Challenges for Large-Field Inflation and Moduli Stabilization

Martin W. Winkler

`arXiv:1501.05812` W. Buchmüller, E. Dudas, L. Heurtier, A. Westphal, C. Wieck, M. W.
`Phys. Lett. B736` W. Buchmüller, C. Wieck, M. W.

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Large-Field Inflation

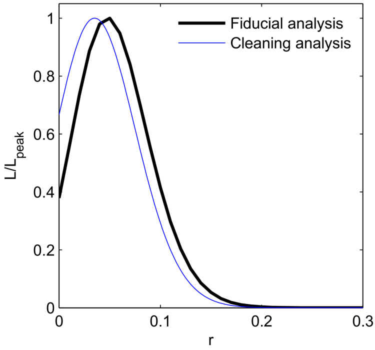
- primordial tensor modes

Lyth, Phys. Rev. Lett. **78** (1997)

$$\frac{\Delta\phi}{M_P} \gtrsim \sqrt{\frac{r}{0.01}}$$

- BICEP2 favors $r \sim 0.05$
- control over potential for $\Delta\phi > 1$
- UV completion: string theory
- axion with shift symmetry

$$\phi \rightarrow \phi + c$$



BICEP2 and Planck, Phys. Rev. Lett. **114** (2015)

Moduli Stabilization and Inflation

- preferred situation: all moduli heavy, one light axion
- typical framework: type IIB orientifold compactifications with fluxes
- fluxes fix complex structure and dilaton
  Giddings et al., Phys. Rev. **D66** (2001)
- Kähler moduli stabilized via gaugino condensates (or instantons)
  Kachru et al., Phys. Rev. **D68** (2003)

$$W = W_{\text{flux}} + W_{\text{NP}}$$

- inflation
  - aligned natural inflation: axions in W_{NP}
    Kim et al., JCAP **01** (2005)
  - F-term axion monodromy inflation: axions in W_{flux}
    Marchesano et al., JHEP **09** (2014), Hebecker et al., Phys. Lett. **B737** (2014)

Effective Supergavity Approach

- study Kähler moduli stabilization in large-field inflation

$$\begin{aligned} W &= \tfrac{1}{2} m\phi^2 + W_0 \quad + \mathcal{W}(T) \\ K &= -\tfrac{1}{2}(\bar{\phi} - \phi)^2 \quad + \mathcal{K}(\bar{T} + T) \end{aligned}$$

- inspired by flux-induced F-term axion monodromy

Marchesano et al., JHEP **09** (2014), Hebecker et al., Phys. Lett. **B737** (2014)

$$W = c_0 + c_1 U + c_2 U^2 + \dots = c_0' + c_2 U'^2 + \dots \quad (U' \equiv \phi)$$

- subtleties: flux tuning, no-go theorems

Blumenhagen et al., JHEP **01** (2015), Hebecker et al., arXiv:**1411.2032** (2014)

- inflaton potential depends on Kähler moduli stabilization

No-Scale Cancellation

- pure no-scale model

$$W = \frac{m}{2}\phi^2 + W_0$$
$$K = -\frac{1}{2}(\bar{\phi} - \phi)^2 - 3\log(\bar{T} + T)$$

- scalar potential

$$V = e^K\left(|D_\phi W|^2 + \cancel{K_{\bar{T}}\bar{W}K^{\bar{T}T}K_T W - 3|W|^2}\right) \overset{(\bar{\phi}=\phi)}{=} \frac{m^2\phi^2}{(\bar{T}+T)^3}$$

☺ no-scale cancellation kills dangerous $-3|W|^2$

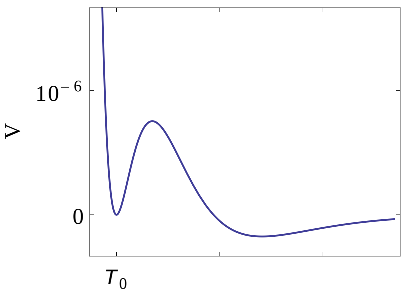
☹ runaway of T

Supersymmetric Moduli Stabilization

- KL model: two gaugino condensates

Kallosh et al., JHEP **12** (2004)

$$W_{\mathrm{KL}} = W_0 + Ae^{-\frac{2\pi T}{N_1}} + Be^{-\frac{2\pi T}{N_2}}$$

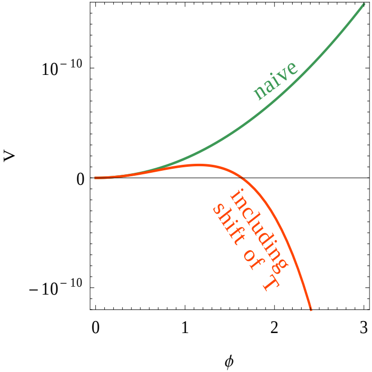


- tune parameters such that $W\big|_{T_0} = \partial_T W\big|_{T_0} = 0$
- metastable supersymmetric Minkowski minimum
- protected by barrier of tunable height

Inflation in the KL Model

- adding the inflaton sector

$$W = W_{\rm KL} + \frac{m}{2}\phi^2 \qquad K = -\frac{1}{2}(\bar{\phi} - \phi)^2 - 3\log(\bar{T} + T)$$



- naive no-scale cancellation ($\bar{\phi} = \phi$)

$$V\Big|_{T_0} = \tilde{m}^2\phi^2 \qquad \left(\tilde{m} = \frac{m}{(2T_0)^{3/2}}\right)$$

- inflation induces ΔT

$$V\Big|_{T_0+\Delta T} = \tilde{m}^2\phi^2 - \frac{3\tilde{m}^2\phi^4}{4} + \mathcal{O}\left(\frac{H}{m_T}\right)$$

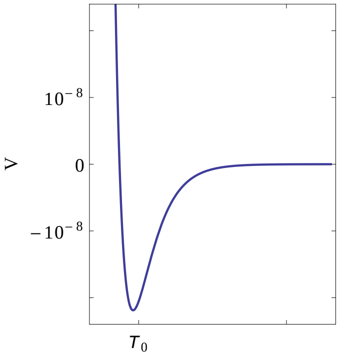
- supersymmetric moduli decouple if $m_T \gg H$

KKLT

- KKLT model: gaugino condensate

Kachru et al., Phys. Rev. **D68** (2003)

$$W_{\mathrm{KKLT}} = W_0 + A e^{-\frac{2\pi T}{N}}$$



- supersymmetric AdS minimum
- uplifted e.g. via F-term
- ~~SUSY~~ $F_X \sim m_{3/2}$
- potential barrier

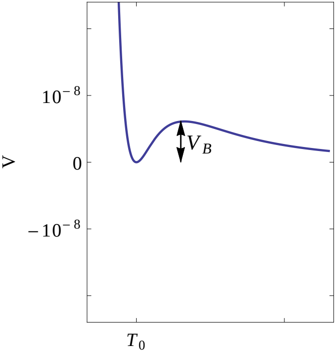
$$V_B \sim m_{3/2}^2$$

KKLT

- KKLT model: gaugino condensate + uplifting sector

Kachru et al., Phys. Rev. **D68** (2003)

$$W_{\text{KKLT}} = W_0 + Ae^{-\frac{2\pi T}{N}} + f\,X$$



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Inflation in KKLT

- adding inflation sector leads to shift

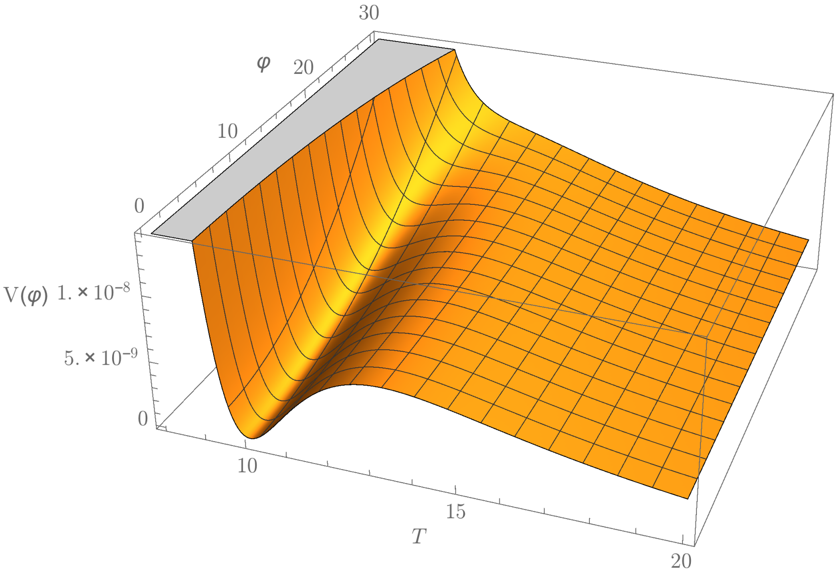
$$\frac{\Delta T}{T_0} \sim \frac{\tilde{m}\phi^2}{m_{3/2}} \qquad\qquad \tilde{m} = \frac{m}{(2T_0)^{3/2}}$$

- $\Delta T \ll T_0$: modulus is stabilized and can be integrated out

$$V \simeq \underbrace{-3\tilde{m}m_{3/2}\phi^2}_{V_0} + \tilde{m}^2\phi^2 - \tfrac{3}{4}\tilde{m}^2\phi^4 \simeq V_0\left(1 - \frac{V_0}{12m_{3/2}^2}\right)$$

- ~~SUSY~~ soft mass can drive inflation
- leading correction leads to flattening effect
- stability bound $m_{3/2} \gg H$

Inflation in KKLT



Large Volume Scenario

- swiss-cheese manifold with big four-cycle and small four-cycle

$$\mathcal{V} = (\bar{T}_b + T_b)^{3/2} - (\bar{T}_s + T_s)^{3/2}$$

- interplay between α'-correction and non-perturbative corrections

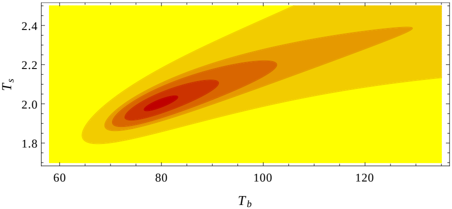
Balasubramanian et al., JHEP **03** (2005)

$$W_{\text{LVS}} = W_0 + Ae^{-\frac{2\pi T_s}{N}} + W_{\text{up}} \qquad K_{\text{LVS}} = -2\log\left(\mathcal{V} + \xi\right)$$

- minimum at exponentially large volume $\mathcal{V} \sim W_0\, e^{\frac{2\pi T_s}{N}}$
- no-scale cancellation between F_{T_b} and W approximately preserved
- potential barrier

$$V_B \sim \frac{W_0^2}{\mathcal{V}^3} \sim \frac{m_{3/2}^2}{\mathcal{V}}$$

Inflation in LVS



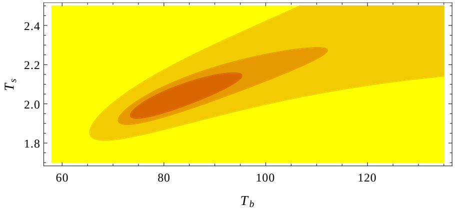
- inflation induces ΔT_b **and** ΔT_s
- stability bound $m_{3/2} \gg H\sqrt{\mathcal{V}}$
- inflaton potential after integrating out $T_{s,b}$ (schematically)

$$V \simeq \tilde{m}^2\phi^2\left(1 - \frac{\tilde{m}^2\phi^2}{V_B}\right) \quad + \quad \frac{1}{\mathcal{V}}\tilde{m}m_{3/2}\phi^2\left(1 - \frac{\frac{1}{\mathcal{V}}\tilde{m}m_{3/2}\phi^2}{V_B}\right)$$

- supersymmetric mass term + volume-suppressed ~~SUSY~~ soft mass
- 4D supergravity description requires $m_{3/2} < M_{\text{KK}} \sim \mathcal{V}^{-2/3}$

  Cicoli et al., JHEP **01** (2014)
- inflation for $\mathcal{V} \leq 1000$ and ~~SUSY~~ soft mass dominant

Inflation in LVS



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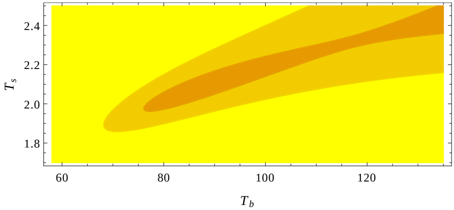

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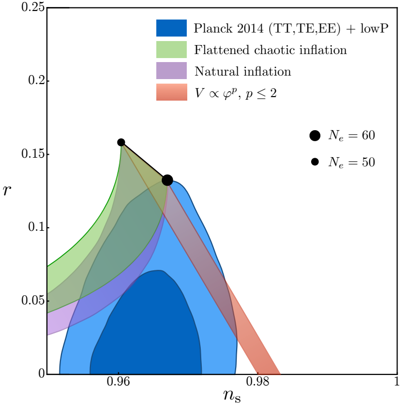
Universal Backreaction

- in KKLT, LVS, Kähler uplifting inflaton potential takes universal form

$$V = \frac{M^2}{2}\varphi^2 - \lambda\varphi^4$$



- type of flattening related to the geometry of internal space?

Conclusion

- (large-field) inflation and moduli stabilization are tightly connected
- if Kähler moduli stabilization breaks SUSY, moduli do not decouple from inflation
- $\cancel{\text{SUSY}}$ induces inflaton soft mass which can drive inflation
- severe constraints to protect moduli during inflation, in particular

$$m_{3/2} \gg H \quad \text{(KKLT)} \qquad\qquad m_{3/2} \gg H\sqrt{\mathcal{V}} \quad \text{(LVS)}$$

- considered schemes share universal predictions for CMB observables