A Model Of EveryThing (MOET)

Flipped

Almost

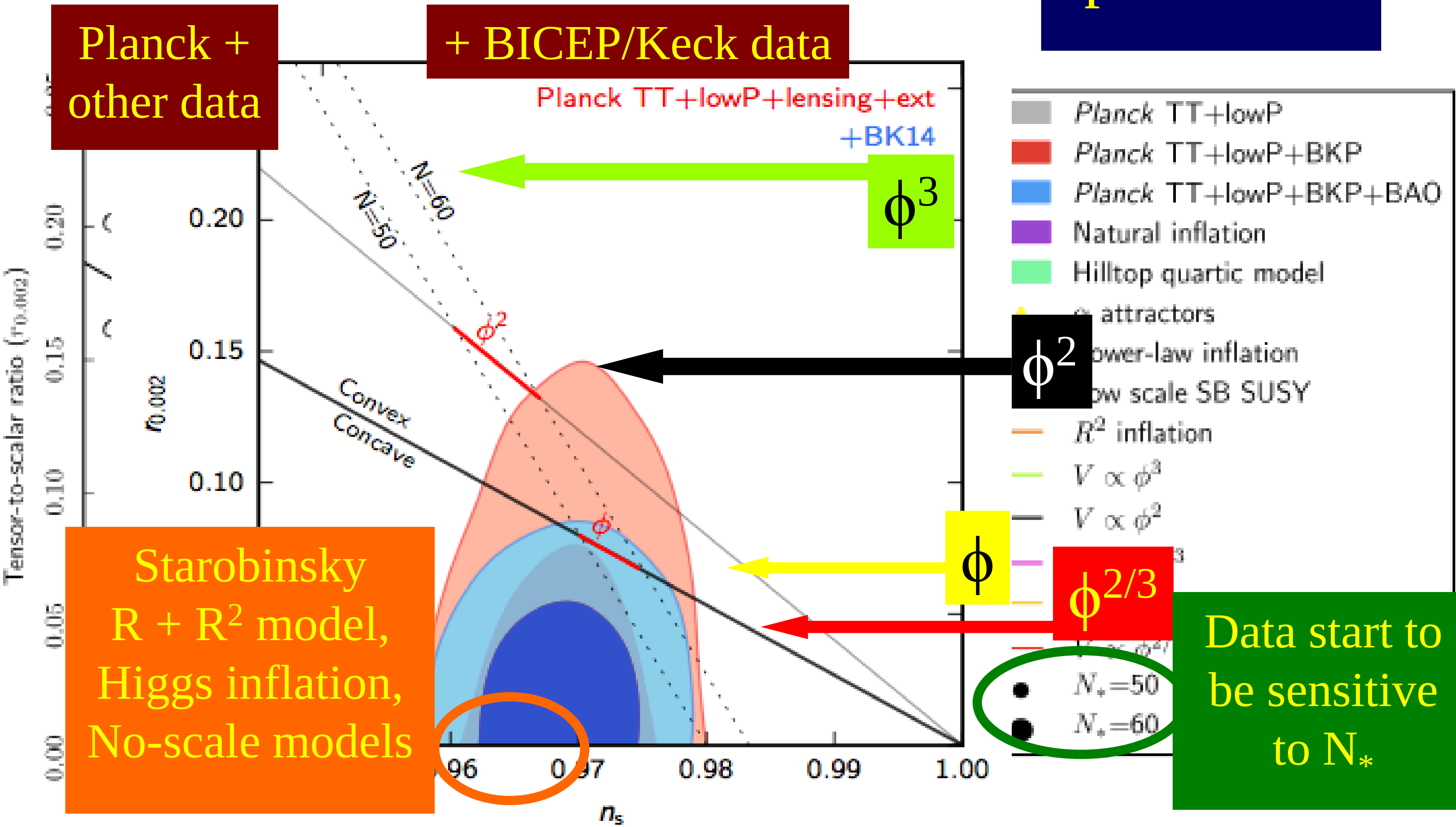
Below the Planck Scale

- 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

Inflationary Landscape

Monomial Single-field potentials



R+R^2 Inflation

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)\,,$$

Starobinsky

where M ≪ M_P

With $\tilde{g}_{\mu\nu} = (1 + \varphi/3M^2)g_{\mu\nu}$

and $\varphi' = \sqrt{\frac{3}{2}}\ln\left(1 + \frac{\varphi}{3M^2}\right)$

conformally equivalent to:

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

$$V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2$$

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

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.

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

JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

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.)

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

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

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

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

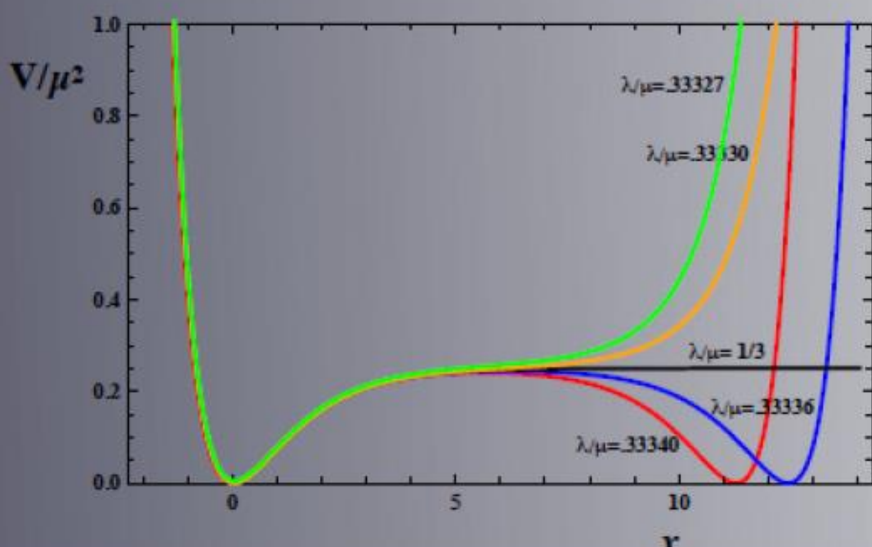
The potential becomes:

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

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

For λ=μ/3, this is exactly the R + R² potential

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



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

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**

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:

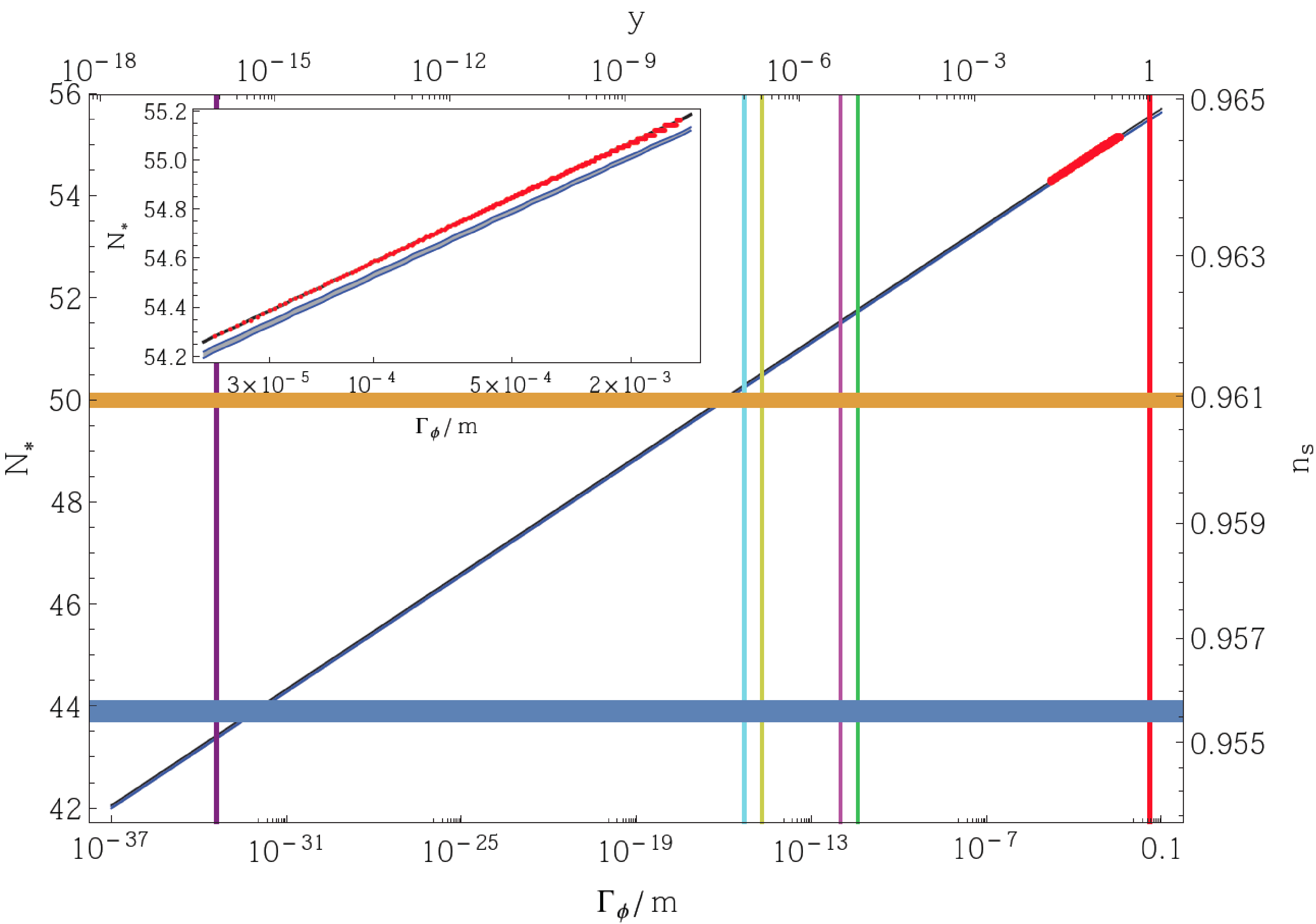
Amplitude of perturbations

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

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

Flipped SU(5)×U(1) GUT Model

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

- Fields:
  - Matter:
    $$F_i = (\mathbf{10}, 1)_i \ni \{d^c, Q, \nu^c\}_i$$
    $$\bar{f}_i = (\bar{\mathbf{5}}, -3)_i \ni \{u^c, L\}_i \, ,$$
    $$\ell^c_i = (\mathbf{1}, 5)_i \ni \{e^c\}_i \, ,$$
  - Higgs:
    $$H = (\mathbf{10}, 1) \, , \quad \bar{H} = (\overline{\mathbf{10}}, -1) \, , \quad h = (\mathbf{5}, -2) \, , \quad \bar{h} = (\bar{\mathbf{5}}, 2) \, ,$$
  - Singlets: $\phi_a = (\mathbf{1}, 0), \ a = 0, \dots, 3.$
- 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: $D^a D^a = \left(\frac{3}{10} g_5^2 + \frac{1}{80} g_X^2 \right) \left(|\tilde{\nu}^c_i|^2 + |\tilde{\nu}^c_H|^2 - |\tilde{\nu}^c_{\bar{H}}|^2 \right)^2$
- 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: $\tau_p = 4.6 \times 10^{35} \times \left(\frac{M_{32}}{10^{16}\ \mathrm{GeV}} \right)^4 \times \left(\frac{0.0374}{\alpha_5(M_{32})} \right)^2$ yrs

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

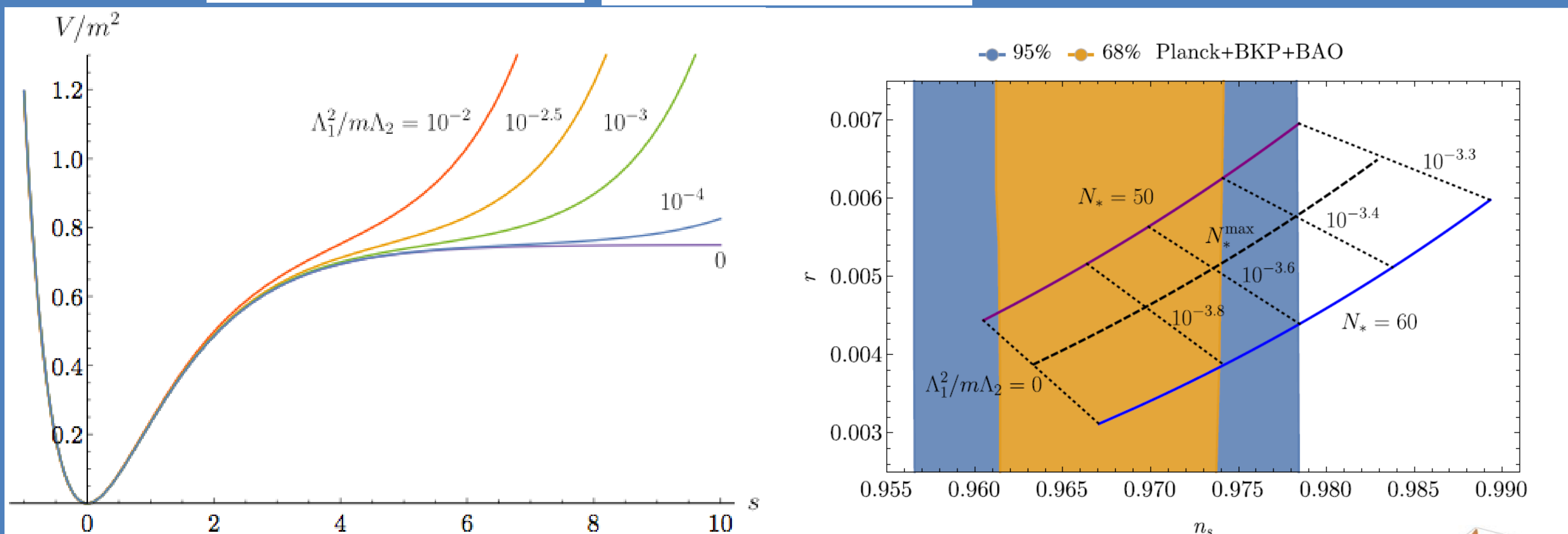
$$V_F \simeq \frac{3}{4}m^2\left(1 - e^{-\sqrt{2/3}\,s}\right)^2 + \frac{3}{4}\sinh^2(\sqrt{2/3}\,s)\sum_i |\lambda_6^{i0}|^2\left(|\tilde{\nu}_{\bar{H}}^c|^2 + |\tilde{\nu}_i^c|^2\right)$$
$$+ \frac{1}{8}m^2 e^{\sqrt{2/3}s}\left(|\tilde{\nu}_{\bar{H}}^c|^2 + \sum_i |\tilde{\nu}_i^c|^2\right) + \cdots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

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

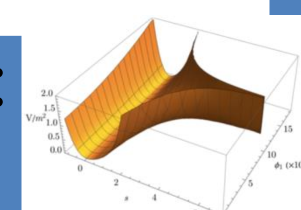
Starobinsky-Like Inflation in Scenario (2)

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

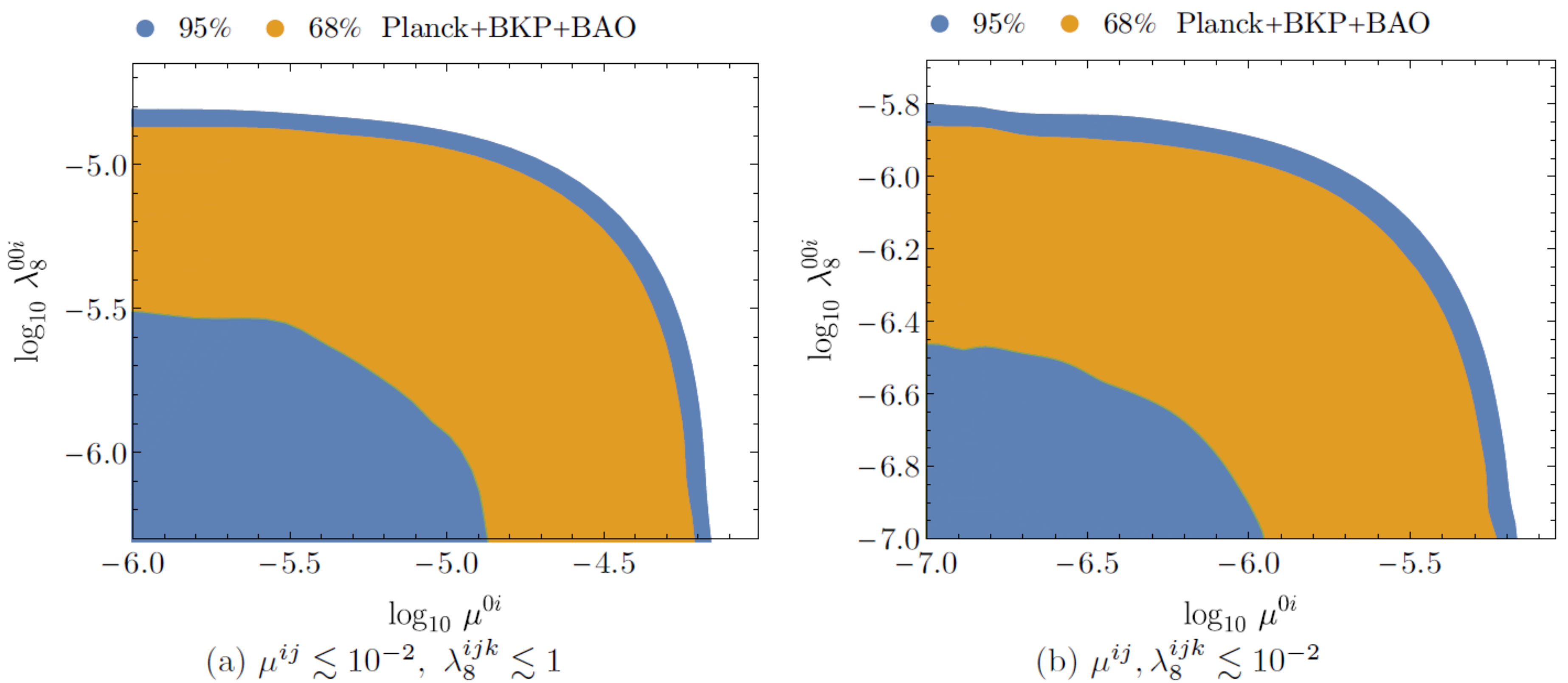


- Multi-field effects not a problem, steep valley:



Full Numerical Calculations

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



- Constraints including numerical calculations of evolution of inflaton and other scalar fields

Neutrino Masses & Mixing

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

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

- 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 $|y| < 2.7 \times 10^{-5} \left(1 + 0.56 \frac{m_{1/2}^2}{m_{3/2}^2}\right)^{-1} \left(\frac{100\,\mathrm{GeV}}{m_{\mathrm{LSP}}}\right)$
- With entropy factor Δ, if inflaton couples to neutrinos:

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

- Normal neutrino mass hierarchy preferred

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

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

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

- Weak or strong reheating? Much much extra entropy?

Entropy Release & Baryogenesis

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

- Entropy release

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

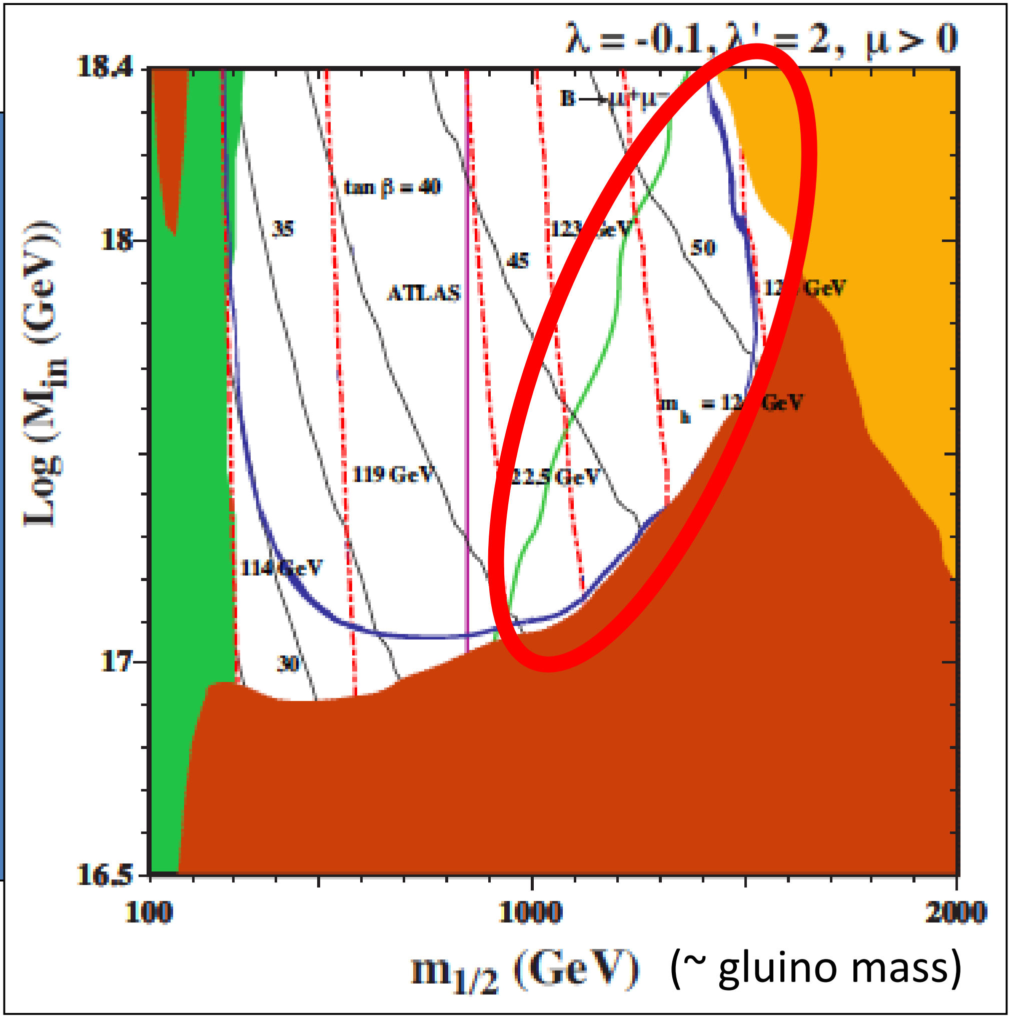
- Relaxes gravitino production constraint, little effect on number of inflationary e-folds: $\Delta N_*^{\rm max} \simeq -4\times 10^{-3}\ln\Delta$
- Standard leptogenesis if inflaton couples to neutrinos:

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

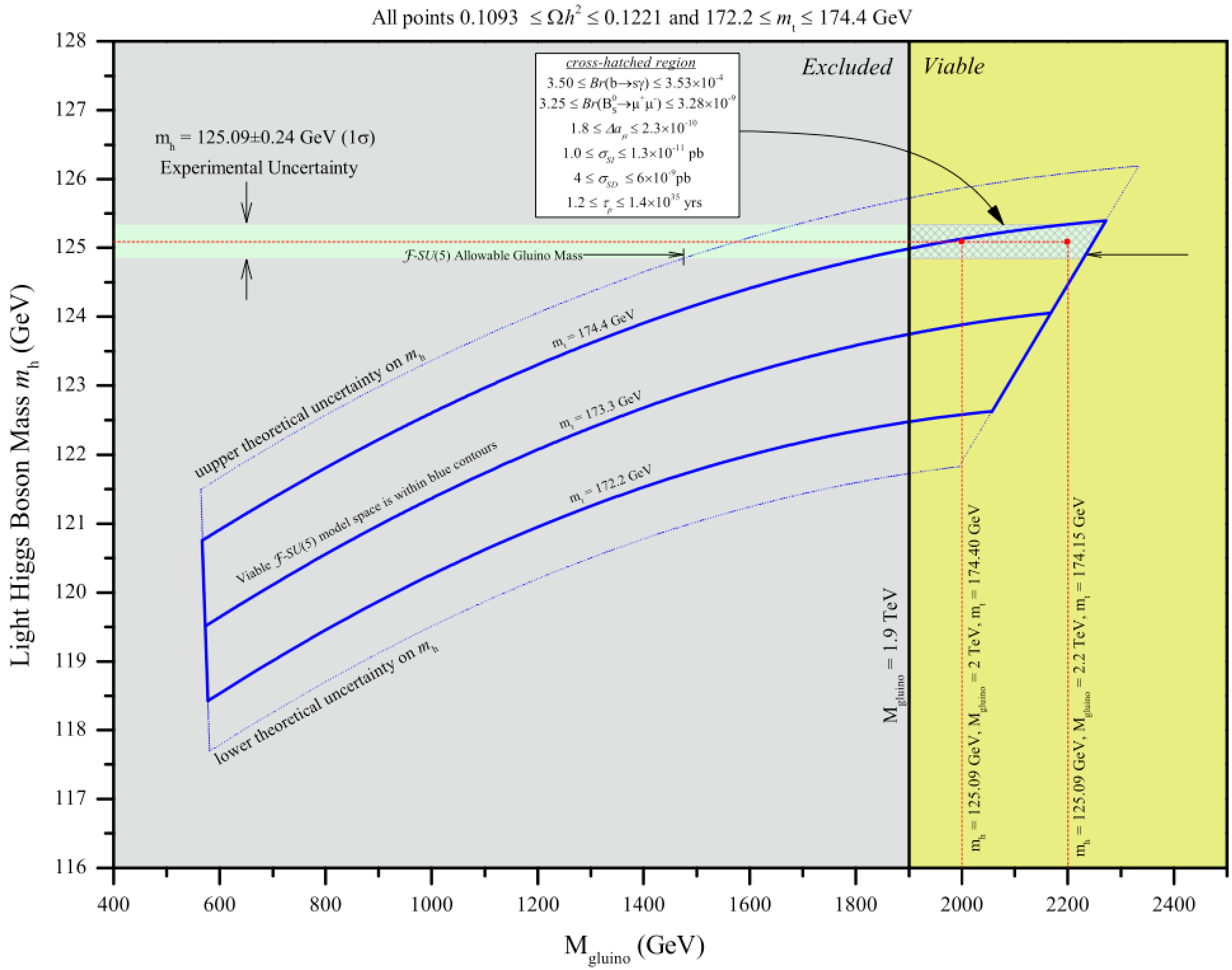
$$\boxed{\frac{n_B}{s} \simeq 3.8\times 10^{-11}}\,\delta f\lambda^2_{1,2,3,7}\lambda_6^{-2}\left(\frac{43/4}{g_{d\Phi}}\right)^{1/4}\left(\frac{915/4}{g_{\rm reh}}\right)^{1/4}\left(\frac{g_{\rm dec}}{915/4}\right)\left(\frac{y}{10^{-5}}\right)$$
$$\times\left(\frac{5\times 10^{15}\,{\rm GeV}}{\langle\Phi\rangle}\right)^2\left(\frac{m^2_{F,\bar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

No-Scale Framework for Particle Physics & Dark Matter

- Incorporating **LHC constraints**, **Higgs mass**, **flavour**, **supersymmetric dark matter**, Starobinsky-like inflation, leptogenesis, neutrino masses, …



JE, Nanopoulos & Olive, arXiv:1310.4770


All points $0.1093 \leq \Omega h^2 \leq 0.1221$ and $172.2 \leq m_t \leq 174.4$ GeV
cross-hatched region
$3.50 \leq Br(b\to s\gamma) \leq 3.53\times10^{-4}$
$3.25 \leq Br(B_s^0\to\mu^+\mu^-) \leq 3.28\times10^{-9}$
$1.8 \leq \Delta a_\mu \leq 2.3\times10^{-10}$
$1.0 \leq \sigma_{SI} \leq 1.3\times10^{-11}$ pb
$4 \leq \sigma_{SD} \leq 6\times10^{-9}$ pb
$1.2 \leq \tau_p \leq 1.4\times10^{35}$ yrs
Excluded
Viable
$m_h = 125.09\pm0.24$ GeV (1σ)
Experimental Uncertainty
$\mathcal{F}$-$SU(5)$ Allowable Gluino Mass
uupper theoretical uncertainty on m_h
$m_t = 174.4$ GeV
$m_t = 173.3$ GeV
$m_t = 172.2$ GeV
Viable $\mathcal{F}$-$SU(5)$ model space is within blue contours
lower theoretical uncertainty on m_h
$M_{gluino} = 1.9$ TeV
$m_h = 125.09$ GeV, $M_{gluino} = 2$ TeV, $m_t = 174.40$ GeV
$m_h = 125.09$ GeV, $M_{gluino} = 2.2$ TeV, $m_t = 174.15$ GeV
Light Higgs Boson Mass m_h (GeV)
M_{gluino} (GeV)

Flipped A Almost Model of Everything 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