Aspects of string phenomenology on particle cosmology

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9TH AEGEAN SUMMER SCHOOL

Einstein's Theory of Gravity and its Modifications: from Theory to Observations

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String theory: Quantum Mechanics + General Relativity

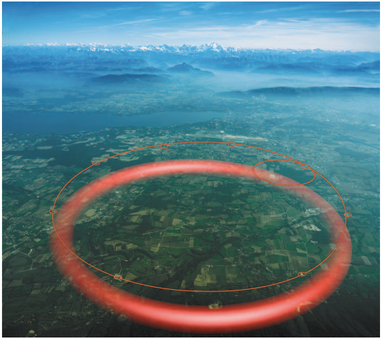
Main predictions → inspirations for BSM physics

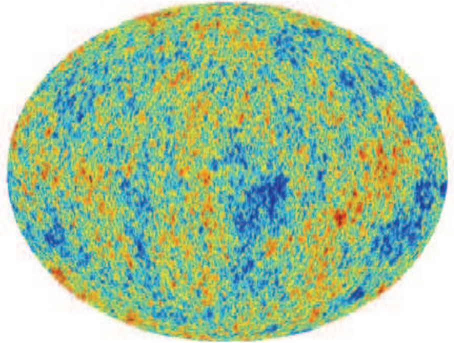
- Spacetime supersymmetry but arbitrary breaking scale
- Extra dimensions of space six or seven in M-theory
- Brane-world description of our Universe

  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

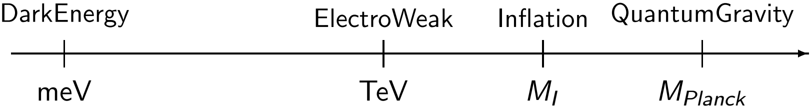
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

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



DarkEnergy	ElectroWeak	Inflation	QuantumGravity
meV	TeV	M_I	M_{Planck}

Relativistic dark energy   70-75% of the observable universe

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

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

Two length scales:

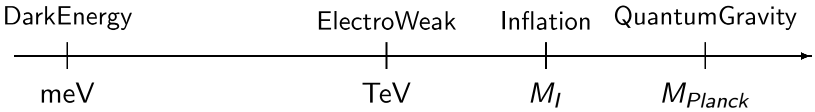
- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

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

  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



DarkEnergy ElectroWeak Inflation QuantumGravity

meV TeV M_I M_{Planck}

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

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

  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:

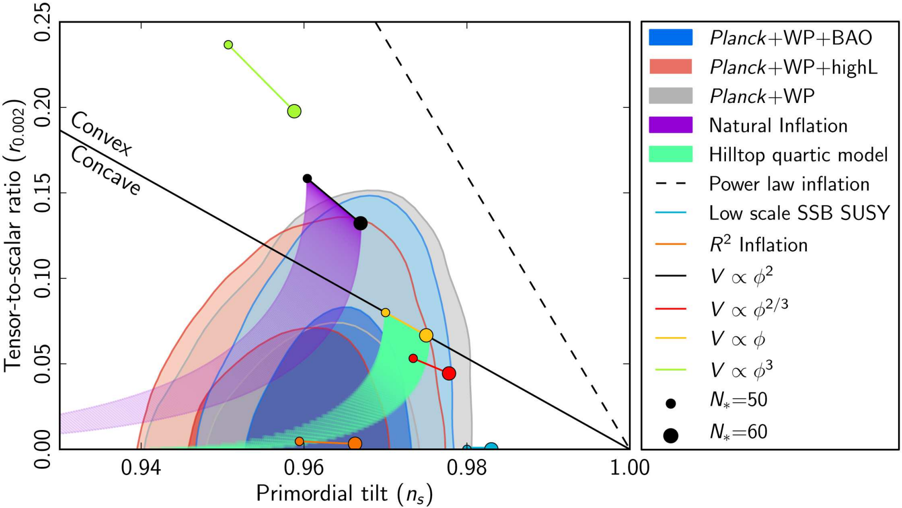
$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 \qquad M^2 = \frac{3}{4\alpha}$$

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


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

  → model independent treatment in the decoupling sgoldstino limit

  $\Rightarrow$ minimal SUSY extension that evades stability problem [14]

Non-linear supersymmetry ⇛ goldstino mode χ

Volkov-Akulov '73

Effective field theory of SUSY breaking at low energies

Analog of non-linear σ-model ⇛ constraint superfields

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

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

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

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

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

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

Non-linear SUSY transformations:

$$\delta\chi_\alpha = \frac{\xi_\alpha}{\kappa} + \kappa\,\Lambda^\mu_\xi\,\partial_\mu\chi_\alpha \qquad \Lambda^\mu_\xi = -i\left(\chi\sigma^\mu\bar{\xi} - \xi\sigma^\mu\bar{\chi}\right)$$

κ: goldstino decay constant (SUSY breaking scale) $\qquad \kappa = (\sqrt{2}m_{susy})^{-2}$

Volkov-Akulov action:

Define the 'vierbein': $\quad E^a_\mu = \delta^a_\mu + \kappa^2\, t^a_\mu \qquad t^a_\mu = i\chi\overset{\leftrightarrow}{\partial}_\mu\sigma^a\bar{\chi}$

$\delta(\det E) = \kappa\,\partial_\mu\left(\Lambda^\mu_\xi\,\det E\right) \Rightarrow$ invariant action:

$$S_{VA} = -\tfrac{1}{2\kappa^2}\int d^4x\,\det E = -\tfrac{1}{2\kappa^2} - \tfrac{i}{2}\chi\sigma^\mu\overset{\leftrightarrow}{\partial}_\mu\bar{\chi} + \ldots$$

Non-linear SUSY in supergravity

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

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

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

- 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: $(\underset{\nwarrow}{\mathcal{R}} - 6W_0)^2 = 0$ 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 $(\phi > 1)$ [20]

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

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

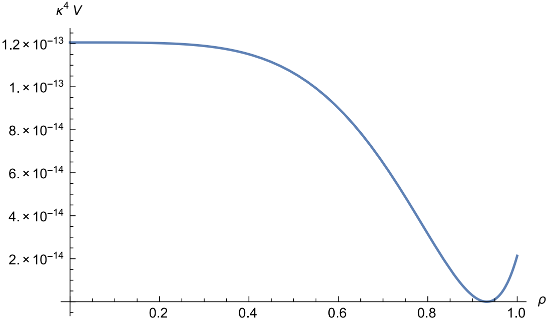
- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  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 [20] [30]

Case 1: R-symmetry restored during inflation

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

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

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

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

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

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

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

$\Rightarrow r \lesssim 10^{-4}$, $H_* \lesssim 10^{12}$ GeV assuming $\rho_{\rm end} \lesssim 1/2$

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

Answer: Yes in a 'weaker' sense: perturbative expansion [16]

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 [36]

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? [7] [11] [30]

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

can also be described by a generalized linear multiplet [26]

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

- $b > 0 \Rightarrow$ 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:

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

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

Scalar potential for $b = 0$

$$V = a^2(p-3)l^p + c^2p^2l^3$$

can be obtained for $p = 2$ and l the string dilaton:

- all geometric moduli fixed by fluxes in a SUSY way
- D-term contribution : D-brane potential (uncancelled tension)
- F-term contribution : tree-level potential (away from criticality)

String realisation : framework of magnetised branes

minimisation and spectrum

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

In the limit $\Lambda \approx 0$ $(p = 2) \Rightarrow$ [32]

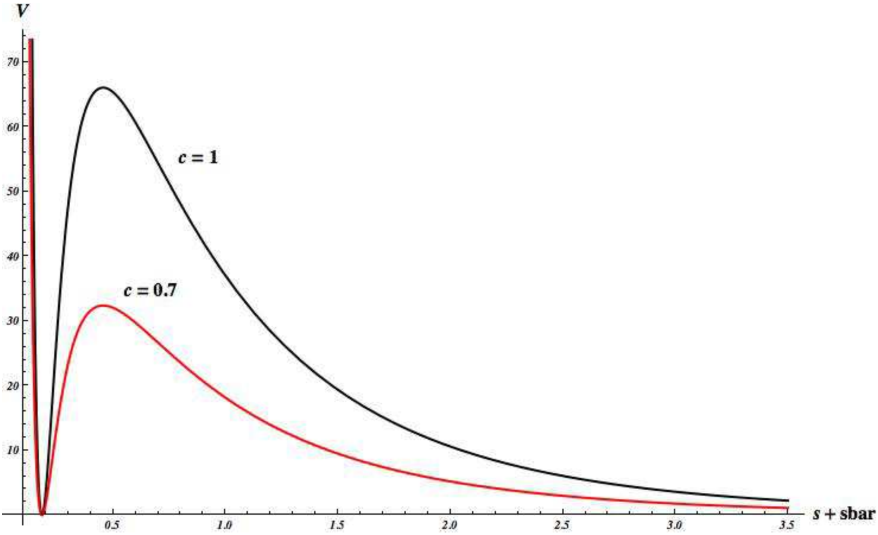
$b/l = \rho \approx -0.183268 \quad \Rightarrow \langle l \rangle = b/\rho$

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

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



[30]

Properties and generalizations

- Metastability of the ground state: extremely long lived

  $I \simeq 0.02$ (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 [21]

  $K = -p\ln(S + \bar{S}) + b(S + \bar{S}) \quad ; \quad W = a$ 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

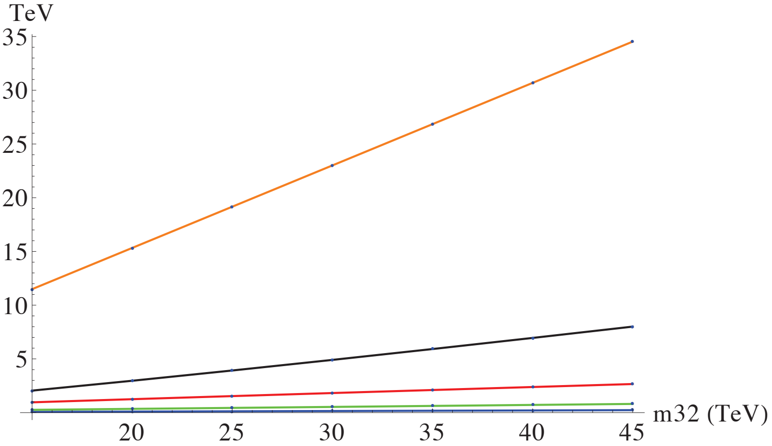
  $\Rightarrow$ one extra parameter
- alternatively: add an S-dependent factor in Matter kinetic terms

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

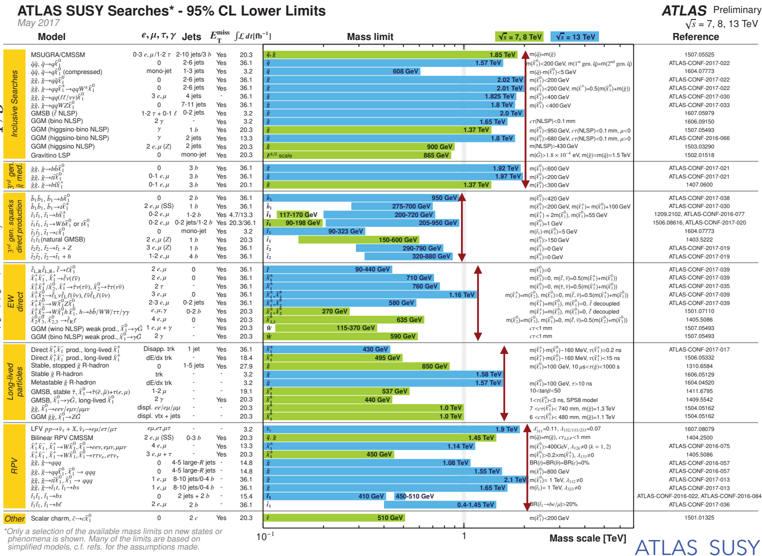
  $\Rightarrow$ suppressed compared to scalar masses and A-terms

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 [20]

SUSY SEARCHES SUMMARY



ATLAS SUSY Searches* - 95% CL Lower Limits
May 2017

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

Legend: 🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde q,\tilde g$ 1.85 TeV	m($\tilde q$)=m($\tilde g$)	1507.05525
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde q$ 1.57 TeV	m($\tilde\chi^0_1$)<200 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	ATLAS-CONF-2017-022
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde q$ 608 GeV	m($\tilde q$)-m($\tilde\chi^0_1$)<5 GeV	1604.07773
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde g$ 2.02 TeV	m($\tilde\chi^0_1$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^\pm_1\to qqW^\pm\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde g$ 2.01 TeV	m($\tilde\chi^0_1$)<200 GeV, m($\tilde\chi^\pm$)=0.5(m($\tilde\chi^0_1$)+m($\tilde g$))	ATLAS-CONF-2017-022
	$\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\nu\nu)\tilde\chi^0_1$	3 e,μ	4 jets	-	36.1	🟦 $\tilde g$ 1.825 TeV	m($\tilde\chi^0_1$)<400 GeV	ATLAS-CONF-2017-030
	$\tilde g\tilde g$, $\tilde g\to qqWZ\tilde\chi^0_1$	0	7-11 jets	Yes	36.1	🟦 $\tilde g$ 1.8 TeV	m($\tilde\chi^0_1$) <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde\ell$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde g$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde g$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde g$ 1.37 TeV	m($\tilde\chi^0_1$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde g$ 1.8 TeV	m($\tilde\chi^0_1$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde g$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	m($\tilde G$)>1.8×10^{-4} eV, m($\tilde g$)=m($\tilde q$)=1.5 TeV	1502.01518
3rd gen. $\tilde g$ med.	$\tilde g\tilde g$, $\tilde g\to b\bar b\tilde\chi^0_1$	0	3 b	Yes	36.1	🟦 $\tilde g$ 1.92 TeV	m($\tilde\chi^0_1$)<600 GeV	ATLAS-CONF-2017-021
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	Yes	36.1	🟦 $\tilde g$ 1.97 TeV	m($\tilde\chi^0_1$)<200 GeV	ATLAS-CONF-2017-021
	$\tilde g\tilde g$, $\tilde g\to b\bar t\tilde\chi^+_1$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde g$ 1.37 TeV	m($\tilde\chi^0_1$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_1$	0	2 b	Yes	36.1	🟦 $\tilde b_1$ 950 GeV	m($\tilde\chi^0_1$)<420 GeV	ATLAS-CONF-2017-038
	$\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi^\pm_1$	2 e,μ (SS)	1 b	Yes	36.1	🟦 $\tilde b_1$ 275-700 GeV	m($\tilde\chi^0_1$)<200 GeV, m($\tilde\chi^\pm_1$)= m($\tilde\chi^0_1$)+100 GeV	ATLAS-CONF-2017-030
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\tilde\chi^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde t_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde\chi^\pm_1$) = 2m($\tilde\chi^0_1$), m($\tilde\chi^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi^0_1$ or $t\tilde\chi^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde t_1$ 🟩 90-198 GeV 🟦 205-950 GeV	m($\tilde\chi^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$	0	mono-jet	Yes	3.2	🟦 $\tilde t_1$ 90-323 GeV	m($\tilde t_1$)-m($\tilde\chi^0_1$)=5 GeV	1604.07773
	$\tilde t_1\tilde t_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde t_1$ 150-600 GeV	m($\tilde\chi^0_1$)>150 GeV	1403.5222
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	🟦 $\tilde t_2$ 290-790 GeV	m($\tilde\chi^0_1$)=0 GeV	ATLAS-CONF-2017-019
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+h$	1-2 e,μ	4 b	Yes	36.1	🟦 $\tilde t_2$ 320-880 GeV	m($\tilde\chi^0_1$)=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi^0_1$	2 e,μ	0	Yes	36.1	🟦 $\tilde\ell$ 90-440 GeV	m($\tilde\chi^0_1$)=0	ATLAS-CONF-2017-039
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to\tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	36.1	🟦 $\tilde\chi^\pm_1$ 710 GeV	m($\tilde\chi^0_1$)=0, m($\tilde\ell,\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2$, $\tilde\chi^+_1\to\tilde\tau\nu(\tau\tilde\nu)$, $\tilde\chi^0_2\to\tilde\tau\tau(\nu\tilde\nu)$	2 τ	-	Yes	36.1	🟦 $\tilde\chi^\pm_1$ 760 GeV	m($\tilde\chi^0_1$)=0, m($\tilde\tau,\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	ATLAS-CONF-2017-035
	$\tilde\chi^\pm_1\tilde\chi^0_2\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	36.1	🟦 $\tilde\chi^\pm_1,\tilde\chi^0_2$ 1.16 TeV	m($\tilde\chi^\pm_1$)=m($\tilde\chi^0_2$), m($\tilde\chi^0_1$)=0, m($\tilde\ell,\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1Z\tilde\chi^0_1$	2-3 e,μ	0-2 jets	Yes	36.1	🟦 $\tilde\chi^\pm_1,\tilde\chi^0_2$ 580 GeV	m($\tilde\chi^\pm_1$)=m($\tilde\chi^0_2$), m($\tilde\chi^0_1$)=0, $\tilde\ell$ decoupled	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1h\tilde\chi^0_1$, $h\to b\bar b/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde\chi^\pm_1,\tilde\chi^0_2$ 270 GeV	m($\tilde\chi^\pm_1$)=m($\tilde\chi^0_2$), m($\tilde\chi^0_1$)=0, $\tilde\ell$ decoupled	1501.07110
	$\tilde\chi^0_2\tilde\chi^0_3$, $\tilde\chi^0_{2,3}\to\tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde\chi^0_{2,3}$ 635 GeV	m($\tilde\chi^0_2$)=m($\tilde\chi^0_3$), m($\tilde\chi^0_1$)=0, m($\tilde\ell,\tilde\nu$)=0.5(m($\tilde\chi^0_2$)+m($\tilde\chi^0_1$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde\chi^0_1\to\gamma\tilde G$	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde W$ 🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde\chi^0_1\to\gamma\tilde G$	2 γ	-	Yes	20.3	🟩 $\tilde W$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	Yes	36.1	🟦 $\tilde\chi^\pm_1$ 430 GeV	m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)~160 MeV, τ($\tilde\chi^\pm_1$)=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	dE/dx trk	-	Yes	18.4	🟩 $\tilde\chi^\pm_1$ 495 GeV	m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)~160 MeV, τ($\tilde\chi^\pm_1$)<15 ns	1506.05332
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde g$ 850 GeV	m($\tilde\chi^0_1$)=100 GeV, 10 μs<τ($\tilde g$)<1000 s	1310.6584
	Stable $\tilde g$ R-hadron	trk	-	-	3.2	🟦 $\tilde g$ 1.58 TeV		1606.05129
	Metastable $\tilde g$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde g$ 1.57 TeV	m($\tilde\chi^0_1$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde\tau$, $\tilde\chi^0_1\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde\chi^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde\chi^0_1\to\gamma\tilde G$, long-lived $\tilde\chi^0_1$	2 γ	-	Yes	20.3	🟩 $\tilde\chi^0_1$ 440 GeV	1<τ($\tilde\chi^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g$, $\tilde\chi^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde\chi^0_1$ 1.0 TeV	7 <$c\tau$($\tilde\chi^0_1$)< 740 mm, m($\tilde g$)=1.3 TeV	1504.05162
	GGM $\tilde g\tilde g$, $\tilde\chi^0_1\to Z\tilde G$	displ. vtx + jets	-	-	20.3	🟩 $\tilde\chi^0_1$ 1.0 TeV	6 <$c\tau$($\tilde\chi^0_1$)< 480 mm, m($\tilde g$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde\nu_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde q,\tilde g$ 1.45 TeV	m($\tilde q$)=m($\tilde g$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde\chi^\pm_1$ 1.14 TeV	m($\tilde\chi^0_1$)>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	🟩 $\tilde\chi^\pm_1$ 450 GeV	m($\tilde\chi^0_1$)>0.2×m($\tilde\chi^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde g\tilde g$, $\tilde g\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde g$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^0_1$, $\tilde\chi^0_1\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde g$ 1.55 TeV	m($\tilde\chi^0_1$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi^0_1$, $\tilde\chi^0_1\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde g$ 2.1 TeV	m($\tilde\chi^0_1$)= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde g\tilde g$, $\tilde g\to\tilde t_1t$, $\tilde t_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde g$ 1.65 TeV	m($\tilde t_1$)= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde t_1\tilde t_1$, $\tilde t_1\to bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde t_1$ 410 GeV 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\ell$	2 e,μ	2 b	-	36.1	🟦 $\tilde t_1$ 0.4-1.45 TeV	BR($\tilde t_1\to be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde c\to c\tilde\chi^0_1$	0	2 c	Yes	20.3	🟩 $\tilde c$ 510 GeV	m($\tilde\chi^0_1$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Direct, one-step and two-step decays

Simplified and pMSSM inspired models

Higher reach for electro-weakinos

Limits on the long lived chargino

Limits for RPV models

ATLAS_SUSY_Summary

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 [25]

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 $\alpha < 0$, 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 [24]

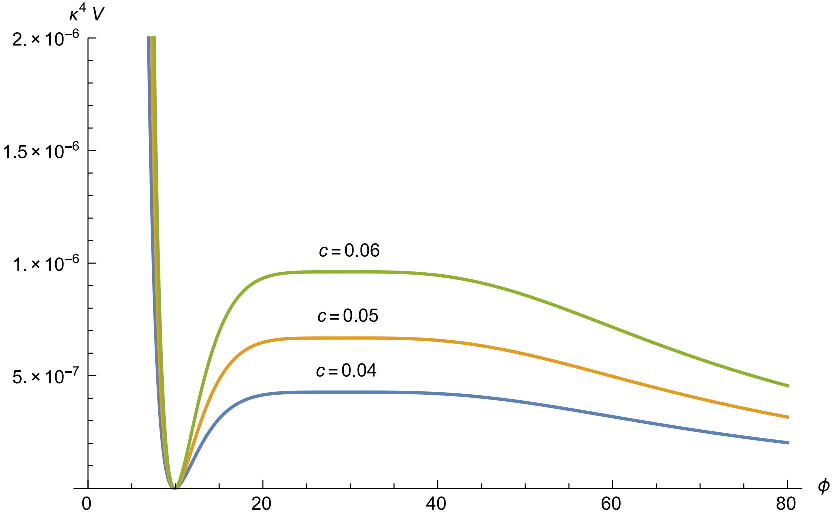
b controls $\phi_{min} \sim 1/g_s$ choose it of order 10

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

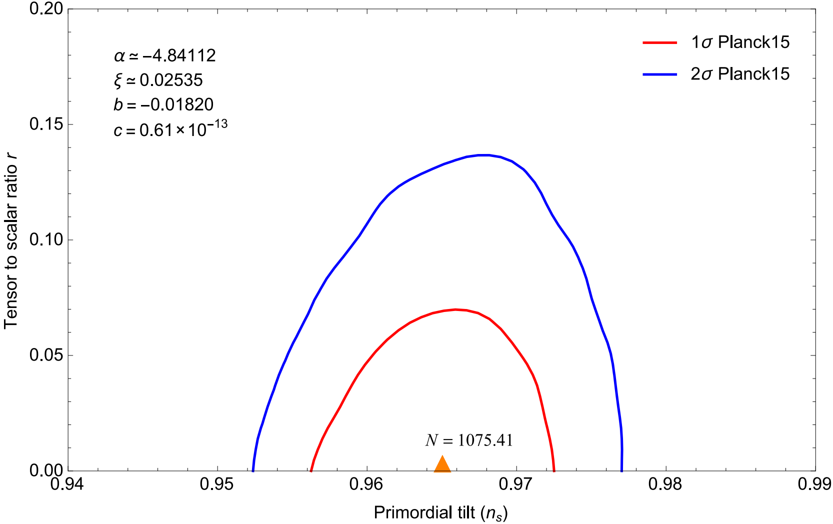
During inflation:

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

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

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

$\mathcal{C} = 1.53$ vs at $\xi = 0$: $\mathcal{C}_0 = 1.52$, $m^0_{3/2} = 17.27$, although $\langle\phi\rangle_0 \approx 9.96$ [16]


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

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

S$\not{U}$SY 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