Scale hierarchies and string phenomenology

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Dedicated to the memory of Maria Krawczyk

I want the ILC! by Maria Krawczyk #mylinearcollider, YouTube 2015

String theory: Quantum Mechanics + General Relativity

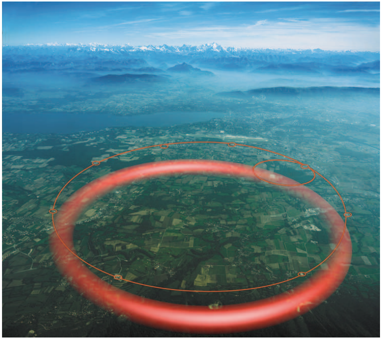
Main predictions $\rightarrow$ inspirations for BSM physics

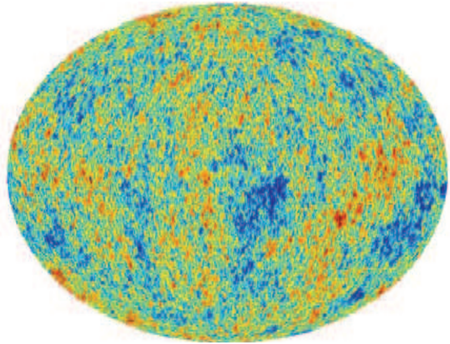
- Spacetime supersymmetry   but arbitrary breaking scale
- Extra dimensions of space   six or seven in M-theory
- Brane-world description of our Universe

  matter and gauge interactions may be localised in less dimensions
- Landscape of vacua
- $\cdots$

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

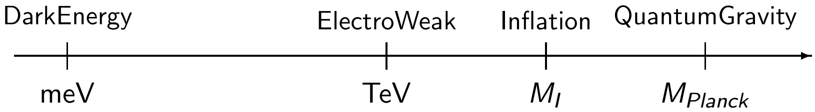
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

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



Relativistic dark energy 70-75% of the observable universe

negative pressure: $p = -\rho \;\Rrightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2}Rg_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4}T_{ab} \;\Rrightarrow\; \rho_\Lambda = \frac{c^4\Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

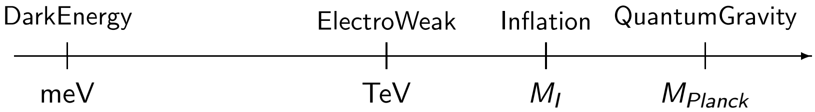
- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$

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

Inflation in supergravity: main problems

- slow-roll conditions: the eta problem $\Rightarrow$ fine-tuning of the potential

$$\eta = V''/V\,, \quad V_F = e^K\left(|DW|^2 - 3|W|^2\right), \quad DW = W' + K'W$$

K: Kähler potential, W: superpotential

canonically normalised field: $K = X\bar{X} \Rightarrow \eta = 1 + \dots$

- trans-Planckian initial conditions $\Rightarrow$ break validity of EFT

no-scale type models that avoid the η-problem

- stabilisation of the (pseudo) scalar companion of the inflaton

chiral multiplets $\Rightarrow$ complex scalars

- moduli stabilisation, de Sitter vacuum, ...

Starobinsky model of inflation

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

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

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

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

$\rightarrow$ model independent treatment in the decoupling sgoldstino limit

$\Rightarrow$ minimal SUSY extension that evades stability problem [13]

Non-linear supersymmetry $\Rightarrow$ goldstino mode χ

Volkov-Akulov '73

Effective field theory of SUSY breaking at low energies

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

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

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

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

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

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

R-symmetry with $[\theta]_R = [\chi]_R = 1$ and $[X]_R = 2$ $\qquad F = \frac{1}{\sqrt{2}\kappa} + \dots$

Non-linear SUSY in supergravity

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

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

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

- V can have any sign   contrary to global NL SUSY
- NL SUSY in flat space $\Rightarrow f = 3\,m_{3/2}M_p$
- 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

Non-linear Starobinsky supergravity [10]

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

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

- 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

- however inflaton different from goldstino superpartner
- also initial conditions require trans-planckian values for ϕ $(\phi > 1)$ [19]

Inflation from supersymmetry breaking

I.A.-Chatrabhuti-Isono-Knoops '16, '17

Inflaton : goldstino superpartner in the presence of a gauged R-symmetry

- linear superpotential $W = f\,X \Rightarrow$ no η-problem

$$\begin{aligned} V_F &= e^K \left(|DW|^2 - 3|W|^2\right) \\ &= e^K \left(|1 + K_X X|^2 - 3|X|^2\right)|f|^2 \qquad K = X\bar{X} \\ &= e^{|X|^2}\left(1 - |X|^2 + \mathcal{O}(|X|^4\right)|f|^2 = \mathcal{O}(|X|^4) \quad \Rightarrow \eta = 0 + \dots \end{aligned}$$

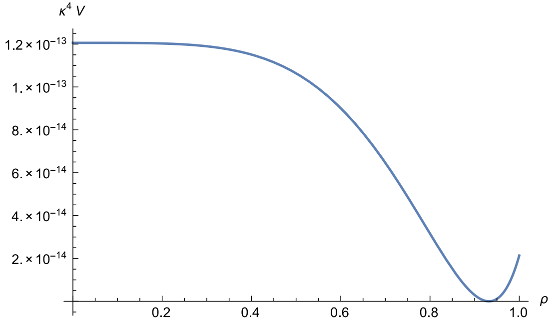
- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  no large field initial conditions

- gauge R-symmetry: (pseudo) scalar absorbed by the $U(1)_R$
- vacuum energy at the minimum: tuning between V_F and V_D

Two classes of models

- Case 1: R-symmetry is restored during inflation (at the maximum)



- Case 2: R-symmetry is (spontaneously) broken everywhere

(and restored at infinity)

example: toy model of SUSY breaking [19] [27]

Case 1: R-symmetry restored during inflation

$$\mathcal{K}(X,\bar{X}) = \kappa^{-2}X\bar{X} + \kappa^{-4}A\,(X\bar{X})^2 \qquad A>0$$

$$W(X) = \kappa^{-3} f\,X \qquad \Rightarrow$$

$$f(X) = 1 \qquad (+\beta \ln X \text{ to cancel anomalies but } \beta \text{ very small})$$

$$\mathcal{V} = \mathcal{V}_F + \mathcal{V}_D$$

$$\mathcal{V}_F = \kappa^{-4} f^2 e^{X\bar{X}(1+AX\bar{X})}\left[-3X\bar{X} + \frac{\left(1+X\bar{X}(1+2AX\bar{X})\right)^2}{1+4AX\bar{X}}\right]$$

$$\mathcal{V}_D = \kappa^{-4}\frac{q^2}{2}\left[1+X\bar{X}(1+2AX\bar{X})\right]^2$$

Assume inflation happens around the maximum $|X| \equiv \rho \simeq 0 \quad \Rightarrow$

Case 1: predictions

slow-roll parameters

$$\eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right) = 2\left(\frac{-4A + x^2}{2 + x^2}\right) + \mathcal{O}(\rho^2) \qquad x = q/f$$

$$\epsilon = \frac{1}{2\kappa^2}\left(\frac{V'}{V}\right)^2 = 4\left(\frac{-4A + x^2}{2 + x^2}\right)^2 \rho^2 + \mathcal{O}(\rho^4) \simeq \eta^2\rho^2$$

η small: for instance $x \ll 1$ and $A \sim \mathcal{O}(10^{-1})$

inflation starts with an initial condition for $\phi = \phi_*$ near the maximum

and ends when $|\eta| = 1$

$\Rightarrow$ number of e-folds $N = \int_{end}^{start} \frac{V}{V'} = \kappa \int \frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{|\eta_*|} \ln\left(\frac{\rho_{\rm end}}{\rho_*}\right)$

Case 1: predictions

amplitude of density perturbations $A_s = \frac{\kappa^4 V_*}{24\pi^2 \epsilon_*} = \frac{\kappa^2 H_*^2}{8\pi^2 \epsilon_*}$

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

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

Planck '15 data : $\eta \simeq -0.02$, $A_s \simeq 2.2 \times 10^{-9}$, $N \gtrsim 50$

$$\Rightarrow r \lesssim 10^{-4},\ H_* \lesssim 10^{12}\ \text{GeV}$$

Question: can a 'nearby' minimum exist with a tiny +ve vacuum energy?

Answer: Yes in a 'weaker' sense: perturbative expansion [15] [20]

valid for the Kähler potential but not for the slow-roll parameters

generic V (not fine-tuned) $\Rightarrow 10^{-9} \lesssim r \lesssim 10^{-4}$, $10^{10} \lesssim H_* \lesssim 10^{12}$ GeV [33]

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 connected or independent? [8] [11] [27]

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

[24] [23]

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

- $b > 0 \Rrightarrow$ SUSY local minimum in AdS space with $l = b/p$
- $b \leq 0 \Rrightarrow$ 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:

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

- $b > 0$: $\mathcal{V} = \mathcal{V}_F + \mathcal{V}_D$ SUSY AdS minimum remains
- $b = 0$: SUSY breaking minimum in AdS ($p < 3$)
- $b < 0$: SUSY breaking minimum with tuneable cosmological constant Λ

minimisation and spectrum

Minimisation of the potential: $V' = 0,\ V = \Lambda$

In the limit $\Lambda \approx 0$ $(p = 2)$ $\Rightarrow$ [29]

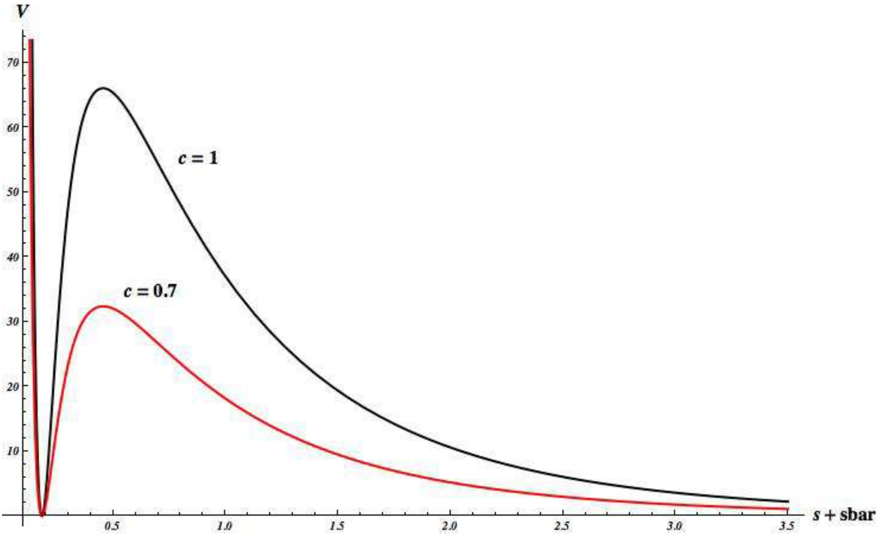
$b/l = \rho \approx -0.183268 \quad \Rightarrow \langle l \rangle = b/\rho$

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

Physical spectrum:

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

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



[27]

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)

- Toy model classically equivalent to [20]

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

- Dilaton shift can be identified with $B - L \supset$ 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' SU$\not{}$SY sector

  $\Rightarrow$ one extra parameter

- alternatively: add an S-dependent factor in Matter kinetic terms

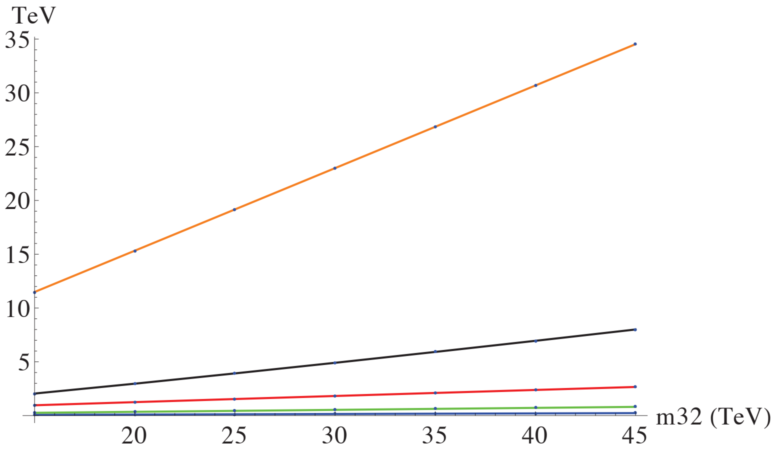
  $K = -\ln(S + \bar{S}) + (S + \bar{S})^{-\nu} \sum \Phi\bar{\Phi}$ for $\nu \gtrsim 2.5$

  or the $B - L$ unit charge of SM particles $\Rightarrow$ 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

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 [19]

Case 2 example: toy model of SUSY breaking

I.A.-Chatrabhuti-Isono-Knoops '16

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 [23]

without destroying the properties of the SM minimum

$\Rightarrow$ study possible corrections to the Kähler potential

only possibility compatible with the gauged shift symmetry [30]

Extensions of the SUSY breaking model

Parametrize the general 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:

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

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

Slow-roll inflation

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

they control the shape of the potential

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

$\Rightarrow$ allowed regions of the parameter space with $|\xi|$ small

additional independant parameters: a, c, b

SM minimum with tuneable cosmological constant Λ: $V' = 0$, $V = \Lambda \approx 0$

$\xi = 0 \Rightarrow b\phi_{min} = \rho_0$, $\frac{a^2}{bc^2} = \lambda_0$ with ρ_0, λ_0 calculable constants [22]

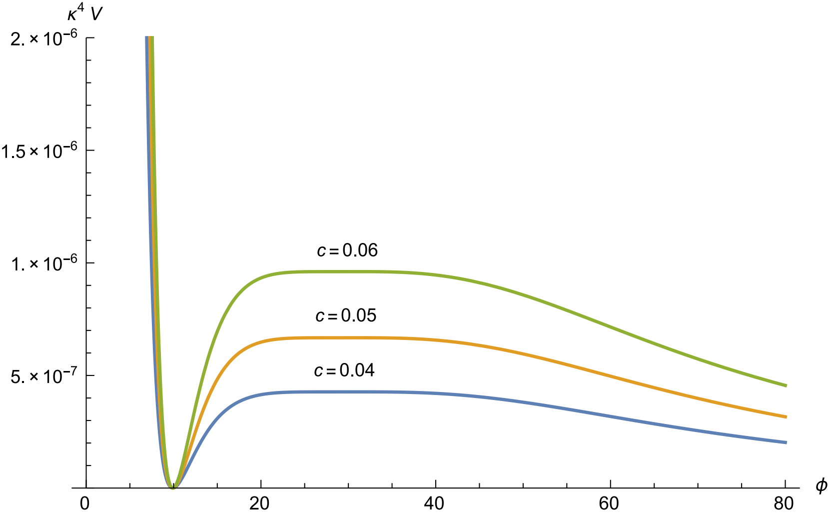
b controls $\phi_{min} \sim 1/g_s$ choose it of order 10

tuning determines a in terms of c overall scale of the potential

$\xi \neq 0 \Rightarrow \rho_0, \lambda_0$ become functions $l(\xi, \alpha), \lambda(\xi, \alpha)$

numerical analysis $\Rightarrow$ mild dependence

$\xi = 0.025,\ \alpha = -4.8,\ p = 2,\ b = -0.018$



Fit Planck '15 data and predictions

$p = 1$: similar analysis $\Rightarrow$

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

N	n_s	r	A_s
889	0.959	4×10^{-22}	2.205×10^{-9}

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

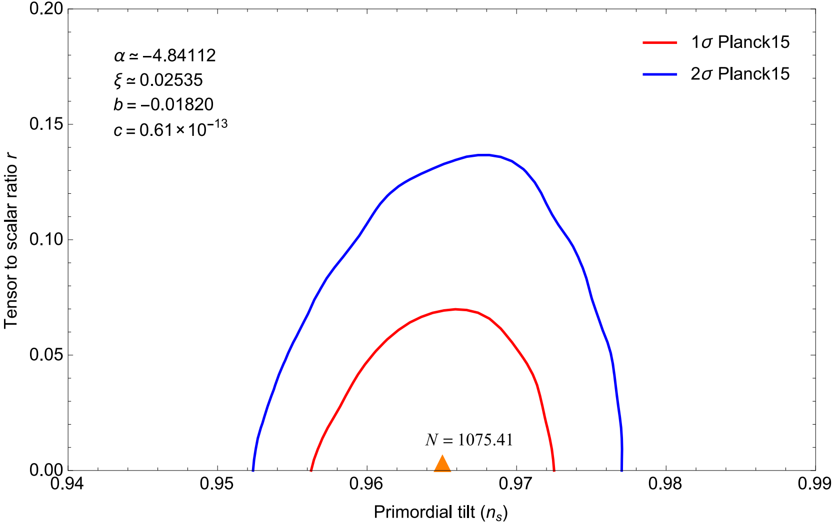
During inflation:

$H_* = \kappa\sqrt{\mathcal{V}_*/3} = 5.09$ TeV, $m^*_{3/2} = 4.72$ TeV, $M^*_{A_\mu} = 6.78$ TeV

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

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

$\mathcal{C} = 1.53$ vs at $\xi = 0$: $\mathcal{C}_0 = 1.52$, $m^0_{3/2} = 17.27$, although $\langle\phi\rangle_0 \approx 9.96$ [15]


0.20
0.15
0.10
0.05
0.00
0.94
0.95
0.96
0.97
0.98
0.99
$\alpha \simeq -4.84112$
$\xi \simeq 0.02535$
$b = -0.01820$
$c = 0.61 \times 10^{-13}$
1σ Planck15
2σ Planck15
$N = 1075.41$
Tensor to scalar ratio r
Primordial tilt (n_s)

Conclusions

String pheno: consistent framework for particle physics and cosmology

Challenge of scales: at least three very different (besides M_{Planck})

electroweak, dark energy, inflation, SUSY?

their origins may be connected or independent

$\not{S}$USY 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?)

General class of models with inflation from SUSY breaking:

(gauged) R-symmetry restored (case 1) or broken (case 2) during inflation

small field, avoids the η-problem, no (pseudo) scalar companion