Critical Aspects of Moduli Fixing

Michael Ratz

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Modular Invariance Approach to the Lepton and Quark Flavour Problems: from Bottom-up to Top-down, MITP, Mainz, Germany

Based on:
V. Knapp-Pérez, X.-G. Liu, H.P. Nilles, S. Ramos-Sánchez & M.R., Phys.Lett.B 844 (2023) 138106

Outline

&

Disclaimers

Before we start. . .

Apologies and disclaimers:

- This talk will not have extensive references to all activities that contribute to this exciting field, sorry!
- The ↗ symbols provide you with links to the respective references.
- I will suppress many details which are not essential to get the big picture.

Philosophy of this talk

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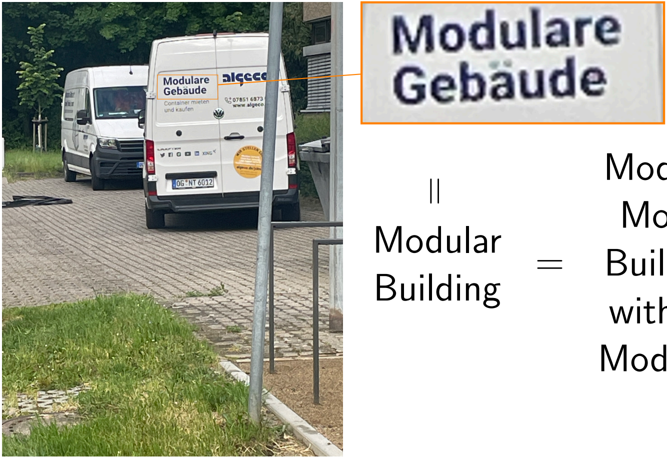
Modular
Building

Philosophy of this talk ☺



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Modular Building = Modular Model Building without Model(s)

Modular flavor symmetries

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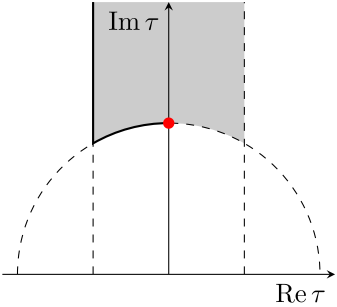
talks by **Gui-Jun Ding**, **João Penedo** & **Morimitsu Tanimoto**



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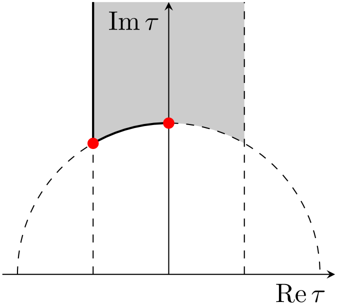

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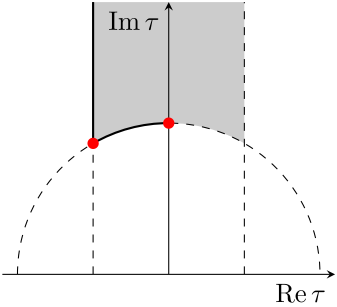

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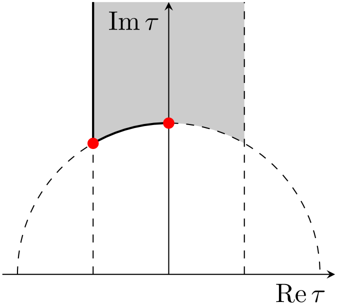

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- ☞ Challenge: find mechanisms that explain values of τ close to but not precisely at the critical points

String compactifications

- ☞ Violins: need to be built in such a way that the oscillating strings produce the right sounds

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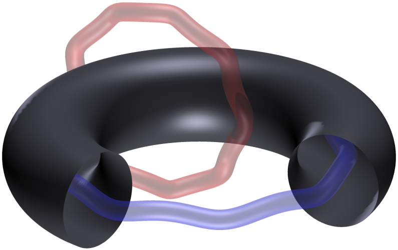

- String compactifications: twist the strings in such a way that the excitations carry the quantum numbers of the standard model particles

String phenomenology

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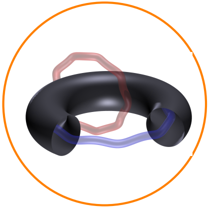

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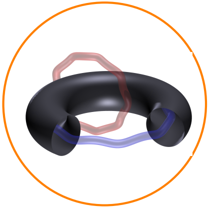

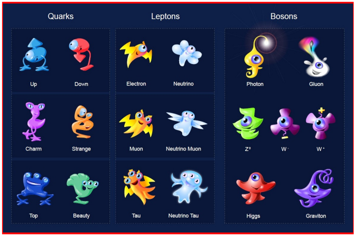

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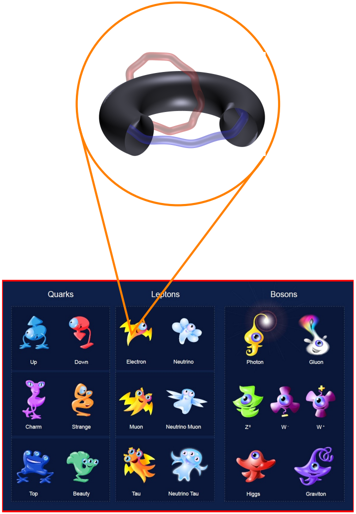

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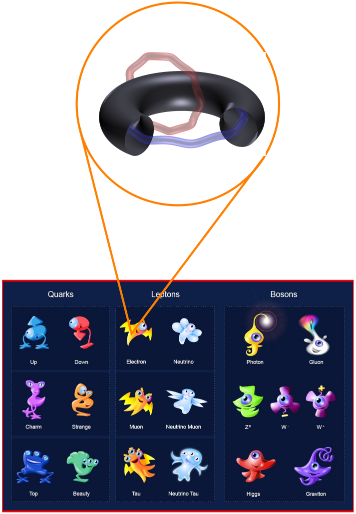


String phenomenology

String phenomenology

not easy either

hard

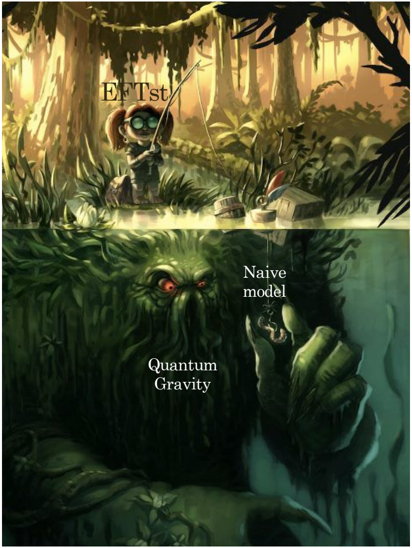
Moduli Fixing

in

Realistic

String Compactifications

Strings and the real world



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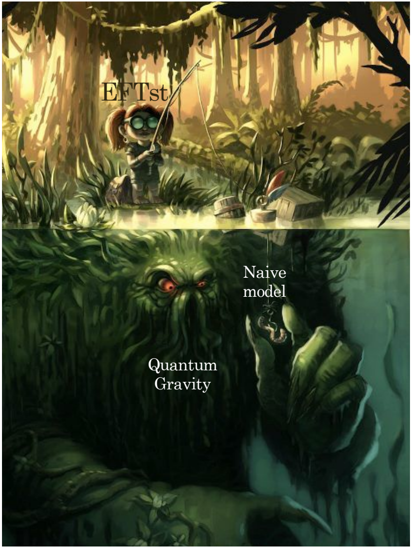

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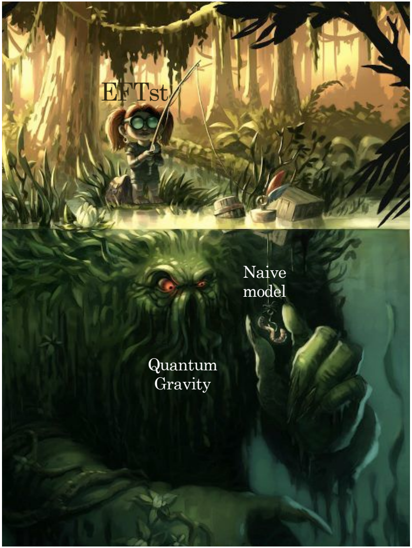

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. . . and so are top-down models which are inconsistent with observation

Particle physics from heterotic orbifolds

☞ Heterotic orbifolds have a long and rich history in providing us with potentially realistic models

Ibáñez, Kim, Nilles & Quevedo [1987];. . . ; Ramos-Sánchez & MR [2024]

as opposed to unrealistic

substantial literature

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- exactly 3 generations (vector-like exotics can be consistently decoupled)
- no (fractionally charged or other) exotics

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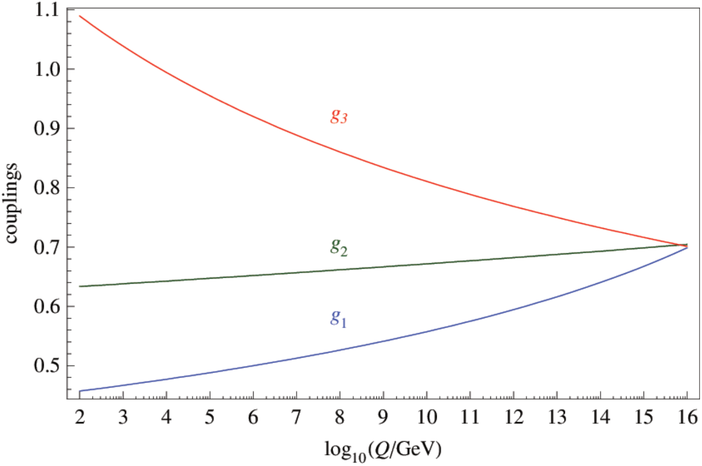
☞ In order to make these statements we need to make sure that the compact dimensions are stabilized at appropriate sizes

Appropriate compactification radii

cf. e.g. Dienes [1997]

☞ tension between $M_{\mathsf{GUT}} \simeq$ few $\cdot\, 10^{16}$GeV and typical compactification radii



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string tension

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Moduli fixing

cf. e.g. McAllister & Quevedo [2023]

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- ☞ What we can do is to assume that 6 dimensions are compact and then show that the fields describing the internal geometry get stabilized at appropriate values
- ☞ In practice even this is too hard
- ➥ Let's just toy with one geometric modulus plus dilaton

Large hierarchies in Nature

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Witten [1981];. . .

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Why?

$\mathcal{O}(10)$

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Witten [1981];...

$$\Lambda \sim M_\mathrm{P}\,\exp\left(-b/g^2\right)$$

RG invariant scale

$\mathcal{O}(1)$ coupling

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Witten [1981];...

$$\Lambda \sim M_{\mathrm{P}}\,\exp\left(-b/g^2\right)$$

➥ hierarchically small gravitino mass

Nilles [1982];...

$$m_W \sim m_{3/2} \sim \frac{\Lambda^3}{M_{\mathrm{P}}^2}$$

...provided that SUSY is broken

Breakdown of global SUSY

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see e.g. Shadmi & Shirman [2000]

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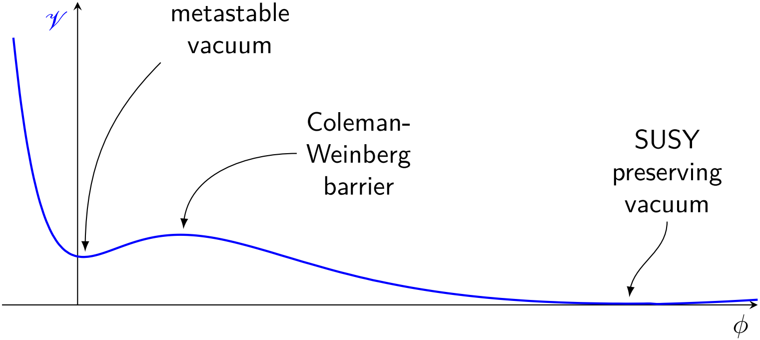
- ☞ However, very simple settings of supersymmetric QCD have **metastable** vacua which break SUSY Intriligator, Seiberg & Shih [2006];. . .



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- Effective description around metastable minimum: Intriligator & Seiberg [2007]

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$$\mathscr{W}_{\mathrm{ISS,eff}} = f_X\, X$$

local description of CW potential

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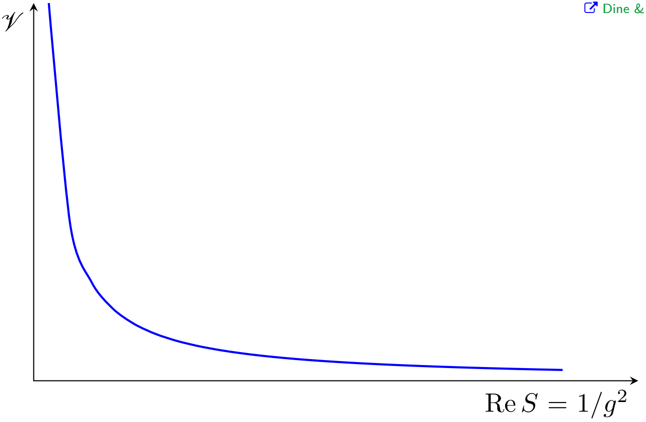
...works for a fixed gauge coupling...

Problem with string theory embedding

cf. talk by **Nicole Righi**

☞ **However**: embedding into string theory $\curvearrowright$ run-away problem

Dine & Seiberg [1985];...



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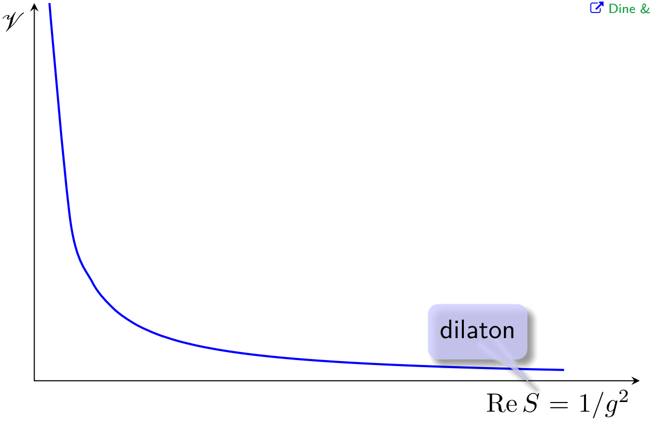

Constant + exponential scheme

Kachru, Kallosh, Linde & Trivedi [2003]

- KKLT type proposal: $\begin{cases} K_{\text{toy KKLT}} = -\ln(S+\overline{S}) \\ \mathscr{W}_{\text{toy KKLT}} = \underbrace{c}_{\text{constant}} - \underbrace{B\,\mathrm{e}^{-b\,S}}_{\text{non-perturbative}} \end{cases}$

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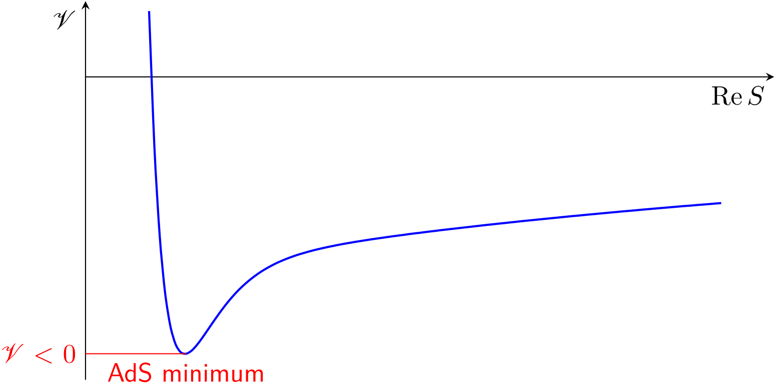

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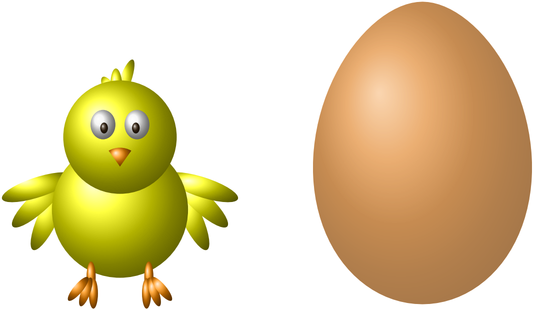

Chicken or egg problem

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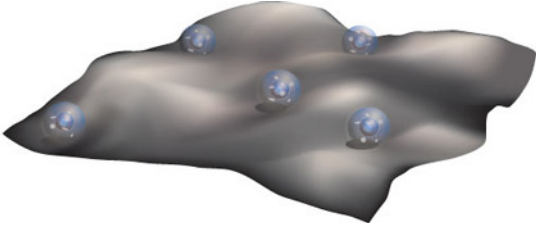
- ☞ Philosophy of flux compactifications: many vacua, in some of them c might be small by accident



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- Philosophy of flux compactifications: many vacua, in some of them c might be small by accident
- Alternative proposal: hierarchically small expectation of the perturbative superpotential due to an approximate $\mathrm{U}(1)_R$ symmetry

Kappl, Nilles, Ramos-Sánchez, MR, Schmidt-Hoberg & Vaudrevange [2009]

$$c \to \langle \mathscr{W}_{\text{pert}} \rangle \sim \langle \phi \rangle^N$$

typical VEV $\ll M_\text{P}$

$N = \mathcal{O}(10)$ order of explicit $\mathrm{U}(1)_R$ breaking

FI terms and breakdown of modular invariance

- ☞ The overwhelming majority of potentially realistic heterotic orbifold models has a Fayet–Iliopoulos (FI) D-term

$$\xi_{\mathrm{FI}} = \frac{\operatorname{tr} q_{\mathrm{anom}}}{192\pi^2} M_{\mathrm{P}}^2$$

FI terms and breakdown of modular invariance

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$\mathcal{O}(100)$

$$\xi_{\mathrm{FI}} = \frac{\mathrm{tr}\, q_{\mathrm{anom}}}{192\pi^2} M_{\mathrm{P}}^2 \;\sim \vartheta_{\mathrm{Cabibbo}}^2\, M_{\mathrm{P}}^2$$

FI terms and breakdown of modular invariance

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$$\xi_{\mathrm{FI}}=\frac{\mathrm{tr}\,q_{\mathrm{anom}}}{192\pi^2}M_{\mathrm{P}}^2\sim\vartheta_{\mathrm{Cabibbo}}^2\,M_{\mathrm{P}}^2$$

chiral superfield with nontrivial $\mathrm{U}(1)$ charges

- ☞ This does not signal an inconsistency but simply means that some “matter” fields have to acquire VEVs of the order $\vartheta_{\mathrm{Cabibbo}}\,M_{\mathrm{P}}$

Atick, Dixon & Sen [1987]

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Atick, Dixon & Sen [1987]

- ☞ This gives rise to Froggatt–Nielsen type scenarios

Binétruy, Lavignac & Ramond [1996]

FI terms and breakdown of modular invariance

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↗ Atick, Dixon & Sen [1987]

☞ This gives rise to Froggatt–Nielsen type scenarios

↗ Binétruy, Lavignac & Ramond [1996]

☞ Given that virtually all "matter" fields carry some nontrivial modular weights, this means that modular symmetry is broken spontaneously by the VEVs needed to cancel the FI term

Putting things together

"exp+const"
scheme

☞ The exp + constant scheme allows us to fix the dilaton in an adS supersymmetric vacuum

Kachru, Kallosh, Linde & Trivedi [2003];...

Putting things together

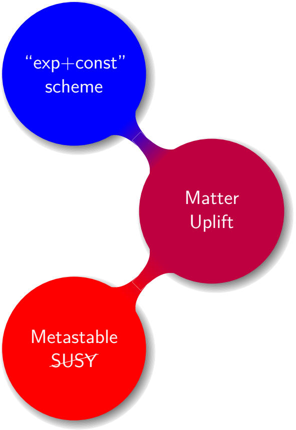
"exp+const"
scheme

Metastable
~~SUSY~~

☞ Metastable SUSY breaking yields a positive contribution to the vacuum energy

Intriligator, Seiberg & Shih [2006];...

Putting things together



"exp+const" scheme

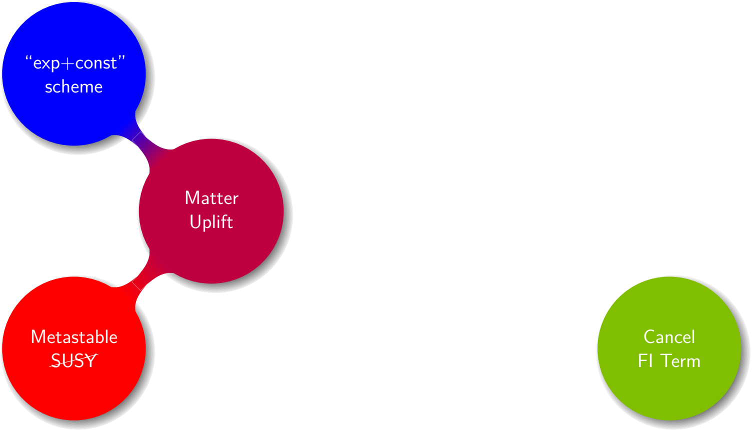
Matter Uplift

Metastable $\cancel{\text{SUSY}}$

☞ Uplifting via matter fields leads to a distinctive pattern of soft masses

↗ Lebedev, Nilles & MR [2006];...

Putting things together



“exp+const” scheme

Matter Uplift

Metastable ~~SUSY~~

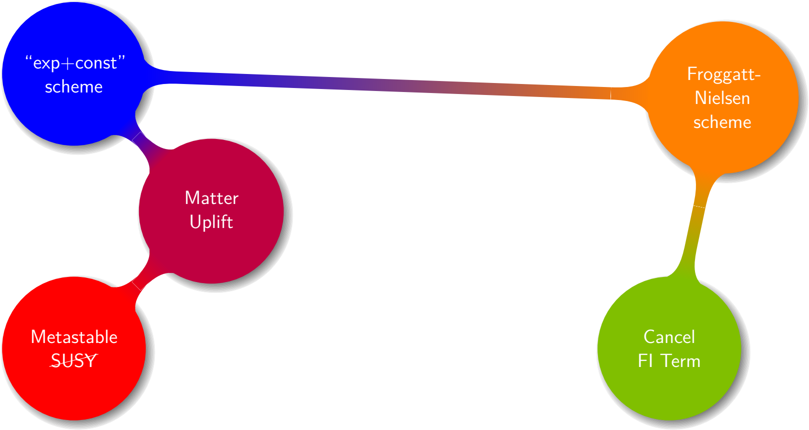
Cancel FI Term

☞ The FI term induces VEVs of matter fields

Putting things together

☞ Among other things this leads to flavor hierarchies a la Froggatt–Nielsen. . . Binétruy, Lavignac & Ramond [1996];. . .

Putting things together



“exp+const” scheme

Matter Uplift

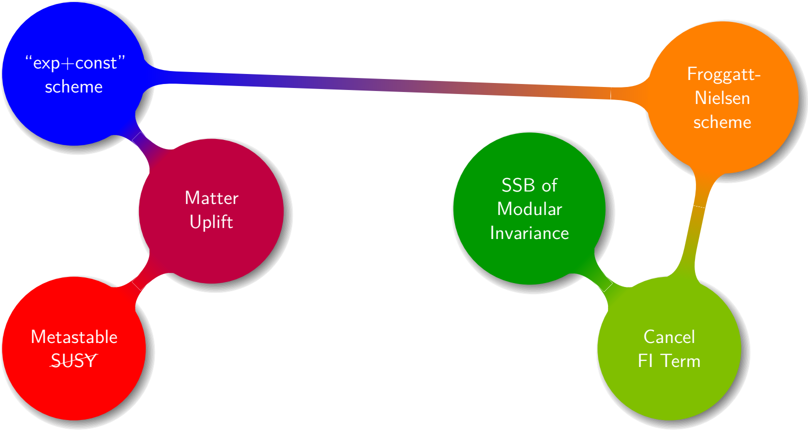
Metastable ~~SUSY~~

Froggatt-Nielsen scheme

Cancel FI Term

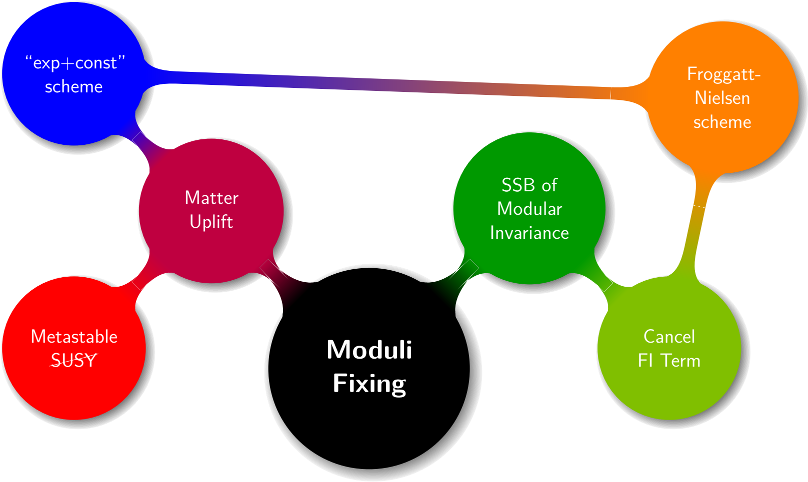
☞ Moderate hierarchy gets enhanced by approximate R symmetries to yield a tiny constant ↗ Kappl, Nilles, Ramos-Sánchez, MR, Schmidt-Hoberg & Vaudrevange [2009];. . .

Putting things together



☞ . . . and it leads to a spontaneous breakdown of modular invariance by matter field VEVs

Putting things together



☞ As we shall see, these effects can move the modulus τ slightly away from the symmetry enhanced points

Modular invariant gaugino condensation

Font, Ibáñez, Lüst & Quevedo [1990]; Nilles & Olechowski [1990]; Cvetic, Font, Ibanez, Lüst & Quevedo [1991];...

☞ Modular covariant superpotential describing gaugino condensate

$$\mathscr{W}_{\mathsf{gc}}(S,\tau)=\frac{\Omega(S)\,H(\tau)}{\eta^6(\tau)}$$

Dedekind η-function

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$$\mathscr{W}_{\mathsf{gc}}(S,\tau) = \frac{\Omega(S)\,H(\tau)}{\eta^6(\tau)}$$

- Ingredients

$$\Omega(S) = B\,\mathrm{e}^{-b\,S}$$

β-function coefficient

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$$H(\tau) = \left(\frac{E_4(\tau)}{\eta^8(\tau)}\right)^n \left(\frac{E_6(\tau)}{\eta^{12}(\tau)}\right)^m \mathcal{P}(j(\tau))$$

Eisenstein series

integers

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Klein j-function

polynomial

Modular invariant gaugino condensation

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Dent [2002]; Kobayashi, Shimizu, Takagi, Tanimoto & Tatsuishi [2019]; Ishiguro, Kobayashi & Otsuka [2021]
Novichkov, Penedo & Petcov [2022]; Ishiguro, Okada & Otsuka [2022]; Leedom, Righi & Westphal [2023]; talk by **Nicole Righi**

- ☞ Vacua away from the critical lines

Leedom, Righi & Westphal [2023]; talk by **Nicole Righi**

- ☞ Uplifting via Shenker terms

Involving matter fields

☞ Kähler and superpotential

Knapp-Perez, Liu, Nilles, Ramos-Sánchez & MR [2023]

$$K = -\ln(S+\overline{S}) - 3\ln(-\mathrm{i}\,\tau + \mathrm{i}\,\overline{\tau}) + (-\mathrm{i}\,\tau + \mathrm{i}\,\overline{\tau})^{-k_X}\,\overline{X}X - (-\mathrm{i}\,\tau + \mathrm{i}\,\overline{\tau})^{-2k_X}\,\frac{(\overline{X}X)^2}{\Lambda_{\mathrm{ISS}}^2}$$

ISS field

local description
of Coleman–Weinberg
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small constants induced by matter fields of various modular weights

gaugino condensate

effective description of ISS sector

Fixing τ close to i

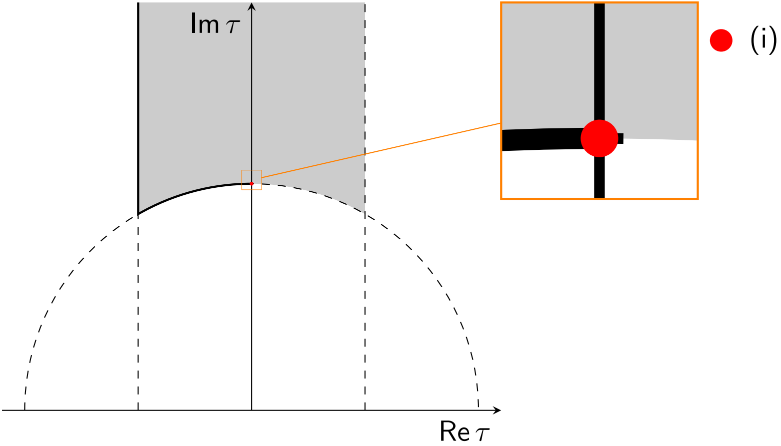
Knapp-Perez, Liu, Nilles, Ramos-Sánchez & MR [2023]

$$(m,n) = (0,1)\ ,\quad c_1 = 2\cdot 10^{-8}\ ,\ (k_c, k_X) = (1,0)$$

$$b = 10\ ,\ B = 1\ ,\ \Lambda_{\mathrm{ISS}} = 10^{-9}$$

c_2	f_X	k_Y	τ	$\langle\mathscr{V}\rangle$
0	0	0	i	< 0
$2\mathrm{e}^{\mathrm{i}\,\pi/3}\cdot 10^{-8}$	0	0	$-0.014 + 1.015\,\mathrm{i}$	< 0
0	$3.49\cdot 10^{-8}$	0	i	$\simeq 0$
0	$6\cdot 10^{-8}$	1	$1.010\,\mathrm{i}$	$\simeq 0$
$2\mathrm{e}^{\mathrm{i}\,\pi/3}\cdot 10^{-8}$	$5\cdot 10^{-8}$	0	$-0.018 + 1.011\,\mathrm{i}$	$\simeq 0$
$2\mathrm{e}^{\mathrm{i}\,\pi/3}\cdot 10^{-8}$	$8.5\cdot 10^{-8}$	1	$-0.018 + 1.021\,\mathrm{i}$	$\simeq 0$

Stabilization of τ



- ☞ No matter fields, only τ, with or without uplift

Fixing τ close to i

↗ Knapp-Perez, Liu, Nilles, Ramos-Sánchez & MR [2023]

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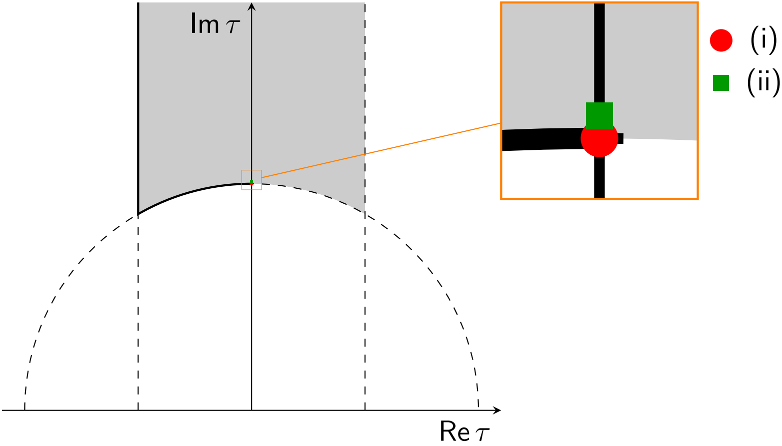

- ☞ Breaking of modular invariance by matter fields

Fixing τ close to i

Knapp-Perez, Liu, Nilles, Ramos-Sánchez & MR [2023]

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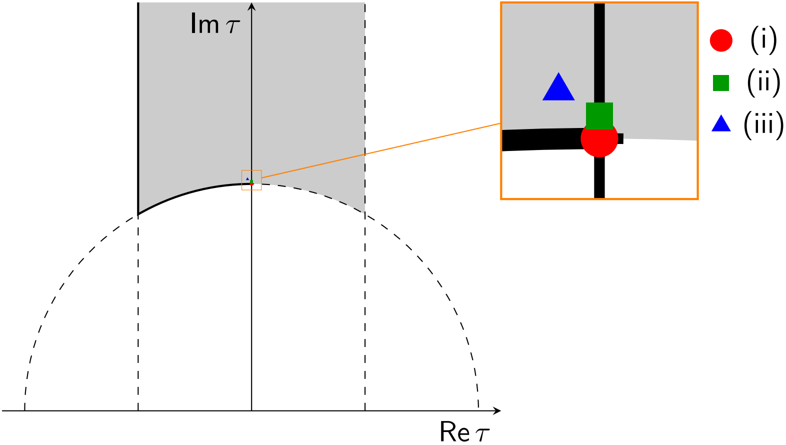

☞ Spontaneous breakdown of modular invariance by matter field and uplift

Fixing τ close to $\omega := \mathrm{e}^{2\pi\,\mathrm{i}\,/3}$

Knapp-Perez, Liu, Nilles, Ramos-Sánchez & MR [2023]

- Kähler and superpotential

$$K = -\ln(S+\overline{S}) - 3\ln(-\mathrm{i}\,\tau + \mathrm{i}\,\overline{\tau}) + (-\mathrm{i}\,\tau + \mathrm{i}\,\overline{\tau})^{-k_X}\,\overline{X}X - (-\mathrm{i}\,\tau + \mathrm{i}\,\overline{\tau})^{-2k_X}\,\frac{(\overline{X}X)^2}{\Lambda_{\mathrm{ISS}}^2}$$

ISS field

local description of Coleman–Weinberg potential

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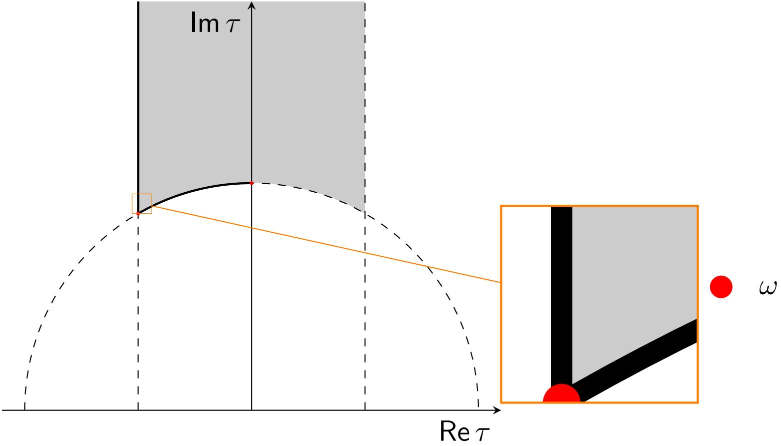
$$(m,n) = (1,0)\;,\; c_1 = 2\cdot 10^{-8}\;,\; c_2 = 0\;,\; b = 10\;,\; B = 1\;,\; k_c = 0\;,\; f_X = 0$$

fixes

$$\tau_{\mathsf{AdS}} \simeq -0.48 + 0.88\,\mathrm{i}\;,\; S \simeq 2.15 \text{ and } \mathscr{V} \simeq -1.28\cdot 10^{-12} < 0$$

Stabilization of τ



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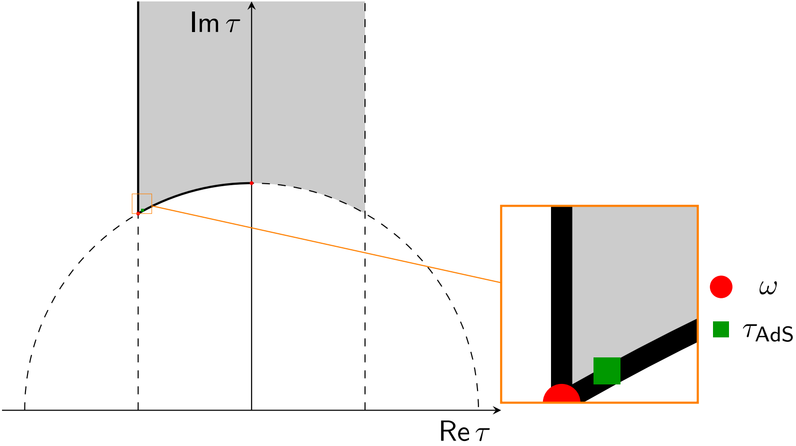
Stabilization of τ



☞ Spontaneous breakdown of modular invariance by matter field

Fixing τ close to ω

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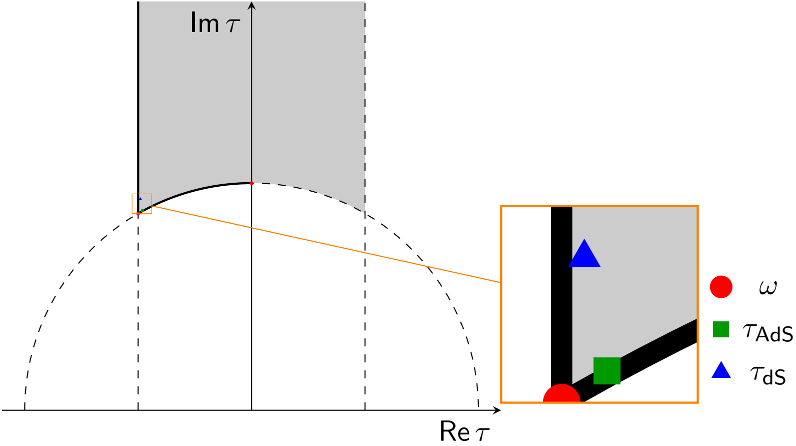
$$(m,n) = (1,0)\ ,\ c_1 = 2\cdot 10^{-8}\ ,\ c_2 = 0\ ,\ b = 10\ ,\ B = 1\ ,\ k_c = 0$$

$\Lambda_{\mathrm{ISS}} = 10^{-7}\ ,\ k_X = 0\ ,\ k_Y = 1$ and $f_X \simeq 6\cdot 10^{-8}$

fixes

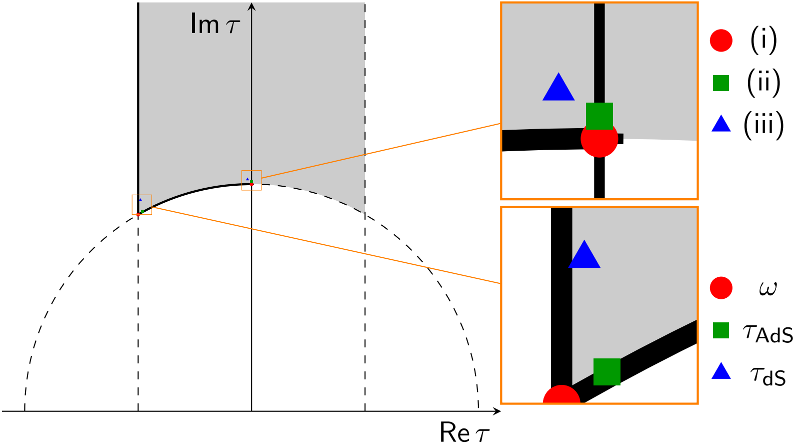
$\tau_{\mathsf{dS}} \simeq -0.49 + 0.94\,\mathrm{i}$ and $S \simeq 2.16$

Stabilization of τ



☞ Spontaneous breakdown of modular invariance by matter field and uplift

Stabilization of τ



☞ Survey of all cases

Summary

&

Outlook

Summary

- ☞ Delicate interplay between perturbative and nonperturbative effects can fix the dilaton and the modulus τ

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Summary

- ☞ Delicate interplay between perturbative and nonperturbative effects can fix the dilaton and the modulus τ
- ☞ Crucial ingredients:
  1. spontaneous breakdown of modular invariance when fields of nontrivial modular weights attain VEV
  2. positive contributions to the vacuum energy from (metastable) dynamical supersymmetry breaking
- ☞ Spontaneous breaking of modular invariance by matter fields unavoidable in explicit string models:
  1. cancellation of FI term
  2. breaking of extra gauge symmetries

Outlook

☞ Loose ends:

1. explicit stabilization of matter field VEVs

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- ☞ Further insights from top-down models
- ☞ More precision

Thank you very much!

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Backup slides

R symmetries

☞ Discrete R symmetries arise as remnants of the Lorentz symmetry of compact dimensions and are arguably on the same footing as the fundamental symmetries $\mathcal{C}$, $\mathcal{P}$ and $\mathcal{T}$

▸ back

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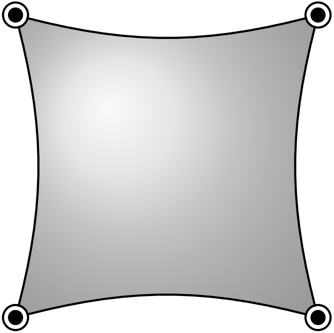
- ☞ Example: order four discrete R symmetry $\mathbb{Z}_4^R$ from $\mathbb{Z}_2$ orbifold plane



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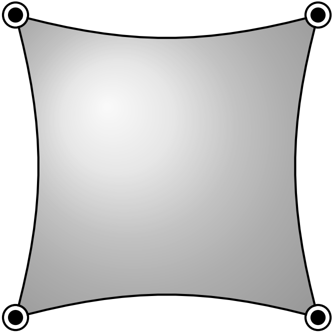

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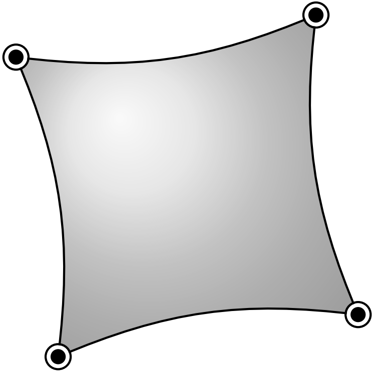

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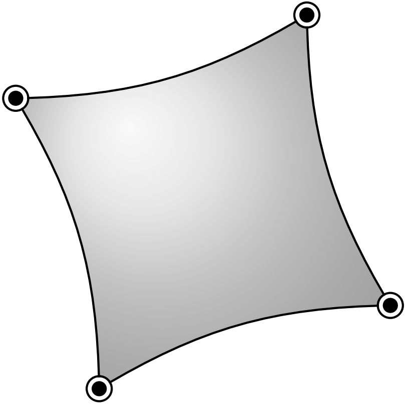

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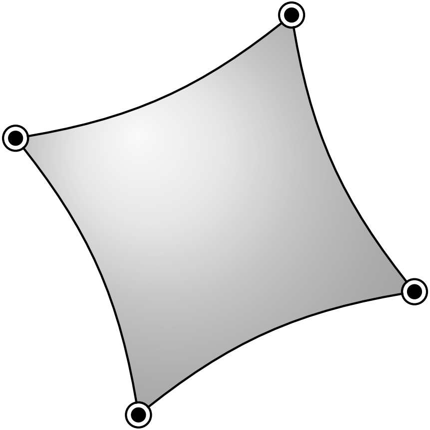

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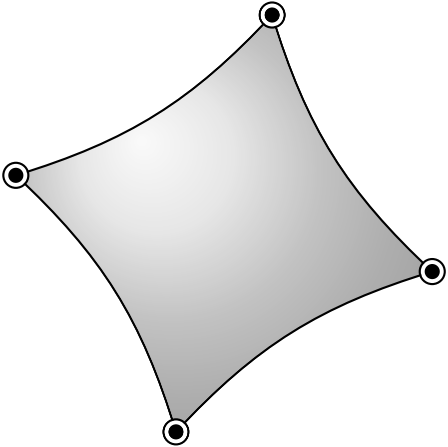

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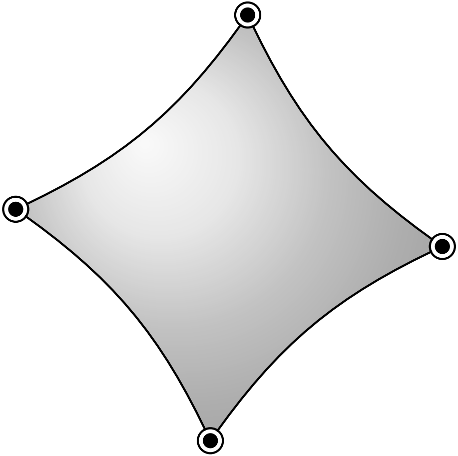

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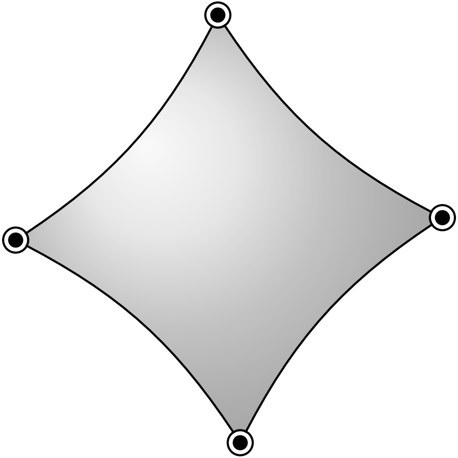

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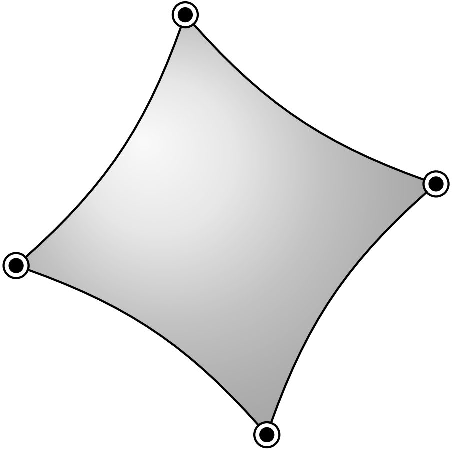

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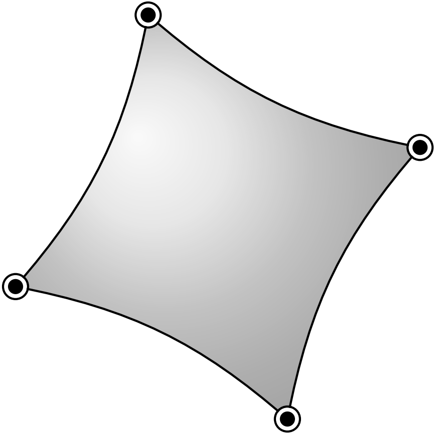

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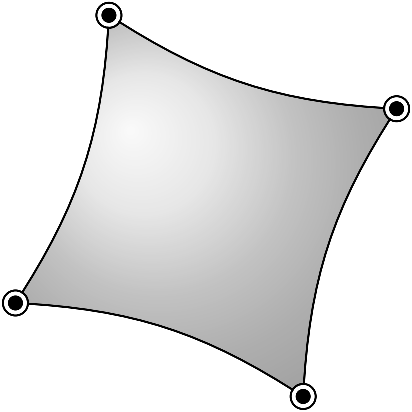

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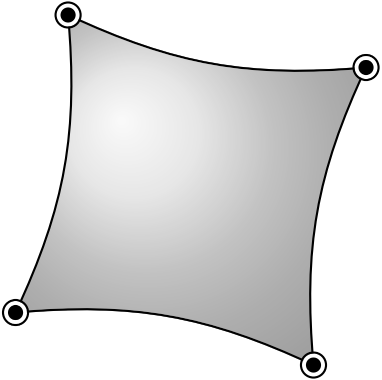

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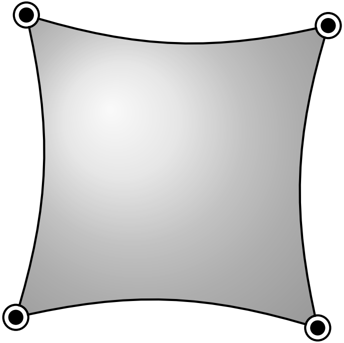

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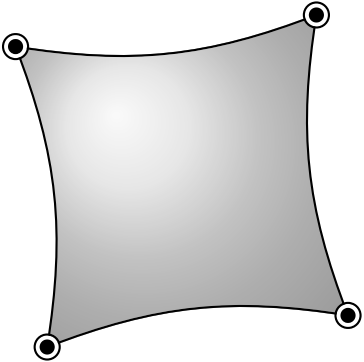

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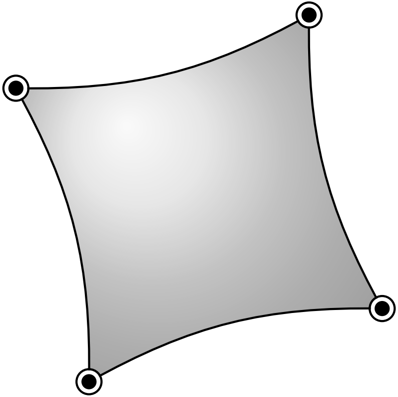

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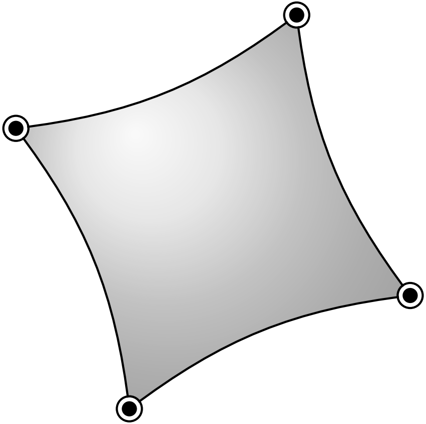

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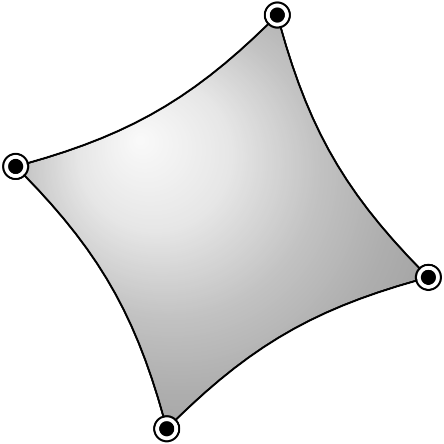

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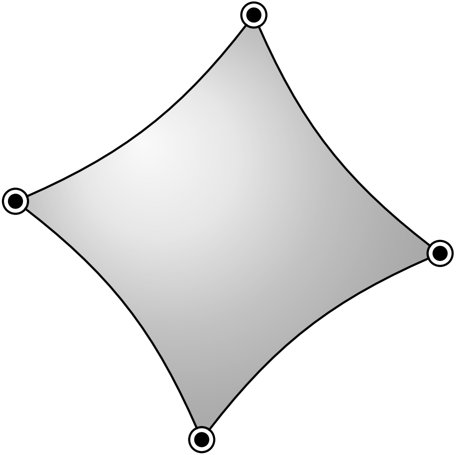

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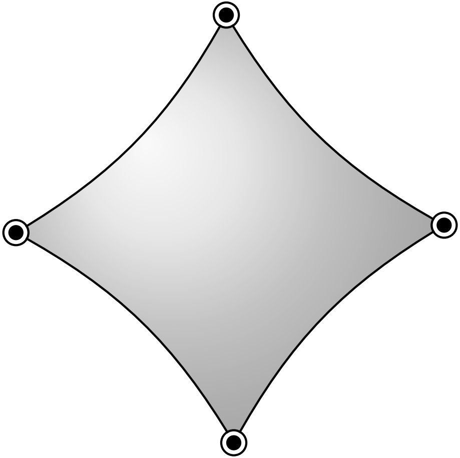

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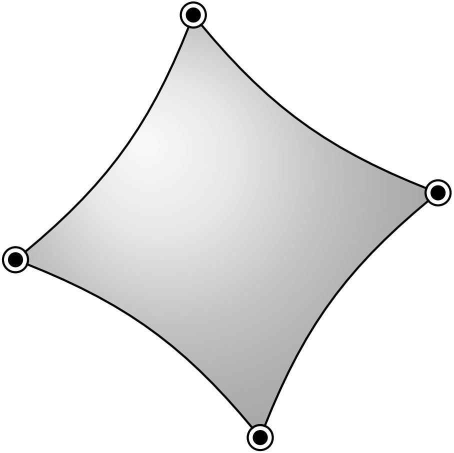

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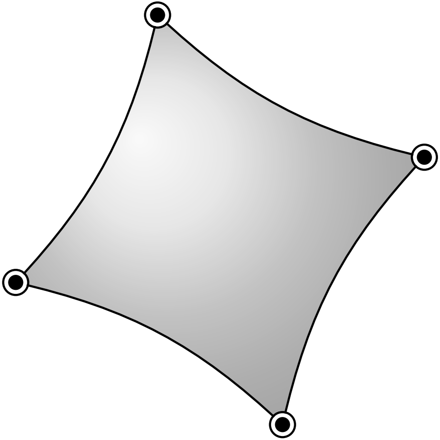

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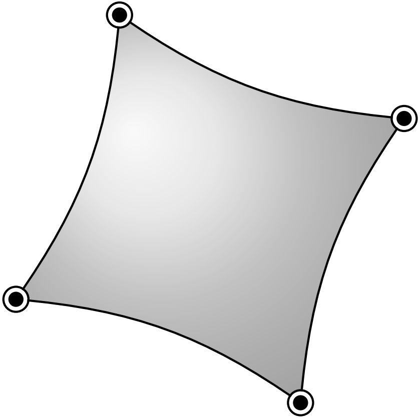

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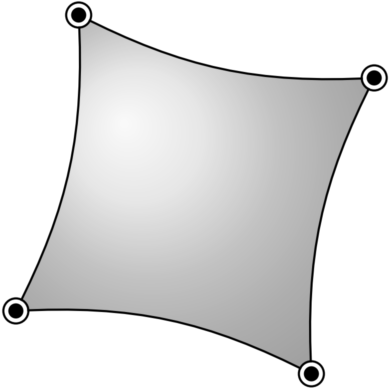

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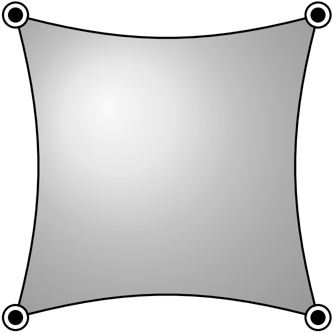

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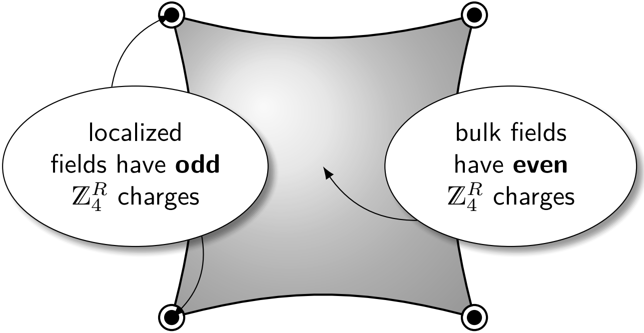

localized fields have **odd** $\mathbb{Z}_4^R$ charges

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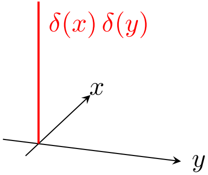
Interlude: Field theory vs. string theory



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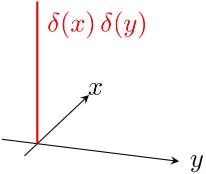

- ☞ In field theory it is hard to figure out whether or not localized states transform nontrivially under discrete rotations in compact dimensions
- ☞ In string theory it follows from H-momentum conservation that localized (twisted) states have odd $\mathbb{Z}_4^R$ charges while bulk (untwisted) have even $\mathbb{Z}_4^R$ charges

Hierarchically small $\langle \mathscr{W} \rangle$

Two observations:

1. in the presence of an exact $\mathrm{U}(1)_R$ symmetry

$$\frac{\partial \mathscr{W}}{\partial \phi_i} = 0 \quad \curvearrowright \quad \langle \mathscr{W} \rangle = 0$$

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fields

superpotential

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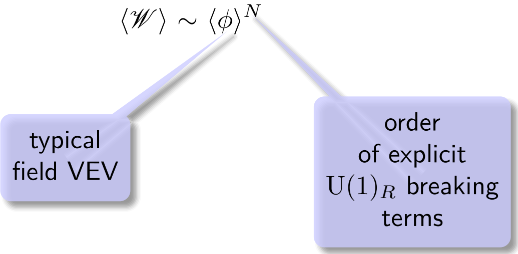
2. for approximate R symmetries



$$\langle\mathscr{W}\rangle\sim\langle\phi\rangle^N$$

typical field VEV

order of explicit $\mathrm{U}(1)_R$ breaking terms

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (I)

aim: show that

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Consider a superpotential

$$\mathscr{W} = \sum c_{n_1\cdots n_M}\,\phi_1^{n_1}\cdots\phi_M^{n_M}$$

with an exact R symmetry

$$\mathscr{W} \mapsto \mathrm{e}^{2\,\mathrm{i}\,\alpha}\,\mathscr{W}\;, \quad \phi_j \mapsto \phi_j' = \mathrm{e}^{\mathrm{i}\,r_j\,\alpha}\,\phi_j$$

where each monomial in $\mathscr{W}$ has total R charge 2

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (II)

Consider a field configuration $\langle \phi_i \rangle$ with

$$F_i = \frac{\partial \mathscr{W}}{\partial \phi_i} = 0 \quad \text{at } \phi_j = \langle \phi_j \rangle$$

Under an infinitesimal $\mathrm{U}(1)_R$ transformation, the superpotential transforms nontrivially

$$\mathscr{W}(\phi_j) \mapsto \mathscr{W}(\phi_j') = \mathscr{W}(\phi_j) + \sum_i \frac{\partial \mathscr{W}}{\partial \phi_i} \Delta\phi_i$$

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This is only possible if $\langle\mathscr{W}\rangle = 0\,$!

bottom-line:

$$\frac{\partial\mathscr{W}}{\partial\phi_i} = 0 \qquad \curvearrowright \qquad \langle\mathscr{W}\rangle = 0$$

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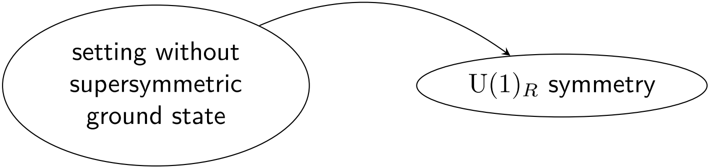

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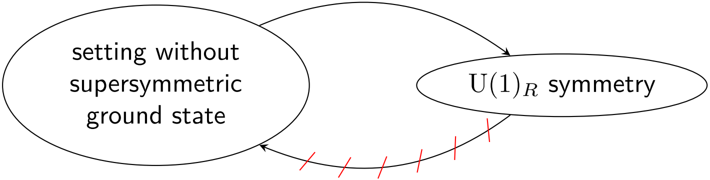

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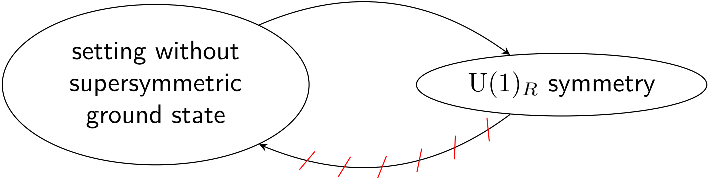

setting without supersymmetric ground state

$\mathrm{U}(1)_R$ symmetry

❸ In local SUSY : $\dfrac{\partial\mathscr{W}}{\partial\phi_i} = 0$ and $\langle\mathscr{W}\rangle = 0$ imply $D_i\mathscr{W} = 0$

(That is, a $\mathrm{U}(1)_R$ symmetry implies Minkowski solutions.)

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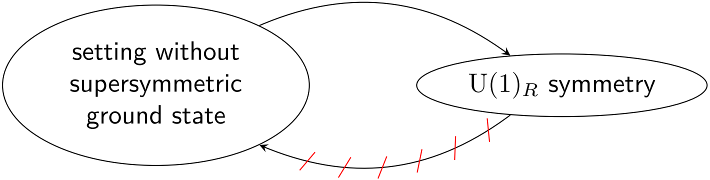

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❹ in 'no-scale' type settings

Weinberg [1989]

solutions of global SUSY F term eq.'s = stationary points of supergravity scalar potential

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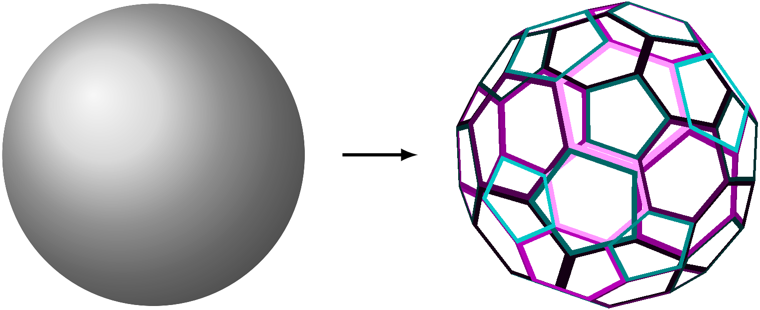
- Such an **approximate** $\mathrm{U}(1)_R$ symmetries can be a consequence of discrete $\mathbb{Z}_N^R$ symmetries
- Confirmed in various field-theoretic examples

Explicit
string theory
realization

Origin of high-power discrete R symmetries

- Discrete R symmetries arise as remnants of Lorentz symmetries of compact space



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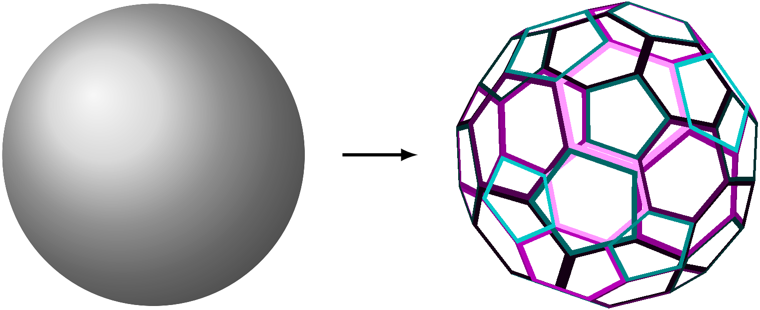

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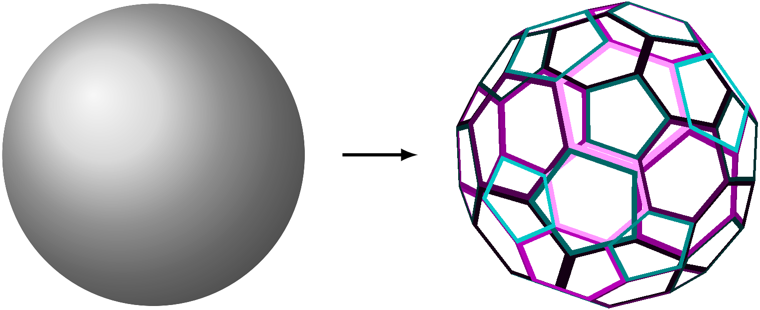

- ☞ Orbifolds break $\mathrm{SO}(6) \simeq \mathrm{SU}(4)$ Lorentz symmetry of compact space to discrete subgroups
- ☞ For example: a $\mathbb{Z}_2$ orbifold plane leads to $\mathbb{Z}_4^R$ symmetry

An example

Brümmer, Kappl, MR & Schmidt-Hoberg [2010]

☞ Studied the previous example ('heterotic benchmark model IA') with 23 SM singlets s_i getting a VEV

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- Search for solutions $|s_i| < 1$, and find/argue that they exist

Note: in order to prove the existence a full understanding of coupling coefficients is required

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- All fields acquire positive m^2
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- Superpotential VEV $\langle \mathscr{W} \rangle \sim \langle s_i \rangle^9 \ll 1$ (as expected)

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- ☞ All fields acquire positive m^2 (no flat directions; not destroyed by supergravity corrections)
- ☞ Superpotential VEV $\langle \mathscr{W} \rangle \sim \langle s_i \rangle^9 \ll 1$ (as expected)

bottom-line:

straightforward embedding in heterotic orbifolds

General picture

☞ The more fields are switched on, the lower N we obtain examples:

- model with 23 fields $\curvearrowright N = 9$
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References

References I

Joseph J. Atick, Lance J. Dixon, and Ashoke Sen. String Calculation of Fayet-Iliopoulos d Terms in Arbitrary Supersymmetric Compactifications. *Nucl. Phys.*, B292:109–149, 1987. doi: 10.1016/0550-3213(87)90639-0.

Pierre Binétruy, Stéphane Lavignac, and Pierre Ramond. Yukawa textures with an anomalous horizontal abelian symmetry. *Nucl. Phys.*, B477:353–377, 1996.

Robert H. Brandenberger and C. Vafa. Superstrings in the Early Universe. *Nucl. Phys. B*, 316:391–410, 1989. doi: 10.1016/0550-3213(89)90037-0.

Felix Brümmer, Rolf Kappl, Michael Ratz, and Kai Schmidt-Hoberg. Approximate R-symmetries and the mu term. *JHEP*, 04:006, 2010. doi: 10.1007/JHEP04(2010)006.

Mirjam Cvetic, A. Font, Luis E. Ibanez, D. Lüst, and F. Quevedo. Target space duality, supersymmetry breaking and the stability of classical string vacua. *Nucl. Phys. B*, 361:194–232, 1991. doi: 10.1016/0550-3213(91)90622-5.

Thomas Dent. Breaking CP and supersymmetry with orbifold moduli dynamics. *Nucl. Phys. B*, 623:73–96, 2002. doi: 10.1016/S0550-3213(01)00629-0. [Erratum: Nucl.Phys.B 629, 493–493 (2002)].

References II

Keith R. Dienes. String theory and the path to unification: A Review of recent developments. *Phys. Rept.*, 287:447–525, 1997. doi: 10.1016/S0370-1573(97)00009-4.

Michael Dine and Nathan Seiberg. Couplings and Scales in Superstring Models. *Phys. Rev. Lett.*, 55:366, 1985. doi: 10.1103/PhysRevLett.55.366.

A. Font, Luis E. Ibáñez, D. Lüst, and F. Quevedo. Supersymmetry breaking from duality invariant gaugino condensation. *Phys. Lett.*, B245:401–408, 1990. doi: 10.1016/0370-2693(90)90665-S.

Luis E. Ibáñez, Jihn E. Kim, Hans Peter Nilles, and F. Quevedo. Orbifold compactifications with three families of SU(3) x SU(2) x U(1)**n. *Phys. Lett.*, B191:282–286, 1987.

Kenneth Intriligator, Nathan Seiberg, and David Shih. Dynamical SUSY breaking in meta-stable vacua. *JHEP*, 04:021, 2006.

Kenneth A. Intriligator and Nathan Seiberg. Lectures on Supersymmetry Breaking. *Class. Quant. Grav.*, 24:S741–S772, 2007. doi: 10.1088/0264-9381/24/21/S02.

References III

Keiya Ishiguro, Tatsuo Kobayashi, and Hajime Otsuka. Landscape of Modular Symmetric Flavor Models. *JHEP*, 03:161, 2021. doi: 10.1007/JHEP03(2021)161.

Keiya Ishiguro, Hiroshi Okada, and Hajime Otsuka. Residual flavor symmetry breaking in the landscape of modular flavor models. *JHEP*, 09:072, 2022. doi: 10.1007/JHEP09(2022)072.

Shamit Kachru, Renata Kallosh, Andrei Linde, and Sandip P. Trivedi. De Sitter vacua in string theory. *Phys. Rev.*, D68:046005, 2003. doi: 10.1103/PhysRevD.68.046005.

Rolf Kappl, Hans Peter Nilles, Sául Ramos-Sánchez, Michael Ratz, Kai Schmidt-Hoberg, and Patrick K.S. Vaudrevange. Large hierarchies from approximate R symmetries. *Phys. Rev. Lett.*, 102:121602, 2009.

Victor Knapp-Perez, Xiang-Gan Liu, Hans Peter Nilles, Saúl Ramos-Sánchez, and Michael Ratz. Matter matters in moduli fixing and modular flavor symmetries. *Phys. Lett. B*, 844:138106, 2023. doi: 10.1016/j.physletb.2023.138106.

References IV

Tatsuo Kobayashi, Yusuke Shimizu, Kenta Takagi, Morimitsu Tanimoto, and Takuya H. Tatsuishi. A_4 lepton flavor model and modulus stabilization from S_4 modular symmetry. *Phys. Rev. D*, 100(11):115045, 2019. doi: 10.1103/PhysRevD.100.115045. [Erratum: Phys.Rev.D 101, 039904 (2020)].

Oleg Lebedev, Hans Peter Nilles, and Michael Ratz. de Sitter vacua from matter superpotentials. *Phys. Lett.*, B636:126–131, 2006. doi: 10.1016/j.physletb.2006.03.046.

Jacob M. Leedom, Nicole Righi, and Alexander Westphal. Heterotic de Sitter beyond modular symmetry. *JHEP*, 02:209, 2023. doi: 10.1007/JHEP02(2023)209.

Liam McAllister and Fernando Quevedo. Moduli Stabilization in String Theory. 10 2023.

Ann E. Nelson and Nathan Seiberg. R symmetry breaking versus supersymmetry breaking. *Nucl. Phys.*, B416:46–62, 1994. doi: 10.1016/0550-3213(94)90577-0.

Hans Peter Nilles. Dynamically broken supergravity and the hierarchy problem. *Phys. Lett.*, B115:193, 1982.

References V

Hans Peter Nilles and M. Olechowski. Gaugino condensation and duality invariance. *Phys. Lett.*, B248:268–272, 1990. doi: 10.1016/0370-2693(90)90290-M.

P. P. Novichkov, J. T. Penedo, and S. T. Petcov. Modular flavour symmetries and modulus stabilisation. *JHEP*, 03:149, 2022. doi: 10.1007/JHEP03(2022)149.

Saúl Ramos-Sánchez and Michael Ratz. Heterotic Orbifold Models. 1 2024.

Yael Shadmi and Yuri Shirman. Dynamical supersymmetry breaking. *Rev. Mod. Phys.*, 72:25–64, 2000. doi: 10.1103/RevModPhys.72.25.

Steven Weinberg. The cosmological constant problem. *Rev. Mod. Phys.*, 61: 1–23, 1989. doi: 10.1103/RevModPhys.61.1.

Edward Witten. Dynamical Breaking of Supersymmetry. *Nucl. Phys.*, B188:513, 1981. doi: 10.1016/0550-3213(81)90006-7.

Edward Witten. Strong coupling expansion of calabi–yau compactification. *Nucl. Phys.*, B471:135–158, 1996.