

# Scale hierarchies and string phenomenology

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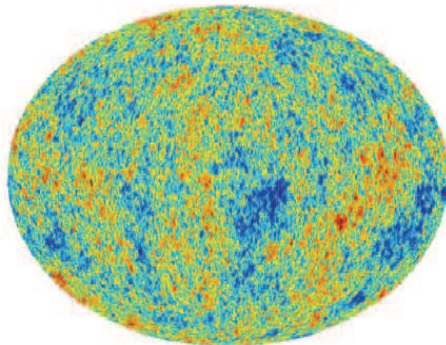
# String theory: Quantum Mechanics + General Relativity

Main predictions → 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
- ...

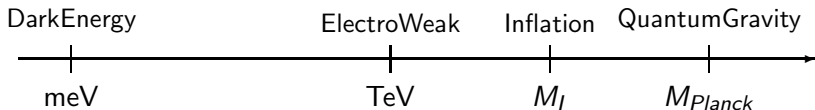
# Connect string theory to the real world

- 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?

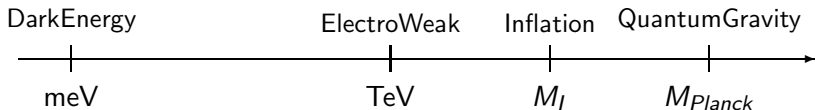


# Problem of scales

- 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)
- ⇒ 3 very different scales besides  $M_{Planck}$  :



# 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.-Ghilenca-Knoops '14, I.A.-Knoops '15

- 2 Inflation connected or independent? [14] [19]

# 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

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

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  $W = a e^{bS}$

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

$$b < 0 \Rightarrow \text{non perturbative}$$

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

# Scalar potential

$$\mathcal{V}_F = a^2 e^{\frac{b}{f}} l^{p-2} \left\{ \frac{1}{p} (pl - b)^2 - 3l^2 \right\} \quad l = 1/(s + \bar{s})$$

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:

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

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



# minimisation and spectrum

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

In the limit  $\Lambda \approx 0$  ( $p = 2$ )  $\Rightarrow$  [21]

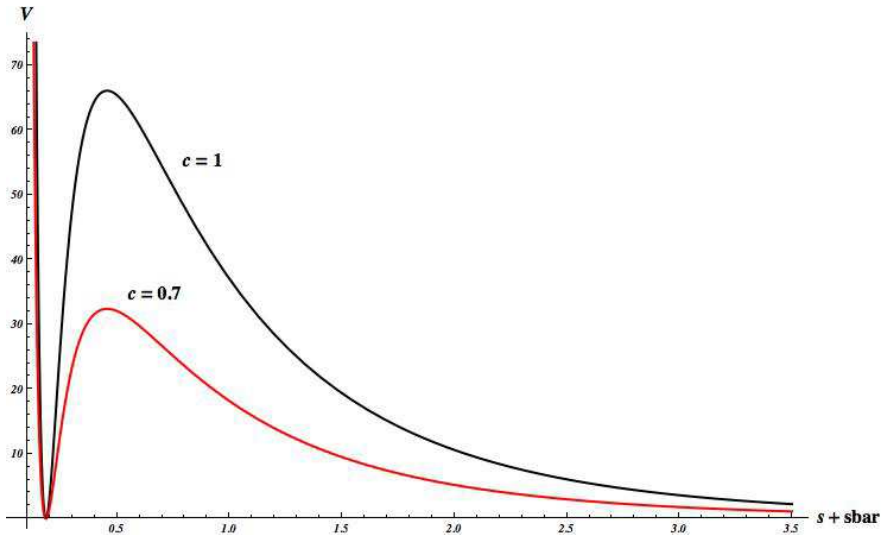
$$b/l = \rho \approx -0.183268 \quad \Rightarrow \quad \langle l \rangle = b/\rho$$

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

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



[19]

# Properties and generalizations

- Metastability of the ground state: extremely long lived

$$f \simeq 0.02 \text{ (GUT value } \alpha_{GUT}/2) \quad m_{3/2} \sim \mathcal{O}(\text{TeV}) \Rightarrow$$

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

- Add visible sector (MSSM) preserving the same vacuum

matter fields  $\phi$  neutral under R-symmetry

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

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

- Toy model classically equivalent to [7]

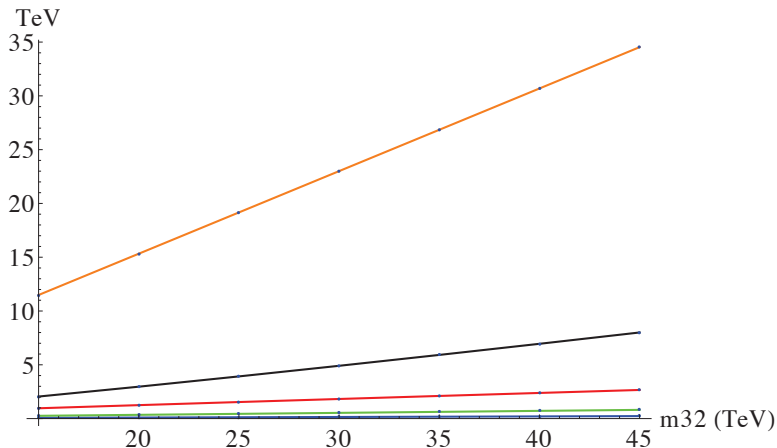
$$K = -p \ln(S + \bar{S}) + b(S + \bar{S}) \quad ; \quad W = a \quad \text{with } V \text{ ordinary } U(1)$$

- Dilaton shift can be identified with  $B - L \supset$  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
$$K = -\ln(S + \bar{S}) + (S + \bar{S})^{-\nu} \sum \Phi \bar{\Phi} \quad \text{for } \nu \gtrsim 2.5$$
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 [6]

# 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  $X_{NL}^2 = 0 \Rightarrow$

$$\begin{aligned} X_{NL}(y) &= \frac{\chi^2}{2F} + \sqrt{2}\theta\chi + \theta^2 F & y^\mu &= x^\mu + i\theta\sigma^\mu\bar{\theta} \\ &= F\Theta^2 & \Theta &= \theta + \frac{\chi}{\sqrt{2}F} \end{aligned}$$

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


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

# Non-linear SUSY in supergravity

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

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

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

- $V$  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

# Starobinsky model of inflation

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

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

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



# 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:  $\text{Re } T = e^{\sqrt{\frac{2}{3}}\phi}$
- $C \sim \mathcal{R}$  is unstable during inflation

⇒ add higher order terms to stabilize it

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

- SUSY is broken during inflation with  $C$  the goldstino superfield

→ model independent treatment in the decoupling sgoldstino limit

⇒ minimal SUSY extension that evades stability problem

# Non-linear Starobinsky supergravity

$$K = -3 \ln(T + \bar{T} - X\bar{X}) \quad ; \quad W = MXT + fX + W_0 \quad \Rightarrow$$

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

- 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  $\phi$  ( $\phi > 1$ ) [6]

# Inflation from the SUSY breaking sector

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  $|\eta| = |V''/V| \ll 1$   
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 **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  $\alpha < 0$ ,  $\xi$   
they control the shape of the potential

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

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

additional independent parameters:  $a, c, b$

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

$\xi = 0 \Rightarrow b\phi_{min} = \rho_0$ ,  $\frac{a^2}{bc^2} = \lambda_0$  with  $\rho_0, \lambda_0$  calculable constants [9]

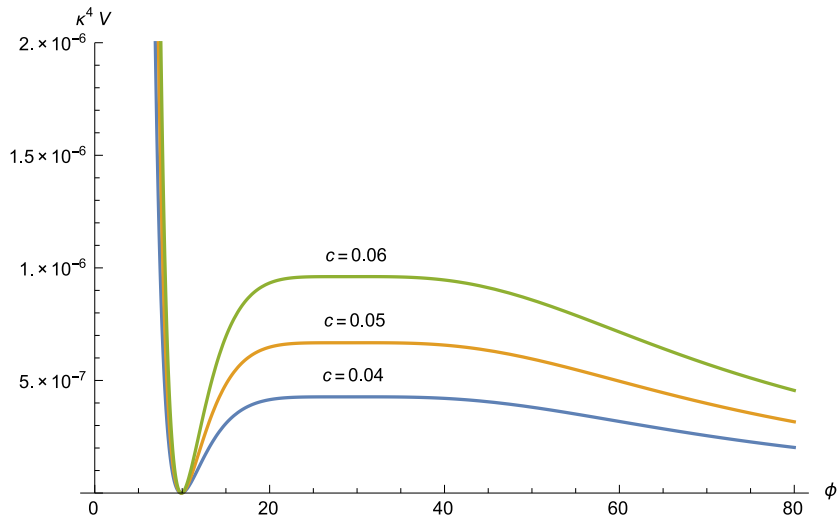
$b$  controls  $\phi_{min} \sim 1/g_s$  choose it of order 10

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

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

numerical analysis  $\Rightarrow$  mild dependence

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



# Fit Planck '15 data and predictions

inflation starts with an initial condition for  $\phi = \phi_*$  near the maximum and ends when  $|\eta| = 1$

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

Predictions for the power spectrum of perturbations in CMB:

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

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

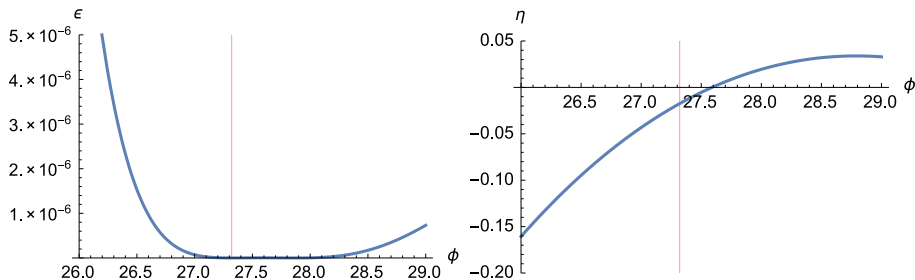
tensor – to – scalar ratio  $r = 16\epsilon_*$

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

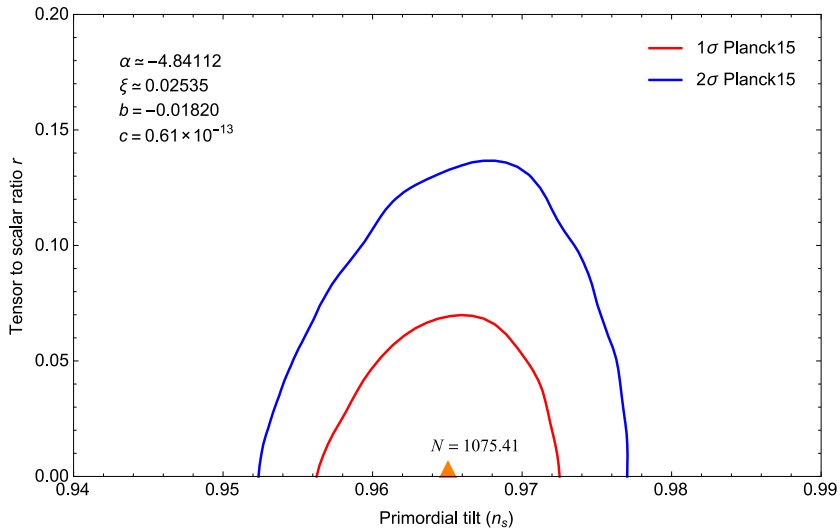
# Fit Planck '15 data and predictions

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



N	$n_s$	$r$	$A_s$
1075	0.965	$3 \times 10^{-23}$	$2.259 \times 10^{-9}$





$p = 1$ : 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	$4 \times 10^{-22}$	$2.205 \times 10^{-9}$

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:

$$H_* = \kappa \sqrt{\mathcal{V}_*/3} = 5.09 \text{ TeV}, \quad m_{3/2}^* = 4.72 \text{ TeV}, \quad M_{A_\mu}^* = 6.78 \text{ TeV}$$

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

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

$$\mathcal{C} = 1.53 \text{ vs at } \xi = 0: \mathcal{C}_0 = 1.52, \quad m_{3/2}^0 = 17.27, \text{ although } \langle \phi \rangle_0 \approx 9.96$$

# Conclusions

String phenomenology:

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

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?)