# Scale hierarchies and string cosmology

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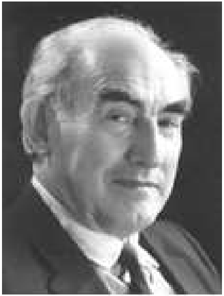
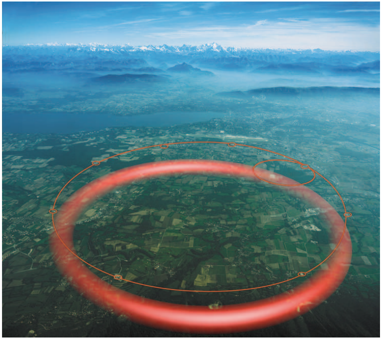
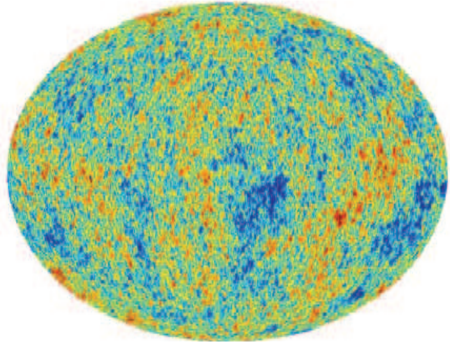


# String theory

- 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

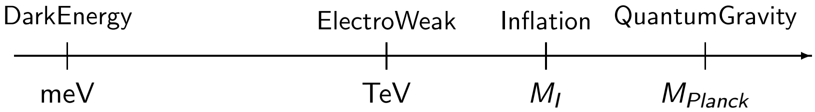
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

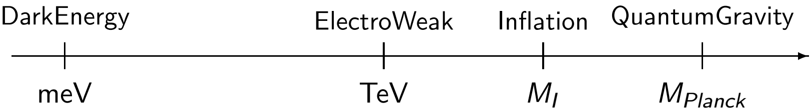
- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

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



# 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 $m_{SUSY} \sim$ 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? [21]

# 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 [17]

# 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 ($p < 3$) [15]
- $b < 0$: SUSY breaking minimum with tuneable cosmological constant $\Lambda$

# 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

# Type I string theory with magnetic fluxes $B_{ij}$ on 2-cycles of the compactification manifold

- Dirac quantization: $B = \dfrac{m}{nA} \equiv \dfrac{p}{A}$ [12] $\Rightarrow$ 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 [13] I.A.-Derendinger-Maillard '08

  its form is fixed by the axion shift symmetry

  $\Rightarrow$ break SUSY with tuneable vacuum energy

  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: $6 \times 6$ antisymmetric matrix $F$ complexification $\Rightarrow$

$F_{(2,0)}$ on holomorphic 2-cycles: potential for $\tau$ superpotential

$F_{(1,1)}$ on mixed (1,1)-cycles: potential for $J$ FI D-terms

# $N = 1$ SUSY conditions $\Rightarrow$ moduli stabilization

1. $F_{(2,0)} = 0 \ \Rightarrow \tau$ matrix equation for every magnetized $U(1)$

   $$\tau^{\mathrm{T}} p_{xx} \tau - (\tau^{\mathrm{T}} p_{xy} + p_{yx} \tau) + p_{yy} = 0$$ [9]

   $\nearrow$

   $T^6$ parametrization: $(x^i, y^i)$ $i = 1,2,3$ $z^i = x^i + \tau^{ij} y^i$

   need ‘oblique’ (non-commuting) magnetic fields to fix off-diagonal components of the metric $\leftarrow$ but can be made diagonal

2. $J \wedge J \wedge F_{(1,1)} = F_{(1,1)} \wedge F_{(1,1)} \wedge F_{(1,1)} \ \Rightarrow J$

   vanishing of a Fayet-Iliopoulos term: $\xi \sim F \wedge F \wedge F - J \wedge J \wedge F$

   magnetized $U(1) \rightarrow$ massive absorbs RR axion

   one condition $\Rightarrow$ need at least 9 brane stacks

3. Tadpole cancellation conditions : introduce an extra brane(s) [10]

# break SUSY in AdS vacuum I.A.-Derendinger-Maillard '08

$N = 2$ non-linear supersymmetry $\Rightarrow$

General form of the localized dilaton potential:

$$V(\phi, d) = \frac{e^{-\phi}}{g^2}\left\{\left(\sqrt{1-\underset{\substack{\nearrow \\ \text{DBI action}}}{d^2}} - 1\right) + \underset{\substack{\nearrow \\ \text{FI-term}}}{\xi d} + \delta T\right\}$$

$d$: D-auxiliary in $2\pi\alpha'$-units

$\delta T$: tension leftover RR tadpole cancellation $\Rightarrow \delta T = 1 - \sqrt{1-\xi^2}$

$d$ elimination $\Rightarrow$ $d = \frac{\xi}{\sqrt{1+\xi^2}}$

$$V_{\min} = \delta\bar{T} e^{-\phi} \quad ; \quad \delta\bar{T} = \sqrt{1+\xi^2} - \sqrt{1-\xi^2}$$

# Dilaton fixing

add a 'non-critical' dilaton potential

$\Rightarrow$ AdS vacuum with tuneable string coupling

$$V_{\rm non-crit} = \delta c\, e^{-2\phi} \qquad \delta c\text{: central charge deficit}$$

minimization of $V = V_{\rm non-crit} + V_D \Rightarrow \delta c < 0$

$$e^{\phi_0} = -\frac{2\,\delta c}{3\,\delta T} \qquad V_0 = \frac{\delta c^3}{3\,\delta T^2} \qquad \underset{\nwarrow \text{curvature in Einstein frame}}{R_0} = -\delta T\, e^{3\phi_0}$$

e.g. replace a free coordinate by a CFT minimal model of central charge $1 + \delta c$

→ generalize: add a dilaton potential preserving the axion shift symmetry

$\Rightarrow$ break SUSY with tuneable vacuum energy [8]

I.A.-Knoops '14, '15

# minimisation and spectrum

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

In the limit $\Lambda \approx 0$ $(p = 2) \Rightarrow$ [7] [23]

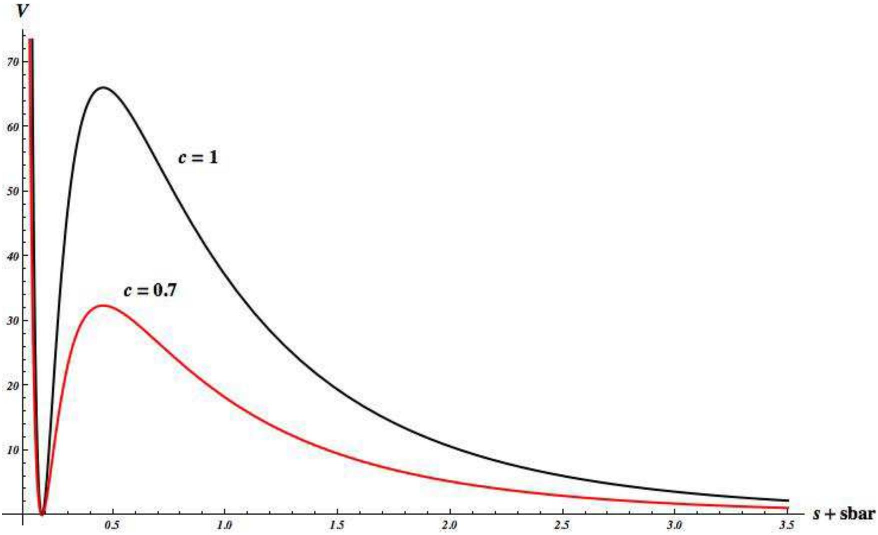
$b/l = \rho \approx -0.183268 \quad \Rightarrow \langle l \rangle = b/\rho$

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

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



[21]

# 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 $\phi$ 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 [6]

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

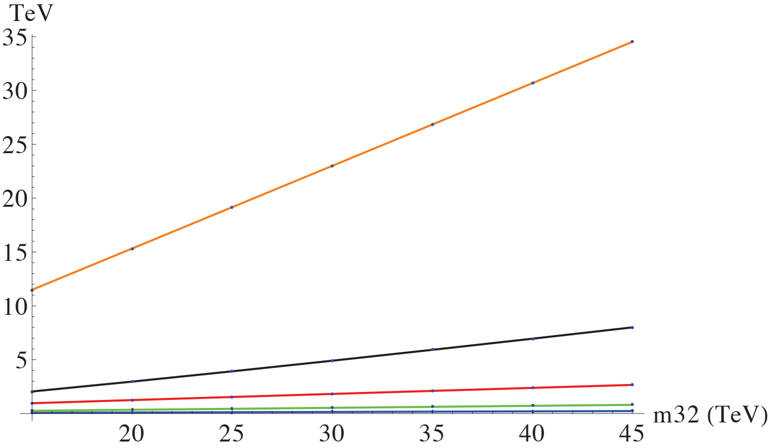
  $\Rightarrow$ one extra parameter
- alternatively: add an $S$-dependent factor in Matter kinetic terms

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

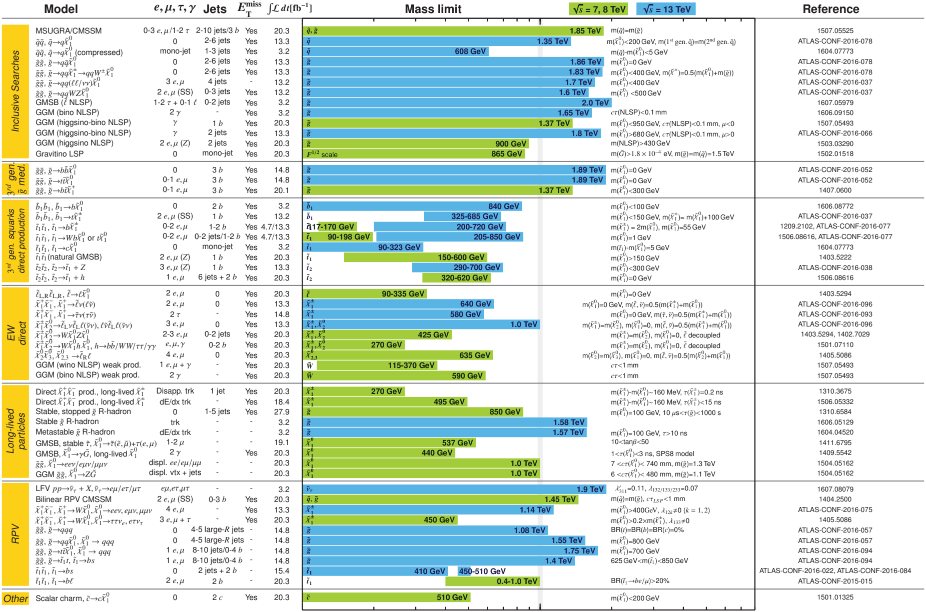


The masses of sbottom squark (yellow), stop (black), gluino (red), lightest chargino (green) and lightest neutralino (blue) as a function of the gravitino mass. The mass of the lightest neutralino varies between ∼ 40 and 150 GeV [5]

# ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

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



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

| | Model | $e,\mu,\tau,\gamma$ | Jets | $E_T^{miss}$ | $\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0-3 $e,\mu$/1-2 $\tau$ | 2-10 jets/3 $b$ | Yes | 20.3 | 🟩 $\tilde{q},\tilde{g}$ 1.85 TeV | m($\tilde{q}$)=m($\tilde{g}$) | 1507.05525 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 13.3 | 🟦 $\tilde{q}$ 1.35 TeV | m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$) | ATLAS-CONF-2016-078 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | 🟦 $\tilde{q}$ 608 GeV | m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV | 1604.07773 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 13.3 | 🟦 $\tilde{g}$ 1.86 TeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2016-078 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 13.3 | 🟦 $\tilde{g}$ 1.83 TeV | m($\tilde{\chi}_1^0$)<400 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$)) | ATLAS-CONF-2016-078 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$ | 3 $e,\mu$ | 4 jets | - | 13.2 | 🟦 $\tilde{g}$ 1.7 TeV | m($\tilde{\chi}_1^0$)<400 GeV | ATLAS-CONF-2016-037 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 2 $e,\mu$ (SS) | 0-3 jets | Yes | 13.2 | 🟦 $\tilde{g}$ 1.6 TeV | m($\tilde{\chi}_1^0$) <500 GeV | ATLAS-CONF-2016-037 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ + 0-1 $\ell$ | 0-2 jets | Yes | 3.2 | 🟦 $\tilde{g}$ 2.0 TeV | | 1607.05979 |
| | GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 3.2 | 🟦 $\tilde{g}$ 1.65 TeV | $c\tau$(NLSP)<0.1 mm | 1606.09150 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 20.3 | 🟩 $\tilde{g}$ 1.37 TeV | m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$<0 | 1507.05493 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 2 jets | Yes | 13.3 | 🟦 $\tilde{g}$ 1.8 TeV | m($\tilde{\chi}_1^0$)>680 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$>0 | ATLAS-CONF-2016-066 |
| | GGM (higgsino NLSP) | 2 $e,\mu$ ($Z$) | 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($\tilde{G}$)>$1.8\times10^{-4}$ eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV | 1502.01518 |
| $3^{rd}$ gen. $\tilde{g}$ med. | $\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 $b$ | Yes | 14.8 | 🟦 $\tilde{g}$ 1.89 TeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2016-052 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 14.8 | 🟦 $\tilde{g}$ 1.89 TeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2016-052 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | 🟩 $\tilde{g}$ 1.37 TeV | m($\tilde{\chi}_1^0$)<300 GeV | 1407.0600 |
| $3^{rd}$ gen. squarks direct production | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 3.2 | 🟦 $\tilde{b}_1$ 840 GeV | m($\tilde{\chi}_1^0$)<100 GeV | 1606.08772 |
| | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$ | 2 $e,\mu$ (SS) | 1 $b$ | Yes | 13.2 | 🟦 $\tilde{b}_1$ 325-685 GeV | m($\tilde{\chi}_1^0$)<150 GeV, m($\tilde{\chi}_1^\pm$)= m($\tilde{\chi}_1^0$)+100 GeV | ATLAS-CONF-2016-037 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 0-2 $e,\mu$ | 1-2 $b$ | Yes | 4.7/13.3 | $\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV | m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV | 1209.2102, ATLAS-CONF-2016-077 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 $e,\mu$ | 0-2 jets/1-2 $b$ | Yes | 4.7/13.3 | $\tilde{t}_1$ 🟩 90-198 GeV 🟦 205-850 GeV | m($\tilde{\chi}_1^0$)=1 GeV | 1506.08616, ATLAS-CONF-2016-077 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet | Yes | 3.2 | 🟦 $\tilde{t}_1$ 90-323 GeV | m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV | 1604.07773 |
| | $\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 $e,\mu$ ($Z$) | 1 $b$ | Yes | 20.3 | 🟩 $\tilde{t}_1$ 150-600 GeV | m($\tilde{\chi}_1^0$)>150 GeV | 1403.5222 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$ | 3 $e,\mu$ ($Z$) | 1 $b$ | Yes | 13.3 | 🟦 $\tilde{t}_2$ 290-700 GeV | m($\tilde{\chi}_1^0$)<300 GeV | ATLAS-CONF-2016-038 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$ | 1 $e,\mu$ | 6 jets + 2 $b$ | Yes | 20.3 | 🟩 $\tilde{t}_2$ 320-620 GeV | m($\tilde{\chi}_1^0$)=0 GeV | 1506.08616 |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0 | Yes | 20.3 | 🟩 $\tilde{\ell}$ 90-335 GeV | m($\tilde{\chi}_1^0$)=0 GeV | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 $e,\mu$ | 0 | Yes | 13.3 | 🟦 $\tilde{\chi}_1^\pm$ 640 GeV | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2016-096 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 $\tau$ | - | Yes | 14.8 | 🟦 $\tilde{\chi}_1^\pm$ 580 GeV | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2016-093 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 $e,\mu$ | 0 | Yes | 13.3 | 🟦 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 1.0 TeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2016-096 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$ | 2-3 $e,\mu$ | 0-2 jets | Yes | 20.3 | 🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 425 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled | 1403.5294, 1402.7029 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$ | $e,\mu,\gamma$ | 0-2 $b$ | Yes | 20.3 | 🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 270 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled | 1501.07110 |
| | $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$ | 4 $e,\mu$ | 0 | Yes | 20.3 | 🟩 $\tilde{\chi}_{2,3}^0$ 635 GeV | m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$)) | 1405.5086 |
| | GGM (wino NLSP) weak prod. | 1 $e,\mu$ + $\gamma$ | - | Yes | 20.3 | 🟩 $\tilde{W}$ 115-370 GeV | $c\tau$<1 mm | 1507.05493 |
| | GGM (bino NLSP) weak prod. | 2 $\gamma$ | - | 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 $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | 🟩 $\tilde{\chi}_1^\pm$ 270 GeV | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, $\tau$($\tilde{\chi}_1^\pm$)=0.2 ns | 1310.3675 |
| | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | dE/dx trk | - | Yes | 18.4 | 🟩 $\tilde{\chi}_1^\pm$ 495 GeV | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, $\tau$($\tilde{\chi}_1^\pm$)<15 ns | 1506.05332 |
| | Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | 🟩 $\tilde{g}$ 850 GeV | m($\tilde{\chi}_1^0$)=100 GeV, 10 $\mu$s<$\tau$($\tilde{g}$)<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($\tilde{\chi}_1^0$)=100 GeV, $\tau$>10 ns | 1604.04520 |
| | GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 $\mu$ | - | - | 19.1 | 🟩 $\tilde{\chi}_1^0$ 537 GeV | 10<tan$\beta$<50 | 1411.6795 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 20.3 | 🟩 $\tilde{\chi}_1^0$ 440 GeV | 1<$\tau$($\tilde{\chi}_1^0$)<3 ns, SPS8 model | 1409.5542 |
| | $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | 🟩 $\tilde{\chi}_1^0$ 1.0 TeV | 7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV | 1504.05162 |
| | GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$ | displ. vtx + jets | - | - | 20.3 | 🟩 $\tilde{\chi}_1^0$ 1.0 TeV | 6 <$c\tau$($\tilde{\chi}_1^0$)< 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 | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079 |
| | Bilinear RPV CMSSM | 2 $e,\mu$ (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 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$ | 4 $e,\mu$ | - | Yes | 13.3 | 🟦 $\tilde{\chi}_1^\pm$ 1.14 TeV | m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$) | ATLAS-CONF-2016-075 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$ | 3 $e,\mu$ + $\tau$ | - | Yes | 20.3 | 🟩 $\tilde{\chi}_1^\pm$ 450 GeV | m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$ | 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 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$ | 0 | 4-5 large-$R$ jets | - | 14.8 | 🟦 $\tilde{g}$ 1.55 TeV | m($\tilde{\chi}_1^0$)=800 GeV | ATLAS-CONF-2016-057 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$ | 1 $e,\mu$ | 8-10 jets/0-4 $b$ | - | 14.8 | 🟦 $\tilde{g}$ 1.75 TeV | m($\tilde{\chi}_1^0$)=700 GeV | ATLAS-CONF-2016-094 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$ | 1 $e,\mu$ | 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 $e,\mu$ | 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, $\tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2 $c$ | Yes | 20.3 | 🟩 $\tilde{c}$ 510 GeV | m($\tilde{\chi}_1^0$)<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 $V$ [16]

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

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

additional independant parameters: $a, c, b$

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

$\xi = 0 \Rightarrow b\phi_{min} = \rho_0$, $\frac{a^2}{bc^2} = \lambda_0$ with $\rho_0, \lambda_0$ calculable constants [15]

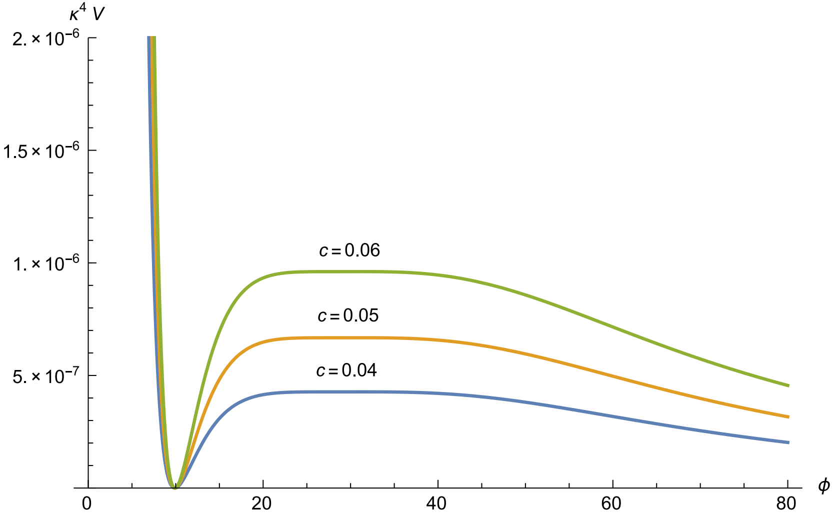
$b$ controls $\phi_{min} \sim 1/g_s$ choose it of order 10

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:

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

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

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

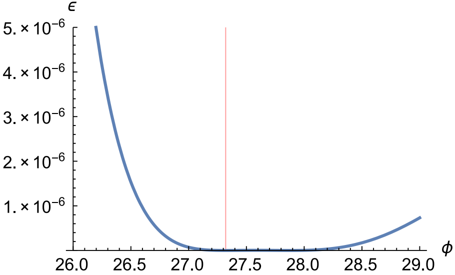
Numerical analysis: fit Planck '15 data and keep the SM minimum

with an infinitesimal cosmological constant

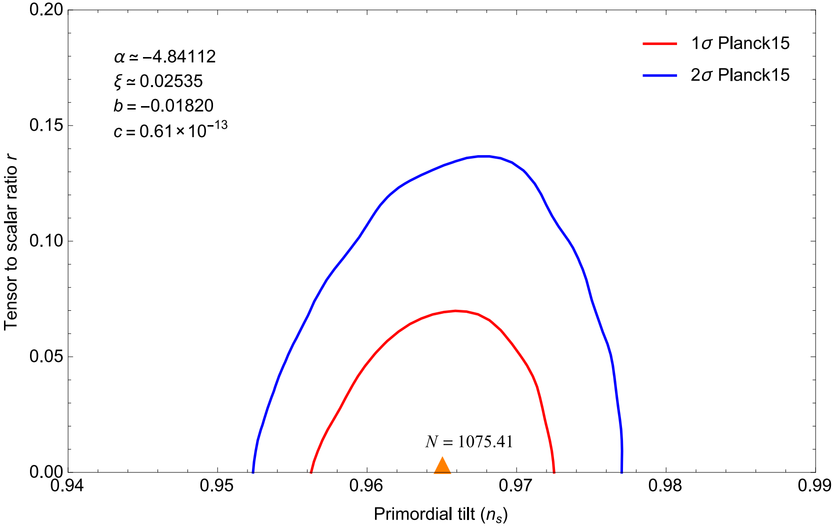
$\Rightarrow$ fine tuning of the parameters of the model

# 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 | $3 \times 10^{-23}$ | $2.259 \times 10^{-9}$ |


$\alpha \simeq -4.84112$
$\xi \simeq 0.02535$
$b = -0.01820$
$c = 0.61 \times 10^{-13}$
1$\sigma$ Planck15
2$\sigma$ 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 | $4 \times 10^{-22}$ | $2.205 \times 10^{-9}$ |

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:

$H_* = \kappa\sqrt{\mathcal{V}_*/3} = 5.09$ 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 $\langle\phi\rangle_0 \approx 9.96$

# 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$\not{\text{U}}$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?)