Inflation and Post-Inflation in LVS

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Burgess, Cicoli, de Alwis, FQ arXiv:1603.06789,
Cicoli, K. Dutta, Maharana, FQ arXiv:1604.08512,
Antusch, Cefala, Orani, Krippendorf, Muia, FQ (wip)
Inflation and Strings

- Some inflationary EFTs describe CMB + other data very well.
- Inflation needs an UV completion.
- Some EFTs of string compactification can describe inflation.
- Challenges: Moduli stabilisation and
  \[ M_{\text{planck}} > M_{\text{string}} > M_{kk} > M_{\text{inf}} \]
• Epochs: Pre-inflation, inflation, post-inflation (pre-BBN)

• Chiral spectrum implies $N=0,1$ in 4D (work with $N=1$)

• Strings relevant in postinflation? (yes: moduli).

“Generically”: If eft is supersymmetric then the moduli survive at low energies until susy breaks:

$$\text{mass}_{\text{moduli}} \approx m_{\text{gravitino}}.$$

(but interesting exceptions!)
Strings vs Simplicity

• \( V \approx \phi^p \) (stringy: axion monodromy)

• Starobinsky (stringy?)

\[
S_f [g_{\mu\nu}, \psi] = \frac{M_p^2}{2} \int d^4 x \sqrt{-g} f(R) + \int d^4 x \sqrt{-g} L_M (g_{\mu\nu}, \psi).
\]

\[
f(R) = R + \frac{R^2}{M^2} \left[ 1 + \frac{R}{M_p^2} + \cdots \right]
\]

\[
V(\phi) = \frac{1}{8} M^2 M_p^2 \left[ \left( 1 - e^{-\sqrt{\frac{2}{3}} \phi} \right)^2 + a_4 e^{\sqrt{\frac{2}{3}} \phi} + \cdots \right]
\]

Strings: only one scale, action \( S \) depends on powers of curvature and Ricci not only \( R \),...
String Scenarios

- IIB (+F-theory)
  - KKLT
  - LVS
  \[ \text{Moduli Stabilisation} \]
- IIA
- Heterotic
- G2 manifolds
Compactification
IIB MODULI STABILISATION

4-cycle size: $\tau$ (Kahler moduli)

3-cycle size: $z$ (Complex structure moduli) + Dilaton $S$


GKP Overview

\[ V_F = e^K [K^{i\bar{j}} (W_i + K_i W) (W_j + K_j W)^* - 3|W|^2] \]

\[ K_{\text{tree}} = -2 \ln \left( \mathcal{V}(T_i) \right), \quad K^{i\bar{j}} K_i K_{\bar{j}} = 3 \]

Fluxes:

\[ W = \int G \wedge \Omega \]

\[ G_3 = F_3 - iS H_3, \quad \int F_3 = 2\pi M, \quad \int H_3 = -2\pi K \]

Fix CS moduli: z and dilaton: S (but runaway in T directions?)
Nonperturbative effects: $W_{np} = \sum A_i e^{-\alpha_i T_i}$

SUSY AdS Vacua: DW=0

Anti D3 brane (SUSY breaking+uplift)

$V_{\text{uplift}} = \frac{D^2}{(T + T^*)^\alpha} = \frac{D^2}{\sqrt{2^{\alpha/3}}} \quad \begin{cases} \alpha = 3 & \text{KKLT} \\ \alpha = 2 & \text{KKLMMT} \end{cases}$
Perturbative corrections to $K$:

$$K = -2 \ln \left( \mathcal{V} + \frac{\xi}{2} \right)$$

$$V_F \propto \left( \frac{K^{SS} |D_S W|^2 + K^{a\bar{b}} D_a W D_{\bar{b}} \bar{W}}{\mathcal{V}^2} \right) + \left( \frac{A e^{-2a\tau}}{\mathcal{V}} - \frac{B e^{-a\tau} W_0}{\mathcal{V}^2} + \frac{C |W_0|^2}{\mathcal{V}^3} \right)$$

$$\mathcal{V} \sim e^{a\tau} \quad \text{with} \quad \tau \sim \Re S \sim 1/g_s > 1.$$

Exponentially large volume for weak coupling
(SUSY broken by Fluxes, AdS)
Extends to any CY with 1 rigid cycle and $h_{11} < h_{12}$
Other de Sitter ‘Uplift’

- From F/D terms, hidden matter CKKMQV 2013
  
  T-branes (Cicoli, FQ, Valandro arXiv:1512.04558)

- From non-perturbative effects on hidden brane at singularities

- ...
Relevant Scales

- **String Scale**

  \[ M_s = \frac{g_s^{1/4} M_P}{\sqrt{4\pi V}} \]

- **Kaluza Klein Scale**

  \[ M_{KK} \simeq \frac{M_P}{\sqrt{4\pi V^{2/3}}} \]

- **Gravitino mass**

  \[ m_{3/2} \simeq \left( \frac{g_s^2}{2\sqrt{2\pi}} \right) \frac{W_0 M_P}{V} \]

- **Volume modulus mass**

  \[ m_V \simeq m_{3/2}/\sqrt{V} \]

- **Vacuum decay rates**

  \[ \Gamma \sim e^{-V^3} \]
Axions

• Model independent axion partner of volume, mass $\approx \exp(-V^{2/3}) \leq 10^{-22}$ eV (dark energy, matter, radiation).
  Similar for fibre moduli and all moduli stabilised by perturbative effects

• Some massive by Stuckelberg effect

• Others massive from non-perturbative effects

• Open string axions (model dependent)
Kahler+Fibre Inflation

- $\alpha=2$ (fibre inflation)  
  Burgess, Cicoli, FQ (2007)

- $\alpha=(\ln V)^{-1}$ (Kahler blow-up inflation)  
  Conlon, FQ (2006)  
  Bond et al (2007)

- $...\alpha=(\ln V)^{-1}$ (polyinstanton inflation)  
  Cicoli, Pedro, Tasinato (2011)
Inflation: Fibre+Kahler

\[ \alpha = 2 \text{ fiber inflation} \]

\[ \alpha = 1, \ r = 3 \times 10^{-3} \]

\[ \alpha << 1 \text{ Kahler, Polyinstanton} \]

Adapted from Kallosh, Linde $\alpha$-attractors
Recent Fibred Developments

\[ V = \frac{V_0}{\nu^{10/3}} \left[ 3 - 4e^{-k\phi/2} + e^{-2k\phi} + R(e^{k\phi} - 1) \right] \]

\[ r \approx \frac{8}{k^2} (n_s - 1)^2 = 6(n_s - 1)^2 \]

- Essentially all known CY are fibred
- Non-fibre moduli give similar results
- Concrete compact CY realisations
- \( F^4 \) corrections to \( V \) similar results
- De Sitter uplift \( \text{D3} \) from nilpotent superfield
- Low \( I \) and positive exponential
- SUSY soft terms \( > 10^{10} \) GeV!

See Kallosh, Wrase's talks
(Cicoli,Westphal et al)

Cicoli et al
Post Inflation
Moduli Domination

2. Moduli can cause cosmological problems: Polonyi '81, Coughlan & Ross '83, Banks, Kaplan, Nelson '93, de Carlos, Casas, Quevedo, Roulet '93.

The typical decay rate of gravitationally coupled scalars is:

\[ \Gamma_\phi \sim \frac{1}{8\pi} \frac{m^3}{M^2_{Pl}} \]

\[ T > O(1 \text{ MeV}), \text{ so } m_\phi \gtrsim 3 \cdot 10^4 \text{ GeV} \]

Coughlan et al 1983, Banks et al, de Carlos et al 1993
Explicit computation of Vacuum misalignement

\[ Y = \frac{\delta \varphi}{M_{\text{pl}}} = \sqrt{\frac{2}{3}} \delta \phi \approx 2 \sqrt{\frac{2}{3}} R \phi_* \approx 0.1 - 1 \]

Number of efoldings:

\[ N_e + \frac{1}{4} N_{\text{mod}} + \frac{1}{4} (1 - 3w_{\text{re}}) N_{\text{re}} \approx 57 + \frac{1}{4} \ln r + \frac{1}{4} \ln \left( \frac{\rho_*}{\rho_{\text{end}}} \right) \]

\[ \left( 55 - \frac{1}{4} N_{\text{mod}} \right) \pm 5 \]

\[ N_{\text{mod2}} \approx \frac{2}{3} \ln \left( \frac{16\pi V^{5/2} (\ln V)^{5/2} Y^4}{10\beta^2} \right) \]

\[ N_e \approx 44.65 + \frac{1}{4} \ln \left( \frac{\rho_*}{\rho_{\text{end}}} \right) \approx 45 \quad n_s \approx 0.955 \]
Figure 1: The left-hand timeline represents the thermal history of the early universe when dark matter is populated in the thermal bath that emerges shortly after inflation. The right timeline represents a possible nonthermal history where dark matter production occurs directly from scalar decay.

The abundance simplifies to $\Omega_{\text{dm}} h^2 \approx 0.12$, where we have used GeV$^2 \cdot c' \approx 1.17 \times 10^{-26}$ cm$^3$/s$^2$.

WIMPs with typical speeds ($v' \approx 0.3 c$) and electroweak cross-sections ($\sigma \approx 1$ pb) yield $\Omega_{\text{dm}} h^2 \approx 0.12$ in agreement with the data, a coincidence often called the WIMP miracle.

Simple SUSY models with thermal WIMPs are in growing conflict with collider data and direct detection experiments [40]. By contrast, nonthermal models posit that dark matter production occurs at temperatures below standard thermal freeze-out leading to dark matter with novel and unexpected experimental signatures. For example, if a heavy relic comes to dominate the energy density following inflation and the dark matter particle is one of its decay products, the resulting relic density is still given by (6) but with $T = T_r$ and $g^\star = g^\star(T_r)$, the value at the time of reheating.

The similarity to the thermal freezeout result (6) arises because when the WIMPs are produced from scalar decay they will rapidly annihilate until their number density reduces to the point where annihilations can no longer occur. This process is essentially instantaneous (on cosmological time scales). If the particles were produced above their freeze-out threshold, they could thermalize via their mutual interactions.

From S. Watson, SUSY 2013
Cosmological evolution of dark radiation

\( \Phi \)

- gg, qq, e^+ e^-, ...
- \( \Phi \) → VISIBLE SECTOR
- \( \Phi \) → DARK RADIATION

THERMALISED

FREE STREAMING
Volume Reheating

*Sequestered scenarios

\[ \Gamma_{\Phi \to a_b a_b} = \frac{1}{48\pi} \frac{m_{\Phi}^3}{M_P^2} \]

\[ \Gamma_{\Phi \to H_u H_d} = \frac{2Z^2}{48\pi} \frac{m_{\Phi}^3}{M_P^2} \]

\[ \Gamma_{\Phi \to B B} = \left( \frac{\lambda}{3/2} \right)^2 \frac{9}{16} \frac{1}{48\pi} \frac{m_{\Phi}^3}{M_P^2} \]

\[ \Gamma_{\Phi \to C \bar{C}} \sim \frac{m_0^2 m_{\Phi}}{M_P^2} \ll \frac{m_{\Phi}^3}{M_P^2} \]

\[ T_{\text{reheat}} \sim \frac{m_{\Phi}^{3/2}}{M_P^{1/2}} \sim 0.6 \text{ GeV} \left( \frac{m_{\Phi}}{10^6 \text{GeV}} \right)^{3/2} \]
Strong Constraint: (No?) Dark Radiation

Energy density:

\[ \rho_{total} = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{eff}\right). \]

Standard Model \( N_{eff} = 3.04 \)

At CMB: WMAP, ACT, SPT

Planck 2015: \( N_{eff} = 3.13 \pm 0.32 \) (68% CL)

\[ 3.12 \kappa \leq \Delta N_{eff} \leq 3.48 \kappa \]

\[ \kappa = \frac{(1 + 9n_a/16)}{n_H Z^2} \]

Simplest \( Z=1 \):

\[ 1.56 \leq \Delta N_{eff} \leq 1.74 \]

General: Strong constraints on matter and couplings!
“Preheating” and Oscillons?

e.g. Hilltop potentials
(Antusch et al):

\[
V(\phi) = V_0 \left(1 - \frac{\phi^p}{v^p}\right)^2
\]

Tachyonic oscillations, oscillons, gravitational waves
No tachyonic oscillations
No Oscillons
No decompactification
(very preliminary)

After Fibre inflation?

\[ R \equiv \frac{m_V(\phi_{\text{min}})}{\sqrt{V(\phi)}/3} \approx 10 < 150 \]
Conclusions

- Concrete string models of inflation $r \leq 10^{-2}-10^{-3}$

- Strings: Inflation only one component, postinflation is very important

- Strings: Post inflation (dark energy, matter, radiation, different thermal history (moduli domination), baryogenesis, cdm,...)

- Correlations (large r no TeV SUSY, etc.)
Consider next the situation where at least one supersymmetry breaks at a small enough scale much room for where we take as benchmark learn a relation between theory, for later purposes it is useful to cast the role of UV scales in terms of string parameters, to emphasize we typically wish to work far from the potential minimum for inflationary Volume Scenario (LVS)\[ of moduli stabilisation of IIB CY orientifold compactifications. Actually the dimensional analysis changes if it happens that • • •

\[ • • • \]

\[ \cdot \cdot \cdot \]

\[ V \]

Constraints

- Quantum corrections: \[ M_{\text{inf}} \gtrsim M/\sqrt{4\pi}, \quad M \sim M_{KK} \]

- Naively Effective Field Theory \[ M_{\text{inf}} \ll M_{KK} \]

- Strong constraint: \[ M_{KK}/\sqrt{4\pi} \lesssim M_{\text{inf}} \ll M_{KK} \]

- N=1 SUSY EFT:

\[ M_{\text{inf}}^4 \sim H^2 M_p^2 \gg \frac{m_{3/2}^2 M_{KK}^2}{16\pi^2} \gg \frac{m_{3/2}^3 M_p}{16\pi^2} \]