UNIVERSITY OF LIVERPOOL

Non-SUSY String Phenomenology from $\mathbb{Z}_2 \times \mathbb{Z}_2$ Heterotic Orbifolds

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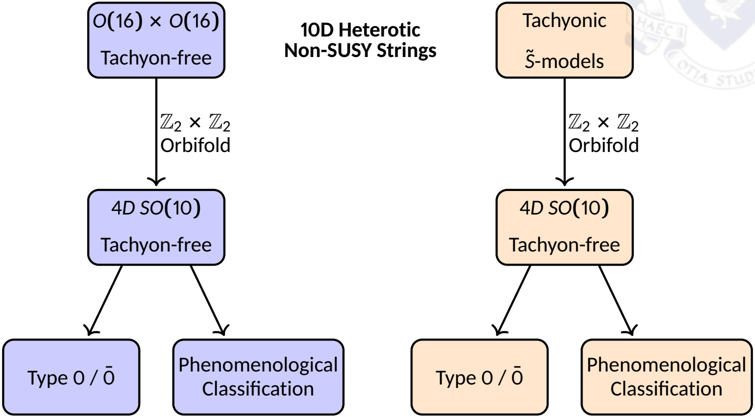
Overview: Non-SUSY $\mathbb{Z}_2 \times \mathbb{Z}_2$ Orbifold Landscape



Tachyonic 10D Heterotic: $SO(32)$, $O(16) \times E_8$, $O(8) \times O(24)$, $(E_7 \times SU_2)^2$, $U(16)$, E_8 [1, 2]
Type 0 10D strings: Type 0A/B, 8 Pin^- ([3])

Outline of Talk 1

1. Free Fermionic Formulation (FFF)
2. 10D Heterotic Strings in FFF
    2.1 10D Tachyonic String: $\tilde{S}$-map
3. S vs $\tilde{S}$ 4D SO(10) Models
4. Partition Function and Cosmological Constant for $\tilde{S}$ SO(10) models
5. Type 0 $\mathbb{Z}_2 \times \mathbb{Z}_2$ Heterotic Orbifolds
6. Type $\overline{0}$ $\mathbb{Z}_2 \times \mathbb{Z}_2$ Heterotic Orbifolds

Free Fermion Construction I

- Worldsheet CFT construction of heterotic string defined at enhanced symmetry point in moduli space [4].
- $D = 10 \implies$ introduction of free fermions on worldsheet

$$\{\underbrace{\psi^\mu, \chi^{i=1,\dots,6}}_{\substack{\text{S'partners} \\ \text{of } X^\mu}} \,||\, \underbrace{\bar{\psi}^{1,2,3,4,5}, \bar{\eta}^{1,2,3}}_{\substack{\text{rank 8} \\ \text{Observable G. G.}}}, \underbrace{\bar{\phi}^{1,2,3,4,5,6,7,8}}_{\substack{\text{rank 8} \\ \text{Hidden G. G.}}}\} \tag{1}$$

- Reduction to $D = 4 \implies$ introduction of

$$\{y^i, w^i \,||\, \bar{y}^i, \bar{w}^i\}, \quad i = 1, \dots, 6 \tag{2}$$

$\longleftrightarrow$ fermionised coordinates of internal T^6 such that $i\partial X^i_L = y^i w^i$.

Free Fermion Construction II

- 1-loop partition function (vacuum → vacuum amplitude) sufficient to get M.I. constraints and consistent 10D models.
- 2 ingredients for Model:
  1. N boundary Condition basis vectors

$$v_i = \{\alpha(f_1), \alpha(f_2), \ldots, \alpha(f_n)\}, \tag{3}$$

     where $\alpha(f) = 0 \implies NS$ and $\alpha(f) = 1 \implies R$.
  2. GGSO phases

$$C\begin{bmatrix} v_i \\ v_j \end{bmatrix} = \pm 1 \text{ or } \pm i, \quad i > j \tag{4}$$

     modular invariance $\implies 2^{N(N-1)/2}$ independent coefficients.

Free Fermion Construction III

- GSO projections to derive Hilbert space:

$$\mathscr{H} = \bigoplus_{\alpha\in\Xi} \prod_{i=1}^{N} \left\{ e^{i\pi v_i\cdot F_\alpha} |S_\alpha\rangle = \delta_\alpha C \begin{pmatrix} \alpha \\ v_i \end{pmatrix}^{*} |S_\alpha\rangle \right\} \mathscr{H}_\alpha \tag{5}$$

- The v_i span Ξ and sectors, α, are their linear combinations.
- Sectors characterised according to mass level:

$$\begin{aligned} M_L^2 &= -\frac{1}{2} + \frac{\xi_L \cdot \xi_L}{8} + N_L \\ M_R^2 &= -1 + \frac{\xi_R \cdot \xi_R}{8} + N_R \end{aligned} \tag{6}$$

where N_L and N_R sum over any oscillators.

Outline of Talk 2

1. Free Fermionic Formulation (FFF)

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3. S vs $\tilde{S}$ 4D SO(10) Models

4. Partition Function and Cosmological Constant for $\tilde{S}$ SO(10) models

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10D Heterotic Strings

- $E_8 \times E_8$ and $O(16) \times O(16)$ [5] heterotic–models have common basis vectors:

$$
\begin{aligned}
v_1 = \mathbb{1} &= \{\psi^\mu,\ \chi^{1,\dots,6} \,\|\, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\},\\
v_2 = z_1 &= \{\bar{\psi}^{1,\dots,5}, \bar{\eta}^{1,2,3}\},\\
v_3 = z_2 &= \{\bar{\phi}^{1,\dots,8}\},
\end{aligned} \tag{7}
$$

  distinguished by GGSO phase: $C\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \pm 1$

- SUSY vector:

$$
S = \mathbb{1} + z_1 + z_2 = \{\psi^\mu, \chi^{1,\dots,6}\} \tag{8}
$$

10D Tachyonic String

- Consider map [6, 7]:

$$S \mapsto \tilde{S} = \{\psi^{\mu}, \chi^{1,\dots,6} \Big\| \bar{\phi}^{3,4,5,6}\} \tag{9}$$

- Model with $\{\mathbb{1}, \tilde{S}\}$ can relate to $O(8) \times O(24)$ tachyonic heterotic string, see [1].
- No massless gravitinos, and untwisted tachyonic states:

$$|0\rangle_L \otimes \bar{\phi}^{3,4,5,6}|0\rangle_R \tag{10}$$

  are invariant under $\tilde{S}$.
- Goal: find tachyon-free $\tilde{S}$-models in $D = 4$.

Viable Standard-like $\tilde{S}$-Model

- In [7] (arXiv:1912.00061) $S \longmapsto \tilde{S}$ applied to phenomenologically viable, supersymmetric model of [9] (arXiv:0802.0470).
- Untwisted moduli field Thirring interactions have the general form

$$J^i(z)J^j(\bar{z}) = :y^i w^i :: \bar{y}^j \bar{w}^j : \quad \text{or} \quad :y^i w^i :: \bar{\Phi}^j \bar{\Phi}^{*j} :, \quad j = 1, \ldots, 22. \tag{11}$$

All projected via asymmetric BCs for $\{y, w \mid \bar{y}, \bar{w}\}^{1,\ldots,6} \longleftrightarrow$ non-geometric orbifolding.

- [9] argued twisted moduli fixed by absence of exact supersymmetric flat directions. Internal space not affected by $S \longmapsto \tilde{S}$.

Outline of Talk 3

1. Free Fermionic Formulation (FFF)

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3. S vs $\tilde{S}$ 4D SO(10) Models

4. Partition Function and Cosmological Constant for $\tilde{S}$ SO(10) models

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$\tilde{S}$ vs S 4D SO(10) Models

$\tilde{S}$-models:

$$
\begin{aligned}
\mathbf{1} &= \{ALL\} \\
\tilde{S} &= \{\psi^\mu, \chi^{1,\dots,6} \,\|\, \bar{\phi}^{3,4,5,6}\} \\
\mathbf{e_i} &= \{y^i, w^i \,\|\, \bar{y}^i, \bar{w}^i\}, \quad i = 1, \dots 6 \\
\mathbf{b_1} &= \{\psi^\mu, \chi^{12}, y^{34}, y^{56} \,\|\, \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,..,5}\} \quad (12) \\
\mathbf{b_2} &= \{\psi^\mu, \chi^{34}, y^{12}, y^{56} \,\|\, \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,..,5}\} \\
\mathbf{b_3} &= \{\psi^\mu, \chi^{56}, y^{12}, y^{34} \,\|\, \bar{y}^{12}, \bar{y}^{34}, \bar{\eta}^3, \bar{\psi}^{1,..,5}\} \\
\mathbf{z_1} &= \{\bar{\phi}^{1234}\}
\end{aligned}
$$

- $SO(10) \times U(1)^3 \times SO(4)^4$ untwisted gauge group
- SUSY explicitly broken by $S \longrightarrow \tilde{S}$
- $2^{12(12-1)/2} = 2^{66}$ independent phases: $C\begin{bmatrix} v_m \\ v_n \end{bmatrix}$, $m > n$

S-models:

$$
\begin{aligned}
\mathbf{1} &= \{ALL\} \\
S &= \{\psi^\mu, \chi^{1,\dots,6}\} \\
\mathbf{e_i} &= \{y^i, w^i \,\|\, \bar{y}^i, \bar{w}^i\}, \quad i = 1, \dots 6 \\
\mathbf{b_1} &= \{\chi^{3456}, y^{34}, y^{56} \,\|\, \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,..,5}\} \quad (13) \\
\mathbf{b_2} &= \{\chi^{1256}, y^{12}, y^{56} \,\|\, \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,..,5}\} \\
\mathbf{z_1} &= \{\bar{\phi}^{1,2,3,4}\} \\
\mathbf{z_2} &= \{\bar{\phi}^{5,6,7,8}\}
\end{aligned}
$$

- $SO(10) \times U(1)^3 \times SO(8)^2$ untwisted gauge group
- SUSY broken by GSO phase
- Independent phases: $2^{66} - 2^{66-8}$

$$
\left\{ C\begin{bmatrix} v_m \\ v_n \end{bmatrix} \,\middle|\, \neg \left(C\begin{bmatrix} S \\ e_i \end{bmatrix} = C\begin{bmatrix} S \\ z_1 \end{bmatrix} = C\begin{bmatrix} S \\ z_2 \end{bmatrix} = -1 \right) \right\} \quad (14)
$$

$\forall\, i \in \{1, .., 6\}$ and $m > n$.

$SO(10)$ Tachyonic Analysis I

- On-shell tachyons will arise when

$$M_L^2 = M_R^2 < 0, \tag{15}$$

- Same 126 Level-matched tachyonic sectors for $SO(10)$ S and $\tilde{S}$-models

Mass Level	Vectorials	Spinorials
$(-1/2, -1/2)$	$\{\bar{\lambda}^m\} \lvert NS\rangle$	$\lvert z_1\rangle\,,\ \lvert z_2\rangle$
$(-3/8, -3/8)$	$\{\bar{\lambda}^m\} \lvert e_i\rangle$	$\lvert e_i + z_1\rangle\,,\ \lvert e_i + z_2\rangle$
$(-1/4, -1/4)$	$\{\bar{\lambda}^m\} \lvert e_i + e_j\rangle$	$\lvert e_i + e_j + z_1\rangle\,,\ \lvert e_i + e_j + z_2\rangle$
$(-1/8, -1/8)$	$\{\bar{\lambda}^m\} \lvert e_i + e_j + e_k\rangle$	$\lvert e_i + e_j + e_k + z_1\rangle\,,\ \lvert e_i + e_j + e_k + z_2\rangle$

$i \neq j \neq k = 1, \ldots, 6$ and $m = 1, \ldots, 22$.

- Conditions on absence/survival under GSO projections of these tachyonic sectors listed in [12] (arXiv:2006.11340) for $\tilde{S}$ and in [13] for S-models.

$\tilde{S}$ vs S Massless Sectors

$\tilde{S}$-Models:

- $\mathbf{16}$'s of $SO(10)$ arise from:

$$
\begin{aligned}
B^{(1)F}_{pqrs} &= b_1 + pe_3 + qe_4 + re_5 + se_6 \\
B^{(2)F}_{pqrs} &= b_2 + pe_1 + qe_2 + re_5 + se_6 \\
B^{(3)F}_{pqrs} &= b_3 + pe_1 + qe_2 + re_3 + se_4
\end{aligned}
$$

$p, q, r, s = 0, 1$.

- $\tilde{S}$-map makes bosonic counterparts massive.
- Vectorial $\mathbf{10}$'s of $SO(10)$ arise through map

$$\tilde{x} = b_1 + b_2 + b_3 = \{\psi^\mu, \chi^{1,\dots,6} \,||\, \bar{\psi}^{1,\dots,5}, \bar{\eta}^{1,2,3}\} \sim S + x$$

$$V^{(1,2,3)B}_{pqrs} = B^{(1,2,3)F}_{pqrs} + \tilde{x} \qquad (16)$$

- *I.e.*

$$
\begin{array}{ccc}
B^{(1,2,3)F} & & \\
 & \searrow^{\tilde{x}} & \\
 & & V^{(1,2,3)B}
\end{array}
$$

S-Models:

- $\mathbf{16}$'s of $SO(10)$ arise from:

$$
\begin{aligned}
B^{(1)F}_{pqrs} &= S + b_1 + pe_3 + qe_4 + re_5 + se_6 \\
B^{(2)F}_{pqrs} &= S + b_2 + pe_1 + qe_2 + re_5 + se_6 \\
B^{(3)F}_{pqrs} &= S + b_3 + pe_1 + qe_2 + re_3 + se_4
\end{aligned}
$$

$p, q, r, s = 0, 1$.

- Vectorial $\mathbf{10}$'s of $SO(10)$ arise through map

$$x = 1 + S + \sum_{i=1}^{6} e_i + \sum_{k=1}^{2} z_k = \{\bar{\psi}^{1,\dots,5}, \bar{\eta}^{1,2,3}\}.$$

$$V^{(1,2,3)B}_{pqrs} = S + B^{(1,2,3)F}_{pqrs} + x \qquad (17)$$

- *I.e.*

$$
\begin{array}{ccc}
B^{(1,2,3)F} & \xrightarrow{S} & B^{(1,2,3)B} \\
\downarrow x & \searrow^{S+x} & \\
V^{(1,2,3)F} & & V^{(1,2,3)B}
\end{array}
$$

No Heavy Higgs for $\tilde{S}$ Models(?)

- Absence of $B^{(1,2,3)B}$ for $\tilde{S}$ PS models means no $n^B_{4R} - n^B_{\bar{4}R}$ PS breaking Higgs.
- No other suitable scalars in model [19].
- $\implies$ No missing partner mechanism either
- SLMs (maybe) only viable $SO(10)$ subgroup for $\tilde{S}$ ($SU(3) \times SU(2) \times U(1)^2$)
- $\implies$ PS $\tilde{S}$ classification only schematic

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Partition Function and Cosmological Constant

- Full PF

$$Z = \int_{\mathscr{F}} \frac{d^2\tau}{\tau_2^2} Z_B \sum_{\alpha,\beta} C\begin{bmatrix}\alpha\\ \beta\end{bmatrix} \prod_f Z\begin{bmatrix}\alpha(f)\\ \beta(f)\end{bmatrix} = \sum_{n.m} a_{mn} \int_{\mathscr{F}} \frac{d^2\tau}{\tau_2^3} q^m \bar{q}^n =: \sum_{m,n} a_{mn} I_{mn}. \tag{18}$$

$(Z_B = \frac{1}{\tau_2}\frac{1}{\eta^2\bar{\eta}^2})$ On-shell tachyon divergences:

$$I_{mn} = \begin{cases} \infty & \text{if} \quad m+n<0 \ \wedge \ m-n \notin \mathbb{Z}\backslash\{0\} \\ \text{Finite} & \text{Otherwise.} \end{cases} \tag{19}$$

- $N_b^0 = N_f^0$ interesting configurations. $\mathcal{O}(10^3)$ found in [12] for $SO(10)$ $\tilde{S}$-models.
- In forthcoming PS classification [13] S and $\tilde{S}$ configuration with $N_b^0 = N_f^0$ are found.

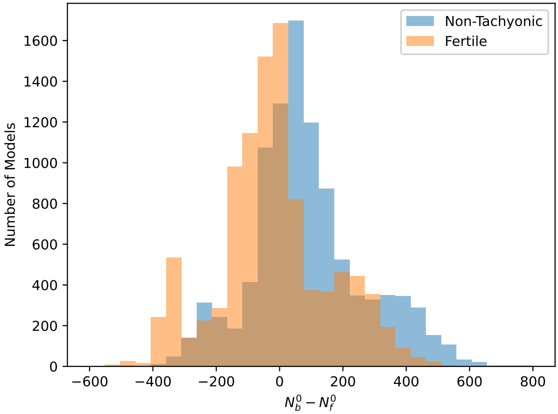
Classification Stats

- Phenomenological statistics from sample of 2×10^9 $SO(10)$ $\tilde{S}$-models.

	Constraints	Total models in sample	Probability
	No Constraints	2×10^9	1
(1)	+ Tachyon-Free	10741667	5.37×10^{-3}
(2)	+ No Observable Enhancements	10741667	5.37×10^{-3}
(3)	+ No Hidden Enhancements	9921843	4.96×10^{-3}
(4)	$+ N_{16} - N_{\overline{16}} \geq 6$	69209	3.46×10^{-5}
(5)	$+ N_{10} \geq 1$	69013	3.45×10^{-5}
(6)	$+ a_{00} = N_b^0 - N_f^0 = 0$	3304	1.65×10^{-6}

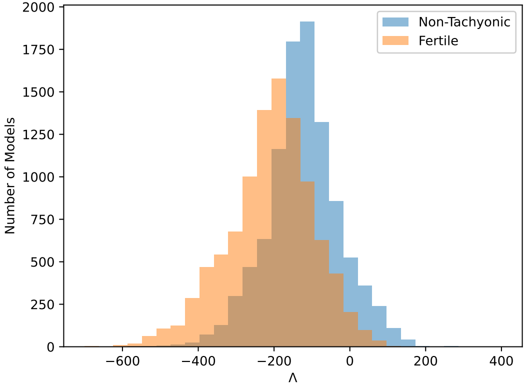
Distribution of $a_{00} = N_b^0 - N_f^0$ for $\tilde{S}$-models

- Distribution of the constant term $a_{00} = N_b^0 - N_f^0$ for a sample of 10^4 non-tachyonic and 10^4 fertile models ($N_{16} - N_{\overline{16}} \geq 6$, $N_{10} \geq 1$)



Distribution of Λ for $\tilde{S}$-models

- Distribution of the cosmological constant for a sample of 10^4 non-tachyonic and 10^4 fertile models



Outline of Talk 5

1. Free Fermionic Formulation (FFF)
2. 10D Heterotic Strings in FFF
   2.1 10D Tachyonic String: $\tilde{S}$-map
3. S vs $\tilde{S}$ 4D SO(10) Models
4. Partition Function and Cosmological Constant for $\tilde{S}$ SO(10) models
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Type 0 $\mathbb{Z}_2 \times \mathbb{Z}_2$ Heterotic Orbifold

- Type 0 models where all massless fermion absent from spectrum explored in [17]
- In [18] (arXiv:2010.06637) we proved their existence in the space of $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifolds.
- All such examples contain physical tachyons at the free fermionic point in the moduli space
- Using analysis of [20] (arXiv:1680.04582) may be tachyon-free away from FF point
- May be instrumental in exploring string dynamics in early universe cosmology(?)

Outline of Talk 6

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4. Partition Function and Cosmological Constant for $\tilde{S}$ SO(10) models
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6. Type $\overline{0}$ $\mathbb{Z}_2 \times \mathbb{Z}_2$ Heterotic Orbifolds

Type $\overline{0}$: No Massless Twisted Boson Models

- Counterpart of type 0: no twisted massless bosons.
- We find tachyon-free Type $\overline{0}$ vacua in [26] (arXiv:2011.12630) for S and $\tilde{S}$ 4D constructions.
- Exhibit maximal gauge group enhancement and spinorial **16** sectors absent.
- Large abundance of massless fermions $\Longrightarrow$ applications for dS cosmology(?)

Conclusion

- Tachyonic 10D string viable starting point for string pheno.
- Potentially stable $\tilde{S}$-models found from asymmetric orbifolding for SLM subgroup.
- Tools for exploring the cosmological constant and $N_b^0 - N_f^0$ for Non-SUSY string developed.
- Existence of 2 extremes in string spectrum of $\mathbb{Z}_2 \times \mathbb{Z}_2$ Heterotic Orbifolds: Type 0 and Type $\overline{0}$.
- Perhaps promising configurations for cosmological scenarios
- More work to be done seeing how these rogue string theories (tachyonic 10D, type 0...) link to wider duality web [27]
  (arXiv:2010.10521, arXiv:0705.0980, arXiv:hep-th/0612116)

Bibliography I

[1] L.J. Dixon and J.A. Harvey, Nucl. Phys. **B274**, 93 (1986)

[2] N. Seiberg and E. Witten, Nucl. Phys. **B276**, 272 (1986)

[3] O. Bergman and M. R. Gaberdiel, Nucl. Phys. B499(1997) 183–204, [hep-th/9701137];
O. Bergman and M. R. Gaberdiel, JHEP07(1999) 022, [hep-th/9906055]

[4] I. Antoniadis and C. Bachas, Nuclear Physics B, 298(3): 586 - 612, 1988.
I. Antoniadis and C. Bachas, and C. Kounnas, *Nuclear Physics B*, 289(0): 87 - 108, 1987.
H. Kawai, and D. C. Lewellen and S. H. H. Tye, *Phys. Rev. Lett.* **34** (1986) 12

[5] L. Alvarez-Gaumé, P. Ginsparg, G. Moore, and C. Vafa, *Phys. Lett.* B 171(1986)155;
L.J. Dixon and J.A. Harvey,Nucl. Phys.B274(1986) 93

[6] A.E. Faraggi, Eur. Phys. Jour.C79(2019) 703

[7] A.E. Faraggi, V. Matyas and B. Percival *Eur. Phys. Jour.* **C80** (2020) 4.

[8] L. J. Dixon and J.A Harvey, Nucl. Phys. **B274**, 93 (1986).

[9] G.B. Cleaver, A.E. Faraggi, E. Manno and C. Timirgaziu, *Phys. Rev.* D78(2008)046009

[10] K. R. Dienes, *Phys. Rev. Lett.* **65** (1990) 1979

[11] A.E. Faraggi, C. Kounnas, S.E.M Nooij and J. Rizos, hep-th/0311058
B. Assel, C. Christodoulides, A.E. Faraggi, C. Kounnas and J. Rizos,
Phys. Lett. **B683** (2010) 306; *Nucl. Phys.* **B844** (2011) 365;
A.E. Faraggi, J. Rizos and H. Sonmez, *Nucl. Phys.* **B886** (2014) 202;
H. Sonmez, *Phys. Rev.* **D93** (2016) 125002.
A.E. Faraggi, G. Harries and J. Rizos, *Nucl. Phys.* **B936** (2018) 472.

Bibliography II

[12] A.E. Faraggi, V. G. Matyas and B. Percival (2020), *arXiv:2006.11340*

[13] A.E. Faraggi, V. G. Matyas and B. Percival (2020), *Classification of Non-supersymmetric Pati-Salam Heterotic String Models* , arXiv:2011.XXXXX

[14] A.E. Faraggi, J. Rizos and H. Sonmez, *Nucl. Phys.* **B927** (2018) 1.
A.E. Faraggi, G. Harries, B. Percival and J. Rizos *Nucl. Phys.* **B953** (2020) 114969

[15] B. Assel *et al*, *Phys. Lett.* **B683** (2010) 306; *Nucl. Phys.* **B844** (2011) 365;
C. Christodoulides, A.E. Faraggi and J. Rizos, *Phys. Lett.* **B702** (2011) 81.

[16] I.Antoniadis, *A possible new dimension at a few TeV*, Phys. Lett. B246(1990)377

[17] M. Bianchi and A. Sagnotti, *Phys. Lett.* **B247** (1990) 517;
C. Angelantonj, *Phys. Lett.* **B444** (1998) 309;
R. Blumenhagen, A. Font, D. Lüst, *Nucl. Phys.* **B558** (1999) 159;
R. Blumenhagen, A. Kumar, *Phys. Lett.* **B464** (1999) 46;
O. Bergman and M.R. Gaberdiel, *JHEP* **03** (1999) 013;
K. Forger, *Phys. Lett.* **B469** (1999) 113;
E. Dudas and J. Mourad, *Nucl. Phys.* **B598** (2001) 189;
C. Angelantonj and A. Armoni, *Nucl. Phys.* **B578** (2000) 239;
D. Israel and V. Niarchos, *JHEP* **11** (2007) 093.

[18] A.E. Faraggi, V. G. Matyas and B. Percival (2020), arXiv:2010.06637.

[19] H. K. Dreiner, J. L. Lopez, D. V. Nanopoulos, D. B. Reiss. *Phys. Rev. Lett.* **B216** (1989) 283;
D. C. Lewellen, *Nucl. Phys.* **B337** (1990) 61;
K. R. Dienes, J. March-Russell, *Nucl. Phys.* **B479** (1996) 113.

[20] I. Florakis and J. Rizos, *Nucl. Phys.* **B913** (2016) 495.

Bibliography III

[21] K.R. Dienes, *Phys. Rev. Lett.* **65** (1990) 1979

[22] K.R. Dienes, *Nucl. Phys.* **B429** (1994) 533.

[23] K.R. Dienes, M. Moshe, and R.C. Myers, *Phys. Rev. Lett.* **74** (1995) 4767.

[24] C. Angelantonj, M. Cardella, S. Elitzur and E. Rabinovici, *JHEP* **1102** (2011) 024, arXiv:1012.5091.

[25] S. Abel, K.R. Dienes and E. Mavroudi, *Phys. Rev.* **D97** (2018) 126017; *JHEP* **2** (2011) 24.

[26] A.E. Faraggi, V. G. Matyas and B. Percival (2020), arXiv:2011.12630.

[27] J. Kaidi (2020), arXiv:2010.10521;
S. Hellerman and I. Swanson, *Phys. Rev. Lett.* **99** (2007) 171601, arXiv:0705.0980;
S. Hellerman and I. Swanson, *JHEP* **07** (2008) 022, arXiv:hep-th/0612116