflation in supergravity at a scale different than m_{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: $B = \frac{m}{nA} \equiv \frac{p}{A}$ $\Rightarrow$ 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 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: $6 \times 5/2 = 15 = 9 + 2 \times 3$

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

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

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 $W = ae^{bS}$

$\int d^2\theta W$ invariant

$b < 0 \Rightarrow$ non perturbative

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 ($p < 3$)
- $b < 0$: SUSY breaking minimum with tunable cosmological constant Λ

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

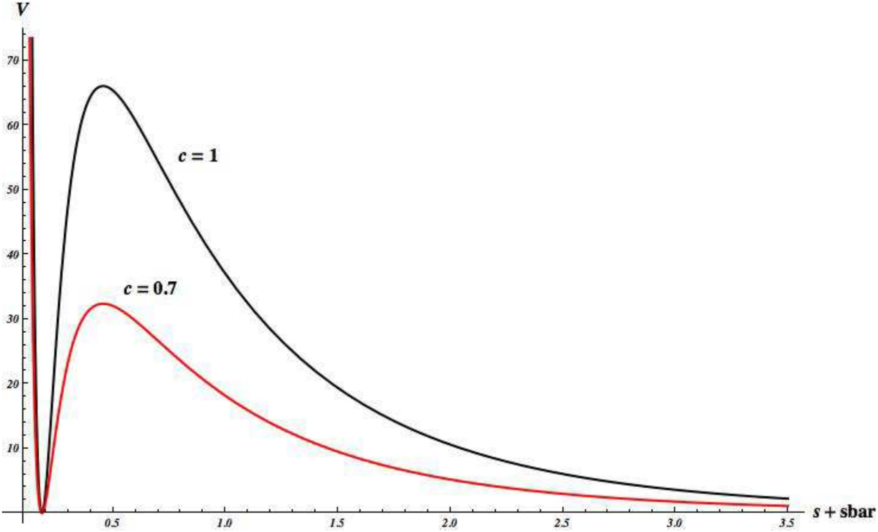
$b/l = \alpha \approx -0.183268$

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

physical spectrum:

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

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

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

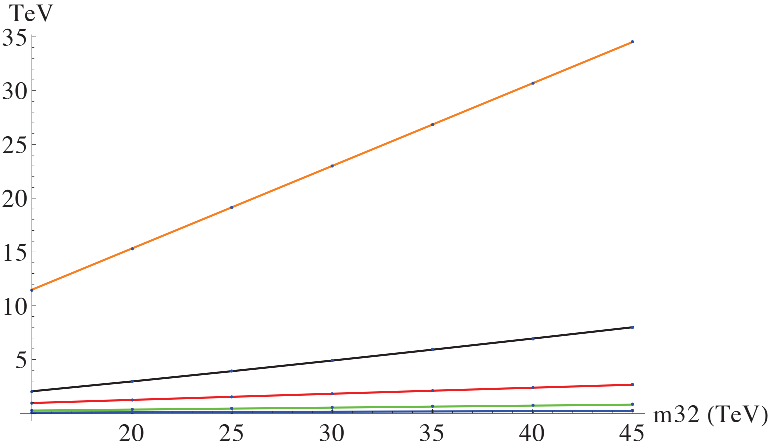
  $\Rightarrow$ soft scalar masses non-tachyonic of order $m_{3/2}$ (gravity mediation)

- 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

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 [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:

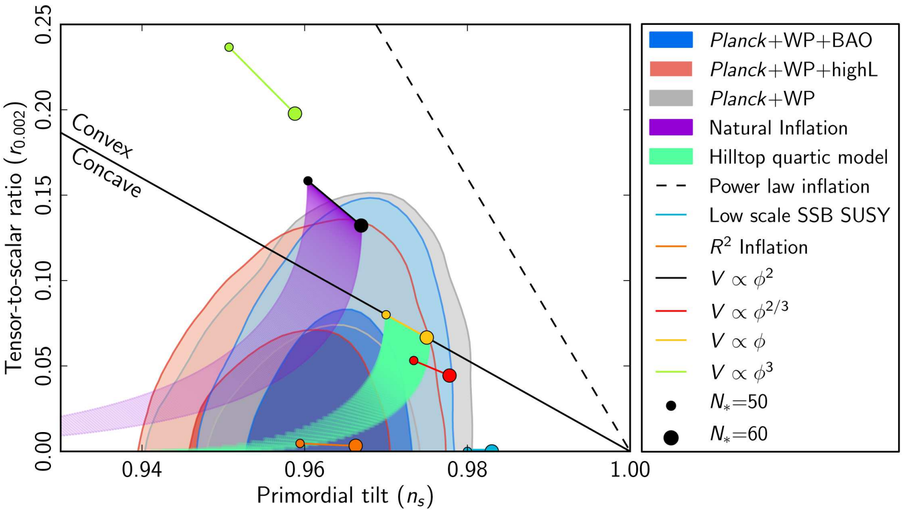
$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 \qquad M^2 = \frac{3}{4\alpha}$$

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



Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Convex
Concave
Planck+WP+BAO
Planck+WP+highL
Planck+WP
Natural Inflation
Hilltop quartic model
Power law inflation
Low scale SSB SUSY
R^2 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

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

- T contains the inflaton: $\mathrm{Re}\, T = e^{\sqrt{\frac{2}{3}}\phi}$
- $C \sim \mathcal{R}$ is unstable during inflation

  $\Rightarrow$ add higher order terms to stabilize it

  e.g. $C\bar{C} \to h(C, \bar{C}) = C\bar{C} - \zeta(C\bar{C})^2$ 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 $S\!\!\!/USY$: no supercharge but still conserved supercurrent

$\Rightarrow$ superpartners exist in operator space (not as 1-particle states)

$\Rightarrow$ constrained superfields: 'eliminate' superpartners

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

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

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

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

$$F = \frac{1}{\sqrt{2}\kappa} + \ldots$$

Non-linear SUSY in supergravity

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

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

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

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

  $\mathcal{R}$ ← chiral curvature superfield
- Minimal SUSY extension of R^2 gravity [20]

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Minimal SUSY extension that evades stability problem:

replace C by the non-linear multiplet X

Non-linear Starobinsky supergravity

$$K = -3\ln(T + \bar{T} - X\bar{X}) \quad ; \quad W = M\,XT + f\,X + W_0 \qquad \Rightarrow$$

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

- axion a much heavier than ϕ during inflation, decouples:

  $m_\phi = \frac{M}{3}e^{-\sqrt{\frac{2}{3}}\phi_0} << m_a = \frac{M}{3}$

- inflation scale M independent from NL-SUSY breaking scale f

  $\Rightarrow$ 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