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Inflation From The MSSM. N=1 Supergravity Setup

Based on works:

Phys. Rev. D101, no.5, 055027 (2020)

Phys. Rev. D100, no.9, 095027 (2019)

Alternative Gravities and Fundamental Cosmology

September 6--10, 2021

Outline

- Some motivations

- Inflation from MSSM - model

  sketch of construction, infl. Potential, properties etc.

- Details of inflation –

  spectral properties, reheating

  some implication(s)

- Summary

  outlook

Aim: **See if MSSM can accommodate Inflation (compatible with recent data)**

- **With only MSSM couplings involved in the inflation process**

- **Predictions?**

Note: ***In most cases inflaton is SM singlet -> unknown mass scale(s), couplings...***

- In works inflation with MSSM states along D-flat directions (but with extra higher order terms) considered:

R. Allahverdi, K. Enqvist, J. Garcia-Bellido and A. Mazumdar, PRL 97, 191304 (2006);

R. Allahverdi, B. Dutta and A. Mazumdar, PRD 75, 075018 (2007)

Summary of the Results

Within the MSSM:

- Inflation is built. Inflaton -- combination of the Higgs, slepton and squark states.

- Fields along flat D-term trajectory & inflation is driven by the electron Yukawa superpotential.

- MSSM parameter $\tan\beta \simeq 13$ is fixed.

Model Gives: (good agreement with data)

$$n_s = 0.9662, \quad r = 0.00118, \quad \frac{dn_s}{d\ln k} = -5.98 \cdot 10^{-4}$$

$$N_e^{\rm inf} = 57.74, \quad \rho_{\rm reh}^{1/4} = 2.61 \cdot 10^7 \text{GeV},$$

$$T_r = 1.35 \cdot 10^7 \text{GeV}.$$

Summary of the Results

- **All parameters involved in the inflation & reheating are known -> model is very predictive.**

→ Close connection established between the particle physics model and inflationary cosmology.

Modeling inflation:

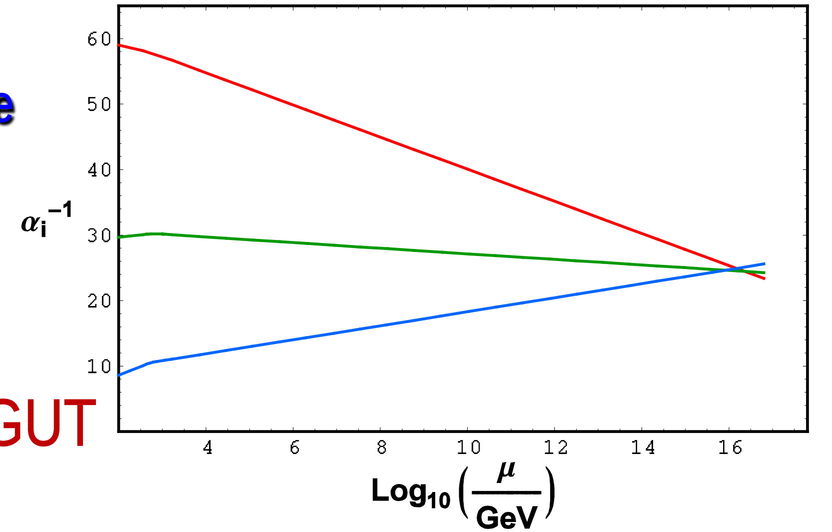
- Self consistent UV completion is important

- Symmetries may play crucial role (for potential flatness):
  SUSY, shift symmetries?

SUSY can guarantee Flatness & consisteny

Motivations for SUSY →

- **Stab. Hierarchy (Light Higgs) ← low SUSY scale**
- **MSSM → Dark Matter Candidate (LSP)**
- **Successful Coupling Unification --** good for GUT



The Setup: MSSM

MSSM States:

$$\Phi_I = \{(q, u^c, d^c, l, e^c)_\alpha, h_u, h_d\}, \quad \alpha = 1, 2, 3 \quad \text{(Chiral superfields)}$$

$$V_G = \{V_Y, V_{SU(2)}, V_{SU(3)}\} \qquad \text{(Vector superfields)}$$

MSSM Superpotential:

$$W_{\text{MSSM}} = e^c Y_E l h_d + q Y_D d^c h_d + q Y_U u^c h_u + \mu h_u h_d.$$

Basis:

$$Y_E = Y_E^{\text{Diag}} = \text{Diag}(\lambda_e, \lambda_\mu, \lambda_\tau), \qquad Y_D = Y_D^{\text{Diag}}, \; Y_U = V_{CKM}^T Y_U^{\text{Diag}}$$

Scalar Potential:

$$V = V_F + V_D$$

N=1 SUGRA (local SUSY)

$$V_F = e^{\mathcal{K}} \left(D_{\bar{J}} \bar{W} \mathcal{K}^{\bar{J}I} D_I W - 3|W|^2 \right) \qquad D_I W = \left(\frac{\partial}{\partial \Phi_I} + \frac{\partial \mathcal{K}}{\partial \Phi_I} \right) W$$

In our case: $V_D = 0$ (Flat D-terms)

Choice of the Kahler potential K:

canonical form $\mathcal{K} \to \sum_I \Phi_I^\dagger e^{-V} \Phi_I$

Let's Make selection:

$$\mathcal{K} = -\ln(1 - \sum_I \Phi_I^\dagger e^{-V} \Phi_I)$$

In small fields' limit

$$\Phi_I \ll 1 \qquad \mathcal{K} \to \sum_I \Phi_I^\dagger e^{-V} \Phi_I$$

Field Configuration: Along Flat D-terms

$$V_D = \frac{g_1^2}{8}\mathcal{D}_Y^2 + \frac{g_2^2}{2}(\mathcal{D}^i_{SU(2)})^2 + \frac{g_3^2}{2}(\mathcal{D}^a_{SU(3)})^2.$$

$$\begin{aligned} D_Y &= |h_d|^2 - |h_u|^2 - 2|\tilde{e}^c_\alpha|^2 + |\tilde{l}_\alpha|^2 \\ &\quad -\tfrac{1}{3}|\tilde{q}_\alpha|^2 + \tfrac{4}{3}|\tilde{u}^c_\alpha|^2 - \tfrac{2}{3}|\tilde{d}^c_\alpha|^2 \ , \\ D^i_{SU(2)} &= \tfrac{1}{2}\left(h^\dagger_d \tau^i h_d - h^\dagger_u \tau^i h_u + \tilde{l}^\dagger_\alpha \tau^i \tilde{l}_\alpha + \tilde{q}^\dagger_\alpha \tau^i \tilde{q}_\alpha\right) \\ D^a_{SU(3)} &= \tfrac{1}{2}\left(\tilde{q}^\dagger_\alpha \lambda^a \tilde{q}_\alpha - \tilde{u}^{c\dagger}_\alpha \lambda^a \tilde{u}^c_\alpha - \tilde{d}^{c\dagger}_\alpha \lambda^a \tilde{d}^c_\alpha q_\alpha\right) . \end{aligned}$$

There are numerous Flat D-term configurations

Consider: $e^c l q u^c$ **-type flat direction**

→ No runaway directions / instabilities for Inflaton potential

$$\langle \tilde{e}^c_1 \rangle = z, \quad \langle h_d \rangle = \begin{pmatrix} z c_\theta \\ 0 \end{pmatrix}, \quad \langle \tilde{l}_2 \rangle = \begin{pmatrix} z s_\theta \\ 0 \end{pmatrix} \begin{array}{c} \uparrow \\ SU(2)_L \\ \downarrow \end{array}$$

$$\langle \tilde{q}_1 \rangle = \begin{array}{c} \leftarrow SU(3)_c \rightarrow \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & z \end{pmatrix} \end{array} \begin{array}{c} \uparrow \\ SU(2)_L \\ \downarrow \end{array}$$

$$\langle \tilde{u}^c \rangle = \begin{pmatrix} 0, & 0, & z c_\varphi \end{pmatrix},$$
$$\langle \tilde{t}^c \rangle = \begin{pmatrix} 0, & 0, & z s_\varphi e^{i\omega} \end{pmatrix},$$

z-mainly inflaton d.o.f

Inflaton Potential

Only one non − vanishing F − term:

$$F^*_{e^-} = -\lambda_e z^2 c_\theta$$

($\boldsymbol{cos\theta \cong 1}$)

Canonically normalized inflaton $\boldsymbol{\phi}$:

$$z = \frac{1}{2}\tanh(\frac{\phi}{\sqrt{2}})$$

$$\mathcal{V}(\phi) = V_F(\phi) \simeq \frac{\lambda_e^2}{16}\tanh^4(\frac{\phi}{\sqrt{2}})$$

θ, φ, ω **- physical d.o.f & should be stabilized / fixed.**

Indeed, this can be achieved:

$$F_{h_u^{(2)}} = 0 \to V_{ud}\lambda_u c_\varphi + V_{td} e^{i\omega} \lambda_t s_\varphi = 0,$$

$$\omega = \pi + \mathrm{Arg}\left(\frac{V_{ud}}{V_{td}}\right), \ \tan\varphi = \frac{\lambda_u}{\lambda_t}\left|\frac{V_{ud}}{V_{td}}\right| \simeq 3 \cdot 10^{-4}$$

$F_{d^c} = 0$ **satisfied by adding W' [extra superpotential term(s)]**

Two possible cases - (i) and (ii):

$$\text{(i)}\ W' = -\lambda q_1 l_2 d^c.$$

$$\langle F^*_{d^c} \rangle = z^2(-\lambda_d c_\theta + \lambda s_\theta) = 0 \to, \ \tan\theta = \frac{\lambda_d}{\lambda}$$

$$\textbf{(ii)}\ W' = \lambda e_1^c (q_1 l_2 u^c)(q_1 h_d d^c)$$

$$\langle F^*_{d^c} \rangle = z^2 c_\theta (-\lambda_d + \lambda z^4 c_\varphi s_\theta) = 0 \rightarrow s_\theta \simeq \frac{\lambda_d}{\lambda z^4}$$

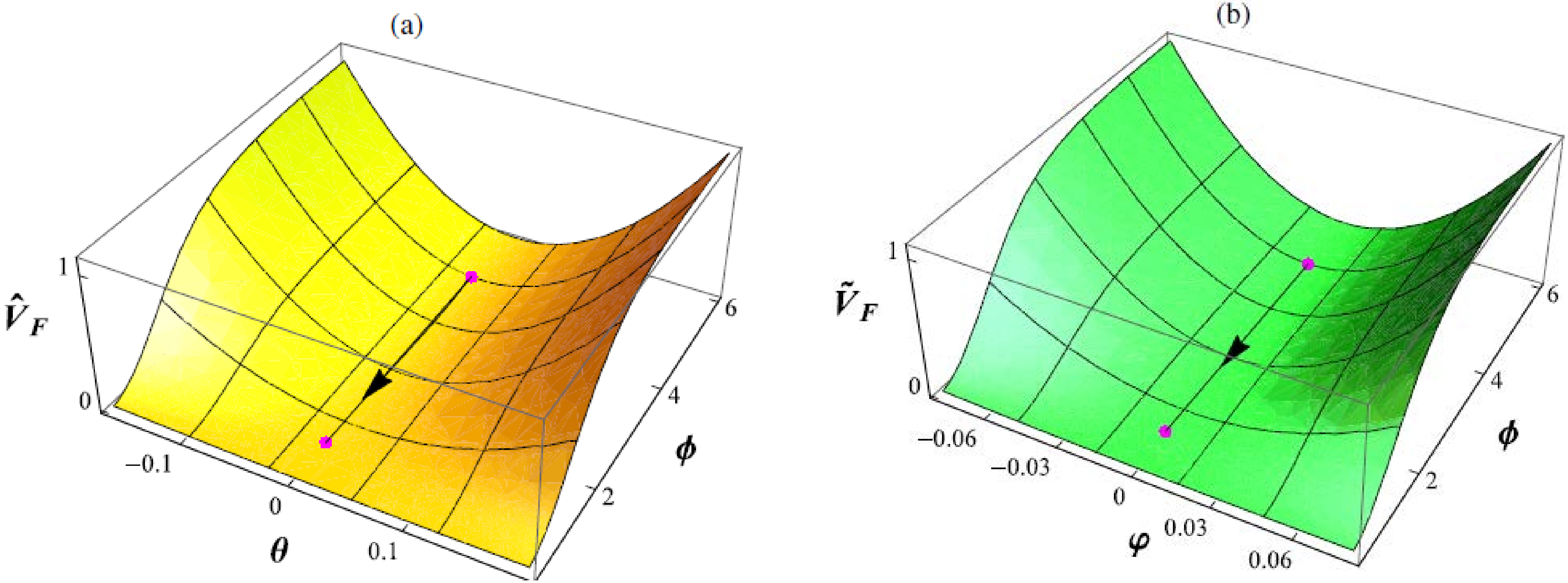
(i) – R-parity violation → Neutrino masses via loops

(ii) - Has no impact for low energy phenomenology..

$$\text{For } \theta < 0.1\ c_\theta \simeq 1 \text{ (considered below)}$$

Obtained for wide range of parameters

Checked Inflaton Potential's stability



(a): Potential's dependance on θ and ϕ. $\hat{V}_F = V_F/(85\lambda_e^2)$ and $\varphi \simeq 3 \cdot 10^{-4}$.
(b): Potential as a function of φ and ϕ. $\tilde{V}_F = V_F/(8\lambda_e^2)$ and $\theta \simeq 0.012$.
Plots corresponds to the case **(i)** and $\omega = \pi + \mathrm{Arg}\left(\frac{V_{ud}}{V_{td}}\right)$. Arrows correspond to the inflaton's path.

All other directions stabilized → consistent construction

Inflation (spectral properties)

$$\mathcal{V}(\phi) = V_F(\phi) \simeq \frac{\lambda_e^2}{16}\tanh^4(\frac{\phi}{\sqrt{2}})$$ -- **Good properties**

$$n_s = 0.9662, \quad r = 0.00118, \quad \frac{dn_s}{d\ln k} = -5.98\cdot 10^{-4}$$

$$N_e^{\rm inf} = 57.74$$

Amplitude of curvature perturbation -

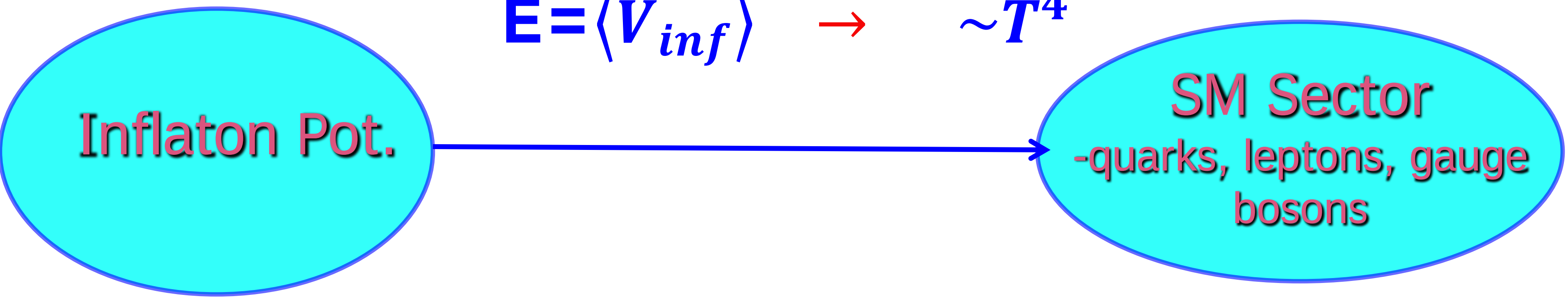
$$A_s^{1/2} = \frac{1}{\sqrt{12}\pi}\left|\frac{\mathcal{V}^{3/2}}{M_{Pl}^3\mathcal{V}'}\right|_{\phi_i} = 4.581\times 10^{-5}$$

$\text{Determines } \mathcal{V}_i \leftrightarrow \lambda_e(M_{Pl}) = 2.435\times 10^{-5}$

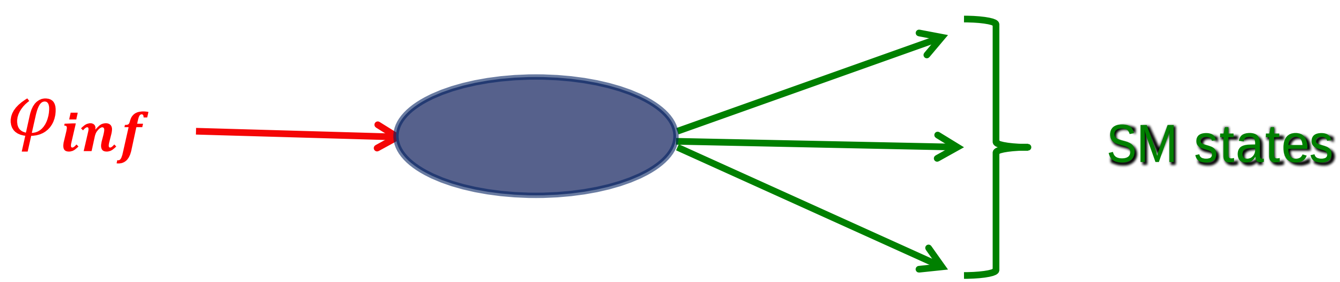
$\rightarrow \tan\beta \simeq 13.12$ **(MSSM parameter fixed)**

Reheating

$$\mathrm{E}=\langle V_{inf}\rangle \quad \rightarrow \quad \sim T^4$$



T_r (reheating temp.)
Via Inflaton decay



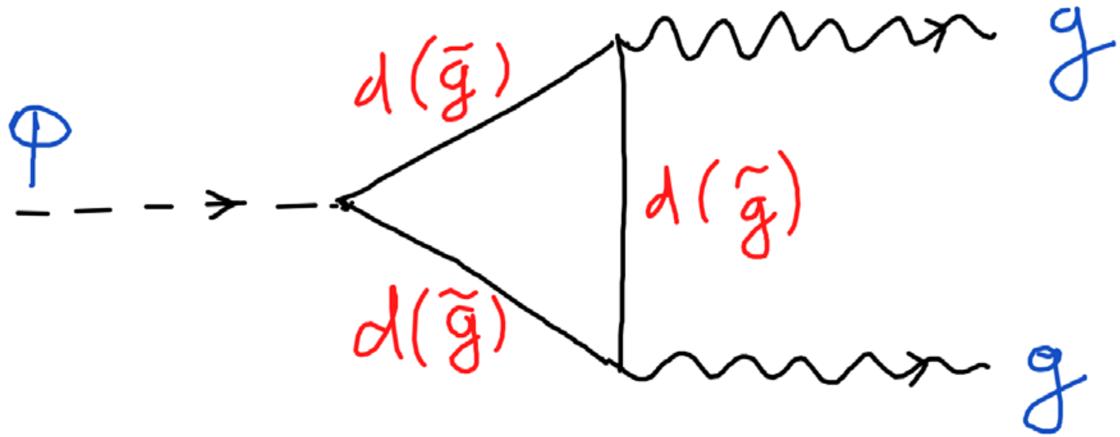
$$T_r = \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{M_{Pl}\Gamma(\phi)}$$

Reheating: Inflaton Decay

Examining all couplings & kinematically allowed channels

Dominant Mode:

$\phi \to gg$



T_r (reheating temp.) Via Inflaton decay

$$\Gamma(\phi) \simeq \Gamma(\phi \to gg) \simeq \frac{m_\phi^3 \alpha_s^2}{48\pi^3} \left(\frac{F'}{F} + \frac{F_g'}{F_g} \right)^2$$

$$\to \quad T_r \simeq 1.35 \cdot 10^7 \mathrm{GeV}$$

$\frac{1}{2} F(\phi) d^T Y_D d^c, \quad F(\phi) = \tanh\frac{\phi}{\sqrt{2}} (1 - \tanh^2\frac{\phi}{\sqrt{2}})^{1/2}$

From gluinos (in loop): $F_g(\phi) = \sinh\frac{\phi}{\sqrt{2}}$

Some Implications: **Neutrino masses**

- If **(i)** $W' = -\lambda q_1 l_2 d^c$ used (for $\mathcal{V}(\phi)$ stability)
  $\rightarrow$ R-parity breaking (L-violation)
  $\rightarrow$ at 1-loop: $\mu_i h_u l_i$ superpotential & soft $B_i h_u \tilde{l}_i$ terms $\rightarrow$

$$\rightarrow m_{\nu_\mu} \approx \frac{\lambda^2 g_2^2}{4c_w^2} \frac{m_d^2}{\tilde{m}} \left(\frac{9}{8\pi^2} \ln \frac{M_{Pl}}{M_Z} \right)^2$$

For $\tilde{m} = 2$ TeV (SUSY scale), $\lambda \lesssim 0.1 \quad \rightarrow \quad m_\nu \lesssim 0.1$ **eV**

- Range $6 \times 10^{-4} \lesssim \lambda \lesssim 0.1 \quad \rightarrow \quad \cos\theta \simeq 1$ (predictive inflation)

- $W' = \lambda q_1 l_2 d^c \rightarrow$ directly 1-loop $\delta m_\nu \sim \frac{3\lambda^2}{8\pi^2} \frac{m_d^2}{\tilde{m}} \lesssim 2 \times 10^{-3}$ eV
  (with $\lambda \lesssim 0.1$)

Good scales for the neutrinos, but would neutrino data (masses & mixings) accommodated? [additional $\bar{\lambda}_{ijk} e_i^c l_j l_k$, $\lambda_{ijk} q_i l_j d_k^c$ terms needed?]

Detailed investigation needed:
Connection between neutrino oscillations & inflation $\leftrightarrow$ Very exciting!

Summary & Outlook

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Summary

- All parameters involved in the inflation & reheating are known -> model is very predictive.

→ Close connection established between the particle physics model and inflationary cosmology.

Outlook, problems/issues to be addressed:

1. Investigate neutrino masses /oscillations (via R-parity viol.)

2. Baryogenesis/Leptogenesis – during inflation B & L are broken

3. GUT embedding [SU(5), SO(10)] – more predictive?

4. What symmetry may support considered Kahler potential? (a'la Kallosh, et al. 2013, 2017 ?)

5. Investigate Other issues /topics [some discussed at this conference]

....

THANK YOU

Backup Slides

Deriving Inflaton Potential

Inflation is due to the F-term potential:

$$V_F = e^{\mathcal{K}} \left(D_{\bar{J}} \bar{W} \mathcal{K}^{\bar{J}I} D_I W - 3|W|^2 \right) , \tag{1}$$

where $D_I W = (\frac{\partial}{\partial \Phi_I} + \frac{\partial \mathcal{K}}{\partial \Phi_I}) W$, $D_{\bar{J}} \bar{W} = (\frac{\partial}{\partial \Phi_J^\dagger} + \frac{\partial \mathcal{K}}{\partial \Phi_J^\dagger}) \bar{W}$;

$\mathcal{K}_{I\bar{J}} = \frac{\partial^2 \mathcal{K}}{\partial \Phi_I \partial \Phi_J^\dagger}$. $\mathcal{K}_{I\bar{M}} \mathcal{K}^{\bar{M}J} = \delta_I^J$.

Considered Kähler potential is:

$$\mathcal{K} = -\ln(1 - \sum_I \Phi_I^\dagger e^{-V} \Phi_I) \ , \tag{2}$$

We consider the following VEV configuration:

$$\langle \tilde{e}^c_1 \rangle = z, \quad \langle h_d \rangle = \begin{pmatrix} z c_\theta \\ 0 \end{pmatrix}, \quad \langle \tilde{l}_2 \rangle = \begin{pmatrix} z s_\theta \\ 0 \end{pmatrix} \begin{array}{c} \uparrow \\ SU(2)_L \\ \downarrow \end{array}$$

$$\begin{array}{cc} & \leftarrow SU(3)_c \rightarrow \\ \langle \tilde{q}_1 \rangle = & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & z \end{pmatrix} \begin{array}{c} \uparrow \\ SU(2)_L \\ \downarrow \end{array} \end{array}$$

$$\begin{aligned} \langle \tilde{u}^c \rangle &= \begin{pmatrix} 0, & 0, & z c_\varphi \end{pmatrix}, \\ \langle \tilde{t}^c \rangle &= \begin{pmatrix} 0, & 0, & z s_\varphi e^{i\omega} \end{pmatrix} \end{aligned} \tag{3}$$

With $\cos\theta \simeq 1$ (fixed), the only non-zero F-term is:

$$F^*_{e^-} = -\lambda_e z^2 \tag{4}$$

giving:

$$V_F = e^{\mathcal{K}} \mathcal{K}^{e^{-\dagger} e^-} |F_{e^-}|^2. \tag{5}$$

The kinetic part, which includes $(\partial z)^2$ is

$$\mathcal{K}_{I\bar{J}} \partial\Phi_I \partial\Phi^*_J \to (\partial V_z)^\dagger \langle \mathcal{K}(z) \rangle \partial V_z, \tag{6}$$

where with (2) and (3) we have:

$$\begin{gathered}
V_z^T = \left(z,\ zc_\theta,\ zs_\theta,\ z,\ zc_\varphi,\ zs_\varphi e^{-i\omega}\right), \\
\langle \mathcal{K}(z) \rangle^T = \tfrac{1}{1-4z^2} \mathbf{1}_{6\times 6} + \tfrac{z^2}{(1-4z^2)^2} \times \\
\begin{pmatrix}
1 & c_\theta & s_\theta & 1 & c_\varphi & s_\varphi e^{-i\omega} \\
c_\theta & c_\theta^2 & c_\theta s_\theta & c_\theta & c_\theta c_\varphi & c_\theta s_\varphi e^{-i\omega} \\
s_\theta & c_\theta s_\theta & s_\theta^2 & s_\theta & s_\theta c_\varphi & s_\theta s_\varphi e^{-i\omega} \\
1 & c_\theta & s_\theta & 1 & c_\varphi & s_\varphi e^{-i\omega} \\
c_\varphi & c_\theta c_\varphi & s_\theta c_\varphi & c_\varphi & c_\varphi^2 & c_\varphi s_\varphi e^{-i\omega} \\
s_\varphi e^{i\omega} & c_\theta s_\varphi e^{i\omega} & s_\theta s_\varphi e^{i\omega} & s_\varphi e^{i\omega} & c_\varphi s_\varphi e^{i\omega} & s_\varphi^2
\end{pmatrix}
\end{gathered} \tag{7}$$

Using (7) in (6) and introducing canonically normalized real scalar ϕ - the inflaton - we obtain

$$\mathcal{K}_{I\bar{J}}\partial\Phi_I\partial\Phi_J^* \to 4\frac{(\partial z)^2}{(1-4z^2)^2} \equiv \frac{1}{2}(\partial\phi)^2. \tag{8}$$

$$\to \;\; z = \frac{1}{2}\tanh(\frac{\phi}{\sqrt{2}}) \;, \tag{9}$$

With these, from (5), we derive the inflaton potential $\mathcal{V}$ to have the form:

$$\mathcal{V}(\phi) = V_F(\phi) \simeq \frac{\lambda_\varepsilon^2}{16}\tanh^4(\frac{\phi}{\sqrt{2}}). \tag{10}$$

Some References

Some earlier works on inflation along D-flat directions by MSSM states (but with extra higher order terms):

R. Allahverdi, K. Enqvist, J. Garcia-Bellido and A. Mazumdar, Phys. Rev. Lett. **97**, 191304 (2006); R. Allahverdi, B. Dutta and A. Mazumdar, Phys. Rev. D **75**, 075018 (2007); For a review and references see: J. Martin, C. Ringeval and V. Vennin, Phys. Dark Univ. **5-6**, 75 (2014).

Inflation with additional singlets by Logarithmic but slightly different Kähler potentials, investigated in works:

R. Kallosh and A. Linde, JCAP **1307**, 002 (2013); R. Kallosh, A. Linde and D. Roest, JHEP **1311**, 198 (2013).

S. Ferrara and R. Kallosh, Phys. Rev. D **94**, no. 12, 126015 (2016); R. Kallosh, A. Linde, T. Wrase and Y. Yamada, JHEP **1704**, 144 (2017).