Some recent issues in string phenomenology

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(including recent original work with
Knochel/Weigand, Witkowski/Romineve/Mangat, Unwin)

(partial) Outline

- Strings at LHC
- SM / MSSM Model building ; GUTs
- Low-scale SUSY
- High-scale SUSY
- Moduli stabilization, Uplifting
- Dark radiation
- Landscape issues

Strings at LHC

Lüst, Stieberger, Taylor, Anchordoqui,
Goldberg, Nawata, Schlotterer, Dong, Han, Huang, Shiu,....

- So far, no new physics (except 125-GeV-Higgs) at LHC
- Nevertheless, let's start with the most exciting option: Excited string states may still be discovered at LHC 14
- Prerequisite: low string scale

  Antoniadis; Arkani-Hamed/Dimopoulos/Dvali; Randall/Sundrum....

- Need either
  a) One warped extra dimension or
  b) $d \geq 2$ large (flat) extra dimensions

Strings at LHC (continued)

- Great plus: Model-independent predictions for production and decay rates, mass ratios, etc.

  [We are talking e.g. about $gg \to g^* g^*$, with g^* an open-string exctited state. This would not apply to KK-modes, which are model-dependent]

- At the moment (7-8 TeV), we have the bound $M \gtrsim 4.8 TeV$.

Stringy extra U(1)s

Dong, Han, Huang, Shiu, Anchordoqui, Antoniadis, Goldberg, Lüst, Taylor,....

- Another interesting issue (not to be discussed here) are extra heavy U(1)s (e.g. Z's), which are fairly generic in string models....

... a more conservative approach to string phenomenology is

SM / MSSM model building

- Historic path: Heterotic string on CYs / torus orbifolds

- A strong point remains the ease or 'naturalness' of the group-theoretic embedding $G_{SM} \subset SU(5)/SO(10) \subset E_8$

- Problem: If GUT motivation 'dies' due to absence of low-scale SUSY (see, however, below), part of this beauty is lost

- For recent work in the orbifold context see e.g.

  Nilles, Ratz, Krippendorf, Winkler, Vaudrevange,....

- Plus: Explicitness of models, Landscape scans possible

- Interesting current issue: Understanding blowup....

  Groot Nibbelink, Honecker, Rühle, Blaszczyk, Vaudrevange, Trapletti,...

Heterotic model building (continued)

- Minus: Orbifolds, even with blowup, are very special

- Hence, desire to build models on CYs....

  Ovrut, Donagi, Bouchard, He, Candelas, Pantev,....
- Until recently, complicated case-by-case study required
- For recent progress (algorithms!) see

  Anderson, Gray, Lukas, He, Palti,....

- Overall Minus: Moduli stabilization, in particular fine-tuning of Λ und 'uplift'

  See however: Anderson, Gray, Lukas, Ovrut, Cicoli, de Alwis, Westphal, ...

Intersecting branes

- Another option is that of intersecting D6 branes (type IIA) or intersecting D7 branes (type IIB)
- While GUTs are possible in this context, they are in no way enforced by the structure of the theory
- In the CY context, the type IIA side is problematic due to the difficulty of identifying lagrangian submanifolds (which the branes must wrap)
- Continuous progress is however made in the 'laboratory' of type IIA orbifold models (rigid branes, discrete torsion, axions, discrete gauge symmetries....)

Honecker, Blaszczyk, Staessens, Vanhoof,....
Berasaluce-Gonzalez, Ibanez, Soler, Uranga

Intersecting branes (continued)

- On the (mirror dual) type IIB side, things look much better due to the holomorphicity of the D7-branes (also due to moduli stabilization, see below)

- However, the interest has moved to F-theory (being more generic and solving the problem of a large top Yukawa in the GUT context)

see talk of T. Weigand

'Stringy' (CFT) Models

- The strong point is that CFT constructions are, in principle, more generic than 'geometric', 10d-SUGRA-based models
- Statistical analyses (in restricted classes) are possible (in fact, the 'landscape' has first emerged in this setting)
- Gepner models, free fermionic constructions

Schellekens, Gato-Rivera, Faraggi, Rizos, Gepner,....

Discrete gauge symmetries

- A generic feature of string compactifications, with both theoretical and phenomenological (e.g. flavor, proton-decay) interest....

  Uranga, Camara, Marchesano, Schellekens, Berasaluce-Gonzalez, Montero, Retolaza

Low-scale SUSY

- All of the above is usually discussed in the context of 4d $\mathcal{N} = 1$ SUSY (i.e. building the MSSM, possibly with extensions)

- At the high scale, this is also enforced by control issues

- Lowering the SUSY scale to $\sim TeV$ is motivated by
  a) Naturalness
  b) Precision gauge unification

- However, LHC has weakened the naturalness argument (sizeable Higgs mass + SUSY-exclusion-bounds)

- The crucial formula (strongly simplified) is

$$m_h^2 \simeq m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2} \left(\ln \left(\frac{m_{\tilde{t}}^2}{m_t^2} \right) + \frac{A_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2} \right) \right)$$

Low-scale SUSY (continued)

- We see that at least one of the SUSY-breaking parameters must be high very high, making the Z mass unnatural
- The situation can be improved in the NMSSM or using other tree-level corrections, but no convincing way out is seen
- Depending on ingenuity and determination of the authors, fine tuning is between 10^{-4} and 10^{-1}, but....
- Keywords are mini-split, light third generation, Dirac gauginos, etc. etc.
- Much of this can also be realized in string theory....
  Aparicio/Cerdeno/Ibanez, Acharya/Kane/Kumar, ../Heckman/Wecht
  Krippendorf/Nilles/Ratz/Winkler, Dudas et al....
- However, chances for guessing the correct, natural model before the data decrease due to the degree of complexity
- Also: Involved model-building is a form of tuning....

High-scale SUSY

- What if we had to accept that the SM is fine-tuned with SUSY broken at a high scale?

- Given the landscape/anthropic arguments, this is not necessarily a disaster for string phenomenology

- However, we have to face the question of why none of the a priori abundant, natural SUSY scenarios has won the statistical competition

- Clearly, this needs input concerning 'the measure', which is only discussed in a relatively small community at present

  Bousso, Susskind, Vilenkin, Nomura,....

- For a quantitative attempt in this direction (but in the inflationary context) see

  Pedro, Westphal, 13

High-scale SUSY (continued)

- Concrete ideas of why we don't see natural SUSY involve dark matter overproduction and/or the cosmological moduli problem (see also later)

  Bose/Dine/Draper

- Putting aside the 'Why', we may simply start doing conventional string phenomenology with high-scale SUSY...

  Knochel/Weigand/AH, Ibanez/Marchesano/Regalado/Valenzuela, Chatzistavrakidis/Erfani/Nilles/Zavala, Higaki/Ibe/Takahashi, Ibanez/Valenzuela, Mangat/Rompineve/Witkowski/AH, ...

- Obvious issues include DM, axions, flavor, Higgs-quartic-coupling/vacuum stability, GUTs (proton decay und unification), dark radiation, ...

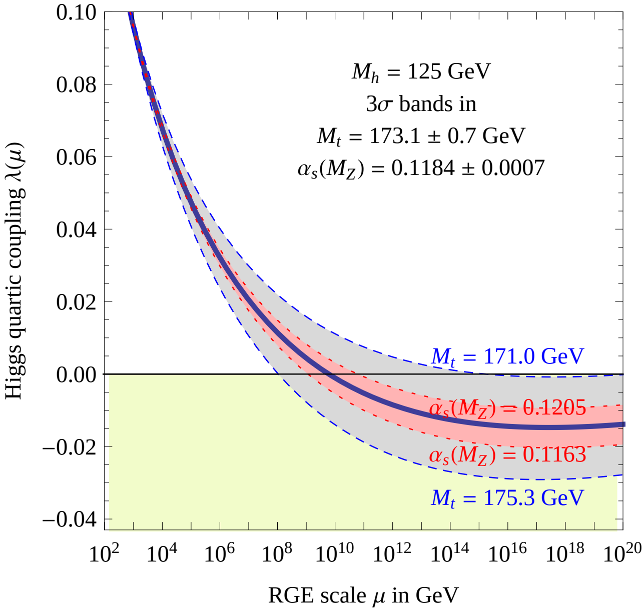
Higgs quartic coupling

- The subject has a long history
- Well-known:
  In the SM with low m_h, λ runs to zero at some scale $< M_P$
  (vacuum stability bound)

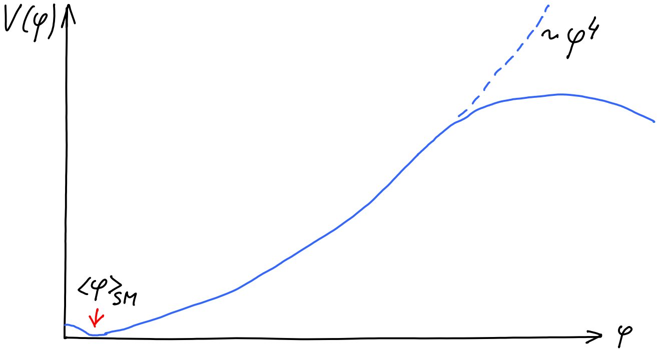
Lindner, Sher, Zaglauer '89
Froggatt, Nielsen '96
Gogoladze, Okada, Shafi '07
...
Shaposhnikov, Wetterich 09'
Giudice, Isidori, Strumia, Riotto, ...
Masina '12

- It has been attempted to turn this into an m_h prediction

Higgs quartic coupling, from Degrassi et al., 1205.6497



The resulting metastable potential



Two examples:

Higgs mass prediction from $\lambda = 0$ at 'unification scale'

Gogoladze, Okada, Shafi, '07

- A prediction of $m_h = 125 \pm 4$ GeV was made (but strong model dependence)

Higgs mass prediction from $\lambda = 0$ at M_P

Shaposhnikov, Wetterich, '09

- Assume UV fixpoint of 4d quantum gravity....

Weinberg '79; Reuter '98; Reuter et al. '98. . . '11

- In 2009, with $m_t \simeq 171$ GeV, this gave a prediction of $m_h = 126$ GeV

String-phenomenologist's perspective

- Natural guess: The special scale $\mu(\lambda = 0)$ is the SUSY-breaking scale

AH/Knochel/Weigand, Ibanez/Marchesano/Regalado/Valenzuela

- Crucial formula:

$$\lambda(m_s) = \frac{g^2(m_s) + g'^2(m_s)}{8} \cos^2(2\beta)$$

- Reminder:

$$M_H^2 = \begin{pmatrix} |\mu|^2 + m_{H_d}^2 & b \\ b & |\mu|^2 + m_{H_u}^2 \end{pmatrix} = \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix}$$

$$\sin(2\beta) = \frac{2m_3^2}{m_1^2 + m_2^2}$$

Need this to be 1!

- Of course, high-scale SUSY has been considered before

Arkani-Hamed, Dimopoulos '04
Giudice, Romanino '04
...

- Also, relations $\tan\beta \leftrightarrow \lambda(m_s) \leftrightarrow m_h$ have been discussed

cf. the 140-GeV-Higgs-mass-prediction of Hall/Nomura, '09

- A possible goal:

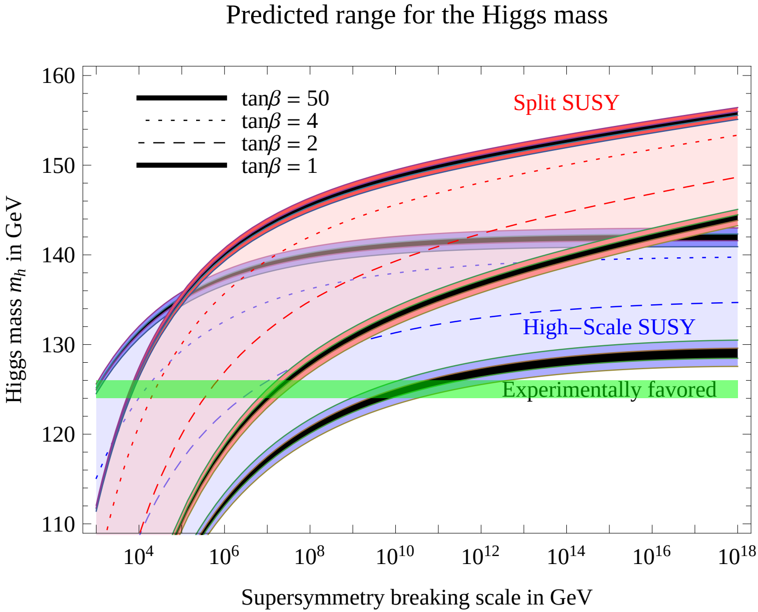
  Identify a special structure/symmetry leading to $\tan\beta = 1$ (i.e. to $\lambda = 0$)

- Indeed, such a structure is known in heterotic orbifolds:

Shift symmetry: $\boxed{K_H \sim |H_u + \overline{H}_d|^2}$

Lopes-Cardoso, Lüst, Mohaupt '94
Antoniadis, Gava, Narain, Taylor '94
Brignole, Ibanez, Munoz, Scheich, '95...'97

NNLO, from Degrassi et al., 1205.6497



In more detail: $K_H = f(S,\overline{S})|H_u + \overline{H}_d|^2$

Assuming $F_S \neq 0$ and $m_{3/2} \neq 0$ this gives

$$m_1^2 = m_2^2 = m_3^2 \quad = \quad \left| m_{3/2} - \overline{F}^S f_{\overline{S}} \right|^2 + m_{3/2}^2 - F^S \overline{F}^S (\ln f)_{S\overline{S}}$$

- In the language of higher-dimensional gauge theories, it is easy to see the physical origin:

5d SU(6) $\rightarrow$ SU(5)$\times$U(1) ; $35 = 24 + 5 + \overline{5} + 1$; Higgs$= \Sigma + iA_5$

cf. Gogoladze, Okada, Shafi '07

Comments

- This simple understanding of the shift-symmetry lets us hope that it is more generic

  heterotic WLs ↔ type IIA / D6-WLs ↔ type IIB / D7-WLs or positions

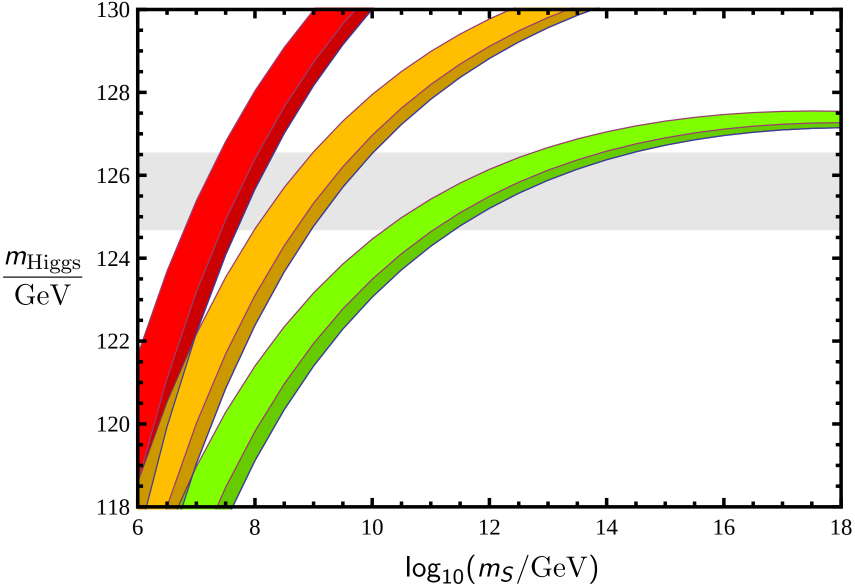
- These and other origins of the Higgs-shift-symmetry and of $\tan\beta = 1$ have recently also been explored in

  Ibanez, Marchesano, Regalado, Valenzuela '12
  Ibanez, Valenzuela '13

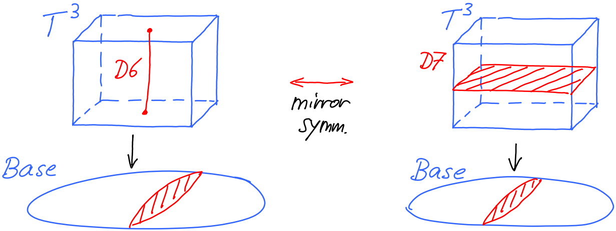
- In particular, they observe that to get $\tan\beta = 1$, a $\mathbb{Z}_2$ exchange symmetry acting on H_u, H_d is sufficient; the rest is done by the usual tuning...

$$M_H^2 = \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix}$$

A-term corrections for $A_t^2 = m_S^2$ and $A_t^2 = 6 m_S^2$



- The D7 shift symmetry is easy to visualize in SYZ picture...



An aside on Inflation:

- The status of axion monodromy may have fundamentally improved with a recent series of papers:

  Marchesano/Shiu/Uranga, 1404.3040
  Blumenhagen/Plauschinn 1404.3542
  AH/Kraus/Witkowski 1404.3711

  as well as:

  Ibanez/Valenzueala
  Arends,AH,. . . , Lüst, Mayrhofer, Weigand
  Franco/Galloni/Retolaza/Uranga

  See L. McAllister's talk for more refs.

- They share the idea of a shift-symmetry in K, weakly broken by W

- Our version uses precisely the D7 ('complex-structure') shift-symmetry above, plus standard type-IIB fluxes

From unstable high-scale to metastable low-scale theories

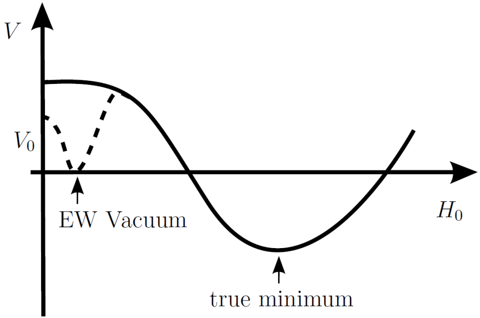
- So far, we argued that SUSY should appear at least at the scale μ_λ.
- In fact, it takes very little effort to avoid this naive expectation:
- Let string theory produce a high-scale NMSSM, with a large SUSY mass M for the singlet S, and a small soft mass:

  Giudice/Strumia '11

$$W = \kappa S H_u H_d + \frac{1}{2} M S^2 \,, \qquad V_{\rm soft} \supset m_s^2 |S^2|$$

- Integrating out S creates a negative quartic potential!

- This leads to an interesting UV→IR effective-theory running picture:



- 'Our' minimum is generated only radiatively, as λ runs from negative to positive values in a loop-calculation based on an unstable vacuum.

(String-) GUTs with High-Scale SUSY

original work based on paper with J. Unwin;
see also Gato-Rivera/Schellekens, Lin/Weigand

- If SUSY is broken far above 1 TeV, precision unification fails

- Naively, one might think that GUTs lose their motivation since the "$\mathbf{10} + \overline{\mathbf{5}}$" spectrum follows from anomaly cancellation

- This can be argued as follows: Foot, Lew, Volkas, Joshi '89 Knochel, Wetterich '11

  Starting from the **(3,2)** of the SM, anomaly cancellation allows only

$$\textbf{I}: \quad (3,2)_{1/6} + (\overline{3},1)_{-2/3} + (\overline{3},1)_{1/3} + (1,2)_{-1/2} + (1,1)_{1}$$

$$\textbf{II}: \quad (3,2)_{Y} + (\overline{3},1)_{-Y-1/2} + (\overline{3},1)_{-Y+1/2} + (1,2)_{-3Y} + (1,1)_{3Y-1/2} + (1,1)_{3Y+1/2}$$

$$\textbf{III}: \quad (3,2)_{Y} + (\overline{3},2)_{-Y-1/2} + (\overline{3},2)_{-Y+1/2} + (3,2)_{-Y} + (\overline{3},2)_{Y-1/2} + (\overline{3},2)_{Y+1/2}\,.$$

- ...thus, the SM spectrum (i.e. 'choice **I**')
  has a 30% chance whithout any deeper motivation

- However, the threefold replication of 'choice **I** requires explanation
  (statistically, one would expect some combination of the choices **I**, **II** and **III**)

  By contrast:

- In an $SU(5)$ GUT (e.g. with hypercharge-flux-breaking), a simple choice of flux numbers explains the threefolds replication of the $\mathbf{10} + \overline{\mathbf{5}}$ spectrum

- One can take this (plus, possibly, simplicity) as a motivation to consider GUTs even without low-scale SUSY

F-theory corrections to unification

Donagi/Wijnholt; Blumenhagen '08

- It is then natural to consider F-theory corrections to maintain precision unification in high-scale SUSY scenarios

Ibanez, Marchesano, Regalado, Valenzuela '12

- In contrast to previous discussions, I want to argue that both
classical ('Blumenhagen type') and
loop ('Donagi/Wijnholt-type')
corrections have to be added

- The argument is based on the type I / heterotic 1-loop formula

Bachas, Kiritsis '96

$$\mathcal{L} \sim R_I^2\Big[\tfrac{1}{g_I}\mathrm{Tr}_f[F^4] + \Big\{\int_0^\infty dl \sum_w e^{-w^2 l/2\pi}\Big\}\Big(\mathrm{Tr}_f[F^4]+\tfrac{1}{8}\mathrm{Tr}_f[F^2]^2\Big)\Big]+\cdots \,,$$

F-theory corrections to unification (continued)

- Rewriting this in type IIB variables gives

$$\mathcal{L} \sim \frac{1}{g_s} \mathsf{Tr}_f \left[F^4\right] + \mathsf{Tr}_{\mathrm{Adj}} \left[F^4\right] \mathrm{Log}(1/\epsilon)$$

- Here we clearly see both the classical ('Blumenhagen') and loop (Donagi/Wijnholt) terms

GUT implementation

Dolan/Marsano/Schäfer-Nameki '11

- Start from

$$\alpha_i^{-1}(m_Z) = \alpha_{\mathrm{GUT}}^{-1} + \frac{1}{2\pi} b_i^{\mathrm{MSSM}} \log\left(\frac{M_{\mathrm{KK}}}{m_Z}\right) + \delta_i^{\mathrm{MSSM}} + \delta_i^{\mathrm{tree}} + \delta_i^{\mathrm{loop}} ,$$

GUT implementation (continued)

- More specifically

$$\delta_i^{\rm MSSM} = \frac{1}{2\pi}\left(b_i^{\rm SM} - b_i^{\rm MSSM}\right)\log\left(\frac{M_{\rm SUSY}}{m_Z}\right)$$

$$\delta_i^{\rm loop} = \frac{1}{2\pi} b_i^{5/6} \log\left(\frac{\Lambda}{M_{\rm KK}}\right)$$

Conlon; Conlon/Palti '09

$$\delta_i^{\rm tree} = \frac{b_i^H}{g_s}\int_S \left[f_Y \wedge i^* B_- - \frac{1}{10} f_Y \wedge f_Y - f_Y \wedge f_S\right]$$

Mayrhofer/Palti/Weigand '13

- This allows for a full phenomenological analysis

The strategy of Ibanez/Marchesano/Regalado/Valenzuela

- Let W_0 and g_s take its natural, $\mathcal{O}(1)$ values
- Implement the above formulae (without loop-effect)
- One finds $M_{\rm GUT} \simeq 3 \times 10^{14}$ GeV and $M_{\rm SUSY} \simeq 5 \times 10^{10}$ GeV
- The unavoidable dimension-6 proton decay must be suppressed by localization of X, Y gauge bosons away from the matter curves

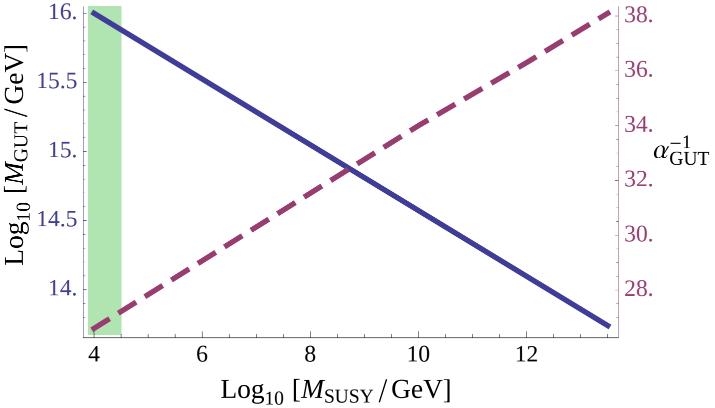
see also Hamada/Kobayashi '12; Kakizaki '13

Our strategy

- We believe (see below) that it is very hard to suppress X, Y-induced proton decay
- Then $M_{\rm GUT}$ must be kept high which (based on the RG-analysis) forces $M_{\rm SUSY}$ to remain low(ish)

Running/proton-decay constraints

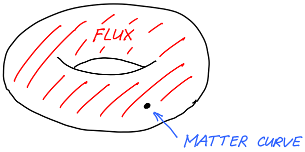
$$M_{\mathrm{GUT}} \simeq 4.25 \times 10^{15}\ \mathrm{GeV} \left(\frac{10^5\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^{2/9} \left(\frac{3.3}{\Lambda/M_{\mathrm{KK}}}\right)^{1/3}$$



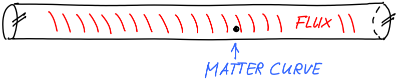
The crucial X, Y-localization issue

see also Klebanov/Witten '03; Beasley/Heckman/Vafa
Cecotti/Cheng; Conlon/Palti/Dudas/Camara;
Font/Ibanez/Aparicio/Marchesano;...

- Let $S = T^4 = T^2 \times T^2$, with the matter curve on the small T^2



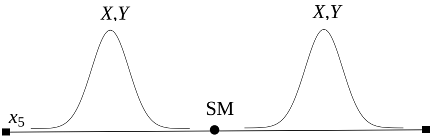
- The best localization arises for $T^2 = S^1 \times S^1$



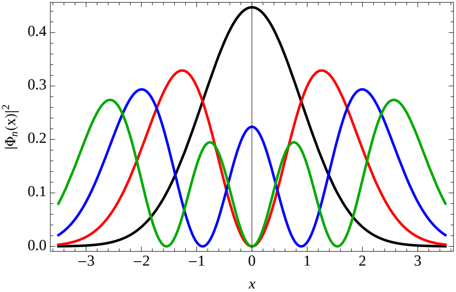
- The X, Y wavefunctions now correspond to those of a scalar field on a line with linearly varying mass term

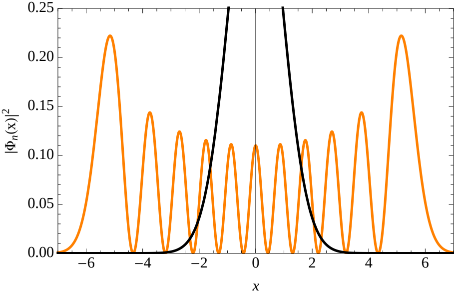
- The relevant equation of motion is precisely the Schrödinger equation of a harmonic oscillator

Hayashi/Kawano/Tsuchiya/Watari '09



- Including higher modes (Landau levels):





- One can place the matter curve away from the lowest mode
- But higher modes 'spread out', reaching the matter curve
- Our (toy model) calculation, including summation over higher Landau level modes, gives

$$\frac{\Gamma}{\Gamma_{\rm 4D}} \sim N^2 \geq 1$$

- The only way out appears to be localizing fermions in the same GUT multiplet away from each other
- We believe that this is very difficult
- One can 'split' the multiplets, but this destroys our motivation

See e.g. Font/Ibanez '08; Dudas/Palti '10; Callaghan et a. '11; Krippendorf et al '14

$\Rightarrow$ Strong reasons to expect $M_{\rm SUSY} \lesssim 100$ TeV

Moduli stabilization / Uplifting

- KKLT: $K = -3\ln(T + \overline{T})\,; \qquad W = W_0 + e^{-2\pi T}$

$$\Rightarrow 2\pi\tau \sim \ln(1/W_0)$$

- LVS: $K = -2\ln[\mathcal{V}(T_b, T_s) + \xi]\,; \qquad W = W_0 + e^{-2\pi T_s}$

$$\Rightarrow \mathcal{V} \sim W_0 \exp(\xi^{2/3})$$

(both need uplifting)

- Kähler uplifting:

$$K = -2\ln[(T + \overline{T})^{3/2} + \xi]\,; \qquad W = W_0 + e^{-2\pi T/N}$$

$$\Rightarrow \tau \sim N$$

Moduli stabilization / Uplifting

- In KKLT and KU, getting a large volume is hard (in KU, one has to understand whether large N induces complicated topology, requiring even larger volume)
- In LVS, the volume modulus is lighter than $m_{3/2}$, making cosmology with low scale SUSY even more difficult than usual
- Provocatively stated, it is unclear how to get (believable) low-scale SUSY in intersecting brane models (including F-theory), but that may be OK nowadays...
- The most promising variant for TeV-SUSY appears to be the LVS with sequestering (MSSM from branes at singularity)

Blumenhagen/Moster/Krippendorf/Moster/Quevedo

Moduli stabilization / Uplifting

- However, the crucial claim of sequestering $(m_S \sim m_{3/2}/\mathcal{V}^{\cdots})$ is still under investigation

- In particular, 'moduli mixing' is a threat....

Berg/Conlon/Marsh/Witkowski, Choi/Nilles/Shin/Trapletti, ...
Goodsell/Witkowski - in progress

Uplifting

- The 'classical' warped-anti-D3-uplift is undergoing scrutiny
- Clearly, a better understanding of the backreacted geometry near the $\overline{D3}$ is desirable

McGuirk, Shiu, Sumitomo, Bena, Grana, Van Riet, Zagermann, Blaback, Danielsson, Junghans, Wrase, Giecold, Halmagyi, Massai, Zagermann,...

$\rightarrow$ figure

Uplifting

- Clearly, one could think of ‘simply’ adding an ISS-type sector...
- A (relatively) new player is the (modern version of) D-term uplifting:

$$V_D \sim (\xi - Q\overline{Q})^2 \, ; \qquad V_F \supset m_s^2 |Q|^2$$

- It would be nice, however, to understand what’s going on geometrically
- very importantly, in this setting it is now in principle possible to do everything (i.e. moduli stabilization, uplifting and model building) at once!

Cicoli/Klevers/Krippendorf/Mayrhofer/Quevedo/Valandro
talk by C. Mayrhofer

Landscaping...

- Making proper use of statistics in the landscape is an exciting field which has only started to be explored...

classical papers by Denef/Douglas et al.
more recently McAllister et al., hopefully also in L. McAllister's talk...

Loops...

- Progress badly needed in context of (de-)sequestering (see above)

- Estalishing the 'Berg-Haack-Pajer' conjecture about the form of 'Berg-Haack-Körs' loop correction remains an important opne issue

Berg/Haack/Kang/Sjors; Conlon/Goodsell....

α' corrections in F-theory

Grimm/Savelli/Weissenbacher; Garcia-Etxebarria/Hayashi/Savelli/Shiu;
$\rightarrow$ T. Weigand's talk

Geometric / Non-geometric / Generalized Fluxes / Double Field Theory

- ...a wide open and very exciting field, (hopefully?) one of the main subjects of this meeting
- Pheno applications are of highest interest!

  Aldazabal, Hohm, Blumenhagen, Lüst, Hassler, Massai, Dibitetto, Andriot, Berman, Danielsson,...

- Some of the crucial issues awaiting resolution:
  Moduli stabilization / uplift in type IIA and heterotic models
  Directly constructing de Sitter vacua (without 'uplift')

Cosmology / Light fields / Axiverse / 'Dark Photons'

- The topics above have become a central theme for string phenomenology
- I will leave inflation to L. McAllister's talk
- I will ignore 'Dark Photons' / multiple axions / the QCD-axion merely for reasons of time
  (although especially the QCD axion has become a challenge due to the high inflation scale suggested by BICEP)
- My focus will be on the model independent prediction of Dark Radiation in models with large (perturbatively stabilized) volume
- Note also interesting papers explaining X-ray excess or 3.5 keV line using DR/axions

Angus, Conlon, Marsh, Powell, Witkowski,...

Dark Radiation

- conventional variable: N_{eff}

  (effective number of neutrino species; $N_{eff}^{SM} = 3.046$)

- Plank + WMAP + highL + BAO+H_0:

$$N_{eff} = 3.5 \pm 0.5 \quad (95\% \text{ CL})$$

- $\Rightarrow$ mild preference for $\Delta N_{eff} \neq 0$; strengthened by BICEP

  Here: View this as a bound on dark radiation

- Crucial: Significant improvement expected in the future; Potential to exclude models with $\Delta N_{eff} \neq 0$

- Conventional picture of cosmological evolution with some extra light d.o.f. (DR) :

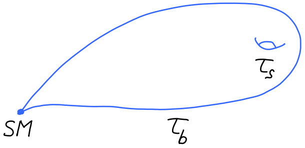
$$\text{Inflaton} \longrightarrow (\text{Modulus } \Phi) \longrightarrow \text{SM} + \text{DR}$$

$$\Delta N_{eff} \sim \frac{\Gamma_{\Phi \to DR}}{\Gamma_{\Phi \to SM}}$$

- In the LVS, the volume is the lightest moduls, Φ, and its imaginary part ('axion') unavoidably becomes DR

Dark radiation in the sequestered Large Volume scenario

Cicoli, Conlon, Quevedo '12
Higaki, Nakayama, Takahashi '12...'13



- sequestered Kähler potential:

$$K = -3\ln\left(T_b + \overline{T}_b - \frac{1}{3}\left[C^i\overline{C}^i + H_u\overline{H}_u + \{zH_uH_d + \text{h.c.}\} + \cdots\right]\right)$$

see e.g. Blumenhagen, Conlon, Krippendorf, Moster, Quevedo, '09

- A straightforward analysis gives:

$$\Gamma_{\Phi \to a_b a_b} = \frac{1}{48\pi} \frac{m_\Phi^3}{M_P^2}$$

$$\Gamma_{\Phi \to H_u H_d} = \frac{2z^2}{48\pi} \frac{m_\Phi^3}{M_P^2}$$

- Conclusion: Need either $z > 2$ or $n_H > 4$.

  (Here n_H counts Higgs doublets
  and one assumes the bound $N_{eff} < 4$.)

- Comment: Shift symmetry singles out $z = 1$,

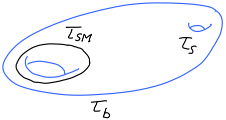
$$K_H \sim |H_u + \overline{H}_d|^2 \, .$$

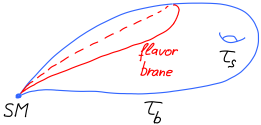
  (It is unclear how to realize $z \gg 1$ at a fundamental level.
  Note that the Kähler metric becomes singular in this limit.)

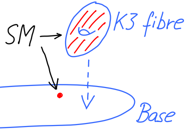
Dark radiation in the general Large Volume scenarios

AH/Mangat/Rompineve/Witkowski '14, Angus '14

- We consider various settings (D-term-stabilized SM cycle in geometric regime, loop-stabilized fibred model, flavor branes)

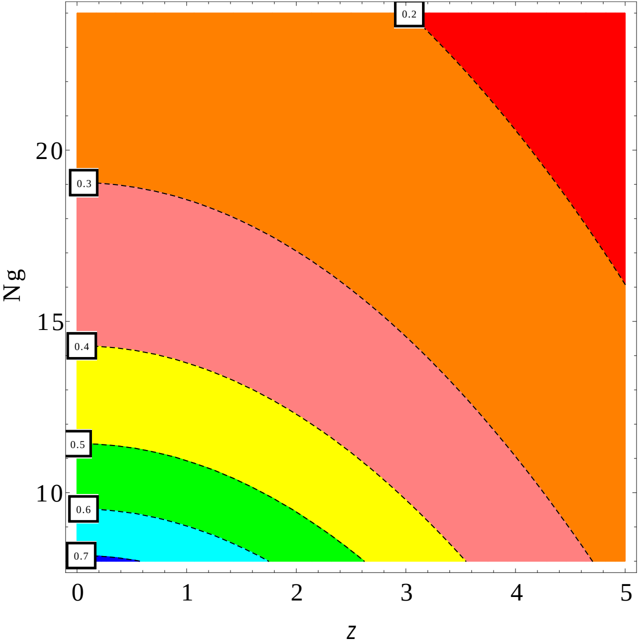






ΔN_{eff}

in LVS
with
flavor-branes



Result:

- Interpreting present 'dark radiation data' as bounds, the sequestered LVS may already be in trouble

  (Although this depends on $T_{reh.}$)

- The 'non-sequestered' or 'de-sequestered' (through flavor branes) LVS provides some more freedom, but still rather limited...

- Thus, discovery of dark radiation is expected in the foreseeable future

- Otherwise, there is the potential of ruling out the LVS altogether

  (Unless one is prepared to accept an anthropically unmotivated tuning)

Summary/Conclusions

- While we still hope for TeV scale SUSY, other playing fields for string phenomenology emerge
- String phenomenology / string cosmology is making continuous progress, but many crucial issues remain unsolved
- It is the arena for those who think that strings have something to say about quantum gravity in this world