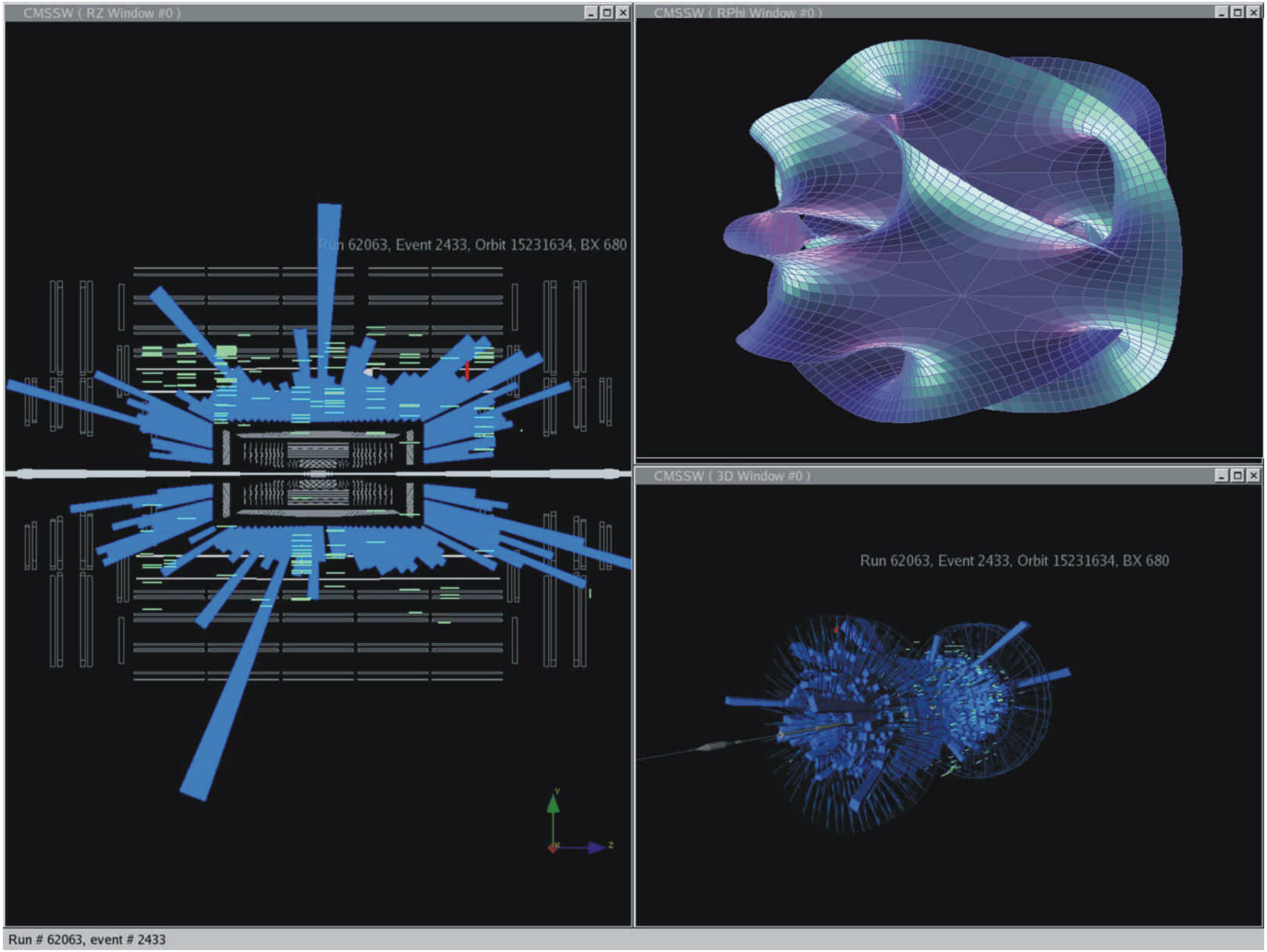

CMSSW (RZ Window #0)
Run 62063, Event 2433, Orbit 15231634, BX 680
CMSSW (RPhi Window #0)
CMSSW (3D Window #0)
Run 62063, Event 2433, Orbit 15231634, BX 680
Run # 62063, event # 2433

Grand Unification in the "Landscape"

(Based on work with Gero v. Gersdorff and Christian Groß)

Outline

- The "old" story: Low-energy observations are predicted by a simpler, more unique high-energy theory.

- The "new" story: Low-energy observations are the result of an accidental (anthropic?) selection from a very large set of consistent theories (the "landscape").

- How does the idea of "Grand Unified Theories" fit into these developments?

- A landscape-inspired mechanism "explaining" the smallness of the unified gauge coupling

The "old" story

- start from the "effective theory" of the known world
- try to unify interactions and degrees of freedom ; increase the symmetry

⟹ find a more unique theory predicting (or at least explaining) some of the low-energy observations

[Obviously, this has worked many times in the past.

Discovery of SUSY at LHC would be another example.

Grand Unification is then the next logical step...]

Supersymmetric Grand Unification

- Standard Model:

$$\underbrace{SU_3 \times SU_2 \times U_1 \quad + \quad \text{Matter}} \quad + \quad \underbrace{\text{Higgs}}$$

fits perfectly into SU_5; with matter in $3 \times (\bar{5} + 10)$

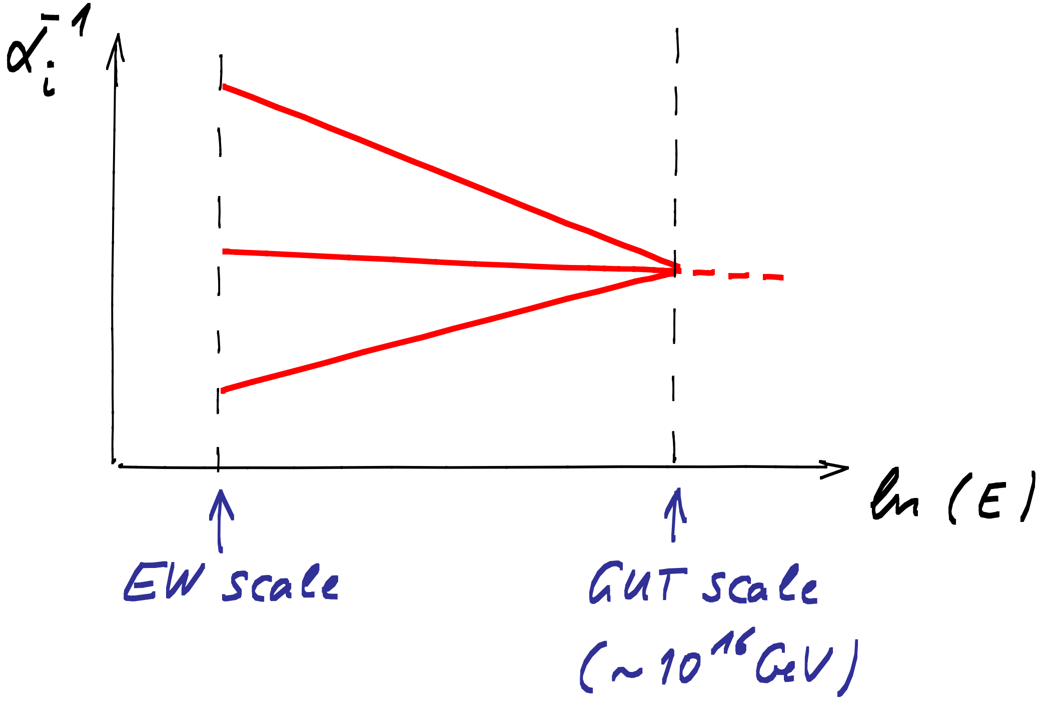
is special anyway...

- Quick reminder:

$$\left(\begin{array}{c|c} 3\times 3 & \\ \hline & 2\times 2 \end{array}\right) \leftarrow 5\times 5$$

U_1 on diagonal

Crucial quantitative evidence:



$\Rightarrow$ prediction of α_3 from α_1 & α_2:

$$\alpha_{3,exp} \approx 0.12$$

$$\alpha_{3,GUT} \approx 0.13$$

(This corresponds to a $+ O(1)$ error in α_3^{-1}, as expected from unknown thresholds)

How seriously should we take this?

- expect $0 < \alpha_3 < 1$
- hit 0.12 with error 0.01

$\Rightarrow$ $\sim$ 3-σ-effect!

The "new" story

- Compactify the (essentially unique) 10d-Superstring-Theory to 4d using a $\underbrace{\text{6d compact space}}$

including fluxes, it is easy to see that $\sim 10^{500}$ or more "geometries" are available

$\Downarrow$

arguably, <u>any</u> reasonable 4d theory arises as a metastable solution of string theory

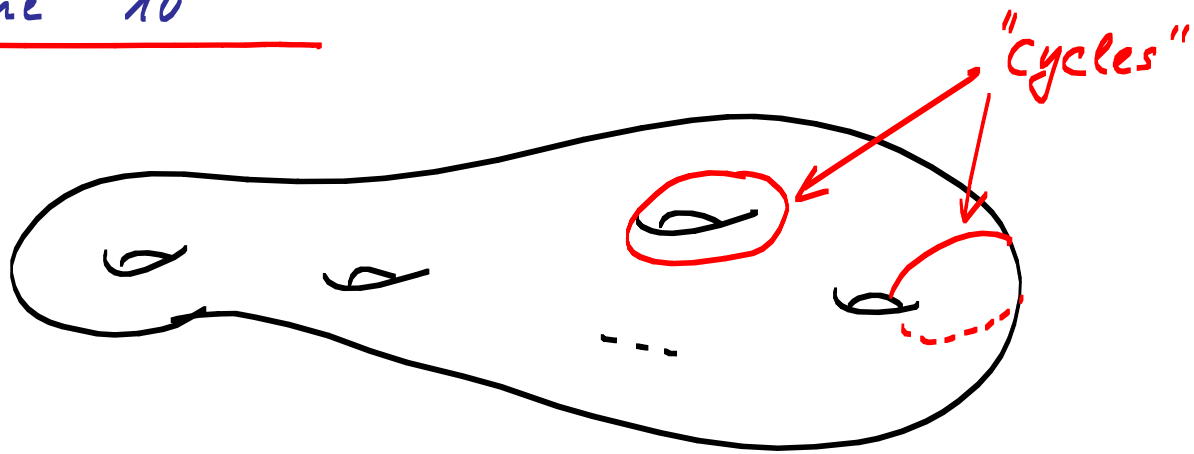
("The landscape")

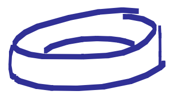
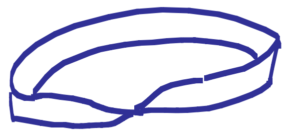
- Thus, $SU_3 \times SU_2 \times U_1$ with "our" matter & couplings could be just "accidental".

(Cf. e.g. statistical analysis of Blumenhagen, Gmeiner, Honecker, Lüst, Weigand, 2005)

Idea behind the "10^{500}"

"CY"



- Some of the fields living on this space take values in "non-trivial bundles" (associated with cycles)
- e.g. for 1-dim. cycles we can have  or  .
- for a 2-dim. cycle, such as S^2 on which a gaug-field lives, the "twisting" is characterized by the "monopole number" $\ldots, -1, 0, 1, 2, \ldots$
- typical CY's have hundreds of cycles ...

So why bother with Grand Unification?

- Because the "3-σ-effect" mentioned earlier remains
- Because "Grand Unification" is generic in certain branches of the landscape:

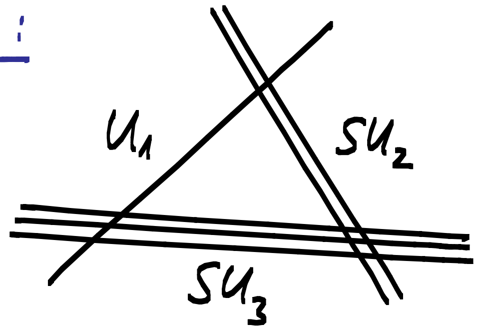
a) Heterotic string: one gauge coupling in 10d (group $E_8 \times E_8$ or SO_{32})

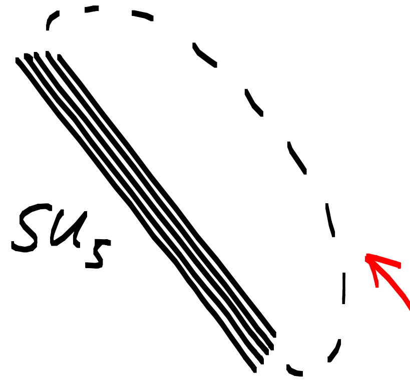
(This is however not the best-understood part of the landscape as far as moduli stabilization / vacuum energy is concerned)

b) Type IIA / IIB with D-branes: each (stack-of) D-branes has its own, independent gauge group

(Moduli stabilization / vacuum energy well-understood, but coupling unification not necessary)

→ GKP/KKLT, ..., specifically in F-theory: Lüst, Mayr, Reffert, Stieberger compare:





Broken to $SU_3 \times SU_2 \times U_1$
e.g. by compact
geometry of this stack

- Thus, in the "intersecting brane" setting, Grand Unification is not generic, but an interesting possibility.
- Recently, promising constructions have emerged in the type IIB / D7-brane case. (Blumenhagen, Braun, Grimm, Weigand)
- Moreover, in the F-theory-setting (a non-pert. generalization of the IIB / D7-brane case), certain problems of brane/GUT models have been overcome (Heckman, Vafa, '08; ...)

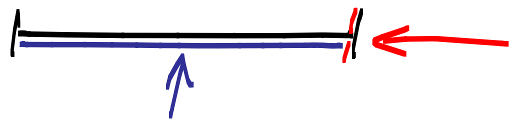
  [Top-Yukawa coupling, E_6-GUTs, ...]

A realistic GUT-coupling from a "micro-landscape"

- In the following, I focus on the "classical" heterotic case
- Moreover, I will only discuss the "last step" of compactification

$$5d,\ SU_5 \longrightarrow 4d,\ SU_3 \times SU_2 \times U_1$$

compact space:



breaking to SM by geometry of 10d space

SU_5 gauge theory coming from 10d $E_8 \times E_8$

- We now consider the 5d gauge theory in more detail:

usually, one writes $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad ; \quad D_\mu = \partial_\mu + i g_5 A_\mu$$

It is more natural to redefine $g_5 A_\mu \rightarrow A_\mu$,

giving:

$$S = -\int d^5x \, \frac{1}{4g_5^2} F_{\mu\nu} F^{\mu\nu}$$

$$= -\int dy \int d^4x \, \frac{1}{4g_5^2} F_{\mu\nu} F^{\mu\nu}$$

$$= -\int d^4x \, \frac{2\pi R}{4g_5^2} F_{\mu\nu} F^{\mu\nu}$$

$$= -\int d^4x \, \frac{1}{4g_4^2} F_{\mu\nu} F^{\mu\nu}$$

Hence: $\boxed{g_4^2 = \frac{g_5^2}{2\pi R}}$

$\Rightarrow$ g_5^2 has dimension [length]

Moreover: $\alpha_{GUT} \approx \frac{g_4^2}{4\pi} \approx \frac{1}{25}$ ("exper." value)

requires a mild hierarchy: $\boxed{R \gg g_5^2}$

Given that $R_6 \cdots R_{10} \sim \ell_{string}$; $g_5^2 \sim \ell_{string}$,

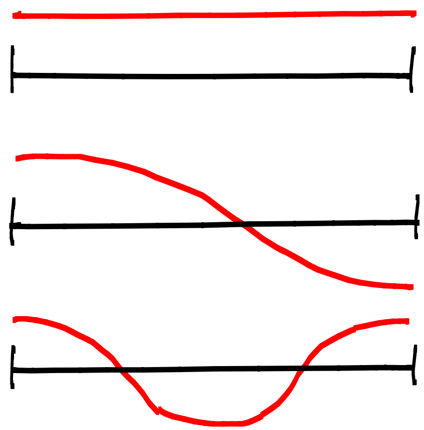
what makes $R = R_5 \gg \ell_{string}$?

(In other words, what makes the last extra dims. somewhat larger, thereby explaining the weak coupling we observe?)

- Clearly, this requires understanding what stabilizes the size of this 5th extra dimension.

2-loop Casimir stabilization

Kaluza-Klein modes on interval:



- each of these modes corresponds to 4d field with R-dependent mass $\Leftarrow$
- each such field is a set of oscillators
- each oscillator has a zero-point energy

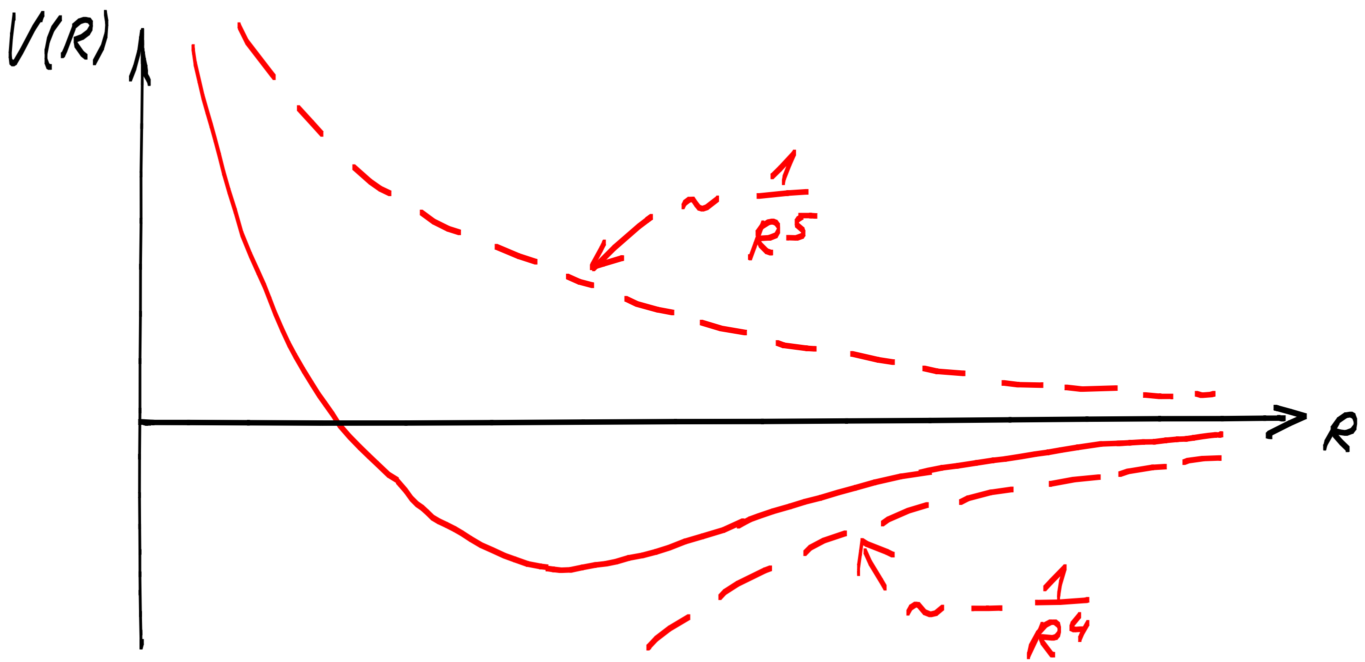
While the full energy is divergent, the R-dependence is calculable.

In fact, by simple dimensional analysis

$$V(R) = V_{1\text{-loop}}(R) + V_{2\text{-loop}}(R) + \cdots$$

$$= \frac{1}{R^4}\left(c^{(1)} + c^{(2)} \frac{g^2}{R} + \cdots \right)$$

If $c^{(1)} < 0$ and $c^{(2)} > 0$, it is easy to get a 2-loop minimum:



- Actually, one finds: $$R_{min} = -\frac{5}{4}\frac{c^{(2)}}{c^{(1)}} g_5^2$$

- Problem: If all $c^{(i)} \sim O(1)$, $g_5^2/R_{min} \sim O(1)$ and the 2-loop minimum is not reliable

- However: If by an accidental cancellation $c^{(1)} \ll 1$, $g_5^2/R_{min} \ll 1$, and higher loops do not affect $V(R)$ near R_{min}

  (Note: This is also precisely what we need to get $\alpha_{GUT} \ll 1$)

Side remark: A similar situation occurs for $\beta(g^2)$ in QCD-like theories, leading to a non-trivial IR-fixed-point (Banks-Zaks fixed point)

Actually: The above holds only for compactifications on a circle, S^1. On an interval, $S^1/\mathbb{Z}_2$, one has

$$V(R) = \frac{1}{R^4}\left(c^{(1)} + c^{(2)} \frac{g_5^2}{R}\left[\ln \frac{R}{g_5^2} + O(1)\right] + \cdots \right)$$

The log is associated with UV-divergences arising on the boundaries (branes). One naively gets $\ln(\Lambda_{cutoff} \cdot R)$.

It is then natural to set $\Lambda_{cutoff} \sim 1/g_5^2$.
(But a slightly different choice does not affect the result.)

The previous parametric analysis remains correct.

SUSY – Breaking

- In fact, $V(R) \equiv 0$ if SUSY is unbroken
- We assume "Scherk–Schwarz" SUSY breaking, where the boundary conditions for bosons / fermions differ by a small number $\omega \ll 1$.
- This can also be understood using a "radion superfield"

$$T = R + iA_5 + \cdots + \theta^2 F_T$$

- ω is then related to a brane-localized superpotential and induces an "F-term" for T:

$$\omega \sim F_T \sim \frac{|W_0|}{M_{P,5}^3}$$

(→ Marti/Pomarol; Kaplan/Weiner; Chacko/Luty)

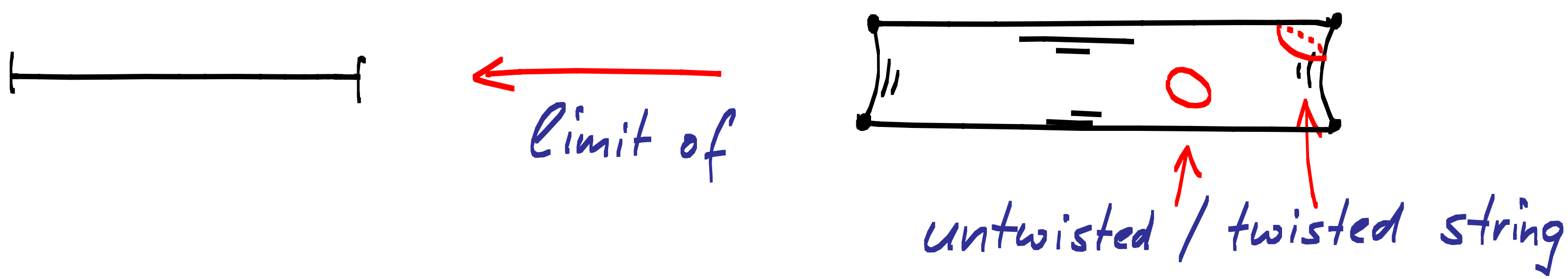
$$\boxed{\text{Since both terms in } V(R) \sim \omega^2, \text{ the SUSY-breaking scale is irrelevant for the position of the minimum}}$$

Thus, all that was said before remains true for (very weakly broken) SUSY.

- We now turn to specific 5d SUSY GUT models ("Orbifold GUTs")

→ Kawamura; Hall/Nomura; ... ~ 2001

- Matter can "live" in bulk or on branes:



5d SUSY-GUT models

GUT-breaking: $SU_5 \longrightarrow SU_3 \times SU_2 \times U_1$ at one boundary

- Higgs on SM-brane
- Matter in bulk or on "Standard-Model brane"

In detail: $\bar{5}$-matter

$$\bar{5} = \underbrace{(\bar{3},1)}_{u} + \underbrace{(1,2)}_{s}$$

← counts # of bulk fields of this type

10-matter

$$10 = \underbrace{(3,2)}_{t} + \underbrace{(\bar{3},1) + (1,1)}_{r}$$

$\Rightarrow \quad r, s, t, u \in (0, 1, 2, 3)$

parameterize our "micro landscape" of $4^4 = 256$ models

- We find:

$$\frac{c^{(1)}}{c^{(2)}} = \pi^3 \, \frac{-160 - 16r - 8s + 96t + 48u}{\frac{2424}{5} - 108r - 36s + 36t + 12u}$$

- From this ratio,

the value of R_{min} and hence α_{GUT} follow.

(We need $c^{(1)} < 0$, $c^{(2)} > 0$, and small ratio to get small g_s^2/R_{min}.)

We find a pert. controlled minimum for $\sim 1/3$ of the models

We find $\frac{1}{20} \gtrsim \alpha_{GUT} \gtrsim \frac{1}{30}$ for 12 models

Uplifting

- One problem still remains: Our minimum is always at $V<0$ (neg. cosmol. constant) and needs to be "uplifted".

- Because of SUSY, we can not simply add a pos. contribution to V.

- However, we can add $\Lambda_5 < 0$ in bulk and compensate by $\Lambda_4 > 0$ at branes. ("warped space" or "supersymmetric Randall-Sundrum model")

- We can then slightly "detune" Λ_4 & Λ_5, maintaining SUSY and introducing a small positive contribution to V

  (→ Bagger / Belyaev '02)

- This completes our construction.

Uplifting in superfield language

N = 1 supergravity perspective:

$$\Omega \sim -(T+\bar{T}) + \Delta\Omega_{loop} \qquad ; \qquad W = W_0$$

$$\Delta\Omega_{loop} \sim \frac{1}{(T+\bar{T})^2} + \frac{g^2}{(T+\bar{T})^3} \ln(M(T+\bar{T}))$$

(cf. "Almost no-scale" proposal of Luty / Okada)

$V(R_{min}) \sim \dfrac{\omega^2}{R_{min}^4}$ is calculable & < 0.

To "uplift", allow for a small warping ($\Lambda_5 \neq 0$):

$$\Lambda_5 = -6k^2 M_{P,5}^3 \qquad ; \qquad e^{-k(T+\bar{T})} = 1 - \text{"small"}$$

- Neglecting the loop-induced Kähler-correction for the moment, we have:

$$\Omega \sim e^{-k(T+\bar{T})} - 1 \quad ; \quad W = W_0 \, e^{-3kT}$$

(→ Luty/Sundrum)

(constant superpotential at IR-brane)

- A Kähler-Weyl rescaling gives

$$\Omega \sim 1 - e^{k(T+\bar{T})} \quad ; \quad W = W_0$$

$$\sim -(T+\bar{T}) + \Delta\Omega_W$$

$$\Delta\Omega_W \sim (T+\bar{T})^2$$

- This has to be combined with our $\Delta\Omega_{loop}$

$$\Rightarrow \quad \Delta\Omega_{tot} \sim - M_{P,5}^3 k (T+\bar{T})^2 + \frac{1}{(T+\bar{T})^2} + \frac{g^2}{(T+\bar{T})^3} \ln(M(T+\bar{T}))$$

$$\delta V \sim \frac{|W_0|^2}{M_{P,5}^6} (\Delta\Omega)_{T\bar{T}}$$

$$\delta V \sim \underline{\underline{\text{const.}}} + \frac{1}{R^4} + \frac{g^2}{R^5} \ln(MR)$$

positive
constant
contribution $\sim \omega^2 M_{P,5}^3 k$

- Uplifting to $\Lambda_4 \approx 0$ implies

$$k(T+\bar{T}) \sim \frac{1}{(RM_{P,5})^3}$$

i.e. warping is indeed small and our unwarped calculation is ok.

Phenomenology

- The main phenomenological implications (in addition to those of 5d SUSY GUTs) come from the fact that the radion superfield (i.e. F_T) dominates SUSY-breaking.

- It couples primarily to gauginos, making them heavy (gaugino mediation)

- Furthermore, if the Higgs comes from an enlarged gauge sector (e.g. SU_6), a very constraint scenario involving $m_{1/2}$, μ, $B\mu$ arises (Burdman/Nomura '02, Choi et al. '03, A.H., March-Russell, Ziegler '08)

- We have determined observational consequences of such a setting in a detailed study (Brümmer, Fichet, A.H., Kraml '09)

Summary / Conclusions

- Two-Loop Casimir stabilization occurs naturally in 5d orbifolds (given only F_T-dominance & suitable matter content).

- With a very mild discrete tuning, it can "explain" the smallness of $\alpha_{GUT} \sim 1/25$

- An elegant way of uplifting the stabilized AdS_4-vacua is to appeal to a small warping ($\Lambda_5 \neq 0$)

- It would be interesting to find 2-loop-Casimir-stabil. in explicit heterotic models, in particular to allow for more moduli (cf. e.g. 6d analysis of Buchmüller / Catena / Schmidt-Hoberg)