Title: The Heterotic Standard Model- A Venue for Early Universe Cosmology

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Abstract:

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A.

HETEROTIC

STANDARD MODEL

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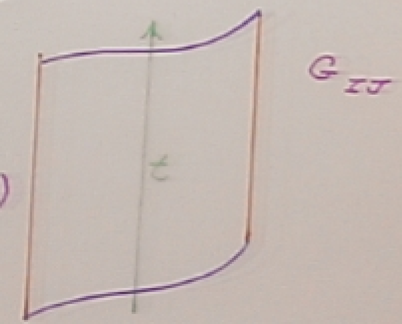
Heterotic Superstring:

A_I^a, $a \in Adj(E_8 \times E_8)$



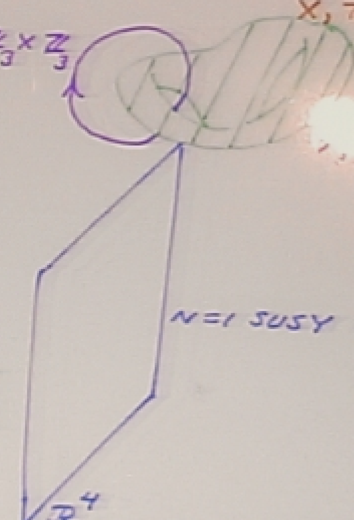
$$\underset{\text{observable}}{E_8} \times \underset{\text{hidden}}{E_8}$$

Observable Sector:

W, $hol(W) = \mathbb{Z}_3 \times \mathbb{Z}_3$

X, $\pi_1(X) = \mathbb{Z}_3 \times \mathbb{Z}_3$

V, $G = SU(4)$



$$E_8 \xrightarrow{SU(4)} Spin(10) \xrightarrow{\mathbb{Z}_3 \times \mathbb{Z}_3} SU(3)_C \times SU(2)_L \times U(1)_Y \times \boxed{U(1)_{B-L}}$$

Spectrum:

a) $\underline{\underline{3}}$ families of quark/leptons. Each family is

$(3,2,1,1)$, $(3,1,-4,-1)$, $(\bar{3},1,2,-1)$ ← quarks

$(1,2,-3,-3)$, $(1,1,6,-3)$ ← leptons

$+$

$\boxed{(1,1,0,3)}$ ← RH neutrino

b) $\underline{\underline{2}}$ pairs of Higgs / $\overline{\text{Higgs}}$ fields. Each pair is

$(1,2,3,0)$, $(1,\bar{2},-3,0)$

c)

NO

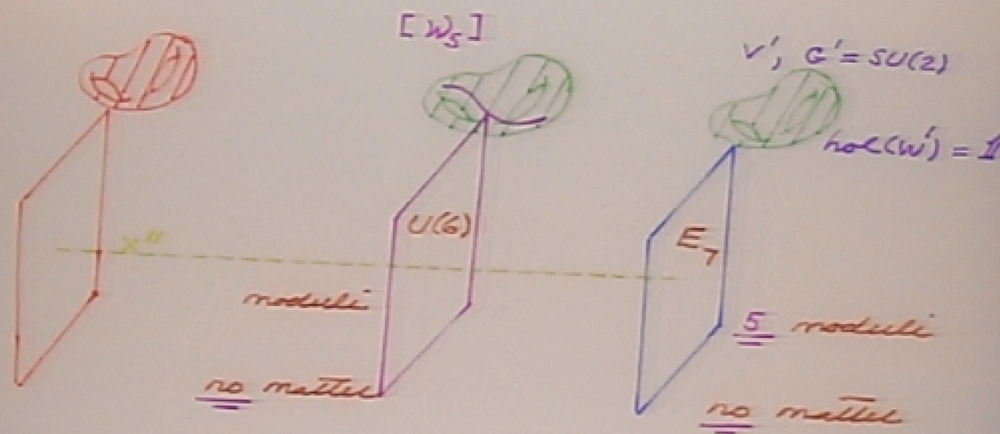
EXOTIC MATTER !

d) $\underline{\underline{6}}$ geometric moduli and $\underline{\underline{19}}$ vector bundle moduli

Hidden Sector:

Two possibilities –

1) Strong Coupling (M-Theory):



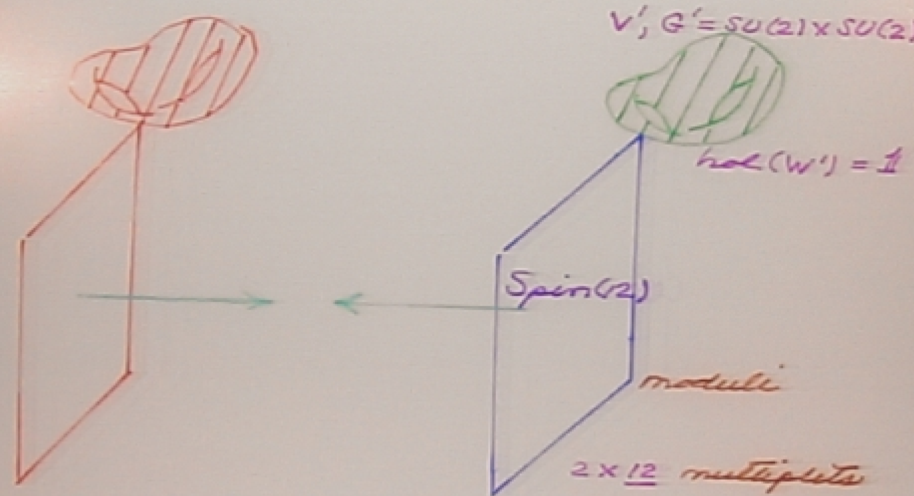
The U(6) gauge group can be spontaneously broken to

$$U(6) \longrightarrow U(1)^6$$

This is the vacuum for

Ekpyrotic Cosmology

2) Weak Coupling



This is vacuum for

Big Crunch / Big Bang Cosmology

Particle Physics Aspects:

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ Spectrum:

The zero mode spectrum is

$$\ker \not{D}_V = \underbrace{\left(H^0(X, \mathcal{O}_X) \otimes 45\right)^{\mathbb{Z}_3 \times \mathbb{Z}_3}}_{\text{gauge fields}} \oplus \underbrace{\left(H^1(X, \mathrm{ad}\, V) \otimes 1\right)^{\mathbb{Z}_3 \times \mathbb{Z}_3}}_{\text{moduli}}$$

$$\oplus \underbrace{\left(H^1(X, V) \otimes 16\right)^{\mathbb{Z}_3 \times \mathbb{Z}_3}}_{q/l \text{ families}} \oplus \underbrace{\left(H^1(X, V^*) \otimes \overline{16}\right)^{\mathbb{Z}_3 \times \mathbb{Z}_3}}_{\text{exotic particles}} \oplus \underbrace{\left(H^1(X, \wedge^2 V) \otimes 10\right)^{\mathbb{Z}_3 \times \mathbb{Z}_3}}_{\text{Higgs / Triplets}}$$

a) Exotic Particles:

$$n_{\overline{16}} = \left(H^1(X, V) \otimes \overline{16}\right)^{\mathbb{Z}_3 \times \mathbb{Z}_3}$$

Can choose V so that

$$n_{16} = \underline{\underline{0}}$$

$\Rightarrow$ No exotic particles!

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6) Doublet-Triplet Splitting

$$n_{10} = (H'(X, \wedge^2 V) \otimes 10)^{\mathbb{Z}_3 \times \mathbb{Z}_3}$$

We find that

$$H'(X, \wedge^2 V) = (1 \oplus \chi_1 \oplus \chi_2 \oplus \chi_1^2 \oplus \chi_2^2 \oplus \chi_1 \chi_2^2 \oplus \chi_1^2 \chi_2)^{\oplus 2}$$

1st $\mathbb{Z}_3$ 2nd $\mathbb{Z}_3$

The Wilson line acts on 10 as

$$10 = (\chi_1^2 (1,2) \overset{5}{\oplus} \chi_1^2 \chi_2^2 (3,1)) \oplus (\chi_1 (1,\bar{2}) \overset{\bar{5}}{\oplus} \chi_1 \chi_2 (\bar{3},1))$$

Tensoring these actions $\Rightarrow (H'(X, \wedge^2 V) \otimes 10)^{\mathbb{Z}_3 \times \mathbb{Z}_3}$ is spanned by $\underline{\underline{2}}$ copies of

$$(1,2,3,0), (1,\bar{2},-3,0)$$

$\Rightarrow$ $\underline{\underline{2}}$ copies of $H, \bar{H}$ pairs. Note, color triplets are projected out $\Rightarrow$

$\Rightarrow$ Doublet-Triplet Splitting!

c) Vector Bundle Moduli: (8)

$$n_1 = H^1(X, ad V)^{\mathbb{Z}_3 \times \mathbb{Z}_3}_{\otimes 1}$$

In general

$$h^1(X, ad V) \simeq \mathcal{O}(10^2)$$

$\Rightarrow$

$$h^1(X, ad V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \simeq \mathcal{O}\left(\frac{10^2}{9}\right) \sim \mathcal{O}(10)$$

An exact calculation $\Rightarrow$ $H^1(X, ad V)^{\mathbb{Z}_3 \times \mathbb{Z}_3}_{\otimes 1}$ is spanned by 19 copies of

$$(1, 1; 0, 0)$$

That is, there are 19 vector bundle moduli ϕ.

Interactions:

1) Higgs μ-Terms:

A "bare" term

$$n_1 = H^1(X, \mathrm{ad}V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \otimes 1$$

In general

$$h^1(X, \mathrm{ad}V) \simeq \mathcal{O}(10^2)$$

$\Rightarrow$

$$h^1(X, \mathrm{ad}V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \simeq \mathcal{O}\left(\frac{10^2}{9}\right) \sim \mathcal{O}(10)$$

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Interactions:

1) Higgs μ-Terms:

A "bare" term

$$\mu H \bar{H} \longleftarrow \text{impossible}$$

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However, a cubic interaction

$$\lambda \phi H \bar{H}$$

can occur, where

$\bar{\partial}$ closed (0,1)-forms

$$\lambda = \int_X \Omega \wedge \mathrm{Tr}(\psi_\phi \wedge \psi_H \wedge \psi_{\bar{H}})$$

λ corresponds to the triple intersection

$$H^1(X, \mathrm{ad}V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \otimes H^1(X, \wedge^2 V) \otimes H^1(X, \wedge^2 V) \longrightarrow H^3(X, \mathcal{O}_X)$$

We find there exist non-zero cubic couplings

$$\lambda_{iab} \phi_i H_a \bar{H}_b$$

where $a, b = 1, 2$ and $i = 1, \ldots, 4$. That is, only $\underline{\underline{4}}$ out of the 19 vector bundle moduli couple. $\Rightarrow$

$$W = \ldots \oplus \lambda_{iab} \langle \phi_i \rangle H_a \bar{H}_b \quad \leftarrow \mu\text{-terms}$$

However, a cubic interaction

$$\lambda \, \phi H \bar{H}$$

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$\bar{\partial}$ closed $(0,1)$-forms

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$$W = \ldots . \oplus \lambda_{iab} \langle \phi_i \rangle H_a \bar{H}_b \quad \leftarrow \mu\text{-Terms}$$

2) Yukawa Couplings:

Yukawa couplings are of the form

$$\lambda_u L H R + \lambda_\alpha L \bar{H} R$$

where

$$\lambda_{\binom{u}{\alpha}} = \int_X \Omega \wedge \mathrm{Tr}\left(\psi_L \wedge \psi_{\binom{H}{\bar{H}}} \wedge \psi_H\right)$$

$\lambda_{\binom{u}{\alpha}}$ corresponds to the triple intersection

$$H^1(X,V) \otimes H^1(X,\mathrm{ad}\,V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \otimes H^1(X,V) \longrightarrow H^3(X,\mathcal{O}_X)$$

We find there exist non-zero Yuk[illegible]a couplings

$$W = \ldots + \lambda_{\binom{u}{\alpha}\alpha a \beta} L_\alpha \left(\begin{smallmatrix} H \\ \bar{H} \end{smallmatrix}\right)_a R_\beta$$

where $\alpha, \beta = 1,2,3$ and $a = 1,2$.

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The Scalar Potential:

a) Perturbative Moduli Couplings:

These correspond to cubic interactions

$$\lambda_\phi \, \phi \, \phi \, \phi$$

where

$$\lambda_\phi = \int_X \Omega \wedge \mathrm{Tr}(\psi_\phi \wedge \psi_\phi \wedge \psi_\phi)$$

This corresponds to the triple intersection

$$H^1(X, \mathrm{ad}V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \otimes H^1(X, \mathrm{ad}V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \otimes H^1(X, \mathrm{ad}V)^{\mathbb{Z}_3 \times \mathbb{Z}_3} \to H^3(X, \mathcal{O}_X)$$

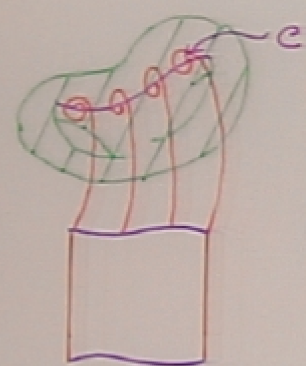
We find these exist non-zero couplings

$$W = \ldots + \lambda_{\phi\, iAB}\, \phi_i \phi_A \phi_B$$

where $i = 1, \ldots, 4$ and $A, B = 1, \ldots, 19$.

6) Non-Perturbative Moduli Couplings:

A) Worldsheet Instantons:



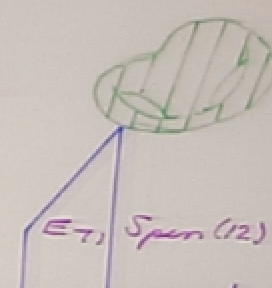
$$\Rightarrow W_i = \mathrm{Pfaff}(\phi)\, e^{A(C) + \int_C B}$$

$$\mathrm{Pfaff}(\phi) = \underbrace{c_{A_1 \ldots A_n} \phi_{A_1} \cdots \phi_{A_n}}_{\text{homogeneous}}$$

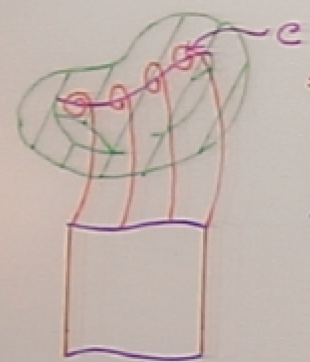
where $A_1, \ldots, A_n = 1, \ldots, 19$. The value of n depends on C.

B) Hidden Sector Gaugino Condensation:

$$W_g = \mathcal{C}\, e^{-\frac{6\pi}{b\alpha_{GUT}}(\overset{\text{dilaton}}{S} + \underset{S^1/Z_2}{\beta T} + \overset{\text{5-brane}}{\epsilon Y})}$$



A) Worldsheet Instantons:



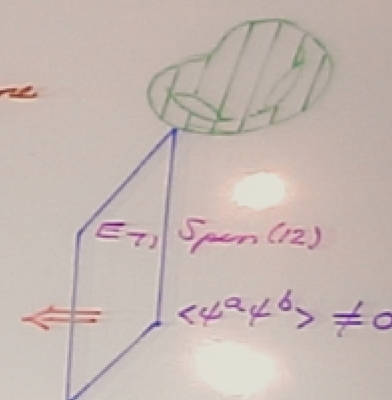
$$\Rightarrow W_i = \mathrm{Pfaff}(\phi)\, e^{A(C) + \int_C B}$$

$$\mathrm{Pfaff}(\phi) = \underbrace{c_{A_1 \ldots A_n} \phi_{A_1} \cdots \phi_{A_n}}_{\text{homogeneous}}$$

where $A_1, \ldots, A_n = 1, \ldots, 19$. The value of n depends on C.

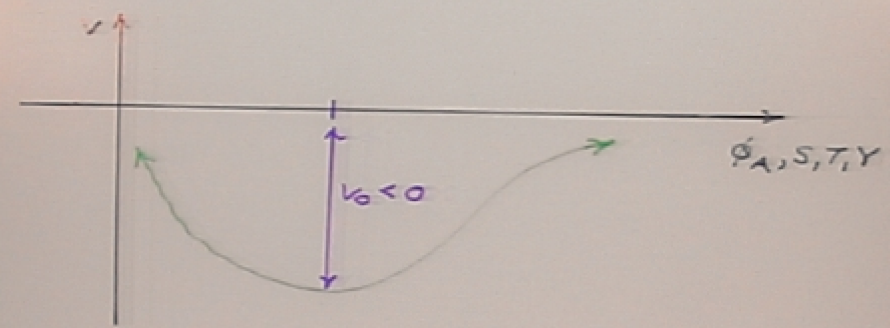
B) Hidden Sector Gaugino Condensation:

$$W_g = \mathbb{C}\, e^{-\frac{6\pi}{b\alpha_{GUT}}(\overset{\text{dilaton}}{S} + \underset{S^1/Z_2}{DT} + E\overset{\text{5-brane}}{Y})}$$



c) Potential Energy:

Putting everything together $\Rightarrow$



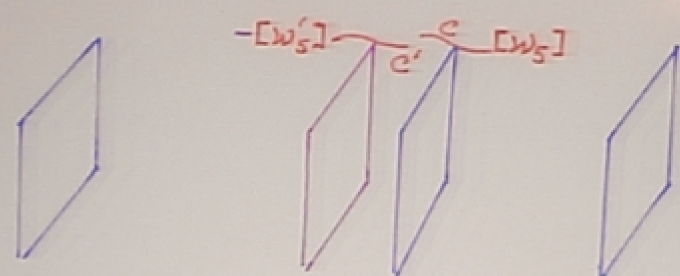
$\Rightarrow$

All moduli stabilized!

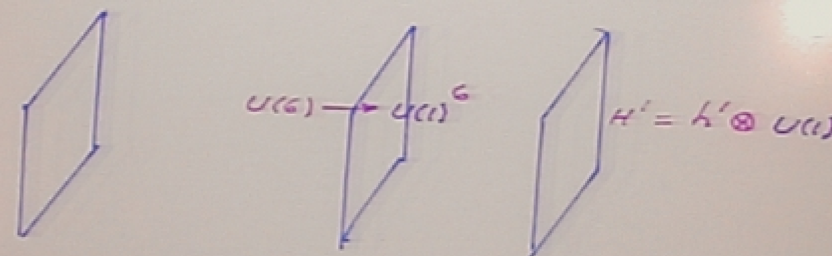
but with a negative cosmological constant

Can we improved by

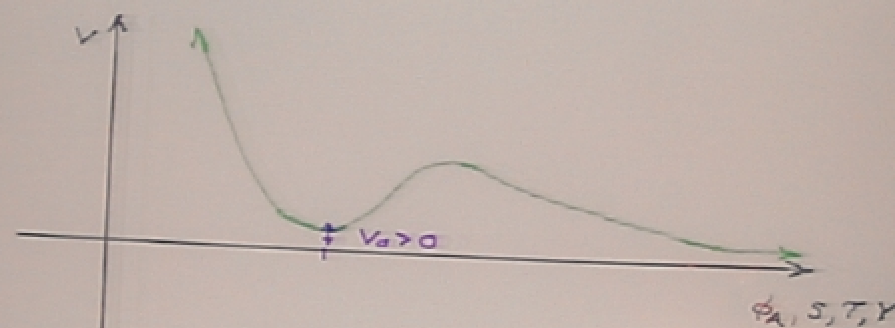
1) add anti five-branes



2) anomalous $U(1)$



1) and/or 2) $\Rightarrow$

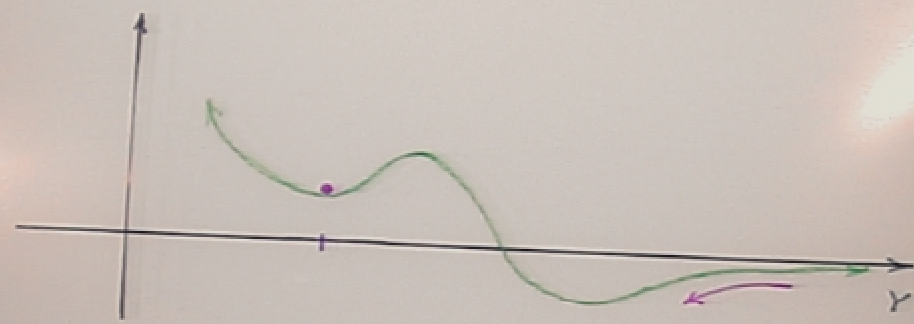


$\Rightarrow$ Quasi-stable vacuum with positive cosmological constant!

This is a multi-dimensional space. Looking in different directions $\Rightarrow$

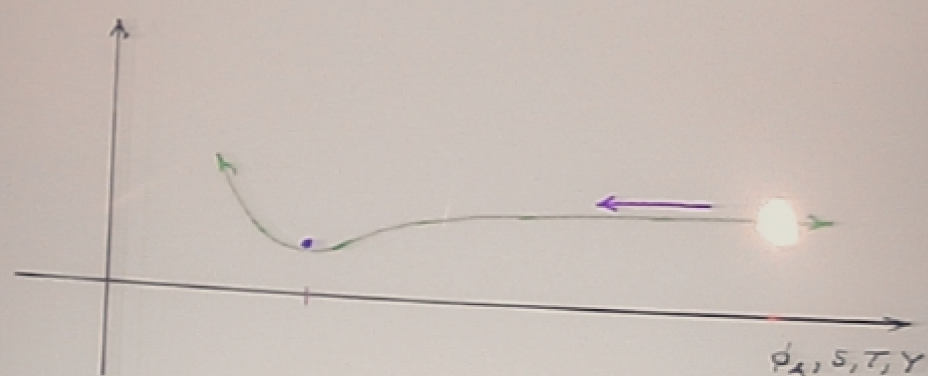
(15)

a) Big Crunch / Big Bang



Buchbinder, Borisov, Ovrut

b) Inflation



Buchbinder