Aspects of Particle Physics & Cosmology of the Superstring – Derived No-Scale Flipped SU (5)

D.V.Nanopoulos

TAMU

HARC

Academy of Athens

A Model Of EveryThing (MOET)

Flipped → A; Almost → Of; Below the Planck Scale → (MOET)

- Simple GUT models (SU(5), SO(10)) not obtained from weakly-coupled string
  - They need adjoint Higgs, …
- **Flipped SU(5)×U(1) derived**, has advantages
  - Small (5-, 10-dimensional) Higgs representations
  - Long-lived proton, neutrino masses, leptogenesis, …
- Construct model of Starobinsky-like inflation within flipped SU(5)×U(1) framework

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331 perature after the GUT transition imposed by the success of conventional BBN [13] prefer a SUSY breaking scale that is $\mathcal{O}(10)$ TeV. This and other key model predictions (r, n_s, neutrino masses, n_B/s, the dark matter density, the SUSY scale, BBN and the Higgs mass m_h) are highlighted in red in Fig. 1.

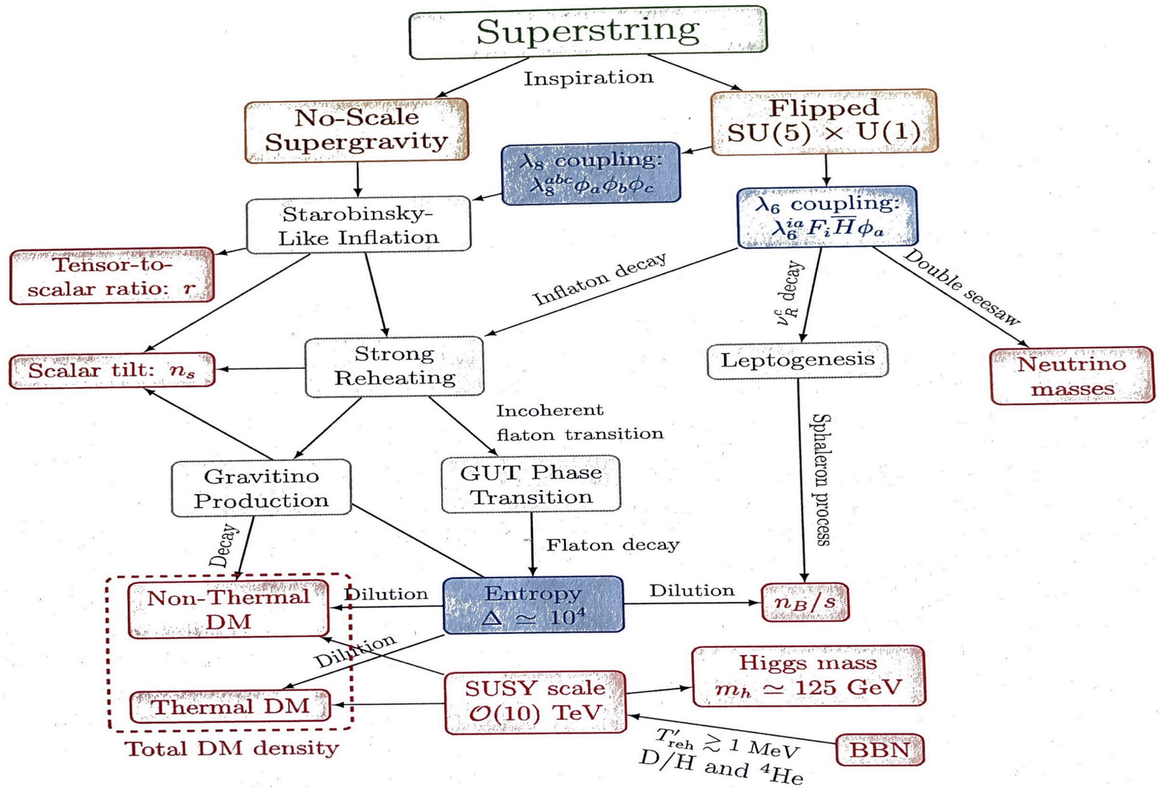


Figure 1: *The general structure of our scenario for particle cosmology.*

The layout of this paper is as follows. In Section 2 we review the construction of our model, reviewing the assignments of matter particles to SU(5)×U(1) representations and the singlet inflaton and flaton fields, and highlighting the importance of the λ_6 coupling. Then, in Section 3 we review some cosmological aspects of our model, focusing on the reheating epoch following inflation, which we assume to be strong, and the subsequent breaking of the GUT symmetry via thermal corrections to the effective potential for the flaton. The amount of entropy, Δ, generated during the transition to the SM gauge group is an important aspect of our analysis. As we discuss in Section 4, strong reheating implies the copious production of gravitinos, which decay subsequently to CDM particles, assumed to be neutralinos. Their

Flipped SU(5)×U(1) GUT Model

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Fields:
  - Matter: $$F_i = (\mathbf{10}, 1)_i \ni \{d^c, Q, \nu^c\}_i \quad \bar{f}_i = (\bar{\mathbf{5}}, -3)_i \ni \{u^c, L\}_i\,, \quad \ell^c_i = (\mathbf{1}, 5)_i \ni \{e^c\}_i\,,$$
  - Singlets: $\phi_a = (\mathbf{1}, 0),\ a = 0, \ldots, 3$

  Higgs: $$H = (\mathbf{10}, 1)\,, \quad \bar{H} = (\overline{\mathbf{10}}, -1)\,, \quad h = (\mathbf{5}, -2)\,, \quad \bar{h} = (\bar{\mathbf{5}}, 2)\,,$$
- Superpotential: $$W = \lambda_1^{ij} F_i F_j h + \lambda_2^{ij} F_i \bar{f}_j \bar{h} + \lambda_3^{ij} \bar{f}_i \ell^c_j h + \lambda_4 H H h + \lambda_5 \bar{H}\bar{H}\bar{h} + \lambda_6^{ia} F_i \bar{H} \phi_a + \lambda_7^a h \bar{h} \phi_a + \lambda_8^{abc} \phi_a \phi_b \phi_c + \mu^{ab} \phi_a \phi_b\,,$$
- No-scale Kähler potential:

$$K = -3 \ln \left[T + \bar{T} - \frac{1}{3} \left(|\phi_a|^2 + |\ell^c|^2 + f^\dagger f + h^\dagger h + \bar{h}^\dagger \bar{h} + F^\dagger F + H^\dagger H + \bar{H}^\dagger \bar{H} \right) \right]$$

- D-terms: $$D^a D^a = \left(\frac{3}{10} g_5^2 + \frac{1}{80} g_X^2 \right) \left(|\tilde{\nu}_i^c|^2 + |\tilde{\nu}_H^c|^2 - |\tilde{\nu}_{\bar{H}}^c|^2 \right)^2$$
- Symmetry breaking: $\mathrm{SU}(5) \times \mathrm{U}(1) \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- Proton lifetime: $$\tau_p = 4.6 \times 10^{35} \times \left(\frac{M_{32}}{10^{16}\ \mathrm{GeV}} \right)^4 \times \left(\frac{0.0374}{\alpha_5(M_{32})} \right)^2 \ \mathrm{yrs}$$

No-Scale Supergravity

Natural vanishing of cosmological constant (tree level) with the supersymmetry scale not fixed at lowest order. (Also arises in generic 4d reductions of string theory.)

$$K = -3\ln(T + T^* - \phi^i {\phi_i}^*/3)$$

$$V = e^{\frac{2}{3}K} \left| \frac{\partial W}{\partial \phi^i} \right|^2$$

Globally supersymmetric potential once K (canonical) picks up a vev

Old No-Scale Supergravity Model of Inflation

Volume 152B, number 3,4 PHYSICS LETTERS

SU(N, 1) INFLATION

John ELLIS, K. ENQVIST, D.V. NANOPOULOS
CERN, Geneva, Switzerland

K.A. OLIVE
Astrophysics Theory Group, Fermilab, Batavia, IL 60510, USA

and

M. SREDNICKI
Department of Physics, University of California, Santa Barbara, CA 93106, USA

Received 7 December 1984

- No ‘holes’ in effective potential with negative cosmological constant

JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

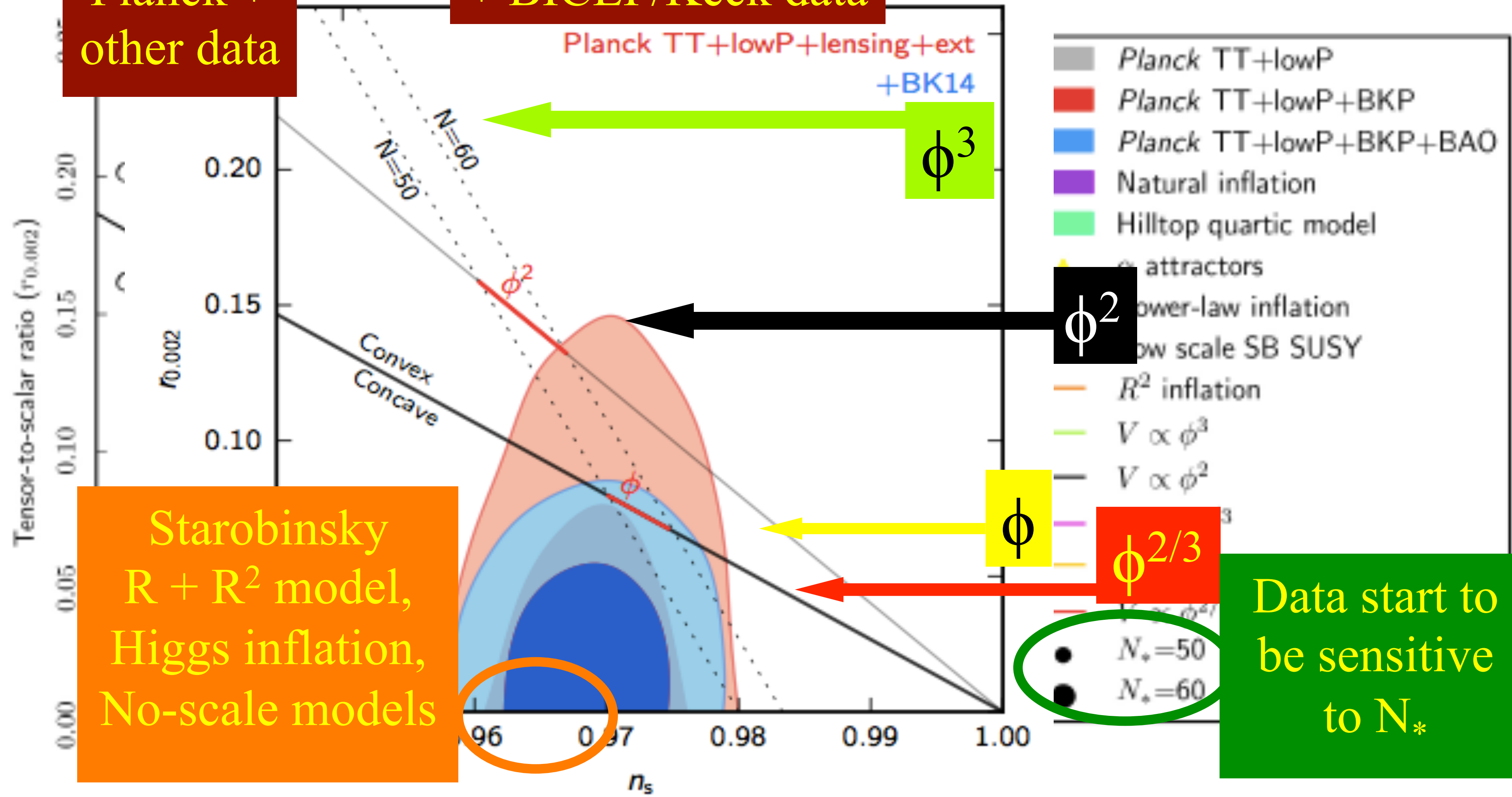
We present a simple model for primordial inflation in the context of SU(N, 1) no-scale $n = 1$ supergravity. Because the model at zero temperature very closely resembles global supersymmetry, minima with negative cosmological constants do not exist, and it is easy to have a long inflationary epoch while keeping density perturbations of the right magnitude and satisfying other cosmological constraints. We pay specific attention to satisfying the thermal constraint for inflation, i.e. the existence of a high temperature minimum at the origin.

Inflationary Landscape

Monomial Single-field potentials

Planck + other data

+ BICEP/Keck data



ϕ^3

ϕ^2

ϕ

$\phi^{2/3}$

Starobinsky $R + R^2$ model, Higgs inflation, No-scale models

Data start to be sensitive to N_*

No-Scale models revisited

Can we find a model consistent with Planck?

Ellis, Nanopoulos, Olive

Start with WZ model: $$W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

Assume now that T picks up a vev: 2<Re T> = c

$$\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2}$$

Redefine inflaton to a canonical field χ

$$\hat{V} = |W_\Phi|^2$$

$$\phi = \sqrt{3c}\tanh\left(\frac{\chi}{\sqrt{3}}\right)$$

No-Scale models revisited

The potential becomes:

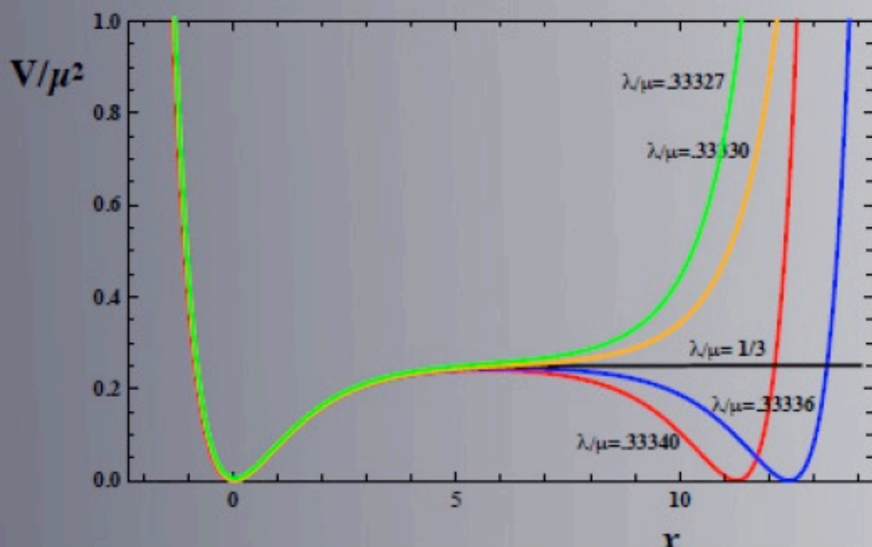
$$V = \mu^2 \left| \sinh(\chi/\sqrt{3}) \left(\cosh(\chi/\sqrt{3}) - \frac{3\lambda}{\mu} \sinh(\chi/\sqrt{3}) \right) \right|^2$$

$$\hat{\mu} = \mu \sqrt{(c/3)}$$

For $\lambda = \mu/3$, this is exactly the $R + R^2$ potential

$$V = \mu^2 e^{-\sqrt{2/3}x} \sinh^2(x/\sqrt{6})$$

$$\chi = (x + iy)/\sqrt{2}$$



Starobinsky-Like Inflation

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Need superpotential: $W \supset m\left(\frac{S^2}{2} - \frac{S^3}{3\sqrt{3}}\right)$
- Identify inflaton *S* with some combination of Φ_a, consider 2 scenarios:
- **1) Hierarchy of scalars*** with one light eigenstate Φ_0^{D}:

$$\mu_D^{ab} = \mathrm{diag}\left(m/2, \mu_D^{11}, \mu_D^{22}, \mu_D^{33}\right) , \qquad \mu_D^{ab} \leq M_{\mathrm{GUT}} \quad : \quad \det \mu^{ab} \ll M_{\mathrm{GUT}}^4$$

- "Starobinsky" condition: $-3\sqrt{3}\,\lambda_{8,D}^{000} = m$

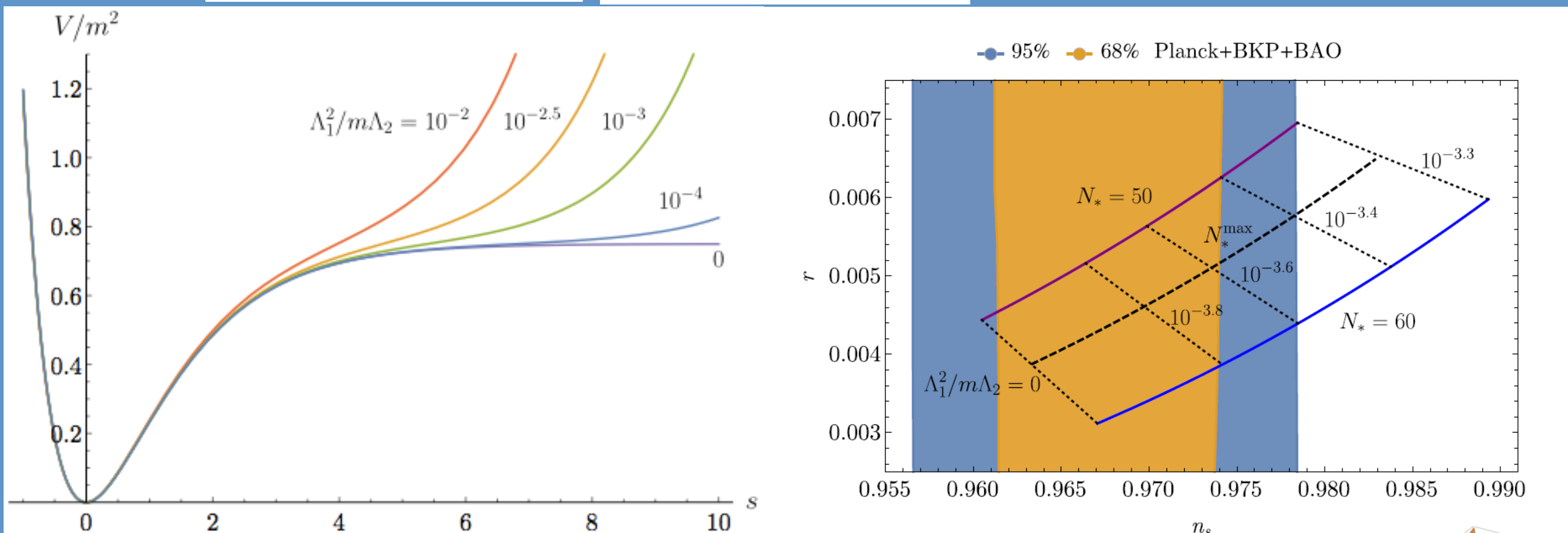
$$V_F \simeq \frac{3}{4}m^2\left(1 - e^{-\sqrt{2/3}\,s}\right)^2 + \frac{3}{4}\sinh^2(\sqrt{2/3}\,s)\sum_i |\lambda_6^{i0}|^2\left(|\tilde{\nu}_{\bar{H}}^c|^2 + |\tilde{\nu}_i^c|^2\right) + \frac{1}{8}m^2 e^{\sqrt{2/3}s}\left(|\tilde{\nu}_{\bar{H}}^c|^2 + \sum_i |\tilde{\nu}_i^c|^2\right) + \cdots .$$

* Consider later scenario **2) no scalar mass hierarchy**

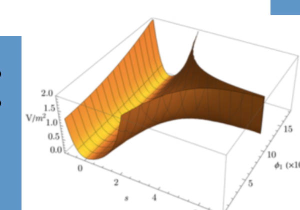
Starobinsky-Like Inflation in Scenario (2)

- Multiple light singlet states: correction to Starobinsky potential: $\Delta V_{\text{inf}} \sim \dfrac{\sqrt{3}\, m \sinh(\sqrt{2/3}\, s)}{2(1+\tanh(s/\sqrt{6}))} \dfrac{\Lambda_1^2}{\Lambda_2} \sim m \dfrac{\sqrt{3}\Lambda_1^2}{8\Lambda_2} e^{\sqrt{2/3}\, s}$

  where $\lambda_8^{00i} S \sim \mu^{0i} \sim \Lambda_1$ $\lambda_8^{0ij} S \sim \mu^{ij} \sim \Lambda_2$



- Multi-field effects not a problem, steep valley:



How many e-Folds of Inflation?

- General expression:

JE, García, Nanopoulos & Olive, arXiv:1505.06986

$$N_* = 67 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_P^4 \rho_{\rm end}}\right) + \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right) - \frac{1}{12}\ln g_{\rm th}$$

- In no-scale supergravity models:

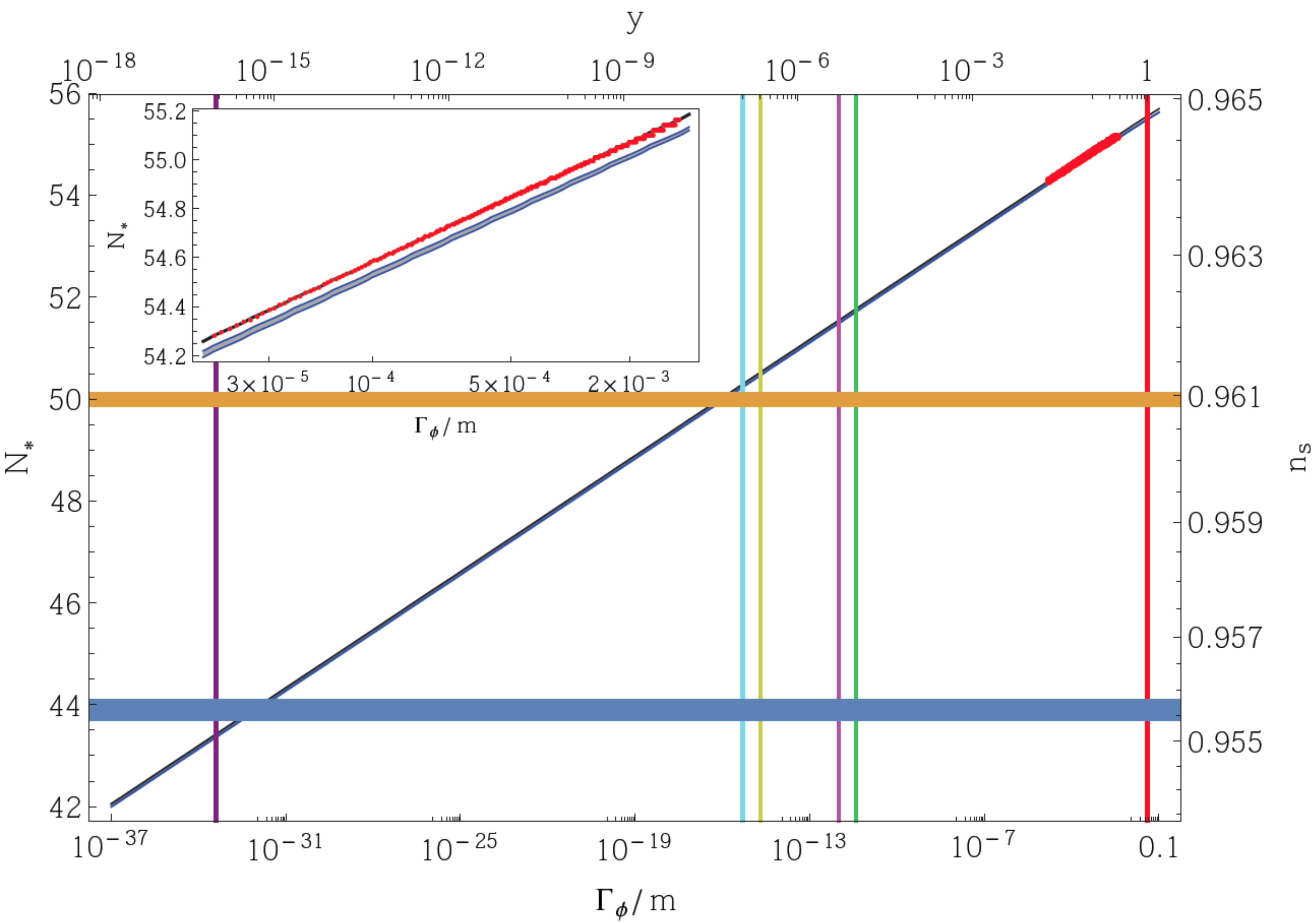
$$N_* = 68.659 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(A_{S*}\right) - \frac{1}{4}\ln\left(N_* - \sqrt{\frac{3}{8}}\frac{\phi_{\rm end}}{M_P} + \frac{3}{4}e^{\sqrt{\frac{2}{3}}\frac{\phi_{\rm end}}{M_P}}\right)$$
$$+ \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\left(2.030 + 2\ln\left(\Gamma_\phi/m\right) - 2\ln(1+w_{\rm eff}) - 2\ln(0.81 - 1.10\ln\delta)\right)$$
$$- \frac{1}{12}\ln g_{\rm th},$$

Amplitude of perturbations

Equation of state during inflaton decay

Inflaton decay rate

- **Prospective constraint on inflaton models?**



y
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
56
54
52
50
48
46
44
42
N_*
0.965
0.963
0.961
0.959
0.957
0.955
n_s
55.2
55.0
54.8
54.6
54.4
54.2
3×10^{-5}
10^{-4}
5×10^{-4}
2×10^{-3}
Γ_ϕ / m
10^{-37}
10^{-31}
10^{-25}
10^{-19}
10^{-13}
10^{-7}
0.1
Γ_ϕ / m

Neutrino Masses & Mixing

- Consider 2 options:
- (A) Inflaton decouples from neutrinos
  - Inflaton decays to Higgs(inos): leptogenesis difficult
- (B) Inflaton couples to neutrinos

$$\mathcal{L}^{(i')}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\nu_{i'} & \nu^c_{i'} & \tilde{S}\end{pmatrix}\begin{pmatrix}0 & \lambda_2^{i'i'}\langle\bar{h}_0\rangle & 0 \\ \lambda_2^{i'i'}\langle\bar{h}_0\rangle & 0 & \lambda_6^{i'0}\langle\tilde{\nu}^c_{\bar{H}}\rangle \\ 0 & \lambda_6^{i'0}\langle\tilde{\nu}^c_{\bar{H}}\rangle & m\end{pmatrix}\begin{pmatrix}\nu_{i'} \\ \nu^c_{i'} \\ \tilde{S}\end{pmatrix} + \text{h.c.}$$

- Double seesaw mass matrix, 2 heavy states, couplings

$W = \lambda_2^{i'j}\left(\cos\theta N_{i'1} - \sin\theta N_{i'2}\right) L_j h_u$ where $\tan 2\theta = -\frac{2\lambda_6^{i'0}\langle\tilde{\nu}^c_{\bar{H}}\rangle}{m}$

- Constraints from neutrino data, easier leptogenesis

Neutrino Masses & Inflaton Coupling

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- To avoid overproduction of dark matter via gravitinos if no later entropy $|y| < 2.7 \times 10^{-5} \left(1 + 0.56 \frac{m_{1/2}^2}{m_{3/2}^2}\right)^{-1} \left(\frac{100\,\text{GeV}}{m_{\text{LSP}}}\right)$
- With entropy factor Δ, if inflaton couples to neutrinos:

$$|\lambda_2^{i'j} \sin\theta| \lesssim 10^{-5}\Delta$$

- Normal neutrino mass hierarchy preferred

$$m_{\nu_1} \simeq 10^{-9} \times \left(\frac{|\lambda_6^{10}|}{10^{-3}}\right)^{-2} \left(\frac{|\langle \tilde{\nu}^c_{\tilde{H}} \rangle|}{10^{16}\ \text{GeV}}\right)^{-2} \left(\frac{m}{3 \times 10^{13}\, GeV}\right)\ \text{eV}$$

$$m_{\nu_2} \simeq |\delta m^2|^{\frac{1}{2}} \simeq 9 \times 10^{-3}\ \text{eV}$$

$$m_{\nu_3} \simeq |\Delta m^2|^{\frac{1}{2}} \simeq 5 \times 10^{-2}\ \text{eV}$$

- Weak or strong reheating? Much much extra entropy?

Entropy Release & Baryogenesis

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Entropy release

$$\Delta \simeq 8 \times 10^3 \lambda_{1,2,3,7}^{-2} \left(\frac{g_{d\Phi}}{43/4}\right)^{1/4} \left(\frac{915/4}{g_{\rm dec}}\right) \left(\frac{\langle\Phi\rangle}{5\times 10^{15}\,{\rm GeV}}\right) \left(\frac{10\,{\rm TeV}}{m^2_{F,\bar{f},\ell^c,\tilde{\phi}_a}/|m_\Phi|}\right)^{1/2}$$

- Relaxes gravitino production constraint, little effect on number of inflationary e-folds: $\Delta N_*^{\rm max} \simeq -4 \times 10^{-3} \ln \Delta$
- Standard leptogenesis if inflaton couples to neutrinos:

$$\epsilon \simeq -\frac{3}{4\pi} \frac{1}{\left(U^\dagger_{\nu^c}(\lambda_2^D)^2 U_{\nu^c}\right)_{11}} \sum_{i=2,3} {\rm Im}\left[\left(U^\dagger_{\nu^c}(\lambda_2^D)^2 U_{\nu^c}\right)^2_{i1}\right] \frac{m}{M_i}$$

$$\frac{n_B}{s} \simeq 3.8 \times 10^{-11} \delta f \lambda^2_{1,2,3,7} \lambda_6^{-2} \left(\frac{43/4}{g_{d\Phi}}\right)^{1/4} \left(\frac{915/4}{g_{\rm reh}}\right)^{1/4} \left(\frac{g_{\rm dec}}{915/4}\right) \left(\frac{y}{10^{-5}}\right) \times \left(\frac{5\times 10^{15}\,{\rm GeV}}{\langle\Phi\rangle}\right)^2 \left(\frac{m^2_{F,\bar{f},\ell^c,\tilde{\phi}_a}/|m_\Phi|}{10\,{\rm TeV}}\right)^{1/2} \left(\frac{m}{3\times 10^{13}{\rm GeV}}\right)^{1/2}$$

$$\mathrm{SU}(5) \times \mathrm{U}(1) \rightarrow \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \ . \quad (\ldots$$

The flat direction is lifted by a non-renormalizable superpotential term of the form

$$W_{\mathrm{NR}} = \frac{\lambda}{n! M_P^{2n-3}} (H\bar{H})^n \ , \quad (\ldots$$

where $M_P \equiv (8\pi G_N)^{-1/2}$ denotes the reduced Planck mass. The effective pot ntial for t flaton field is

$$V_{\text{non-th}}(\Phi) = V_0 - \frac{1}{2} m_\Phi^2 \Phi^2 + \frac{|\lambda|^2}{[(n-1)!]^2 M_P^{4n-6}} \Phi^{4n-2} \ . \quad (\ldots$$

where m_Φ denotes the soft mass of Φ. By minimizing this potential, we h ve

$$\langle \Phi \rangle = \left[\frac{\{(n-1)!\}^2 m_\Phi^2 M_P^{4n-6}}{(4n-2)|\lambda|^2} \right]^{\frac{1}{4(n-1)}} \ . \quad (1\ldots$$

Therefore, to obtain a GUT scale vacuum expectation value (vev) with an $\mathcal{O}(1)$ λ, we shoul have $n \geq 4$. Once the flat direction is lifted, we expect the flaton (and flatino) mass to b of order the supersymmetry-breaking scale. For further details, see [18].

3 The GUT Phase Transition

$$\Omega_\chi h^2 \simeq 10^{-7}\mathrm{GeV}^{-2}\Delta^{-1}\frac{m_{\tilde f}^4}{m_\chi^2} \sim 10^3\Delta^{-1}\left(\frac{m_{\tilde f}}{30\mathrm{TeV}}\right)^4\left(\frac{10\mathrm{TeV}}{m_\chi}\right)^2, \tag{33}$$

where the entropy release is given roughly by [11]

$$\Delta \sim 10^4\left(\frac{30\mathrm{TeV}}{m_{\tilde f}}\right)^{1/2}, \tag{34}$$

so that

$$\Omega_\chi h^2 \sim 10^{-1}\left(\frac{m_{\tilde f}}{30\mathrm{TeV}}\right)^{9/2}\left(\frac{10\mathrm{TeV}}{m_\chi}\right)^2, \tag{35}$$

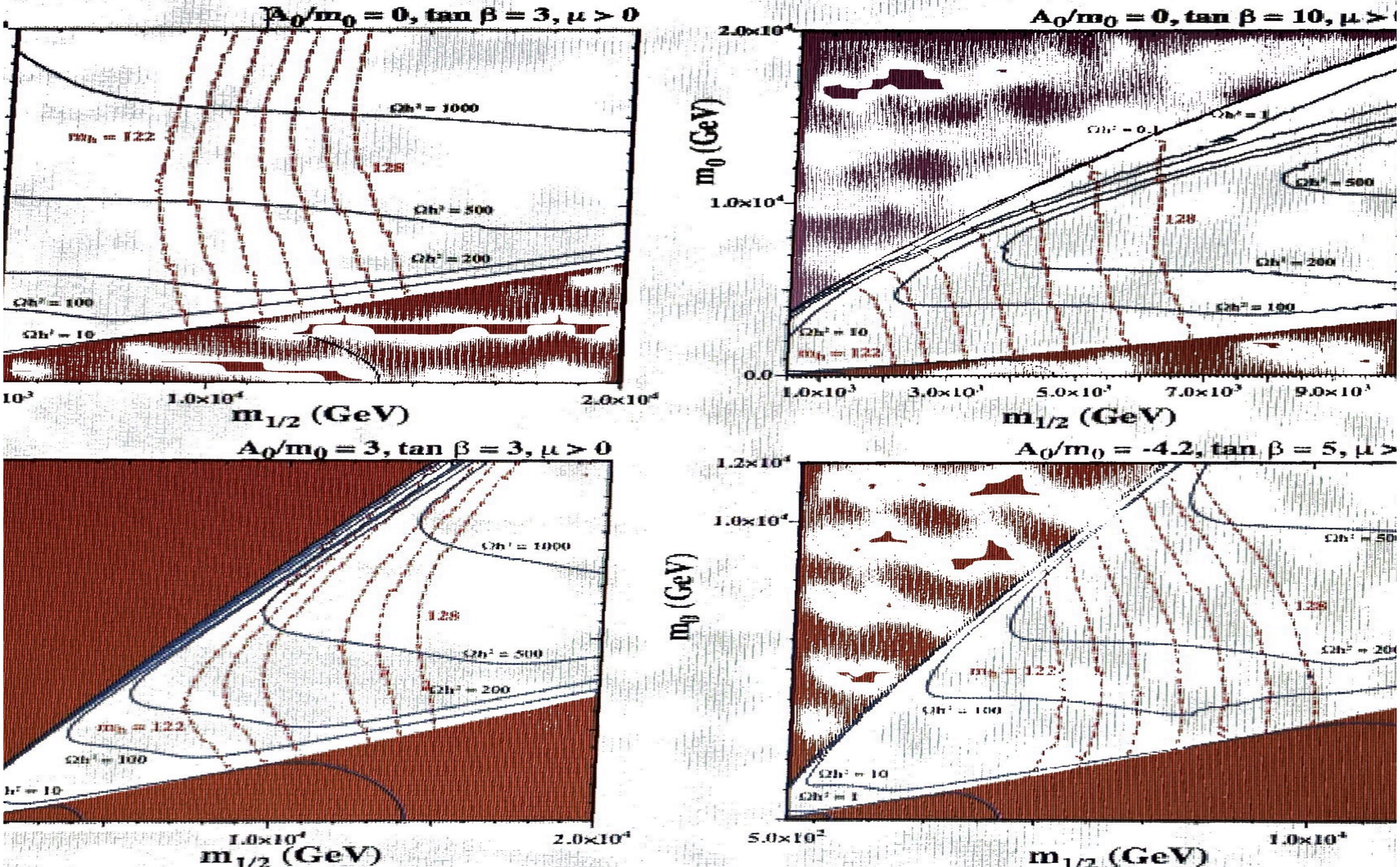
where we have assumed that all relevant couplings are of order 1.

Another cosmological consideration that should be taken into account is successful BBN, which requires the reheating temperature after the transition to be at least 1 MeV, so as to ensure a radiation-dominated universe during BBN. The reheating temperature can be written as [11]

$$T'_{\mathrm{reh}} \sim 10^{-3}\left(\frac{m_{\tilde f}^3 M_P}{M_{\mathrm{GUT}}^2}\right)^{1/2} \sim 1\mathrm{MeV}\left(\frac{m_{\tilde f}}{30\mathrm{TeV}}\right)^{3/2}, \tag{36}$$

and combining Eqs. (35) and (36), we can write

$$\Omega_\chi h^2 \sim 0.1\left(\frac{T'_{\mathrm{reh}}}{1\mathrm{MeV}}\right)^3\left(\frac{10\mathrm{TeV}}{m_\chi}\right)^2. \tag{37}$$



Some $(m_{1/2}, m_0)$ *planes in standard* $SU(5)$ *with* $M_{in} = M_{GUT}$, $\tan\beta = 3$, μ
pper left panel), $M_{in} = M_{GUT}$, $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$, *(upper right pa*
$_{T}$, $\tan\beta = 3$, $\mu > 0$, $A_0/m_0 = 3$, *(lower left panel),* $M_{in} = M_{GUT}$ *GeV,* $\tan\beta$
$/m_0 = -4.2$, *(lower right panel). Here and in the subsequent Figure, the*
p) is charged in the dark red shaded regions, which are therefore excluded,
stent electroweak vacuum in the pink shaded regions, the red dot-dashed line
m_h *calculated using* **FeynHiggs** *[89], and the solid blue lines are contours of*
nce of subsequent entropy generation.

KCL-PH-TH/2021-46, CERN-TH-2021-099
ACT-1-21, MI-HET-751
UMN-TH-4018/21, FTPI-MINN-21/11

Flipped $g_\mu - 2$

John Ellis[a], **Jason L. Evans**[b], **Natsumi Nagata**[c], **Dimitri V. Nanopoulos**[d] and **Keith A. Olive**[e]

[a] *Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, United Kingdom; Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland; National Institute of Chemical Physics and Biophysics, Rävala 10, 10143 Tallinn, Estonia*

[b] *Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China*

[c] *Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113–0033, Japan*

[d] *George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA; Astroparticle Physics Group, Houston Advanced Research Center (HARC), Mitchell Campus, Woodlands, TX 77381, USA; Academy of Athens, Division of Natural Sciences, Athens 10679, Greece*

[e] *William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

ABSTRACT

We analyze the possible magnitude of the supersymmetric contribution to $g_\mu - 2$ in a flipped SU(5) GUT model. Unlike other GUT models which are severely constrained by universality relations, in flipped SU(5) the U(1) gaugino mass and the soft supersymmetry-breaking masses of right-handed sleptons are unrelated to the other gaugino, slepton and squark masses. Consequently, the lightest neutralino and the right-handed smuon may be light enough to mitigate the discrepancy between the experimental measurement of $g_\mu - 2$ and the Standard Model calculation, in which case they may be detectable at the LHC and/or a 250 GeV e^+e^- collider, whereas the other gauginos and sfermions are heavy enough to escape detection at the LHC.

July 2021

Input GUT parameters (masses in units of 10^{16} GeV)		
$M_{GUT} = 1.00$	$M_X = 0.79$	$V = 1.13$
$\lambda_4 = 0.1$	$\lambda_5 = 0.3$	$\lambda_6 = 0.001$
$g_5 = 0.70$	$g_X = 0.70$	$m_{\nu_3} = 0.05$ eV
Input supersymmetry parameters (masses in GeV units)		
$M_5 = 2460$	$M_1 = 240$	$\mu = 4770$
$m_{10} = 930$	$m_{\overline{5}} = 450$	$m_1 = 0$
$M_A = 2100$	$A_0/M_5 = 0.67$	$\tan\beta = 35$
MSSM particle masses (in GeV units)		
$m_\chi = 84$	$m_{\tilde{t}_1} = 4030$	$m_{\tilde{g}} = 5090$
$m_{\chi_2} = 2160$	$m_{\chi_3} = 5080$	$m_{\chi_4} = 5080$
$m_{\tilde{\mu}_R} = 101$	$m_{\tilde{\mu}_L} = 1600$	$m_{\tilde{\tau}_1} = 1010$
$m_{\tilde{q}_L} = 4470$	$m_{\tilde{d}_R} = 4250$	$m_{\tilde{u}_R} = 4170$
$m_{\tilde{t}_2} = 4410$	$m_{\tilde{b}_1} = 4170$	$m_{\tilde{b}_2} = 4400$
$m_{\chi^\pm} = 2160$	$m_{H,A} = 2100$	$m_{H^\pm} = 2100$
Other observables		
$\Delta a_\mu = 150 \times 10^{-11}$	$\Omega_\chi h^2 = 0.13$	$m_h = 122$ GeV
Normal-ordered ν masses:	$\tau_{p\to e^+\pi^0}\vert_{\rm NO} = 4.6 \times 10^{35}$ yrs	$\tau_{p\to \mu^+\pi^0}\vert_{\rm NO} = 4.7 \times 10^{36}$ yrs
Inverse-ordered ν masses:	$\tau_{p\to e^+\pi^0}\vert_{\rm IO} = 1.4 \times 10^{37}$ yrs	$\tau_{p\to \mu^+\pi^0}\vert_{\rm IO} = 9.8 \times 10^{35}$ yrs

Table 1: *Parameters and predictions of an FSU(5) point that yields* $\Delta a_\mu = 150 \times 10^{-11}$.

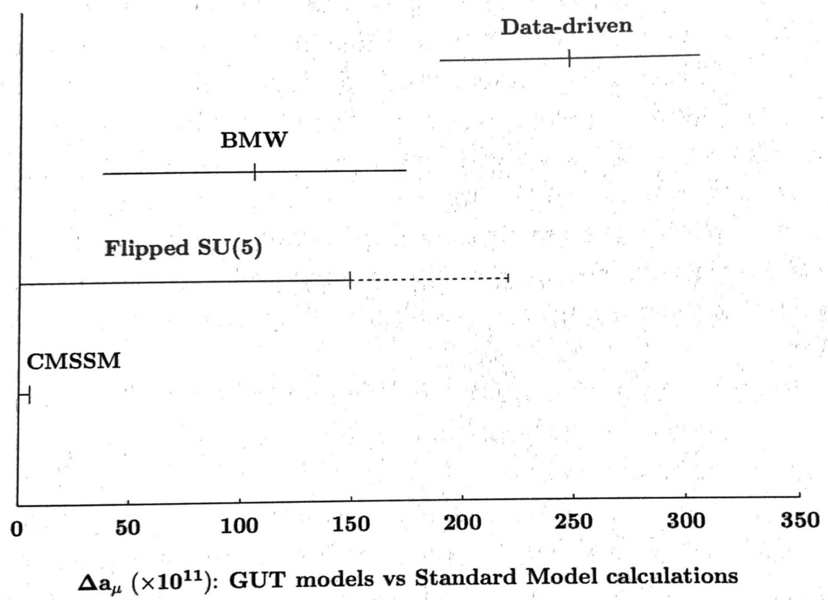


Figure 3: *Comparison of the ranges of the discrepancy in a_μ between the combination of the BNL and Fermilab measurements with the data-driven estimate taken from the Theory Initiative [4] (green line), from the BMW lattice calculation [17] (black range), and the ranges found in flipped SU(5) in this paper (red range, general region shown as solid line, extension in exceptional region shown dashed) and in the CMSSM [9] (blue range).*

to fall quite close to the range of cold dark matter density favoured by Planck [35] and other

I.Antoniadis, D.V. Nanopoulos and J. Rizos

- ~~Inspired~~ → Derived
- Superstring derived SUSY Flipped SU (5)
- FULL CALCULABILITY OF THE EFFECTIVE NO-SCALE SUPERGRAVITY THEORY…!!

Around the fermionic vacuum (all string moduli fixed).

- “REVAMPED” MODEL AEHN/1989

Very Successful Particle Physics Phenomenology

NEW!

Accommodates R^2/ Inflation

i) $F_4 F_5$ bar ϕ_3

ii) Inflaton : $y=\phi_0=\sin\omega\ \phi_3 - \cos\omega\ \phi_3$ bar

$\tan\omega = \phi_4 / \phi_4$ bar

i) Goldstino: $z=\Phi_4$

$$W_I = \zeta^4 \Phi_4 \left(\frac{\gamma}{g_s \sqrt{2\alpha'}} \phi_0 + \delta \zeta \phi_0^2 \right) ,$$

WITH

$$M_I = \zeta^4 \frac{\gamma}{g_s} \frac{1}{\sqrt{2\alpha'}} \simeq \zeta^4 C_6 \cos\omega \frac{1}{\sqrt{2\alpha'}}$$

A Model of Everything

Flipped

Almost

Below the Planck Scale

- Starobinsky-like inflation can be embedded within flipped SU(5)×U(1) model
- Inflaton coupling to neutrinos preferred for baryogenesis – implications for neutrino masses
- Prefer strong reheating after inflation for same reason
- Example how inflation can connect string theory (no-scale supergravity, GUT derived from string) with particle physics accessible to experiment (neutrinos, dark matter, proton decay, LHC, …)

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331


THANK YOU
VERY MUCH

From R^2 Gravity to No-Scale Supergravity

J.Ellis, D.Nanopoulos & K.Olive, *arXiv:1711.11051*

- Pure R^2 gravity $\mathcal{A} = \frac{1}{2}\int d^4x\sqrt{-g}\alpha R^2$
- Is conformally equivalent to De Sitter model

$$\mathcal{A} = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left(\mu^2\tilde{R} - \partial^\mu\phi\partial_\mu\phi - \frac{\mu^4}{4\alpha}\right)$$

- Starobinsky model also has linear R term

$$\mathcal{A} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left(R + \tilde{\alpha}R^2\right)$$

- **Equivalent to SU(1,1)/U(1) no-scale**
- Can introduce conformally-coupled scalars:

$$\mathcal{A} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left[\delta R + \tilde{\alpha}R^2 - 2\kappa^2\sum_{i=1}^{N-1}\left(\partial^\mu\phi^i\partial_\mu\phi_i^\dagger + \frac{1}{3}|\phi^i|^2 R\right)\right]$$

- **Equivalent to generalized no-scale model**