EMERGENCE OF THE WEAK SCALE FROM M THEORY WITH STABILIZED MODULI AND UNIFICATION

-- compactify on manifolds with G_2 holonomy

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Acharya, Bobkov, Kane, Kumar, to be posted soon

Work in progress

- Introduction
- Stringy stuff
- Moduli stabilization

  -- AdS, supersymmetric

  -- AdS, ~~susy~~

  -- deS, ~~susy~~
- Cosmological Constant?
- Gauge coupling unification
- $M_{3/2}$
- Moduli masses
- Soft-breaking Lagrangian
- Phenomenology, LHC
- Summary
- Workshop

Earlier G2 phenomenological work, mainly on embedding SM (SU(5)), at singularities in a manifold with G_2 holonomy, proton decay, hierarchical Yukawas

- Acharya and Witten, th/0109152
- Witten, ph/0201018
- Friedmann and Witten, th/0211269
- Acharya and Valandro, ph/0512144

Don’t discuss these here

Our work -- Generate EW scale in a metastable deSitter vacuum with all input physics ~ unification scale, and all moduli stabilized, and MSSM with softly broken supersymmetry – all simultaneous

Presumably can combine this with Witten, Acharya et al SU(5) embedding (or some extension), so gauge coupling unification natural, etc

PERSPECTIVE

"hierarchy problem" is in a sense the phenomenological way of saying "unify gravity and quantum theory" -- large difference between Planck and EW scales, plus quantum corrections to scalar masses… -- arguably most important problem in particle physics – probably only solvable in string theory

Hierarchy problem has two aspects, stabilize it (at any scale), and explain observed hierarchy ($\sim 10^{16}$) -- supersymmetry alone stabilizes it, but does not explain it

Hidden sector gaugino condensation can explain the hierarchy, by inputting only unification-scale physics and generating the weak scale – long known

In M theory compactified on G_2 can explain hierarchy with moduli stabilization (and consistent with gauge coupling unification) – no small parameters

Embedding of SM/SU(5)/… already examined in same theory – may be very (most?) convenient way to construct full theory that achieves all goals

Also we begin phenomenological studies, particularly LHC

Very generic results

- $M_{3/2}$ ~ few TeV
- Gaugino masses considerably smaller than sfermion masses, and not universal
- Light gluinos, 200-500 GeV → see very quickly at LHC
- Squark masses nearly degenerate and ~ $M_{3/2}$
- Probably bino-like DM, OK relic density

STRINGY

- 7 dimensions form a space X with G_2 holonomy, supersymmetry
- No fluxes -- not needed for stabilization in our case, tend to raise masses to string scale
- In these vacua, non-Abelian gauge fields localized along 3D submanifolds Q at which there is an orbifold singularity [Acharya, th/9812205;th/0011089]
- Chiral fermions localized at points at which there are conical singularities [Acharya and Witten, th/0109152, Acharya and Gukov, th/0409191; Atiyah and Witten, th0107177]

- Joyce and Kovalev have constructed examples of G_2 manifolds without singularities
- Dualities with heterotic and Type IIA vacua suggest the existence of singular examples
- Can extend Kovalev's constructions to include orbifold singularities, and Yang-Mills fields

-- Kovalev constructs G_2 manifolds which can be described as the total space of a fibration – fibres are 4D K3 surfaces – if one allows the generic K3 fibre to have orbifold singularities, then one obtains G_2 manifolds which also have orbifold singularities, and give rise to YM fields in M theory

-- get similar picture from M theory dual of the heterotic string on a CY manifold at large complex structure

So expect lack of G_2 mathematical knowledge will not prevent going ahead with some aspects of the physics

MODULI STABILIZATION

- All G_2 moduli fields s_i have axionic partners t_i which have a shift symmetry in the absence of fluxes (different from heterotic or IIB) – such symmetries can only be broken by non-perturbative effects
- So in zero-flux sector only contributions to superpotential are non-perturbative, from strong dynamics (e.g. gaugino condensation) or instantons – we focus on former
- In M theory the superpotential, and gauge kinetic function, in general depend on all the moduli -- expect the effective supergravity potential has isolated minima
- Expect, and see explicitly, that the hidden sector gaugino condensation produces an effective potential that stabilizes all moduli

CONSTRUCT THE MODULI POTENTIAL GENERATED BY HIDDEN SECTOR GAUGINO CONDENSATION:

- N moduli $z_i = t_i + is_i$, real parts axion fields, imaginary parts zero modes of the metric on X, measure volume of N independent three dimensional cycles in X
- A particle localized at a point p will be charged under a gauge field supported on a 3D submanifold Q if $p \in Q$
- Generically two 3D submanifolds do not intersect in a 7D space so no light matter fields charged under both SM gauge group and hidden sector gauge groups → susy breaking is gravity mediated in these vacua
- Metric, Kahler potentials not yet known for these vacua

However, a set of Kahler potentials, consistent with G_2 holonomy and known to describe some explicit examples, was given by Acharya, Denef, Valandro th/0502060, with

$$K = -3\ln(4\pi^{1/3} V_X)$$

$$V_X = \prod_{i=1}^{N} s_i^{a_i}, \quad \text{with} \quad \sum_{i=1}^{N} a_i = 7/3$$

We assume we can use this. More generally the volume will be multiplied by a function with certain invariances.

We want to study moduli stabilization via gaugino condensation – first hidden sectors with no charged matter, then add hidden sector chiral matter a la Nilles et al, th/0603047, which gives AdS → dS

So

$$W = \sum_{k=1}^{M} A_k e^{ib_k f_k}$$

Keep two terms – enough to find solutions with good properties such as being in supergravity regime, simple enough to do most calculations semi-analytically

$b_k = 2\pi/c_k$ where c_k are dual coxeter numbers of hidden sector gauge groups, A_k are constants of order unity, ratios up to ~ 10, and depend on threshold corrections to gauge couplings, some computed by Friedmann and Witten

The gauge kinetic functions here are integer linear combinations of all the moduli,

$$f_k = \sum_{i=1}^{N} N_i^k z_i \,.$$

The constants (a_i, b_k, A_k, N_i^k) are determined for a given G_2 manifold (but not yet known for relevant ones)

For this kahler potential the metric is

$$K_{i\bar{j}} = \frac{3a_i}{4s_i^2}\delta_{i\bar{j}}$$

The supergravity scalar potential

$$V = e^K (K^{i\bar{j}} F_i \bar{F}_{\bar{j}} - 3|W|^2),$$

is

$$V = \frac{1}{48\pi V_X^3} [\sum_{k=1}^{2} \sum_{i=1}^{N} a_i \nu_i^k \left(\nu_i^k b_k + 3\right) b_k A_k^2 e^{-2b_k \vec{\nu}^k \cdot \vec{a}} + 3 \sum_{k=1}^{2} A_k^2 e^{-2b_k \vec{\nu}^k \cdot \vec{a}}$$
$$+2\cos[(b_1 \vec{N}^1 - b_2 \vec{N}^2) \cdot \vec{t}\,] \sum_{i=1}^{N} a_i \prod_{k=1}^{2} \nu_i^k b_k A_k e^{-b_k \vec{\nu}^k \cdot \vec{a}}$$
$$+3\cos[(b_1 \vec{N}^1 - b_2 \vec{N}^2) \cdot \vec{t}\,] \left(2 + \sum_{k=1}^{2} b_k \vec{\nu}^k \cdot \vec{a}\right) \prod_{j=1}^{2} A_j e^{-b_j \vec{\nu}^j \cdot \vec{a}}]$$

where $\nu_i^k \equiv \frac{N_i^k s_i}{a_i}$ (no sum)

Look for supersymmetric vacua:

Find solutions if axions take on values such that

$$\cos[(b_1\vec{N}^1 - b_2\vec{N}^2)\cdot\vec{t}] = -1$$

and

$$s_i = -\frac{3\,a_i\,(\alpha-1)}{2\,(b_1 N_i^1\alpha - b_2 N_i^2)}; \quad i = 1,2,..,N$$

There are solutions with all moduli stabilized and volume larger than unity so supergravity limit presumably valid

Next extend to vacua with spontaneously broken susy

- Get isolated vacua, so all moduli fixed – AdS
- Study one, two moduli in detail in paper
- Do for many moduli, for case with equal hidden sector gauge kinetic functions – get 2^{N-1} to 2^N solutions, still all AdS
- For hidden sector gauge group SU(P)xSU(Q) get moduli fixed at

$$s^{(c)}_{A,k} = \frac{1}{2\pi}\left(\frac{a_k}{N_k}\right)\left(\frac{L^{(c)}_{A,k}}{B^{(c)}_A}\right)\frac{PQ}{P-Q}\log\left(\frac{A_2 P}{A_1 Q}\right) + \frac{L^{(c)}_{A,k}}{2\pi}\left(\frac{a_k}{N_k}\right)\left(\frac{P-Q}{\log\left(\frac{A_2 P}{A_1 Q}\right)}\right)$$

Will do semi-analytic examples for case when the two hidden sector gauge kinetic functions are equal, get in particular

$$\frac{A_2}{A_1} = \frac{1}{\alpha} e^{-\frac{7}{3}(b_1 - b_2)\nu}$$

and

$$s_i = \frac{a_i \nu}{N_i}$$

with

$$\nu = \frac{3}{14\pi} \frac{P\,Q}{P - Q} \log\left(\frac{A_2 P}{A_1 Q}\right)$$

Next add charged matter in hidden sector to raise minima to deS – some interesting results, surprising – get unique deS vacuum!

Also, if can impose condition that tree level vacuum energy cancels, solution then has $M_{3/2}$ in TeV range!

Include massless quark states Q with N_c colors, N_f flavors -- then for M theory, following Nilles et al get

$$W = A_1 \, e^{i\frac{2\pi}{N_c - N_f}\sum_{i=1}^{N} N_i^{(1)} z_i} \det(Q\tilde{Q})^{-\frac{1}{N_c - N_f}} = A_1 \phi^a \, e^{ib_1 f_1}$$

where one defines an effective meson field

$$\phi \equiv \left(\det(Q\tilde{Q})\right)^{1/2} = \phi_0 e^{i\theta}$$

Chiral fermions localized at pointlike conical singularities, so bulk moduli s_i should have little effect on local physics – so assume hidden sector chiral fermions have modular weight zero and kahler potential is canonically normalized, and for simplest case take one flavor – assume kahler potential slowly varying -- then

$$W = A_1 \phi^a \, e^{i b_1 f} + A_2 e^{i b_2 f}$$

$$K = -3 \ln(4\pi^{1/3} V_X) + \phi \bar{\phi}$$

The N=1 SUGRA scalar potential is then given by:

$$
\begin{aligned}
V \;=\; & \frac{e^{\phi_0^2}}{48\pi V_X^3}\Big[\big(b_1^2 A_1^2 \phi_0^{2a} e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2^2 A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2b_1 b_2 A_1 A_2 \phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)\big) \\
& \times \sum_{i=1}^{N} a_i(\nu_i)^2 + 3(\vec{\nu}\cdot\vec{a})(b_1 A_1^2 \phi_0^{2\alpha} e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2 A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} + (b_1+b_2) A_1 A_2 \phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \\
& \times \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)) + 3(A_1^2 \phi_0^{2a} e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2A_1 A_2 \phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \\
& \times \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)) + \frac{3}{4}\phi_0^2\,(A_1^2 \phi_0^{2\alpha}\left(\frac{a}{\phi_0^2}+1\right)^2 e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} \\
& + 2A_1 A_2 \phi_0^a \left(\frac{a}{\phi_0^2}+1\right) e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta))\Big].
\end{aligned}
\tag{101}
$$

Minimize, lots of analysis – get metastable deS minimum

$$s_i = \frac{a_i \nu}{N_i}, \quad \text{with} \quad \nu \approx \frac{3}{14\pi} \frac{PQ}{Q-P} \log\left(\frac{A_1 Q}{A_2 P}\right)$$

$$\phi_0^2 \approx 1 - \frac{2}{Q-P} + \sqrt{1 - \frac{2}{Q-P}} - \frac{7}{P \log\left(\frac{A_1 Q}{A_2 P}\right)} \left(\frac{3}{2} + \sqrt{1 - \frac{2}{Q-P}}\right)$$

and since ϕ_0^2 is real, positive, must have Q-P>2

Potential at minimum is

$$V_0 = \frac{(A_2 \tilde{x})^2}{64\pi V_X^3} \left[\phi_0^4 + \left(\frac{2\,a\tilde{\alpha}}{\tilde{x}} - 3\right)\phi_0^2 + \left(\frac{a\tilde{\alpha}}{\tilde{x}}\right)^2\right] \frac{e^{\phi_0^2}}{\phi_0^2} \left(\frac{A_1 Q}{A_2 P}\right)^{-\frac{2P}{Q-P}}$$

More analysis – leading order condition for energy density at minimum positive easy to satisfy

$$3 - \frac{8}{Q-P} - \frac{28}{P\log\left(\frac{A_1 Q}{A_2 P}\right)} < 0$$

Metastable, seems to be unique, very different from AdS case

COSMOLOGICAL CONSTANT?

No solution here – can we still do meaningful phenomenology?

Of course, CC problem may be solved by other physics

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Set above V_0 to zero (potential at minimum) at tree level, if

$$P \log\left(\frac{A_1 Q}{A_2 P}\right) = \frac{28(Q-P)}{3(Q-P)-8}$$

Since RHS turns out to be large, radiative corrections should have little numerical effect on phenomenology – also reduces number of parameters by one

We check numerically that varying V_0 has little effect on superpartner masses

[assumes enough G_2 manifolds so A_2/A_1 scans sufficiently finely over their landscape]

GAUGE COUPLING UNIFICATION

$$M_{11} = \frac{m_p}{V_X^{1/2}}$$

where $$V_X = \prod_i s_i^{a_i}$$ ($\sum_i a_i = 7/3$)

$V_X \sim 10^3$-10^4 is the dimensionless volume in 11D Planck units -- for our solutions, $M_{11} > M_{unif}$ so gauge coupling unification normal

($3.6\text{x}10^{16} < M_{11} < 4.3\text{x}10^{18}$ numerically for solutions in sugra region and 240 GeV < $M_{3/2}$ < 24 TeV)

GRAVITINO MASS

$$m_{3/2} = m_p e^{K/2} |W|$$

$$m_p = (8\pi G_N)^{-1/2} = 2.43 \times 10^{18} \text{ GeV}$$

$$m_{3/2} = m_p \frac{e^{\phi_0^2/2}}{8\sqrt{\pi} {V_X}^{3/2}} \left| A_1 \phi_0^a e^{-\frac{2\pi}{P}\mathrm{Im}f} - A_2 e^{-\frac{2\pi}{Q}\mathrm{Im}f} \right|$$

Calculate:

$$m_{3/2} = m_p \sqrt{2}\pi^3 A_2 \left| \frac{P}{Q} \phi_0^{-\frac{2}{P}} - 1 \right| \left(\frac{28Q}{3(Q-P)-8} \right)^{-\frac{7}{2}} e^{-\frac{28}{3(Q-P)-8}} \prod_{i=1}^{N} \left(\frac{7N_i}{3a_i} \right)^{\frac{3a_i}{2}} e^{\phi_0^2/2}$$

where the meson vev is now given by:

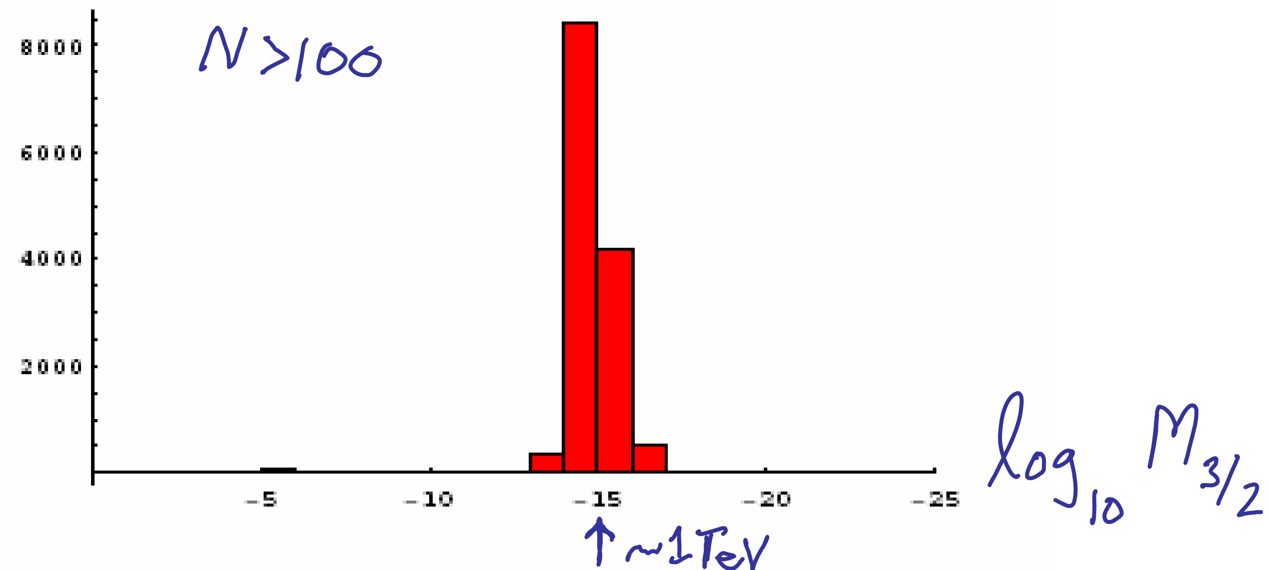
$$\phi_0^2 \approx -\frac{1}{8} + \frac{1}{Q-P} + \frac{1}{4}\sqrt{1 - \frac{2}{Q-P}} + \frac{2}{Q-P}\sqrt{1 - \frac{2}{Q-P}}.$$

Q-P>2, so take Q-P=3 to visualize,

$$m_{3/2} = m_p \sqrt{2}\pi^3 \left| \frac{P}{P+3}\, \phi_0^{-\frac{2}{P}} - 1 \right| \left(\frac{N}{28(P+3)} \right)^{\frac{7}{2}} e^{-28} e^{\phi_0^2/2} \, .$$

$$\phi_0^2 \approx \frac{1}{72}\left(15 + 22\sqrt{3}\right) \approx 0.7376 \, , \quad s_i = \frac{14\,(P+3)}{\pi\, N} \, .$$

Can scan P,N to see typical $M_{3/2}$ (keeping V_X>1 so sugra approximation valid)



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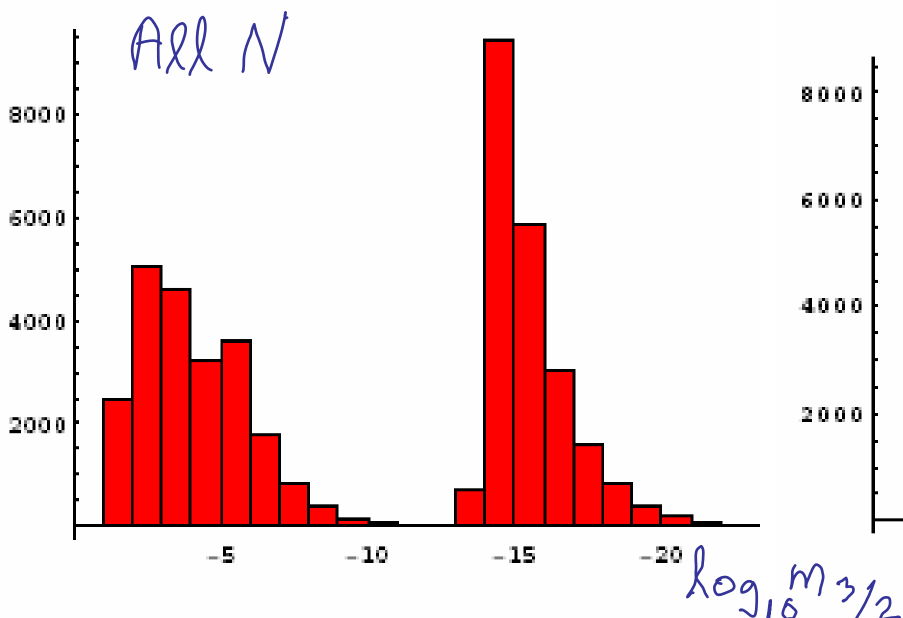

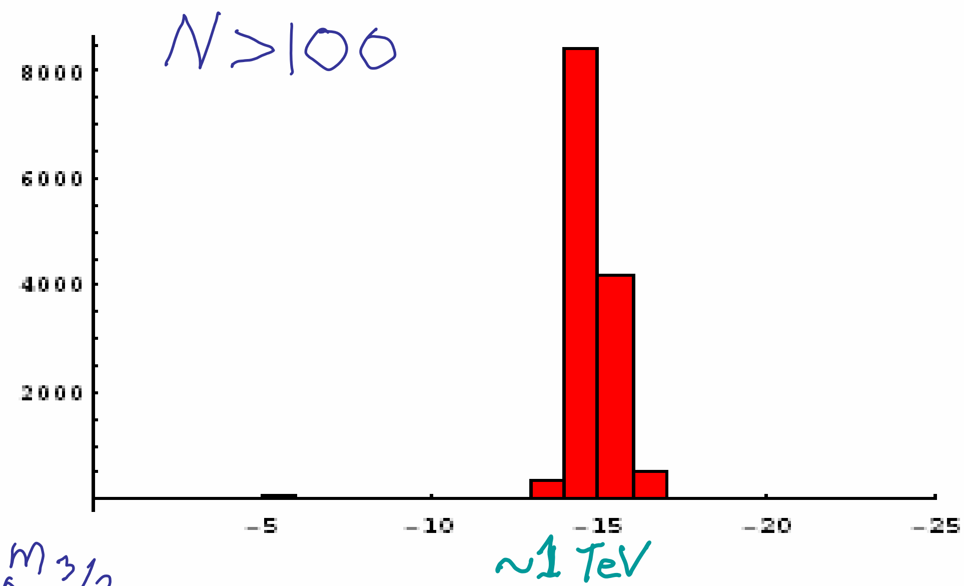

NOTE

- Qualitatively, $M_{3/2} \sim e^{K/2} W m_p$

$(\Lambda_{UNIF}/m_p)^3 \sim 10^{-9}$

$1/V \sim 10^{-6}$

- Condition from setting CC to zero at tree level seems to imply a relation between small CC and $M_{3/2} \sim$ TeV → do not have to *independently* tune CC to be small *and* $M_{3/2}$ to be ~ TeV

- For $M_{3/2}$ such results should be stable against loop corrections since the relevant factor was large

- Note

$$\log\, m_{3/2} \sim P \log\left(\frac{A_1 Q}{A_2 P}\right) + \ldots$$

MODULI MASSES

Geometric moduli Lagrangian kinetic term is non-canonical – redefine so canonical, write mass matrix, diagonalize for simplest case with all a_i=7/(3N) for all moduli – find all eigenvalues positive, with N-1 having

$$M_s \approx 2M_{3/2}$$

and one heavy state with mass ~ 500 $M_{3/2}$

All positive eigenvalues confirms deS minimum indeed a minimum, and metastable (with true minimum at infinity)

Gravitino and moduli problems with BBN etc likely OK but we have not checked carefully yet

SOFT LAGRANGIAN PARAMETERS

- Moduli fields, hidden sector matter fields, etc replaced by vevs, let M_{pl} get large at fixed $M_{3/2}$, get global soft susy breaking Lagrangian
- General calculation requires Kahler metric for soft parameters, Yukawas, μ parameter

  We do a calculation for visible chiral matter fields that generalizes that of Bertolini, Billo, Lerda, Morales, Russo, th/0512067 for toroidal orientifold constructions in IIA to M theory in order to calculate all parameters

- For the tree level gaugino masses the Kahler metric for visible sector chiral matter is not needed

TREE LEVEL GAUGINO MASSES

- Universal since SU(5) or similar unification at unification scale
- With same assumptions as used so far, get

$$M \approx -\frac{e^{-i\gamma W}}{P\log\left(\frac{A_1 Q}{A_2 P}\right)}\left(1+\frac{2}{\phi_0^2\,(Q-P)}+\frac{7}{\phi_0^2\,P\log\left(\frac{A_1 Q}{A_2 P}\right)}\right)\times m_{3/2}$$

NOTE

- Independent of SM or hidden sector gauge kinetic functions
- Independent of details of internal manifold (a_i) and number of moduli N
- Denominator proportional to ln($M_{3/2}$) so gaugino masses suppressed (Conlin and Quevedo found a similar result),

$$M \approx -\frac{e^{-i\gamma W}}{84}\left(1+\frac{2}{3\phi_0^2}+\frac{7}{84\phi_0^2}\right)\times m_{3/2} \approx -e^{-i\gamma W}\,0.024\times m_{3/2}$$

General expression for anomaly mediated contribution to gaugino masses: Gaillard, Nelson, and Wu, th/9905122

$$(M)_a^{am} = -\frac{g_a^2}{16\pi^2}\left[-(3C_a - \sum_\alpha C_a^\alpha)e^{K/2}W^* + (C_a - \sum_\alpha C_a^\alpha)e^{K/2}F^m K_m + 2\sum_\alpha (C_a^\alpha F^m \partial_m \ln(\tilde{K}_\alpha))\right]$$

where C_a are Casimir invariants – for our deS vacuum,

$$(M)_a^{am} = -e^{-i\gamma W}\frac{\alpha_{GUT}}{4\pi}\Big[-(3C_a - \sum_\alpha C_a^\alpha) + \frac{7(C_a - \sum_\alpha C_a^\alpha)}{P\log\left(\frac{A_1 Q}{A_2 P}\right)}\left(1 + \frac{2}{(Q-P)\,\phi_0^2} + \frac{7}{\phi_0^2\, P\log\left(\frac{A_1 Q}{A_2 P}\right)}\right)$$
$$- \frac{2\sum_\alpha C_a^\alpha \sum_i \frac{1}{2\pi}\left(l\,\psi_i^\alpha \sin(2\pi\theta_i^\alpha)\right)}{P\log\left(\frac{A_1 Q}{A_2 P}\right)}\left(1 + \frac{2}{(Q-P)\,\phi_0^2} + \frac{7}{\phi_0^2\, P\log\left(\frac{A_1 Q}{A_2 P}\right)}\right)\Big] \times m_{3/2}. \qquad (194)$$

Putting in numbers, up to the overall phase,

$$(M)^{am}_{U(1)} \approx -0.017 \times m_{3/2}, \quad (M)^{am}_{SU(2)} \approx -0.0005 \times m_{3/2}, \quad (M)^{am}_{SU(3)} \approx +0.0127 \times m_{3/2},$$

and combining the tree level and anomaly mediated contributions (at the unification scale)

$$M_1 \approx -0.041 \times m_{3/2}, \quad M_2 \approx -0.0245 \times m_{3/2}, \quad M_3 \approx -0.011 \times m_{3/2}.$$

NOTE

- Non-universal
- Cancel for gluino (M_3) but add for chargino so predict rather light gluinos and satisfy bounds on chargino more easily

YUKAWAS, trilinears, scalars, μ, Bμ, etc – have to canonically normalize matter field Kahler potential with a flavor matrix $Q_{m'm}$,

$$Y_{\alpha\beta\gamma} = e^{\hat{K}/2} \frac{\hat{W}^\star}{|\hat{W}|} Y'_{\alpha'\beta'\gamma'} Q_{\alpha'\alpha} Q_{\beta'\beta} Q_{\gamma'\gamma}$$

$$Y'_{\alpha\beta\gamma} = C_{\alpha\beta\gamma}\, e^{i2\pi \sum_i l_i^{\alpha\beta\gamma} z^i}$$

TRILINEARS – proportional to Yukawas if matter kahler metric is diagonal – presumably not general – overall size somewhat smaller than $M_{3/2}$ since coefficients small, but not suppressed as much as gaugino masses,

$$A_{\alpha\beta\gamma} \approx e^{-i\gamma_W} 0.024 \left[10.45 + 2\log\left|\frac{C_{\alpha\beta\gamma}}{Y_{\alpha\beta\gamma}}\right| - 7\log\left(\frac{14(P+3)}{N}\right) - \sum_i \left(\left\{ \frac{1}{2}\log\left(\frac{\Gamma(1-\theta_i^\alpha)}{\Gamma(\theta_i^\alpha)}\right) - \frac{1}{2\pi}(l\,\psi_i^\alpha \sin(2\pi\theta_i^\alpha) \right\} + \alpha \to \beta + \alpha \to \gamma \right) \right] \times m_{3/2}$$

SCALARS

$$(m_\alpha^2) = V_0 + (m_{3/2}^2)\left[1 - \frac{9}{4P^2\left(\log\left(\frac{A_1 Q}{A_2 P}\right)\right)^2}\left(1 + \frac{2}{(Q-P)\,\phi_0^2} + \frac{7}{\phi_0^2\, P \log\left(\frac{A_1 Q}{A_2 P}\right)}\right)^2\right.$$

$$\left.\times \frac{1}{4\pi}\sum_i \{l^2\, \psi_{ii}^\alpha\, \sin^2(2\pi\theta_i^\alpha) + l^2\, \psi_i^\alpha\, \sin(4\pi\theta_i^\alpha) - 2l\, \psi_i^\alpha\, \sin(2\pi\theta_i^\alpha)\}\right].$$

so $m_\alpha \approx M_{3/2}$

PHENOMENOLOGY

-- in progress

DARK MATTER

- EWSB fixes magnitude of μ – usually larger than M_1, M_2 so mostly bino-like LSP
- Significant co-annihilation with charginos, so $\Omega_{LSP} \sim \Omega_{DMwmap}$ or less

FLAVOR

- Squarks, sleptons have masses > a TeV, rather degenerate (correction ~ $1/\ln(M_{3/2})$)
- Expect small off diagonal flavor effects from Kahler potential
- So probably “susy flavor problem” OK – outcome, not assumed
- Perhaps some predictions

CP VIOLATION

- One common phase for all soft terms
- Don't know if that can be rotated away until understand μ and its phase – if μ real or has same phase as gaugino masses, then no "susy CP problem" would be automatic – then no EDMs
- Phases of Yukawas not studied yet – depends on origin of small masses

LHC PHENOMENOLOGY

- Have seen explicitly here that it makes sense to go from string theory to superpartner masses – study production cross sections and decays and find LHC signatures
- G_2 spectrum distinctive – will get characteristic signatures that occupy finite regions in signature space
- Generically other approaches occupy different regions – e.g. KKLT has gauginos and scalars suppressed relative to $M_{3/2}$ so comparable production of both, gives e.g. observable charge asymmetries – Quevedo et al only gauginos suppressed, but anomaly mediation gaugino masses also suppressed so no cancellation, so LEP bounds on charginos imply larger gluino masses, smaller cross sections, etc. [GK, Kumar, Shao, ph/0610038]

Lots to do:

- G_2 mathematics, analysis with singularities
- MSSM embeddings -- families
- GUT embedding – 3-2-1? SU(5)? SO(10)? E6? Extra U(1)s?
- Statistics of G_2 vacua
- Inflation
- μ problem – Witten argued μ=0 at unification scale -- not obvious that higher order terms don't allow a μ_{eff} above TeV scale – or relation of μ_{eff} to susy breaking
- In complete theory calculate μ_{eff} from underlying theory (and Bμ)
- Then calculate Higgs vevs, derive EWSB and M_Z from first principles
- Study phase structure and CP violation – can all phases except CKM one be rotated away from both geometry and susy breaking?
- Check flavor-changing effects OK – any predictions?
- Confirm no gravitino, moduli problems
- How does baryogenesis work?
- Strong CP problem, axions
- Neutrino masses – mechanisms?
- Discrete symmetries, R-parity? – LSP stable?
- LHC phenomenology!

GOOD STUFF:

- Reasonable string construction
- Embedding SM forces and quarks, leptons, stabilizing moduli, breaking susy, gauge compling unification, and emergence of full gauge hierarchy, all simultaneously, seems promising
- Seem to have unique metastable deS potential (affect statistics?)
- $M_{3/2}$ ~ TeV emerges if set tree level CC to zero
- Gaugino masses generally suppressed by $\ln M_{3/2}$
- Gluino mass few hundred GeV, easy to see quickly at LHC (maybe at Tevatron)
- Squark, slepton masses ~ $M_{3/2}$
- Probably no flavor problem – maybe opportunities
- Accomodates radiative EWSB in usual susy sense
- Probably ~ bino LSP, OK thermal relic density or smaller
- Can write minimal phenomenological model with only P,N as parameters from which all soft parameters can be calculated, study LHC signatures

Actually – not so nice that dependence on a_i, b_i, A_k, N_i^k, P, Q is weak, since we would like to measure them, learn about them

With good data, some dependence on them remains – need to be able to do stringy calculations to figure it out, e.g. flavor dependence of Kahler potential

Workshop

"Physics and mathematics of G_2 compactifications"

Michigan Center for Theoretical Physics

May 3-5, 2007

International Organizing Committee

Acharya, Bobkov, Gukov, Joyce, Kane, Kumar, Larsen, Liu, Lykken