The Inflaton as a MSSM Higgs and Open String Modulus Monodromy Inflation

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Two big discoveries...

Higgs boson

(ATLAS and CMS, 2012)

Responsible for SSB of EW interactions

Inflation

(BICEP2, 2014)

(still to be confirmed...)

Parametrized by a scalar particle rolling down a potential.

Higgs boson = Inflaton

Reheating ✓
Inflaton = MSSM Higgs boson

Problems of usual Higgs inflation:
• Only quartic potential: not flat enough.
• Quartic coupling could vanish before inflation.
• Too small tensor-to-scalar ratio $r$.
• ...

All of them solved if SUSY is broken at a high scale.

Potential dominated by the SUSY breaking terms $\sim \mathcal{O}(10^{13} \text{ GeV})$

First approx.: $V_H \approx m^2 H^2$

Bezrukov, ’13
Barbon, Espinosa’09
SUSY breaking in Type IIB/F-Theory

Assumption: Closed string fluxes as the main source of SUSY breaking

- Non-vanishing auxiliary field for some closed string moduli.

\[
K = -\log(S + S^*) - 3\log(T + T^*)
\]

Type IIB (CY): \[ W = \int G_3 \wedge \Omega \]

\[
F^S \propto \int G_3^* \wedge \Omega = 0
\]

\[
F^T \propto \int G_3 \wedge \Omega \neq 0
\]

- Important for moduli stabilization.

Size of soft terms: \[ M_{SS} \simeq \frac{g_s^{1/2}}{\sqrt{2}} G_3 \]
Scale of SUSY breaking

Size of soft terms: \( M_{SS} \approx \frac{g_s^{1/2}}{\sqrt{2}} G_3 \)

- Quantization of fluxes: \( \frac{1}{2\pi\alpha'} \int_{\gamma} G_3 \in 2\pi\mathbb{Z} \rightarrow G_3 \sim \frac{\alpha' f}{\text{Vol}(B_3)^{1/2}} \)

- Scales in IIB/F-theory:

\[ M_p^2 \sim \frac{1}{\alpha'^4 g_s^2} \text{Vol}(B_3) \]
\[ M_{GUT} \sim \text{Vol}(S_4)^{-1/4} \]
\[ \alpha_{GUT}^{-1} \sim \frac{1}{\alpha'^2 g_s} \text{Vol}(S_4) \]

\[ M_{SS} \sim f \frac{M_{GUT}^2}{\alpha_G^{1/2} M_p} \]

\( f \sim O(1) \quad \rightarrow \quad M_{SS} \sim 10^{13}\text{GeV} \)

Intermediate SUSY breaking scale
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\begin{align*}
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M_{SS} \simeq f \frac{M_{GUT}^2}{\alpha_{GUT}^{1/2} M_p}
\]

\[ f \sim O(1) \quad \Rightarrow \quad M_{SS} \sim 10^{13} \text{GeV} \]

\[ f \sim O(10^{-10}) \quad \Rightarrow \quad M_{SS} \sim 1 \text{TeV} \]

Low energy SUSY implies a huge fine-tuning of the closed string fluxes...
MSSM Higgs Inflation

Inflaton/Higgs potential generated by breaking SUSY at a high scale.

- Density scalar perturbations:
  
  \[
  \left( \frac{\delta \rho}{\rho} \right) \sim \left( \frac{V}{M_p^4 \epsilon} \right)^{1/2} \sim 10^{-5} \quad \Rightarrow \quad m_+ \sim 10^{12} - 10^{13}\text{GeV}
  \]

  Consistent with closed string fluxes as the main source of SUSY breaking. ✓

- Big tensor-to-scalar ratio: \( r \approx 0.1 - 0.2 \) BICEP2 ✓ (If confirmed...)

\[
\text{Lyth bound: } \frac{\Delta \phi}{M_p} \gtrsim \left( \frac{r}{0.01} \right)^{1/2} \quad \Rightarrow \quad \text{Transplanckian field range?}
\]
1) Identify the Higgs field with an open string modulus position modulus of a system of D7-branes.

2) Transplanckian field range: Monodromy inflation
   - Discrete periodicity
     - the spectrum repeats itself.
   - Closed string fluxes
     - generate the monodromy.

3) Inflation potential: dimensionally reduce DBI+CS for large field in the presence of closed string fluxes.
Toy model with D7-branes at singularities

6 D7-branes at \((\mathbb{C}^2 \times T^2) / \mathbb{Z}_4\)

Gauge group: \(U(3) \times U(2) \times U(1)\)

Matter fields: \(2(3, \bar{2}) + 2(1, \bar{3}) + (1, 2) + (1, \bar{2})\)

One \(U(2)\)-brane + \(U(1)\)-brane can leave the singularity in opposite directions respecting the \(\mathbb{Z}_2\) twist on the torus.

\(z_3 = 2\pi \alpha' \langle H_u + H_d^* \rangle \neq 0\)

Inflaton comes along with gauge symmetry breaking.
Gauge symmetry breaking:

- 2 complex doublets $H_u, H_d$ (8 real scalars)
- 3 Goldstone bosons
- 3 scalars $(H^\pm, h)$
- 2 left $(H, A) \to$ massless complex field $H_u + H_d^*$
- N=1 massive vector multiplets

Discrete shift symmetry:

$$ z_3 \to z_3 + 2\pi R n \quad \text{with} \quad z_3 = 2\pi \alpha' \langle H_u + H_d^* \rangle $$

- Massive states $(W^\pm, Z$ and the scalars $H^\pm, h)$

$$ M \simeq |H_u + H_d^*| < \frac{R}{\alpha'} $$

The physics repeats itself (no new couplings appear with trans-Planckian excursions)
Monodromy

Addition of $G_{(0,3)}$ ISD closed string fluxes

- Non-vanishing potential energy $\rightarrow$ monodromy
- Inflaton potential $\rightarrow$ DBI+CS action (exact in $\alpha'$)

\[
S_{DBI} = -\mu_7 \int d^8\xi \text{Str} \left[ e^{-\phi} \sqrt{-\det (P[E_{\mu\nu}] + \sigma F_{\mu\nu})} \right]
\]

DBI action in the presence of a background for $B_{12} = \frac{g_s \sigma}{2i} G^*_{(0,3)} \phi$

\[
S_{DBI} \approx \mu_7 g_s V_4 \int d^4\xi \ \theta^{1/2} (1 + Z \sigma^2 \partial_{\mu} \phi \partial_{\mu} \bar{\phi} + \ldots)
\]

where $\theta = 1 + \frac{1}{2} |\tilde{G}|^2 |\phi|^2 + \frac{1}{4} |\tilde{G}|^2 |\phi|^4$

\[
V(\varphi) = \mu_7 g_s V_4 \theta^{1/2}(\varphi) \propto \begin{cases} 
|\tilde{G}|^2 |\varphi|^2 & \text{for small field} \\
|\tilde{G}| |\varphi| & \text{for large field}
\end{cases}
\]

where $\varphi \equiv H_u + H_d^*$

Ibáñez, Valenzuela to appear
Supergravity description

Kahler potential

\[ K = - \log[(S + S^*)(U_3 + U_3^*) - \frac{\alpha'}{2}(H_u + H_d^*)(H_u^* + H_d)] \]

Modulus/dilaton dominance \[ V \propto |H_u + H_d^*|^2 \]

Continuous shift symmetry:

\[ H_u - H_d^* \rightarrow H_u - H_d^* + c \quad , \quad c \in \mathbb{C} \]

Consequence of the \( SL(2, \mathbb{Z}) \) symmetry of \( T^2 \)

▷ This field can not be the inflaton since it is frozen at zero vev by the \( Z_2 \) twist.  \( \langle h \rangle = \langle H_u - H_d^* \rangle = 0 \)

▷ All corrections to \( V \) should be \( \propto \mathcal{O}(H_u + H_d^*)^n \)

(in agreement with DBI action)
Control over higher dimensional operators

We have control over perturbative corrections in $\alpha'$
(DBI+CS action is exact in $\alpha'$)

What about corrections in gs?

- Discrete shift symmetry in $H = H_u + H_d^*$
  (physics repeats itself)
- N=2 underlying substructure (Higgs sector form an N=2 hypermultiplet)

$\eta$-problem $\rightarrow$ De-Sitter vacuum: $m^2 \sim H^2 \sim \mathcal{O}(10^{14} \, \text{GeV})$

Requires fine-tuning, but we already need a fine-tuning to have a light SM Higgs...

$\eta$ – problem $\equiv$ EW hierarchy problem
End of inflation: $\langle H \rangle = 0$ (gauge symmetry restored)

Inflaton: $H = H_u + H_d^* \rightarrow m_H^2 \simeq \frac{g_s}{2} |G|^2$

SM Higgs: $h = H_u - H_d^* \rightarrow m_h^2 \simeq 0$

Now $h$ is the lightest field and will play the role of the SM Higgs boson.
(The massive states decouple at high energies)

$$V_{SM} = m^2_h h^2 + \frac{g^2 + g_1^2}{8} \cos^2 2\beta |h|^4$$

Shift symmetry $\rightarrow \lambda \approx 0 \rightarrow \tan \beta \approx 1$
High SUSY breaking scale $\rightarrow m_h(\text{EW}) \approx 126$ GeV
For $M_{SS} \gtrsim 10^{10}$ GeV $\quad \Rightarrow \quad m_H = 126 \pm 3$ GeV
Conclusions

- Inflation and EW symmetry breaking driven by the Higgs sector.
- Hierarchy problem can be translated to conditions on the fluxes and local geometry (anthropic origin in a string landscape like the cosmological constant?)

String Theory

Work in progress...
Thank you very much!
Intermediate SUSY breaking scale

- Natural for String Theory.
- Fine-tuning on the Higgs mass.
- No SUSY particles so far at LHC.
- Role of SUSY: to stabilize the SM vacuum.
- High scale of inflation: $V_{\text{infl}}^{1/4} \approx 2 \times 10^{16} \left( \frac{r}{0.2} \right)^{1/4}$ GeV

$V_{\text{infl}}$ could be generated by breaking SUSY.

$$V_{SS} \approx (m_{3/2} M_p)^2 \quad \Rightarrow \quad M_{SS} \approx \frac{V_0^{1/2}}{M_p} \approx 10^{13} \text{GeV}$$
Higgs mass fine-tuning

Higgs mass matrix:

\[ m_{\text{Higgs}}^2 = \frac{g_s}{8} \left( 2|G_{(0,3)}|^2 + \frac{1}{4}|S_{(0,2)}|^2 - G^*_{(0,3)}S^*_{(0,2)} \right) \left( 2|G_{(0,3)}|^2 + \frac{1}{4}|S_{(0,2)}|^2 \right) + O(\langle F_2 \rangle^2) + O(S_{(2,0)}, G_{(3,0)}) + \ldots \]

In general

\[ \det(m_{\text{Higgs}}^2) \neq 0 \text{ at } M_{\text{GUT}} \]

but due to the running

\[ \det(m_{\text{Higgs}}^2) = 0 \text{ at } M_{\text{SS}} \]

\[ B^2 = m_u^2 m_d^2 \]

Fine-tuning condition at Mss.