Towards Matter Inflation in Effective Heterotic SUGRA

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S. Antusch, K. Dutta, J. Erdmenger
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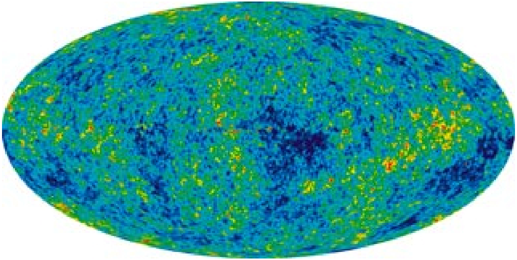
Inflationary paradigm

Inflation = Period of exponential expansion in very early universe.

Guth '81; Linde '82; Albrecht, Steinhardt '82

Inflation is a successful paradigm which

- solves the flatness & horizon problem ($T \approx 2.7K$)
- provides a seed for structure formation ($\frac{\delta T}{T} \sim 10^{-5}$)



WMAP 7 year full sky temperature map

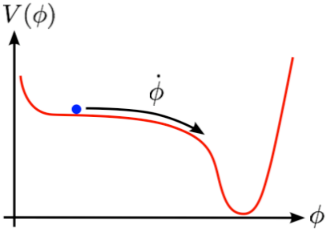
Slow-roll inflation

"Standard" realization: slowly rolling scalar field ϕ

$$ds^2 \approx -dt^2 + a(t)^2 d\vec{x}^2 \ , \ a(t) \approx e^{\mathcal{H}t} \ , \ \mathcal{H} \approx \sqrt{\frac{V(\phi)}{3M_P^2}}$$

$V(\phi)$ must satisfy

$$\epsilon \sim M_P^2 \frac{V'^2}{V^2} \ll 1 \ \& \ \eta \sim M_P^2 \frac{V''}{V} \sim \frac{m_\phi^2}{\mathcal{H}^2} \ll 1$$



η-problem

Slow-roll inflation sensitive to Planck-scale physics:

$$\delta V = c\,\mathcal{O}_4 \frac{\phi^2}{M_P^2} \;\&\; \langle \mathcal{O}_4 \rangle \sim \langle V \rangle \Rightarrow \eta \sim c$$

e.g. F-term inflation in supergravity:

$$V_F = e^{K/M_P^2} \left(K^{i\bar{\jmath}} D_i W\, D_{\bar{\jmath}} \overline{W} - 3 \frac{|W|^2}{M_P^2} \right) \;,\; D_i W = W_i + \frac{K_i W}{M_P^2}$$

with $K = |\Phi|^2 + |X|^2 + \ldots$ & only $\langle W_X \rangle \neq 0$

Copeland, Liddle, Lyth, Stewart, Wands '94; Dine, Randall, Thomas '95

$$V_F = |\langle W_X \rangle|^2 \left(1 + \frac{|\phi|^2}{M_P^2} + \ldots \right) \Rightarrow \eta \sim 1$$

Solution: fine-tune against dots or impose symmetry

Superpotential

Requirements:

1. Solve η-problem by special form of K
   $\rightarrow$ during inflation W should fulfill Stewart '95

$$\langle W \rangle \simeq \langle W_\Phi \rangle \simeq 0 \ , \ \langle W_X \rangle \neq 0$$

2. Inflation ends via hybrid mechanism Linde '93; Dvali, Shafi, Schaefer '94
   $\rightarrow$ at $\langle \phi \rangle = \phi_{cr}$ a tachyonic direction appears

Minimal form of W: Arkani-Hamed, Cheng, Creminelli, Randall '03; Antusch, Dutta, Kostka '09

$$W = \kappa\, X (H^2 - M^2) + \lambda\, f(\Phi)\, H^2$$

During inflation: $\langle X \rangle \simeq \langle H \rangle \simeq 0$

Kähler potential

Usual choice: shift symmetry

e.g. Kawasaki, Yamaguchi, Yanagida '00; Arkani-Hamed, Cheng, Creminelli, Randall '03

$$\Phi \to \Phi + i\alpha$$

Alternative: "Heisenberg symmetry"

Binetruy, Gaillard '87; Ellwanger, Schmidt '87; Gaillard, Murayama, Olive '95; Gaillard, Lyth, Murayama '98

$$T \to T + i\alpha$$
$$\Phi \to \Phi + \beta$$
$$T \to T + \bar{\beta}\,\Phi + \frac{1}{2}|\beta|^2$$

Invariant combination: $\rho = T + \bar{T} - |\Phi|^2$

$$\text{e.g. } K = -3\ln\rho + \ldots$$

Why Matter Inflation?

Why is it interesting to have the inflaton in the matter sector?

- Direct link between particle physics & inflation
- Hybrid phase transition and GUT breaking?
  $\longrightarrow$ Typically $\langle H \rangle \simeq M \sim M_{GUT}$
- Inflaton in visible sector, e.g. right-handed sneutrino?
  $\longrightarrow$ Relate inflation to leptogenesis
- Extra constraints on inflaton potential from particle physics
  $\longrightarrow$ Minimally coupled SM Higgs excluded by EWSB vs. CMB

Matter Fields as Inflatons

Heisenberg symmetry & structure of W
$\rightarrow$ Gauge non-singlet matter field as inflaton

Antusch, Bastero-Gil, Baumann, Dutta, King, Kostka '10

$$\begin{aligned} W &= \kappa X(HH^c - M^2) + \frac{\lambda}{\Lambda}\Phi\Phi^c HH^c \\ K &= -3\ln\rho + |X|^2(1-\beta\rho-\gamma|X|^2) + |H|^2 + |H^c|^2 \\ \rho &= T + \bar{T} - |\Phi|^2 - |\Phi^c|^2 \end{aligned}$$

D-flat trajectory: $\langle\Phi\rangle, \langle\Phi^c\rangle \neq 0$, $\langle H\rangle \simeq \langle H^c\rangle \simeq \langle X\rangle \simeq 0$.

- Inflaton singlet under unbroken gauge group & $m_A \sim g\langle\Phi\rangle$
- 1-loop: $\frac{\delta m_\phi^2}{\mathcal{H}^2} \ll 1$ if SUGRA gaugino mass splittings vanish
- 2-loop: $\frac{\delta m_\phi^2}{\mathcal{H}^2}$ suppressed by $\frac{\kappa^2}{(4\pi)^4}$

Some Generalization

Generalization of previous model:

$$W = a(T_i)\,X\left(b(T_i)\,HH^c - \langle\Sigma\rangle^2\right) + c(T_i)\,f(\Phi^3_\alpha)\,HH^c + \dots$$

$$K = -\sum_{i=1}^{3}\ln\rho_i + \left(\prod_{i=1}^{2}\rho_i^{-q_i^X}\right)\left(|X|^2 + d(\rho_3)|X|^2 - \gamma|X|^4\right)$$
$$+ \left(\prod_{i=1}^{3}\rho_i^{-q_i^H}\right)|H|^2 + \left(\prod_{i=1}^{3}\rho_i^{-q_i^{H^c}}\right)|H^c|^2 + \dots$$

with $\rho_i = T_i + \bar{T}_i - \sum_\alpha|\Phi^i_\alpha|^2$ and $0 \leq q_i^p < 1$

During inflation: $\langle X\rangle \simeq \langle H\rangle \simeq \langle H^c\rangle \simeq \langle\Phi^1_\alpha\rangle \simeq \langle\Phi^2_\alpha\rangle \simeq 0$

Some Comments

- $f(\Phi_{3,\alpha})$ = gauge invariant (D-flat) product of Φ's
  e.g. $N \times \bar{N}$ of $SU(N)$ or $27 \times 27 \times 27$ of E_6 etc.
- Need $K \supset -\gamma|X|^4$ to ensure $m_X \gtrsim \mathcal{H}$ Kawasaki, Yamaguchi, Yanagida '00
- Geometric interpretation: Covi, Gomez-Reino, Gross, Louis, Palma, Scrucca '08
  If $\langle X \rangle \simeq 0$, $\langle W_X \rangle \neq 0$
  $\rightarrow \langle R_{X\bar{X}X\bar{X}} \rangle < 0$ necessary for de Sitter vacua
- Non-canonical kinetic terms $\propto (T + \bar{T} - |\Phi|^2)^{-q}$
- Superpotential couplings either $\sim e^{-aT}$ or $\sim 1 + e^{-aT}$
- $\langle W_X \rangle \propto \langle \Sigma \rangle^2$ with $\langle \Sigma \rangle$ generated dynamically
  $\rightarrow$ Parametrize moduli dependence of $\langle \Sigma \rangle$

$$\langle \Sigma \rangle \propto \prod_{i=1}^{3} \rho_i^{p_i} e^{b_i T_i}$$

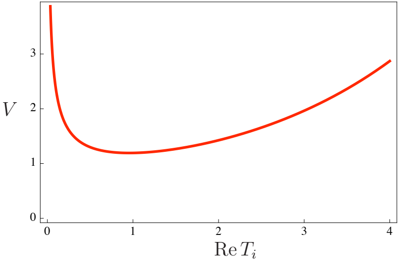
Moduli Stabilization

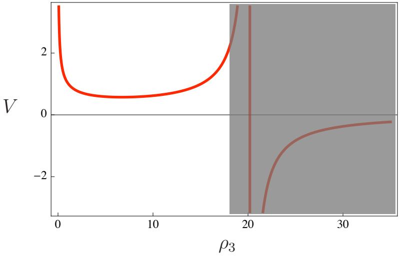
Moduli stabilized for suitable choice of $a(T_i)$, $\langle\Sigma\rangle$ and $d(\rho_3)$

$$\text{e.g. } a(T_i)\langle\Sigma^2\rangle \sim M^2 e^{a_1 T_1 + a_2 T_2}\ ,\ d(\rho_3) \sim -\beta\rho_3$$

$$\rightarrow V \sim \frac{M^4 |e^{a_1 T_1 + a_2 T_2}|^2}{(T_1 + \bar{T}_1)^{n_1}(T_2 + \bar{T}_2)^{n_2}\rho_3^{n_3}(1 + d(\rho_3))}$$

$\longrightarrow \langle \text{Re}\, T_{1,2}\rangle \sim \mathcal{O}(1)$ and $\langle\rho_3\rangle \sim \beta^{-1}$ with masses $\sim \mathcal{H}$





Heterotic Orbifolds

- Heterotic string theory = theory of closed strings
- Contains gauge group $SO(32)$ or $E_8 \times E_8$
- Orbifolds are "toy models" of Calabi-Yau compactifications: $\rightarrow$ obtained as $T^6/\mathbb{Z}_N$
- Strings on oribfolds can be
  - "untwisted" $\leftrightarrow$ closed in T^6 and $T^6/\mathbb{Z}_N$
  - "twisted" $\leftrightarrow$ closed only in $T^6/\mathbb{Z}_N$
- Corresponds to fields living in

$10D$ bulk	$\leftrightarrow$	full orbifold	$\leftrightarrow$	untwisted
$4D$ brane	$\leftrightarrow$	fixed point	$\leftrightarrow$	twisted
$6D$ brane	$\leftrightarrow$	fixed torus	$\leftrightarrow$	twisted

Heterotic Orbifolds

- MSSM-like models exist, e.g. heterotic "mini-landscape" based on $T^6/\mathbb{Z}_6$ or $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)$

  Buchmüller, Hamaguchi, Lebedev, Ratz '05 -'06; Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter '06 -'08; Blaszczyk, Groot-Nibbelink, Ratz, Rühle, Trapletti, Vaudrevange '09

- Heisenberg symmetry at tree-level for untwisted matter fields

$$T_i \sim R_i^2 + iB_i \xrightarrow{\Phi^i_\alpha \neq 0} T_i \sim R_i^2 + iB_i + |\Phi^i_\alpha|^2$$

- Identification of field content could be

T_i	$\leftrightarrow$	3 "universal" untwisted Kähler moduli
Φ^i_α	$\leftrightarrow$	associated untwisted matter fields
X	$\leftrightarrow$	twisted sector field

Moduli Stabilization

- Dilaton S additional modulus
  $\rightarrow$ "Kähler stabilization" using $K_{np} \propto e^{-1/g_s}$

  Shenker '90; Banks, Dine '94; Casas '96; Binetruy, Gaillard, Wu '96 & '97; Gaillard, Lyth, Murayama '98
- T_1 & T_2 stabilized if $\langle W_X \rangle \propto \eta(T_1)^{-p_1}\eta(T_2)^{-p_2} \propto e^{a_1 T_1 + a_2 T_2}$

  Copeland, Liddle, Lyth, Stewart, Wands '94
- Ideally: T_3 & Φ^3_α enter potential only through $\rho_3 \sim R_3^2$
  $\rightarrow$ Avoid superpotential stabilization: $\langle W_{T_3} \rangle \simeq \langle W_{\Phi_{3,\alpha}} \rangle \simeq 0$
- Alternatives to superpotential stabilization:
  - α'-corrections? Candelas, De La Ossa, Green, Parkes '91

$$-\ln \mathcal{V} \rightarrow -\ln(\mathcal{V}+\xi)\ ,\ \xi \propto -\chi = 2(h^{1,1}-h^{2,1})$$

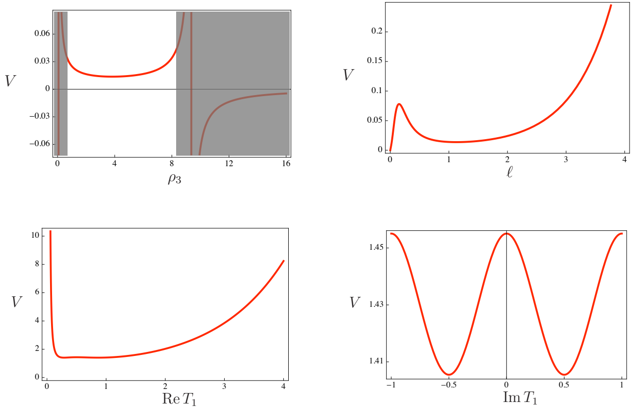
  - Moduli-dependent threshold corrections to $K_{X\bar{X}}$?

    Antoniadis, Gava, Narain, Taylor '92

$$\langle \Phi \rangle = 0 \rightarrow \ln|\eta(T)|^4(T+\bar{T}) \simeq \ln(T+\bar{T}) - \frac{\pi}{6}(T+\bar{T}) + \mathcal{O}(e^{-2\pi T})$$

Moduli Stabilization with Threshold Corrections

In principle: can stabilize T_1, T_2, ρ_3 and $\ell \sim 1/(S + \bar{S})$
$\longrightarrow$ requires some tuning of parameters



Summary & Outlook

Matter inflation

- is phenomenologically interesting
  $\longrightarrow$ Extra constraints, e.g. from leptogenesis/baryogenesis?
- needs certain structure in K and W to work
  $\longrightarrow \langle W \rangle \simeq \langle W_\Phi \rangle \simeq 0$, $\langle W_X \rangle \neq 0$
- seems suitable to embed in heterotic orbifolds
  $\longrightarrow$ Matter fields important for de Sitter vacua & inflation

Open issues

- Better understanding of moduli stabilizaton
  $\longleftrightarrow$ Systematics of corrections to inflaton potential?
- Moduli stabilization after inflation
  $\longrightarrow$ Reheating through moduli or inflaton decays?