BACKREACTION OF HEAVY MODULI FIELDS IN INFLATIONARY MODELS

Based on :

- W.Buchmuller, E.D., L.Heurtier and C.Wieck, arXiv:1407.0253 [hep-th], JHEP 1409 (2014) 053.
- W.Buchmuller, E.D., L.Heurtier, A.Westphal, C.Wieck, M. Winkler, arXiv:1501.05812 [hep-th], JHEP 1504 (2015) 058.
- E.D. and C. Wieck, arXiv:1506.01253 [hep-th] .

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Outline

1) Inflation and supergravity

2) Generic constraints from supersymmetry breaking and heavy-fields (moduli) backreaction

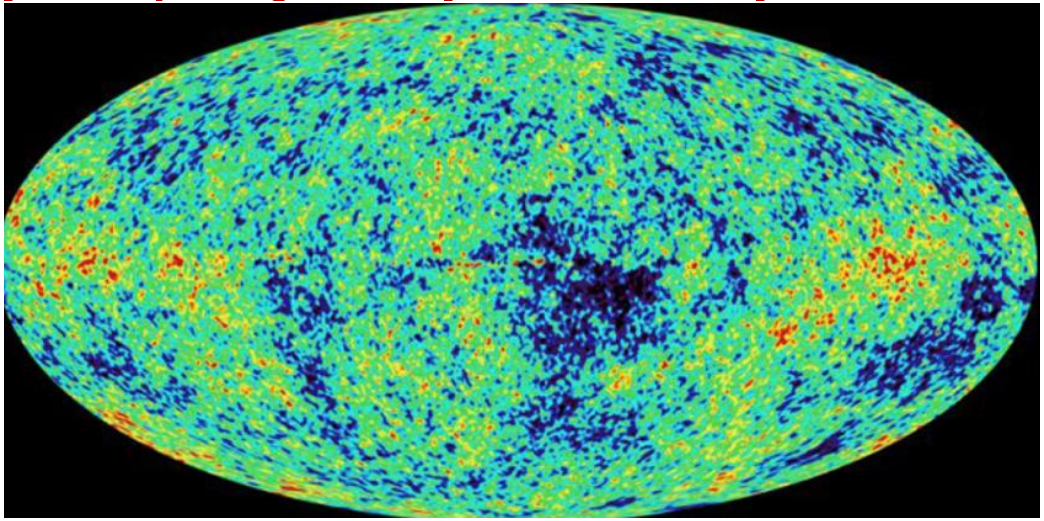
3) Chaotic inflation :
- stabilizer and supersymmetry breaking
- moduli stabilization

4) Plateau models and backreaction

5) Conclusions

1) Inflation and supergravity

Why Supergravity for early cosmology ?



- Inflation with super-Planckian field variations needs an UV completion ⟹ String Theory
- Supersymmetry crucial ingredient in String Theory, supergravity its low-energy effective action

Talks: Blumenhagen,Hebecker,Kallosh,Linde, McAllister, Scalisi, Shiu, Silverstein, Wieck…

- Naively, the simplest chaotic example would be

$$W = \frac{m}{2}\phi^2 \quad , \quad K = \frac{1}{2}(\phi + \bar{\phi})^2$$

where the inflaton is $\varphi = \sqrt{2}\ \mathrm{Im}\ \phi$. This doesn't work, since for large φ the potential is unbounded from below

The problem can be avoided by introducing a « stabilizer » field S, with no shift symmetry (Kawasaki,Yamaguchi,Yanagida)

$$W = mS\phi \quad , \quad K = \frac{1}{2}(\phi + \bar{\phi})^2 + |S|^2 - \xi|S|^4$$

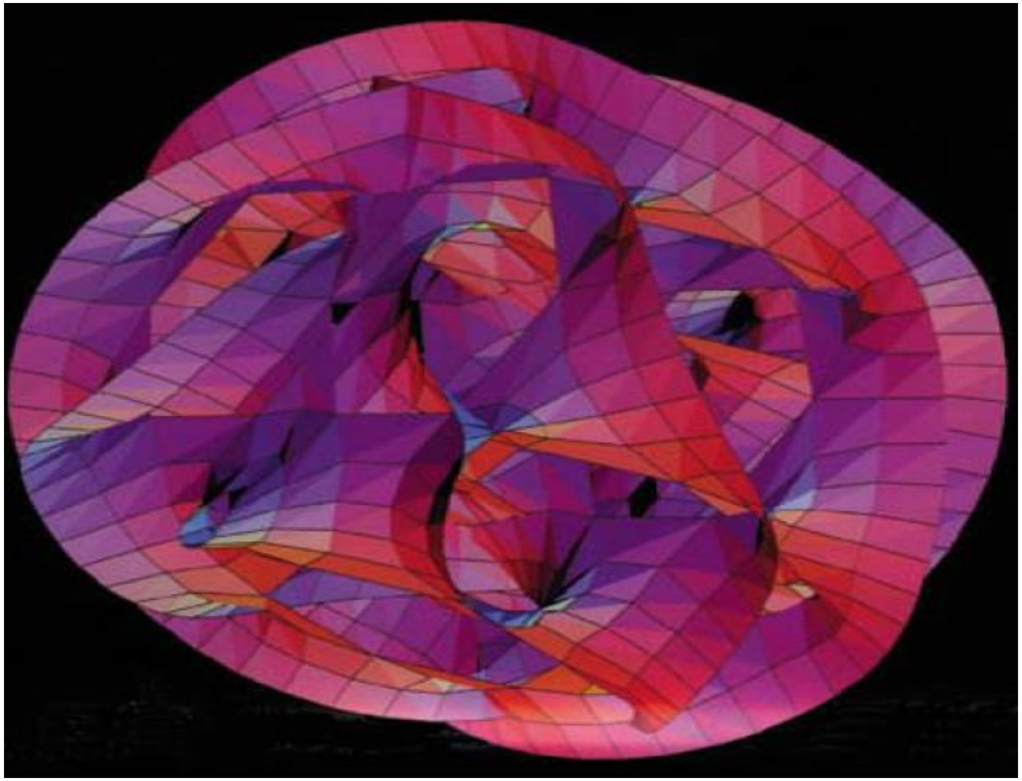
The term in ξ is needed in order to give a large mass to S during inflation.

The model was generalized to (Kallosh,Linde,Rube)

$$W = Sf(\phi)$$

2) Generic constraints from supersymmetry breaking and moduli backreaction

- String theory has (a lot of) scalar moduli fields : dilaton, internal space deformations, D-brane moduli, etc.
Most of them are massless in perturbation theory: needs to make them massive ⇨ moduli stabilization



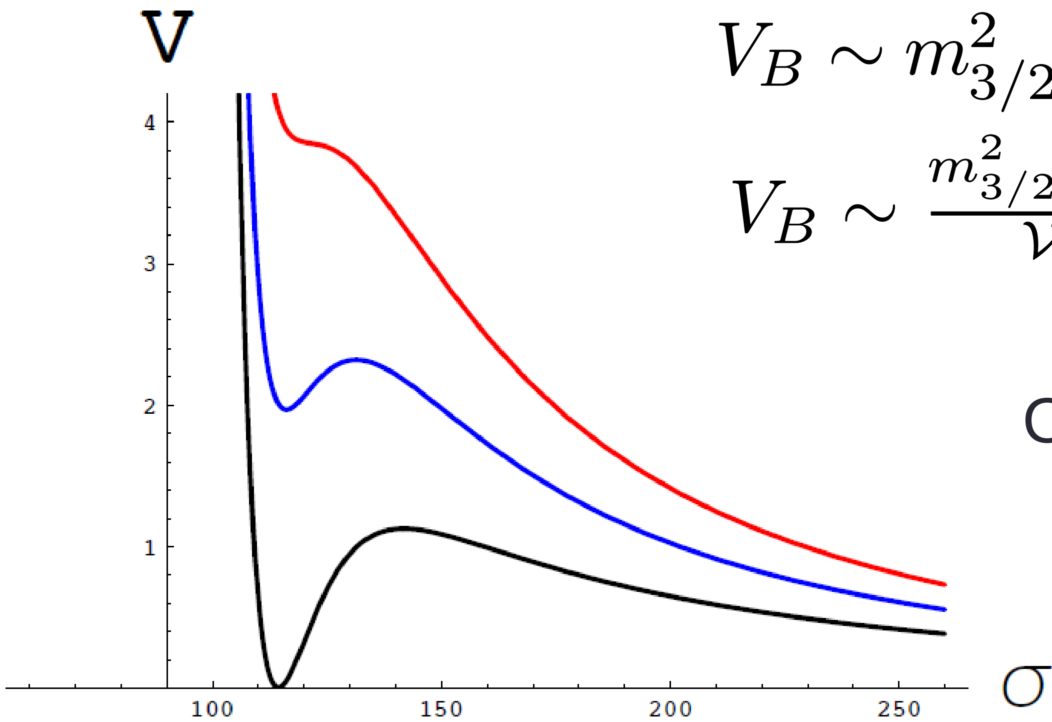
Dictionary:
KKLT = Kachru,Kallosh,Linde,Trivedi
LVS= Large volume scenario
(Conlon,Quevedo +coll.)

- The Kallosh-Linde problem

Traditional mechanisms of moduli stabilization (KKLT,LVS) are compatible with inflation only for very large gravitino mass

$$m_\phi \ll H \lesssim m_{3/2}$$

The reason is the barrier to the runaway



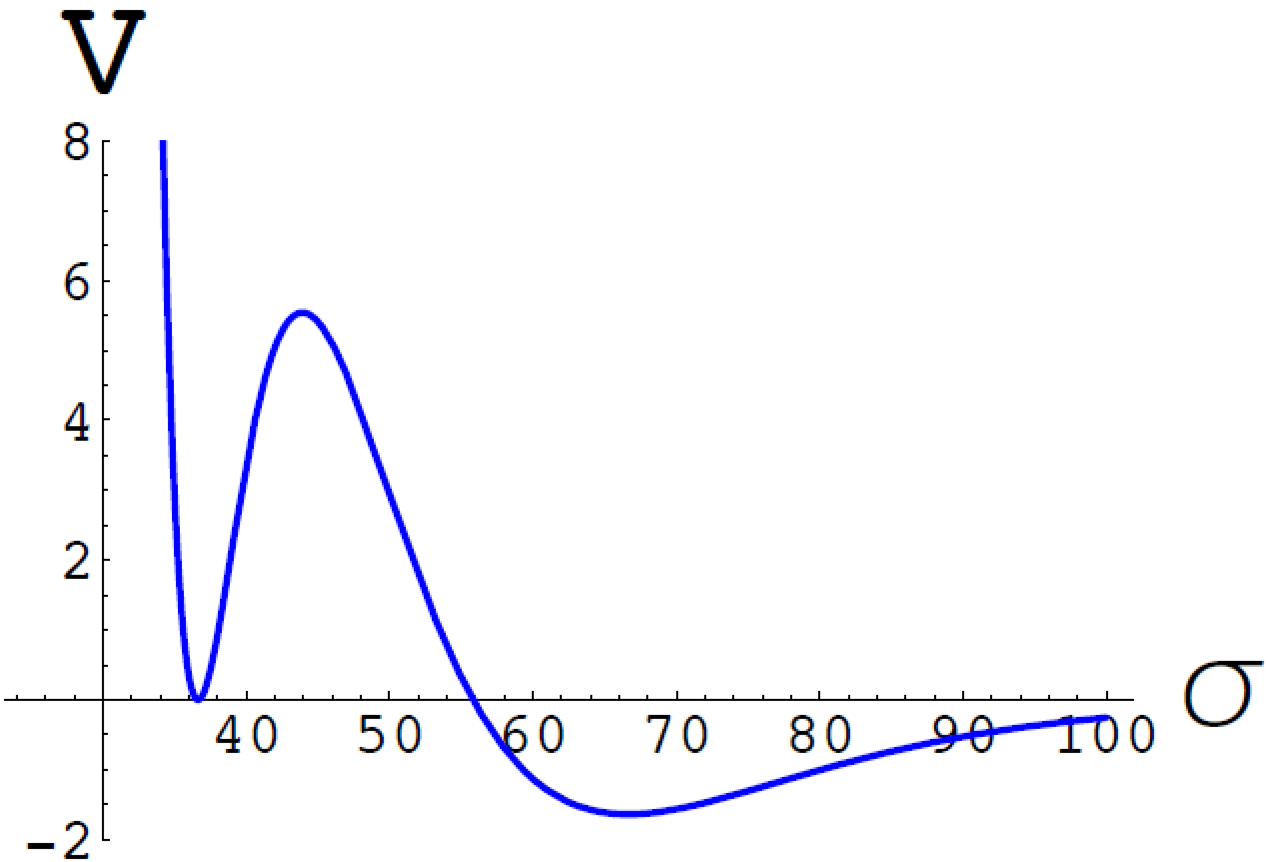
$$V_B \sim m_{3/2}^2 M_P^2 \quad \text{(KKLT)}$$

$$V_B \sim \frac{m_{3/2}^2 M_P^2}{\mathcal{V}} \quad \text{(LVS)}$$

One needs

$$V_{\text{inf}} < V_B$$

The way out is having « strong moduli stabilization » models with a barrier independent on the gravitino mass (KL)



- If moduli are light $m_i < H$, they will directly influence inflation ⇨ multi-field dynamics

- If they are heavy, they can still change dynamics if they participate to SUSY breaking ⇨

non-decoupling effects

Such effects often arise in the process of moduli stabilization.

The discussion and results are different for models :
- with stabilizer (large $W_{\rm inf}(\Phi)$)
- without stabilizer (small $W_{\rm inf}(\Phi)$)

With stabilizer : generic structure

$$K = K(\Phi + \overline{\Phi}, S, \bar{S}, X, \bar{X}, T_\alpha, \overline{T}_\alpha)$$

$$W = MSf(\Phi) + W_1(X, T_\alpha) \, ,$$

inflaton part

modulus + SUSY breaking

SUSY breaking is generating a mixing stabilizer/inflaton

$$V_{\text{soft}} = m_{3/2}(\text{Re S}f_1(\phi) + \text{Im S}f_2(\phi))$$

which forces stabilizer to « track » inflaton trajectory

This generates a backreaction on inflaton potential (talk Wieck)

$$V_{\mathrm{eff}}(\phi) = V_{\mathrm{inf}}(\phi) - m_{3/2}^2 \frac{f_1^2(\phi) + f_2^2(\phi)}{M_S^2(\phi)}$$

Stabilizer mass during inflation

- Without stabilizer : generic structure

$$K = K_0(T_\alpha, \overline{T}_\alpha) + K_1(\Phi + \overline{\Phi}, X, \bar{X}, T_\alpha, \overline{T}_\alpha)$$

$$W = W_{\rm inf}(\Phi) + W_1(X, T_\alpha)\,.$$

One can treat $W_{\rm inf}$ as a perturbation of moduli potential.
Then:

SUSY inflaton potential

$$V = V_0 + V_1 + V_2$$

Moduli potential (end of inflation) $O(W_{\rm inf})$ $O(W_{\rm inf}^2)$

During inflation moduli fields are displaced from their minimum

$$T_\alpha = T_{0,\alpha} + \delta T_\alpha$$

For $m_\alpha > H$, this can be treated perturbatively :

moduli masses

$$V_0(T_\alpha, \bar{T}_\alpha) \simeq \Lambda_0 + \frac{1}{2}\delta\rho_\alpha M^2_{\alpha\beta}\delta\rho_\beta \ ,$$

$$V_1(T_\alpha, \bar{T}_\alpha, \phi) \simeq V_1(T_{0,\alpha}, \bar{T}_{0,\alpha}, \phi) + \delta\rho_\alpha \frac{\partial V_1}{\partial \rho_\alpha}$$

$$V_2(T_\alpha, \bar{T}_\alpha, \phi) \simeq V_2(T_{0,\alpha}, \bar{T}_{0,\alpha}, \phi) \ ,$$

where $\rho_\alpha = (T_\alpha, \bar{T}_\alpha)$. Then $\delta\rho_\alpha = -M^{-2}_{\alpha\beta}\frac{\partial V_1}{\partial \rho_\beta}$ and

$$V_{\rm eff}(\phi) \simeq V_2(T_{0,\alpha}, \bar{T}_{0,\alpha}, \phi) + V_1(T_{0,\alpha}, \bar{T}_{0,\alpha}, \phi) - \frac{1}{2}\frac{\partial V_1}{\partial \rho_\alpha}M^{-2}_{\alpha\beta}\frac{\partial V_1}{\partial \rho_\beta}$$

Naive terms

Backreaction

Explicit expressions can be found in specific models.
In particular, for

$$K = K_0(T_\alpha, \overline{T}_{\bar{\alpha}}) + \frac{1}{2} K_1(T_\alpha, \overline{T}_{\bar{\alpha}})(\Phi + \overline{\Phi})^2$$

$$W = W_{\rm inf}(\Phi) + W_{\rm mod}(T_\alpha)\,,$$

and « small » SUSY breaking $m_F << m_{3/2}$, one finds

$$\begin{aligned} V(\varphi) = \Lambda_0^4 + e^{K_0} \Big\{ & K_1^{-1} |\partial_\Phi W_{\rm inf}(\Phi)|^2 - 3\,|W_{\rm inf}(\Phi)|^2 \\ & + \Big[\Big(K_0^{\alpha\bar{\beta}} K_{0,\alpha} \overline{D}_{\bar{\beta}} \overline{W}_{\rm mod} - 3 \overline{W}_{\rm mod} \Big) W_{\rm inf}(\Phi) + {\rm h.c.} \Big] \Big\} \\ + e^{\frac{3}{2}K_0} \Big(K_\delta \left(m_F^{-1}\right)^{\beta\delta} \Big\{ & - \Big[K_0^{\epsilon\bar{\epsilon}} (K_{\beta\epsilon} + K_\beta K_\epsilon - \Gamma^\gamma_{\beta\epsilon} K_\gamma) \overline{D}_{\bar{\epsilon}} \overline{W}_{\rm mod} \\ & - 3 K_\beta \overline{W}_{\rm mod} \Big] W^2_{\rm inf}(\Phi) + 2 D_\beta W_{\rm mod} |W_{\rm inf}(\Phi)|^2 \Big\} + {\rm h.c.} \Big) \\ + \mathcal{O}\left(\frac{H^2}{m_T^2} \right)\,, & \end{aligned}$$

3) Chaotic inflation

- stabilizer and supersymmetry breaking

(BDHW, arXiv:1407.0253 [hep-th])

Simplest example: gravity-only interactions between the Polony SUSY breaking sector X and the inflaton sector

$$W = mS\phi + fX + W_0$$

$$K = \frac{1}{2}(\phi + \bar{\phi})^2 + S\bar{S} + X\bar{X} - \xi_1 (X\bar{X})^2 - \xi_2 (S\bar{S})^2$$

During inflation, all fields get a large mass, except the inflaton $\varphi = \sqrt{2}\,\mathrm{Im}\,\phi$. However, $\chi = \sqrt{2}\,\mathrm{Im}\,S$ is shifted due to SUSY breaking.

X=0 in what follows. This is ensured if $\xi_1 > 1$ or imposing the constraint $X^2 = 0$ (talks Kallosh,Linde,Scalisi)

X is heavy and can be effectively integrated out

One finds an effective inflaton potential

$$V(\varphi) = f^2 - 3W_0^2 + \frac{1}{2}m^2\varphi^2\left(1 - \frac{4W_0^2}{W_0^2 + m^2 + 2m^2\varphi^2\xi_2}\right)$$

- When the coeff. of $m^2\varphi^2$ decreases significantly, inflation stops. Inflation stops for a maximal value

$$m^2 < W_{0,max}^2 < H^2 = \frac{2m^2}{3}\varphi^2\xi_2$$

If heavy moduli are added, their stabilization has to be done with « low » gravitino mass and $V_B >> m_{3/2}^2 M_P^2$

Ex: KL $\leftrightarrow$ strong moduli stabilization.

- No stabilizer: Moduli stabilization and inflation

BDHWWW, arXiv:1501.05812 [hep-th]

- If chaotic inflation turns out to be correct (large r), check effects of moduli fields, not to destroy inflation.

- Non decoupling SUSY breaking effects are crucial to cure large field behaviour: inflation is driven by soft mass.

Our starting point is

$$K = K_0(T_\alpha, \overline{T}_{\bar{\alpha}}) + \frac{1}{2} K_1(T_\alpha, \overline{T}_{\bar{\alpha}})(\phi + \bar{\phi})^2$$

$$W = W_{\rm mod}(T_\alpha) + \frac{1}{2} m \phi^2 \, .$$

After decoupling of moduli, in the infinitely-massive moduli limit, one expects an effective SUGRA theory with

$$K = \frac{1}{2} \left(\phi + \bar{\phi}\right)^2 \, , \qquad W = \frac{1}{2} \tilde{m} \phi^2$$

plus soft-breaking terms, with scalar potential

$$V = \frac{1}{2} \tilde{m}^2 \varphi^2 + \frac{c}{2} \tilde{m} m_{3/2} \varphi^2 - \frac{3}{16} \tilde{m}^2 \varphi^4 + \dots$$

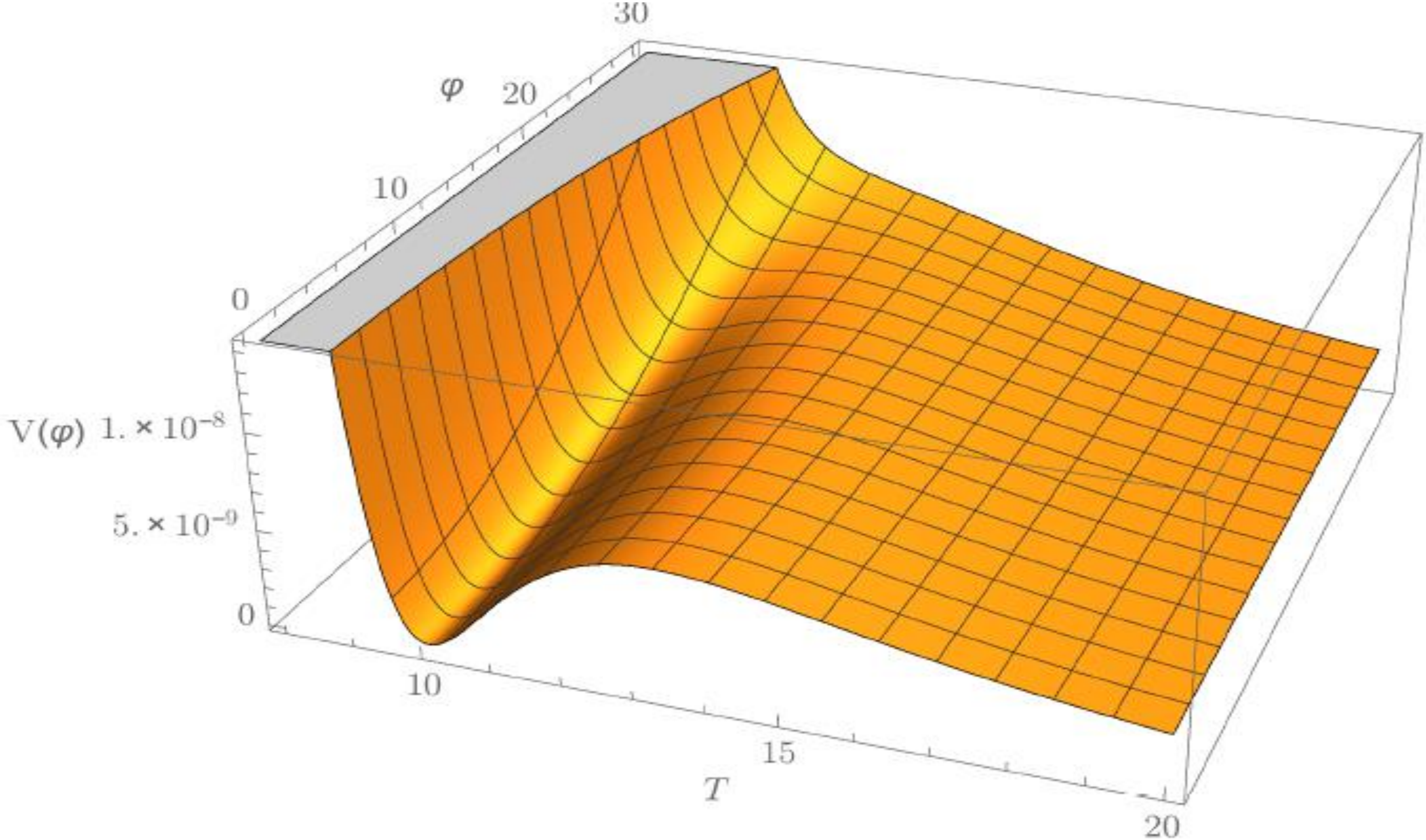


Figure 2: *Scalar potential as defined by Eqs.* (3.17) *as a function of* T *and* φ, *for the same parameter example as in Fig. 1. Apparently, a minimum for the modulus exists for* $\varphi \lesssim \varphi_c \approx 24$. *Beyond this point the modulus runs away towards* $T = \infty$ *and can no longer be integrated out. For* $\varphi < \varphi_c$ *inflation may take place in the valley of the uplifted modulus minimum.*

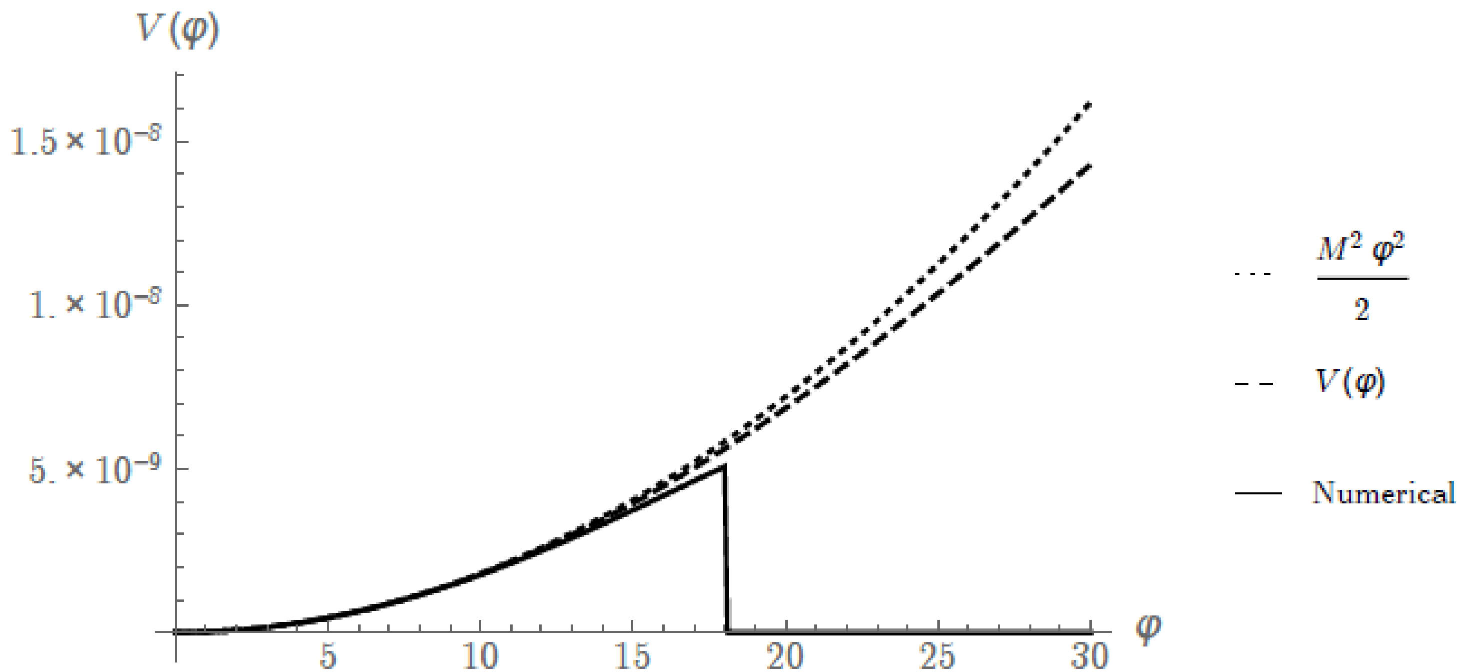


Figure 4: *Effective inflaton potential in LVS for* $W_0 = 1$, $A = 0.13$, $a = 2\pi$, $m = 5.8\times10^{-4}$, *and* $\xi = 1.25$. *With these parameters we find* $T_0 = 0.75$, $\mathcal{V}_0 = 200$, *and* $m_{3/2} = 0.005$. *The dotted line denotes a purely quadratic potential with* $M = 6\times10^{-6}$ *imposed by COBE normalization. The dashed line is the effective potential Eq.* (5.22) *evaluated at all orders in* aT_0. *The solid line is obtained numerically by setting the modulus to its minimum value at each value of* φ. *Since the barrier height and Hubble scale are the same as in the previous example, modulus destabilization occurs at* $\varphi \gtrsim 18$. *Notice that the difference between the dashed and the solid line is comparably large in this example. This is because the relatively small value of* $\mathcal{V}_0$ *limits the precision of the expansion in* $\mathcal{V}^{-1}$.

- Potential flattening and CMB observables

In all our cases, leading-order scalar potential of the type

$$V(\varphi) = \frac{1}{2} m_\varphi^2 \varphi^2 \left(1 - \frac{\varphi^2}{2\varphi_{\rm M}^2} \right)$$

valid for $\varphi < \varphi_c < \varphi_M$. In most cases $m_\varphi^2 \sim m m_{3/2}$ and slow-roll parameters are changed to

$$\epsilon = \frac{2}{\varphi^2} \left(\frac{1 - \frac{\varphi^2}{\varphi_{\rm M}^2}}{1 - \frac{\varphi^2}{2\varphi_{\rm M}^2}} \right)^2 , \qquad \eta = \frac{2}{\varphi^2} \left(\frac{1 - \frac{3\varphi^2}{\varphi_{\rm M}^2}}{1 - \frac{\varphi^2}{2\varphi_{\rm M}^2}} \right)$$

r is large, but smaller than usual chaotic inflation. It fits with PLANCK/BICEP 2015 and is but testable in the coming years.

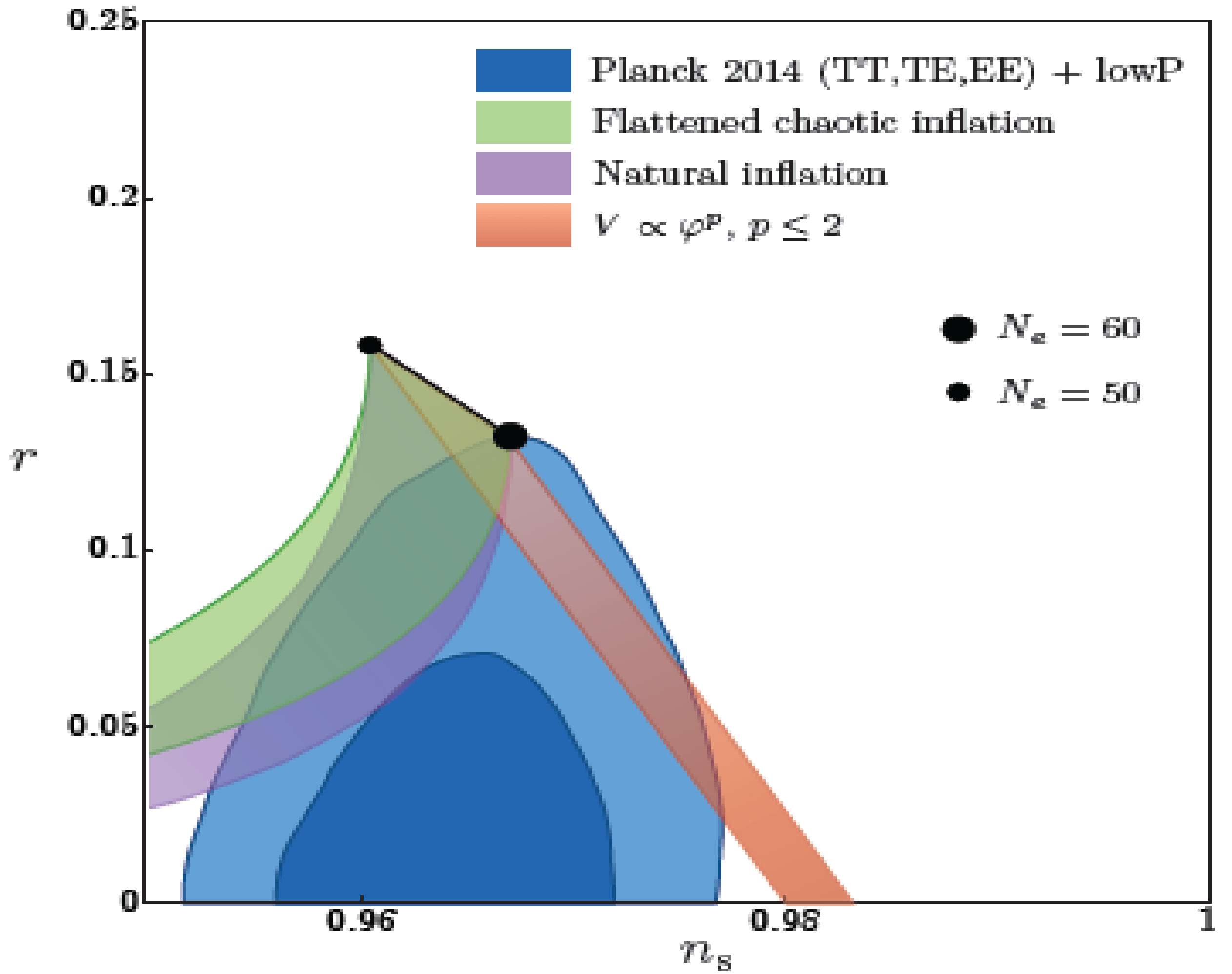


Figure 6: *Prediction for the CMB observables n_s and r of the leading-order effective inflaton potential. In the limit $\varphi_M \to \infty$ the observables asymptote to the predictions of pure quadratic inflation. Decreasing φ_M brings the potential increasingly into the hill-top regime. This leads to the green band of decreasing n_s and r values spanned by the 60 and 50 e-fold curves. Note, once more, that the regime of true hill-top inflation can actually never be reached because moduli destabilization occurs to the left of the would-be local maximum in $V(\varphi)$ at φ_M.*

4) Plateau models and backreaction

(E.D.,C.Wieck)

- Let us reconsider the Starobinsky/Cecotti model, by adding SUSY breaking.

$$K = -3\log\left(\Phi + \overline{\Phi} - |S|^2 + \frac{\xi}{3}|S|^4\right) + k(|X|)$$

$$W = MS(\Phi - 1) + fX + W_0 \,.$$

In the absence of SUSY breaking sector, inflaton potential is

$$V_0 = \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\varphi}\right)^2$$

where $\Phi = e^{\sqrt{\frac{2}{3}}\varphi} + ia$

The backreacted potential is

$$V = V_0 + \frac{f^2}{8} e^{-3\sqrt{\frac{2}{3}}\varphi} - \frac{9W_0^2}{8\xi} e^{-4\sqrt{\frac{2}{3}}\varphi}$$

Main constraint : no singularity in the Kahler metric

$$\Phi + \bar{\Phi} - |S|^2 > 0$$

leading to the bound $W_0 < \sqrt{\xi} M \;\rightarrow\; m_{3/2} < 10^{13} GeV$

similar to the case of chaotic inflation.

Moduli stabilization is then incompatible with KKLT,LVS, KU, one needs strong moduli stabilization.

Other models without stabilizer (Goncharov-Linde;Ellis,Nanopoulos,Olive): high-scale SUSY breaking moduli stabilization models destroy the flatness of the plateau. GL works with strong moduli stabilization.

Conclusions

- Supersymmetry breaking and moduli stabilization are constrained if combined with large-field inflation.

- strong moduli stabilization: low-energy SUSY OK.
  High-scale SUSY constrained to $m_{3/2} < m, H$
  with stabilizer (incompatible models without stabilizer).

- Chaotic inflation: KKLT, LVS : work only for huge $m_{3/2}$ and models without stabilizer. Inflation driven by soft term ! Initial conditions have to be carefully chosen. Flattening effect.

- We considered SUSY breaking + heavy moduli in plateau (Starobinsky,GL and ENO) models. All incompatible with KKLT or LVS moduli stabilization.
- Natural inflation models seem to protected from backreaction.

Monodromy $\Rightarrow$ case similar to chaotic inflation

- Interesting to analyze α-attractor models (Kallosh, Linde, De Roest,Scalisi)

THANK YOU