Aspects of string phenomenology and scale hierarchies

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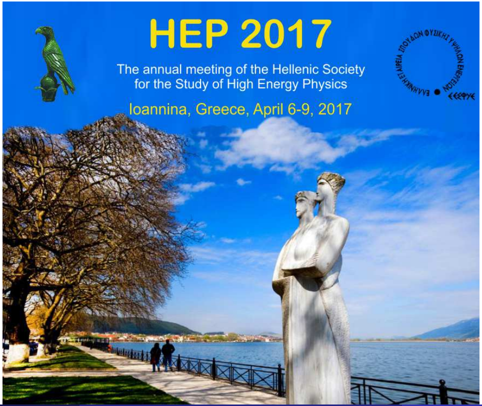


String theory: Quantum Mechanics + General Relativity

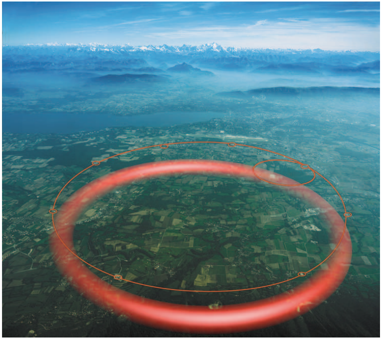
Main predictions → inspirations for BSM physics

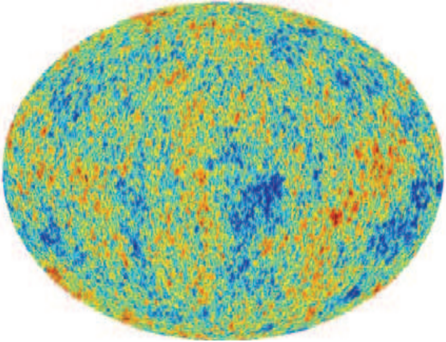
- Spacetime supersymmetry   but arbitrary breaking scale
- Extra dimensions of space   six or seven in M-theory
- Brane-world description of our Universe

  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

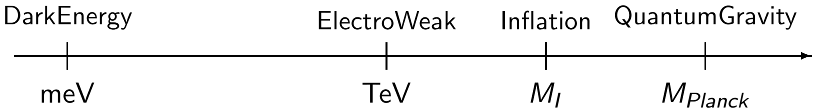
- incorporate Dark Energy

  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} :



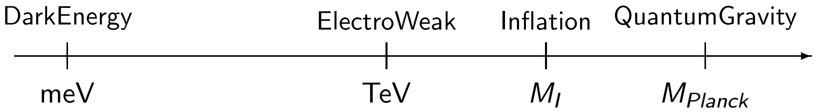
DarkEnergy — meV

ElectroWeak — TeV

Inflation — M_I

QuantumGravity — M_{Planck}

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

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? [15] [23]

Toy model for SUSY breaking

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

with a shift symmetry $S \to S - ic\omega \leftarrow$ 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 [11]

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

minimisation and spectrum

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

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

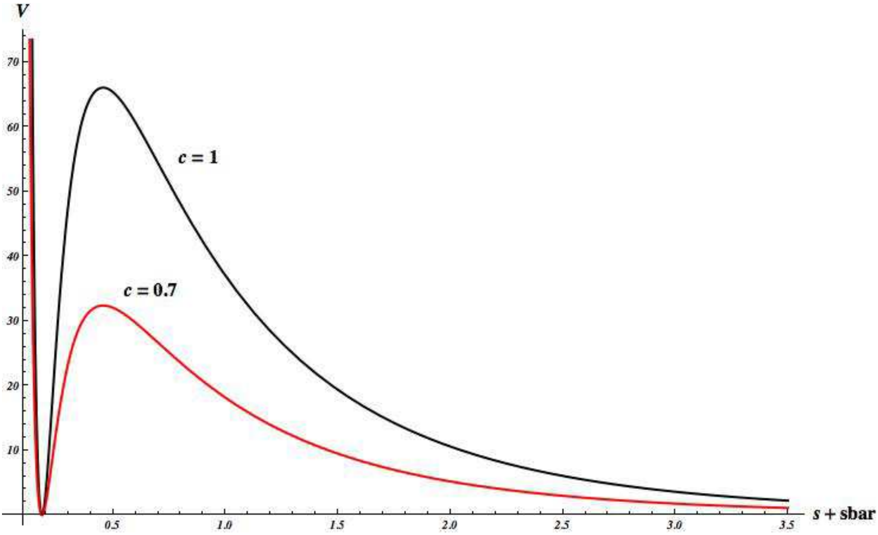
$b/l = \rho \approx -0.183268 \quad \Rightarrow \langle l \rangle = b/\rho$

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

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



[15]

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 [7]

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

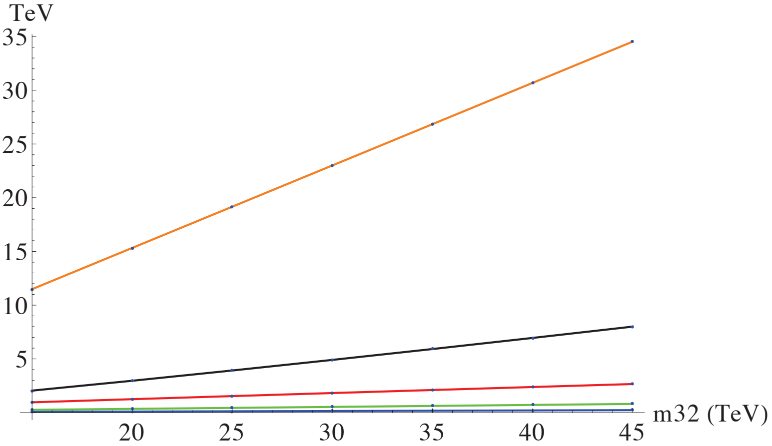
  ⇒ one extra parameter
- alternatively: add an S-dependent factor in Matter kinetic terms

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

  ⇒ similar phenomenology
- distinct features from other models of SUSY breaking and mediation
- gaugino masses at the quantum level

  ⇒ suppressed compared to scalar masses and A-terms

Typical spectrum



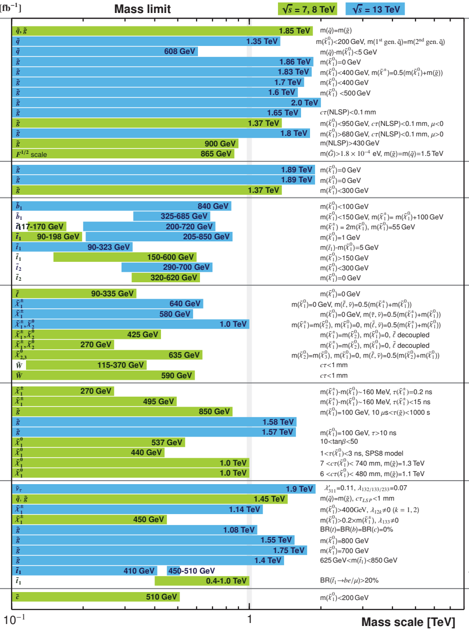
The masses of sbottom squark (yellow), stop (black), gluino (red), lightest chargino (green) and lightest neutralino (blue) as a function of the gravitino mass. The mass of the lightest neutralino varies between $\sim$ 40 and 150 GeV [6]

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 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	13.3	🟦 $\tilde{q}$ 1.35 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (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	13.3	🟦 $\tilde{g}$ 1.86 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^{\pm}_1\to qqW^{\pm}\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$ 1.83 TeV	m($\tilde{\chi}^0_1$)<400 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	13.2	🟦 $\tilde{g}$ 1.7 TeV	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	2 e,μ (SS)	0-3 jets	Yes	13.2	🟦 $\tilde{g}$ 1.6 TeV	m($\tilde{\chi}^0_1$) <500 GeV	ATLAS-CONF-2016-037
	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	14.8	🟦 $\tilde{g}$ 1.89 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	14.8	🟦 $\tilde{g}$ 1.89 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	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	3.2	🟦 $\tilde{b}_1$ 840 GeV	m($\tilde{\chi}^0_1$)<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^{\pm}_1$	2 e,μ (SS)	1 b	Yes	13.2	🟦 $\tilde{b}_1$ 325-685 GeV	m($\tilde{\chi}^0_1$)<150 GeV, m($\tilde{\chi}^{\pm}_1$)= m($\tilde{\chi}^0_1$)+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^{\pm}_1$	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	4.7/13.3	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 205-850 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	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	13.3	🟦 $\tilde{t}_2$ 290-700 GeV	m($\tilde{\chi}^0_1$)<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	🟩 $\tilde{t}_2$ 320-620 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\ell}$ 90-335 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^{\pm}_1$ 640 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-096
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	🟦 $\tilde{\chi}^{\pm}_1$ 580 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-093
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 1.0 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-2016-096
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 425 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	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.	1 e,μ + γ	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	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	20.3	🟩 $\tilde{\chi}^{\pm}_1$ 270 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)=0.2 ns	1310.3675
	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,μ + τ	-	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	-	14.8	🟦 $\tilde{g}$ 1.75 TeV	m($\tilde{\chi}^0_1$)=700 GeV	ATLAS-CONF-2016-094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	14.8	🟦 $\tilde{g}$ 1.4 TeV	625 GeV<m($\tilde{t}_1$)<850 GeV	ATLAS-CONF-2016-094
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	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	-	20.3	🟩 $\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
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.

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 $|\eta| = |V''/V| << 1$ 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 $\alpha < 0$, 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 [9]

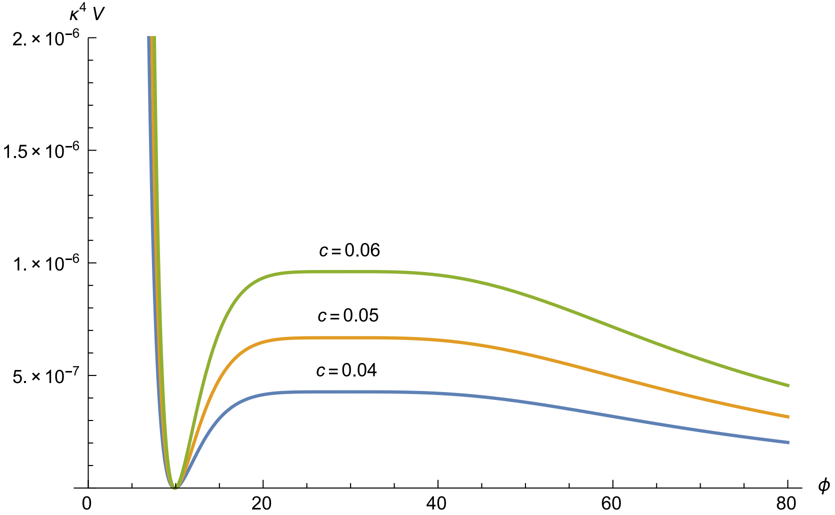
b controls $\phi_{min} \sim 1/g_s$ choose it of order 10

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

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

numerical analysis $\Rightarrow$ mild dependence

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



Fit Planck '15 data and predictions

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

and ends when $|\eta| = 1$

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

Predictions for the power spectrum of perturbations in CMB:

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

$$\text{spectral index} \quad n_s = 1 + 2\eta_* - 6\epsilon_*$$

$$\text{tensor} - \text{to} - \text{scalar ratio} \quad r = 16\epsilon_*$$

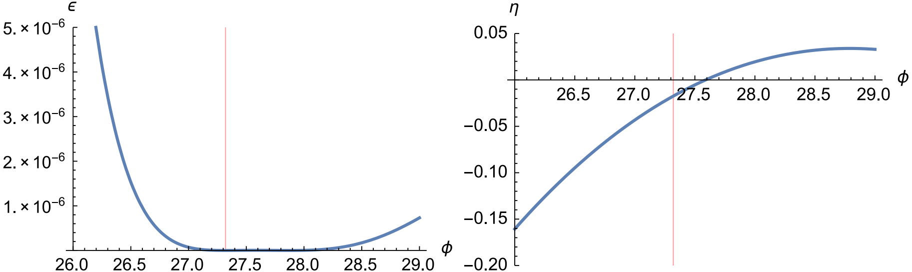
Numerical analysis: fit Planck '15 data and keep the SM minimum

with an infinitesimal cosmological constant

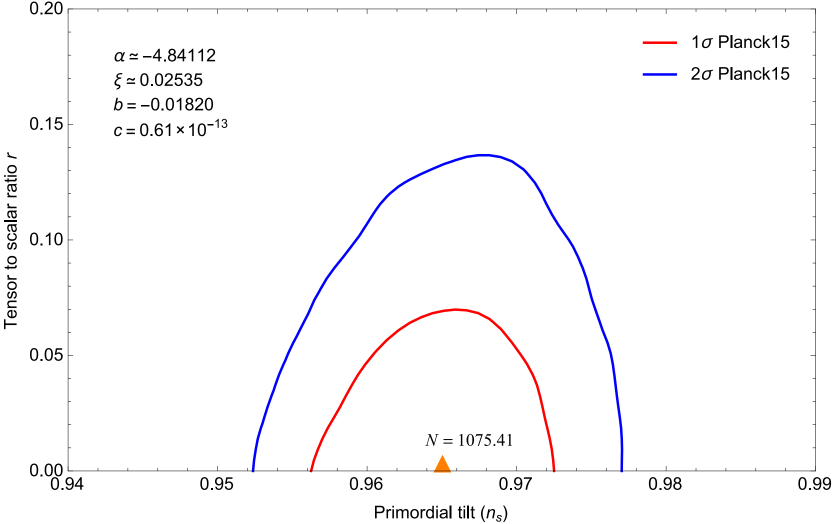
$\Rightarrow$ fine tuning of the parameters of the model

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	3×10^{-23}	2.259×10^{-9}



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

$p = 1$: 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 $\langle\phi\rangle_0 \approx 9.96$ [6] [28]

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 $\Rrightarrow$ constraint superfields

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

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

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

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

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

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

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: $(\underset{\nwarrow}{\mathcal{R}} - 6W_0)^2 = 0$ 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:

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

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

→ model independent treatment in the decoupling sgoldstino limit

$\Rightarrow$ minimal SUSY extension that evades stability problem

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

- however inflaton different from goldstino superpartner

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

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

S$\not{\mathrm{U}}$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?)