Pattern of superpartner masses from string moduli stabilization

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Outline

- Introduction

  Hints on SUSY scale?

- Superpartner masses from string moduli stabilization

  KKLT & LVS

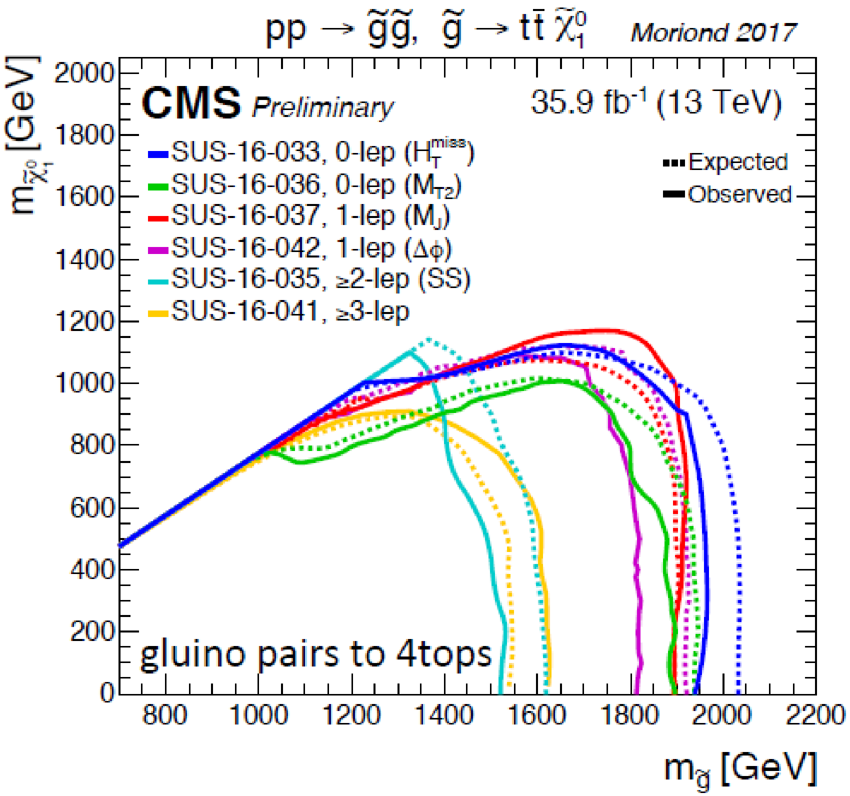
  (Concrete statement in some case, but just qualitative for other cases)

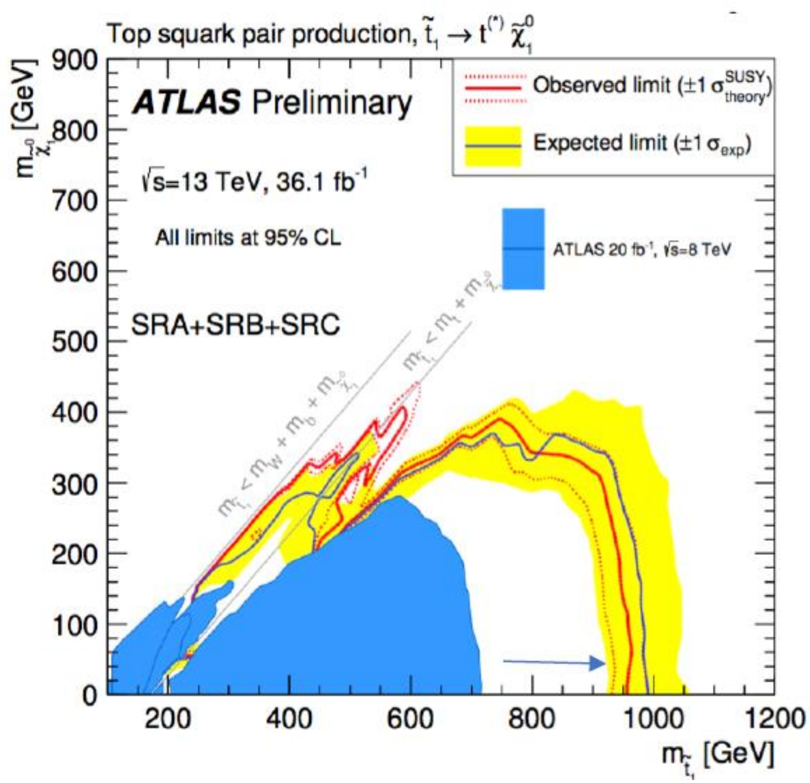
- Conclusion

Well-known motivations for SUSY

* Hierarchy problem
* Unification
* String/M theory
* Dark matter
* ....

No observational evidence yet:





However, although none of them is not convincing enough, the traditional arguments suggesting SUSY near the TeV scale might be still valid.

SUSY scale and the fine tuning for the EWSB:

$$\frac{M_Z^2}{2} \simeq -m_{H_u}^2 - |\mu|^2 + \frac{m_{H_d}^2}{\tan^2\beta}$$

$$= \left[-m_{H_u,\text{bare}}^2 + \frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{M_{\text{mess}}}{m_{\tilde{t}}}\right) + \frac{2y_t^2}{\pi^2}\frac{g_3^2}{4\pi^2} M_{\tilde{g}}^2 \left(\ln\left(\frac{M_{\text{mess}}}{M_{\tilde{g}}}\right)\right)^2 + \ldots\right]$$

$$- |\mu|^2 + \frac{m_{H_d}^2}{\tan^2\beta} \qquad \left(M_{\text{mess}} = \text{Messenger scale of SUSY breaking}\right)$$

➔

$$m_{\tilde{t}} \lesssim 0.5 \left(\frac{10\,\%}{\epsilon_{\text{tuning}}}\right)^{1/2} \left(\frac{3}{\ln(M_{\text{mess}}/m_{\tilde{t}})}\right)^{1/2} \text{TeV}$$

$$M_{\tilde{g}} \lesssim 1.3 \left(\frac{10\,\%}{\epsilon_{\text{tuning}}}\right)^{1/2} \left(\frac{3}{\ln(M_{\text{mess}}/M_{\tilde{g}})}\right) \text{TeV}$$

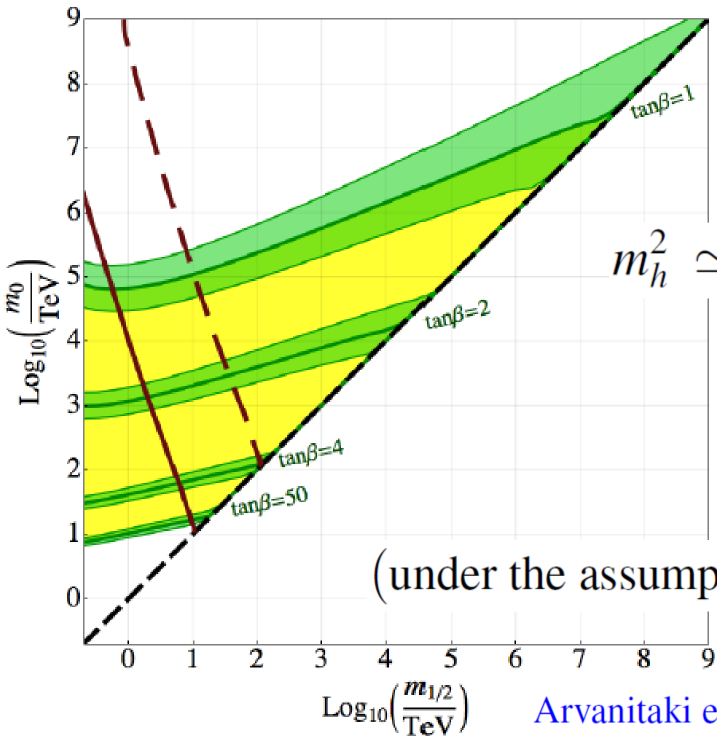
$$\mu \lesssim 0.2 \left(\frac{10\,\%}{\epsilon_{\text{tuning}}}\right)^{1/2} \text{TeV} \qquad \left(\epsilon_{\text{tuning}} = \text{degree of fine tuning}\right)$$

Current LHC bounds on the gluino and stop masses suggest a fine tuning $\epsilon_{\text{tuning}} \lesssim \mathcal{O}(1)\%$.

(cf: scalar/gaugino focus point, radiatively-driven naturalness: $\epsilon_{\text{tuning}} \sim 10\%$)

G. Ross's talk; H. Baer's talk

SUSY scale from the Higgs mass and gauge coupling unification



$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3 y_t^2 m_t^2}{4\pi^2}\left[\ln\left(\frac{m_{\tilde t}^2}{m_t^2}\right) + \frac{|X_t|^2}{m_{\tilde t}^2} - \frac{1}{12}\frac{|X_t|^4}{m_{\tilde t}^4}\right]$$

$$\left(X_t = A_t - \mu \cot\beta\right)$$

(under the assumption $m_{1/2} = m_{\text{higgsinos}} \sim m_{\text{gauginos}}$)

Arvanitaki et al., 2012

Precision gauge coupling unification might constrain not just the overall SUSY scale, but even the pattern of superpartner masses:

$$\left(\frac{\mu}{M_{\text{SUSY}}}\right)\left(\frac{m_H}{M_{\text{SUSY}}}\right)^{1/4}\left(\frac{M_{\tilde W}}{M_{\text{SUSY}}}\right)^{1/3}\left(\frac{M_{\tilde W}}{M_{\tilde g}}\right)^{7/3}\left(\frac{\tilde q}{m_{\tilde \ell}}\right)^{1/4} \simeq 1 \quad \left(M_{\text{SUSY}} \sim 1\ \text{TeV}\right)$$

Langacker & Polonsky, 1993; Carena, Pokorski & Wagner, 1993
Krippendorf, Nilles, Ratz & Winkler, 2013

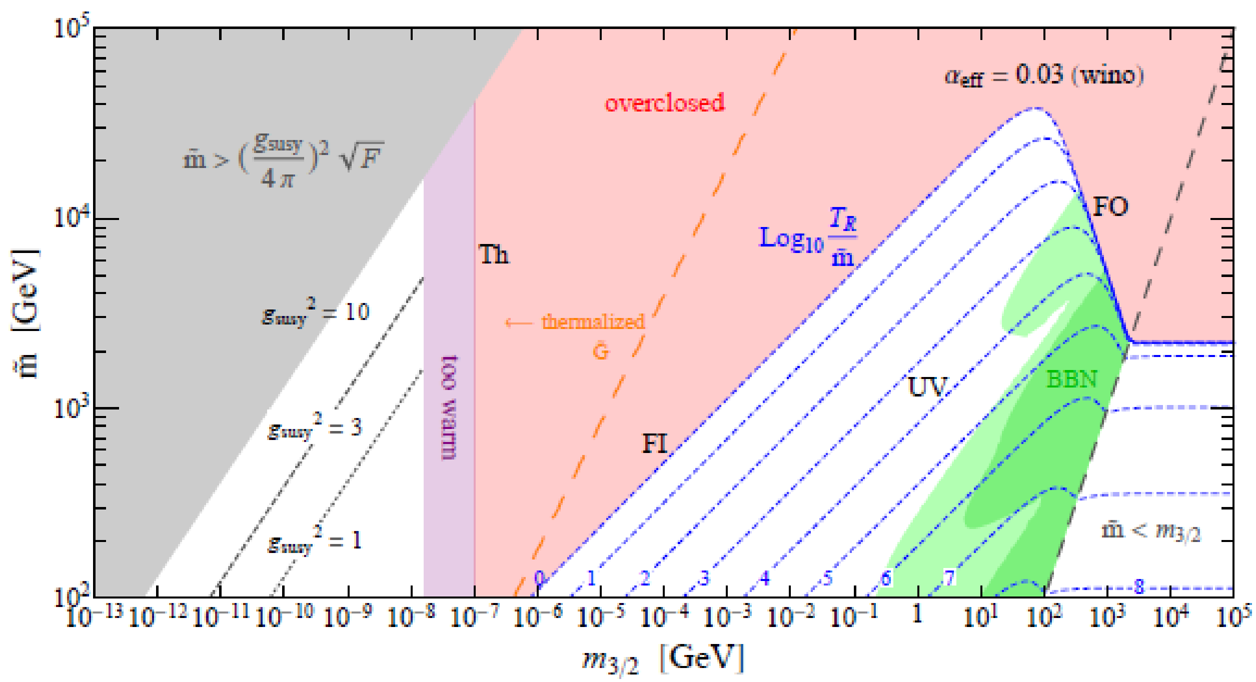
SUSY scale from LSP dark matter

Stable LSP (neutralino or gravitino) with T_R > $\tilde{m}$ = MSSM LSP mass

* Thermal freeze-out neutralino DM (no subsequent dilution)

* Gravitino DM produced by thermal scattering or the decays of MSSM superparticles

Hall, Ruderman & Volansky, 2013



To summarize, although we don’t have any observational evidence yet, SUSY has a reasonably good chance to be near the TeV scale, and may reveal herself in the on-going LHC experiments, or direct detection of the LSP dark matter, or the future collider experiments (FCC, CSC).

Superpartner masses from string moduli stabilization

An interesting framework which may allow us to compute superpartner masses starting from fundamental theory is string moduli stabilization at dS vacuum, which inevitably involves SUSY breaking.

There are two reasonably well-understood concrete schemes of string moduli stabilization, yielding an interesting pattern of superpartner masses:

KKLT

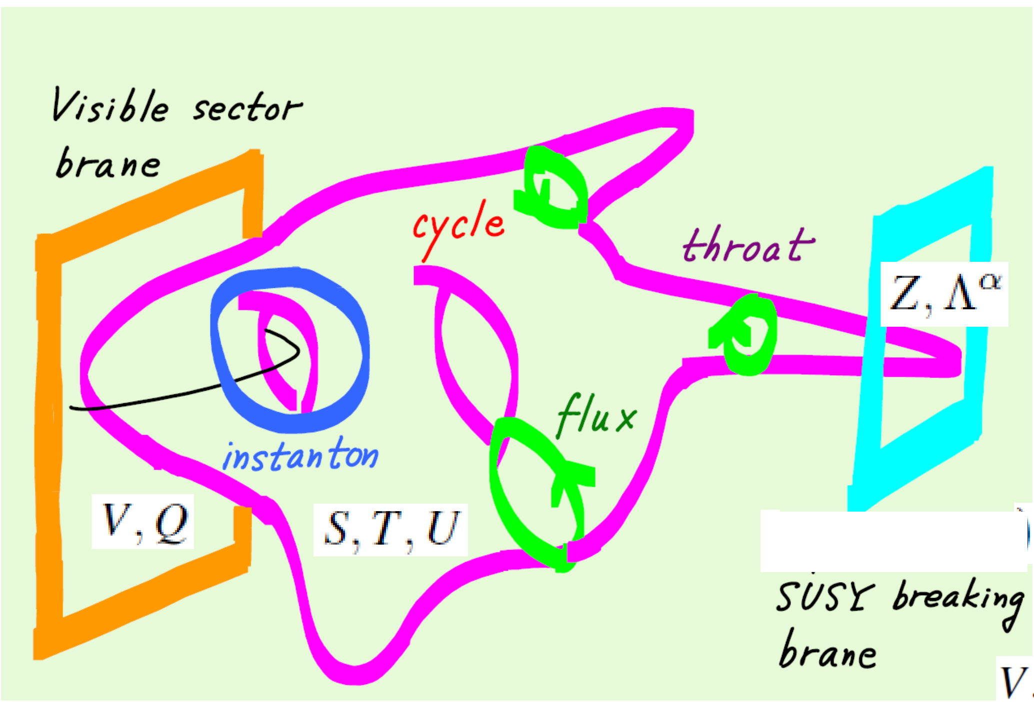
Large Volume Scenario (LVS)

KKLT moduli stabilization

- Flux stabilization of all moduli except for the Kähler moduli $\{T\}$
- Non-perturbative stabilization of $\{T\}$ by instantons (or gaugino condensation): Some of $\{T\}$ can be stabilized by the uplifting potential.
- (Sequestered) SUSY-breaking at the tip of warped throat

Giddings, Kachru & Polchinski, 2002
Kachru, Kallosh, Linde & Trivedi, 2003

Flux compactification involving warped throat:



Relevant 4D degrees of freedom:

S = dilaton

T = Kähler moduli in bulk

U = complex structure moduli in bulk

Z = complex structure modulus describing the collapsing throat

Λ^α = Goldstino superfield localized at the end of throat

Volkov & Akulov; Samuel & Wess

V, Q = visible gauge and matter superfields

Mass scales in KKLT setup:

Normalization: $\mathrm{Im}(S) \equiv \mathrm{Im}(S) + \frac{1}{4\pi}, \quad \mathrm{Im}(T) \equiv \mathrm{Im}(T) + \frac{1}{4\pi}$

$\Rightarrow$ $\mathrm{Re}(T) \sim \mathrm{Re}(S) = \mathcal{O}(1)$

$$M_{\text{string}} \sim \frac{M_{\text{Planck}}}{4\pi s^{1/4}\tau^{3/4}} \sim 10^{17}\,\text{GeV} \quad (s \equiv \mathrm{Re}(S),\, \tau \equiv \mathrm{Re}(T))$$

$$M_{\text{KK}} \sim \left(\frac{s}{\tau}\right)^{1/4} M_{\text{string}}$$

$$m_{S,U} \sim \frac{M_{\text{KK}}^3}{M_{\text{string}}^2} \sim 10^{16}\,\text{GeV}$$

$m_Z \sim e^{-A} M_{\text{Planck}} \sim \sqrt{m_{3/2} M_{\text{Planck}}} \sim 10^{11}\,\text{GeV}$: exponentially small warping

$$\left(e^{-3A} \sim \langle Z \rangle \sim e^{-8\pi^2 N_{RR}\langle S\rangle/N_{NS}} \;:\; N_{RR,NS} = \text{integer-valued RR and NS fluxes}\right)$$

$m_{3/2} \sim e^{-2A} M_{\text{Planck}} \sim 10^2\,\text{TeV}$: Superpotential fined-tuned for small cosmological constant in the presence of warped SUSY breaking

$$m_T \sim m_{3/2} \ln(M_{\text{Planck}}/m_{3/2}) \sim 10^4\,\text{TeV}$$

4D effective SUGRA of KKLT compactification:

To take into account the SUSY breaking by the supergravity multiplet, we use the chiral compensator formulation of 4D SUGRA.

Gates, Grisaru, Rocek& Siegel, 1983

In such formulation, there can be two SUSY-breaking (but Poincare invariant) auxiliary components in SUGRA multiplets:

$$2\mathcal{E} = \sqrt{-g}\left[1 + i\theta\sigma^\mu\bar{\psi}_\mu - \theta\theta\left(\mathbf{M}^* + \bar{\psi}_\mu\sigma^{\mu\nu}\bar{\psi}_\nu\right)\right]$$

$$C = C_0 + \sqrt{2}\theta\tilde{C} + \theta\theta\mathbf{F}^C$$

Super-Weyl invariance: $\mathcal{E} \to e^{6\Omega}\mathcal{E}, \quad C \to e^{-2\Omega}C$

A convenient gauge choice: $\mathcal{E} \to e^{6(\sqrt{2}\theta\tilde{\tau}+\theta\theta F^\tau)}\mathcal{E}, \quad C \to e^{-2(\sqrt{2}\theta\tilde{\tau}+\theta\theta F^\tau)}C$

$$\Rightarrow \quad M^* = 0, \quad \tilde{C} = 0.$$

In this gauge, SUSY breaking by supergravity multiplets can be described entirely by

$$C = C_0 + \theta\theta F^C$$

within **an effective global SUSY formulation** in which the SUGRA multiplet describing the curved superspace are all replaced by their vacuum values, unless we are interested in the interactions of $g_{\mu\nu}$ or ψ_μ:

$$g_{\mu\nu} = \eta_{\mu\nu}, \quad \psi_\mu = H_\mu = 0, \ldots$$

$$\Rightarrow \quad \int d^4x \sqrt{g} \left[\int d^4\theta C C^* \left\{ -3 \exp\left(-\frac{K}{3}\right) \right\} + \left\{ \int d^2\theta \left(\frac{1}{4} f_a W^{a\alpha} W^a_\alpha + C^3 W \right) + \text{h.c} \right\} \right]$$

The compensator couplings are constrained by the residual Weyl invariance

$$C \to e^{-2\sigma} C, \quad g_{\mu\nu} \to e^{2(\sigma+\sigma^*)} g_{\mu\nu}, \quad \theta^\alpha \to e^{-\sigma+2\sigma^*}\theta^\alpha, \quad \Lambda^\alpha \to e^{-\sigma+2\sigma^*}\Lambda^\alpha$$

$$\left(\Lambda^\alpha = \frac{\lambda^\alpha}{M_*^2} + \theta^\alpha + \ldots : \lambda^\alpha = \text{Goldstino fermion} \right)$$

One may fix the gauge further to arrive at the Einstein frame:

$$C_0 = e^{K/6}$$

In conventional SUGRA without the nonlinear SUSY sector of Λ^α,

$$\begin{aligned} F^I &= -e^{K/2} K^{I\bar{J}} (D_J W)^* \\ \frac{F^C}{C_0} &= m_{3/2}^* + \frac{1}{3} F^I \partial_I K \qquad \left(m_{3/2} = e^{K/2} W \right) \end{aligned}$$

$$V = e^K \left[K^{I\bar{J}} D_I W (D_J W)^* - 3|W|^2 \right]$$

In the presence of the nonlinear SUSY sector, these on-shell expressions of F and V are modified.

KC, Falkowski, Nilles & Olechowski, 2005

However, for the case of warped nonlinear sector, the modification is rather simple at leading order in $e^{-A} \ll 1$.

Flux stabilization of S, U, Z: Giddings, Kachru & Polchinski, 2002

$$W_{\text{flux}} = F(U) + \frac{N_{RR}}{2\pi i} Z \ln Z + \mathcal{O}(Z^2) - 4\pi i S \Big(H(U) + N_{NS} Z + \mathcal{O}(Z^2) \Big)$$

$$\left(\text{Integer-valued flux:} \quad N_{RR} = \int_{\Sigma} F_3, \quad N_{NS} = -\int_{\tilde{\Sigma}} H_3 \right)$$

$\Sigma =$ Collapsing 3-cycle along the throat

For generic form of flux-induced superpotential,

$$m_{S,U} \sim \frac{M_{KK}^3}{M_{\text{string}}^2}$$

$$\langle Z \rangle \sim \exp\left(- \frac{8\pi^2 N_{RR} S_0}{N_{NS}} \right) \sim e^{-3A}$$

$$\left(S_0 = \langle S \rangle, \quad ds^2 = e^{-2A} \eta_{\mu\nu} dx^\mu dx^\nu + \left(dy^2 \right)_{CY} \right)$$

$$m_Z \sim e^{-A} M_{\text{string}}$$

The remained Kähler moduli can be stabilized by

i) non-perturbative superpotential induced by D-brane instantons or hidden gaugino condensation, Kachru, Kallosh, Linde & Trivedi, 2003

or

ii) the uplifting potential induced by SUSY-breaking at the tip of throat

(in some case, the D-term potential of an anomalous $U(1)$ gauge symmetry)

KC & Jeong, 2006

Bobkov, Braun, Kumar & Raby, 2010

$$\{T\} = \{T_i\} + \{T_\alpha\}$$

$\{T_i\}$ = Kähler moduli stabilized by non-perturbative superpotential

$\{T_\alpha\}$ = Kähler moduli which don't get non-perturbative superpotential, so are stabilized by the uplifting potential

(Some of $\mathrm{Im}(T_\alpha)$ can be identified as the QCD axion solving the strong CP problem.)

After integrating out the heavy S, U, Z, as well as the relevant non-perturbative dynamics, the effective superpotential is given by

$$W_{\rm eff} = W_0 + \sum_i A_i \exp\Big(-8\pi^2(k_i T_i + \ell_i S_0)\Big) + y_Q QQQ + ...$$

To give a nearly vanishing cosmological constant, the flux-induced superpotential should be tuned as

$$W_0 = \langle W_{\rm flux}\rangle \sim e^{-2A} \sim e^{-8\pi^2 \ell_0 S_0} \quad \left(\ell_0 = \frac{2N_{RR}}{N_{NS}} > 0\right)$$

Effective Kähler potential of the Kähler moduli $\{T\}$, visible sector matter Q, and the Goldstino superfield Λ^α: KC, Falkowski, Nilles & Olechowski, 2005

$$-3CC^* \exp\left(-\frac{K_{\rm eff}}{3}\right) = CC^*\left\{-3\exp\left(\frac{K_{\rm mod}(T+T^*)}{3}\right) + Y_Q(T+T^*)Q^*Q\right\}$$

$$+\left\{e^{-3A}C^{*3}\Lambda^2\Big(\gamma_0(T+T^*)+\gamma_1(T+T^*)Q^*Q+\dots\Big)+\text{h.c}\right\}$$

$$+\, e^{-4A}C^2C^{*2}\Lambda^2\bar{\Lambda}^2\Big(\beta_0(T+T^*)+\beta_1(T+T^*)Q^*Q+\dots\Big)+\dots$$

$$\left(\Lambda^2=\Lambda^\alpha\Lambda_\alpha,\quad \Lambda^2\bar{\Lambda}^2=\Lambda^\alpha\Lambda_\alpha\bar{\Lambda}_{\dot\alpha}\bar{\Lambda}^{\dot\alpha}\right)$$

Samuel & Wess, 1983

For the operators involving Λ^α localized at the end of throat, the associated compensator superfield should appear in the combination $e^{-A}C$.

The low energy consequences of the operators involving $e^{-3A}C^3$ are suppressed by more powers of e^{-A} compared to those from other operators.

10D SUGRA computation: $\beta_0 = T$-independent constant of $\mathcal{O}(1)$

Giddings & Maharana, 2005

Visible sector gauge kinetic function:

$$f_a = k_a T_{\rm vis} + \ell_a S_0$$

A particularly interesting case is that the Kähler modulus $T_{\rm vis}$ in the visible sector gauge kinetic function is stabilized by the uplifting potential, in which $\mathrm{Im}(T_{\rm vis})$ is allowed to be identified as the QCD axion solving the strong CP problem.

KC & Jeong, 2006

Bobkov, Braun, Kumar & Raby, 2010

For successful gauge coupling unification, k_a and ℓ_a are assumed to be universal for $SU(3)_c \times SU(2)_W \times U(1)_Y$.

On-shell expression for the auxiliary F-components in the presence of warped non-linear SUSY sector involving Λ^α:

$$F = \text{conventional SUGRA expression} \times \left(1 + \mathcal{O}(e^{-A})\right)$$

Moduli potential: $\quad V = V_F + V_{\text{lift}}$

$$V_F = e^{K_{\text{mod}}} K^{I\bar{J}}_{\text{mod}} (D_I W_{\text{mod}})(D_J W_{\text{mod}})^*, \quad V_{\text{lift}} = e^{-4A} \beta_0 e^{2K_{\text{mod}}/3} + \mathcal{O}(e^{-5A})$$

$$\left(W_{\text{mod}} = W_0 + \sum_i A_i e^{-8\pi^2 (k_i T_i + \ell_i S_0)}, \quad W_0 = \langle W_{\text{flux}} \rangle \sim e^{-8\pi^2 \ell_0 S_0}\right)$$

SUSY breaking in KKLT compactification

Origin of SUSY breaking

KC, Falkowski, Nilles, Olechowski & Pokorski, 2004
KC, Falkowski, Nilles & Olechowski, 2005

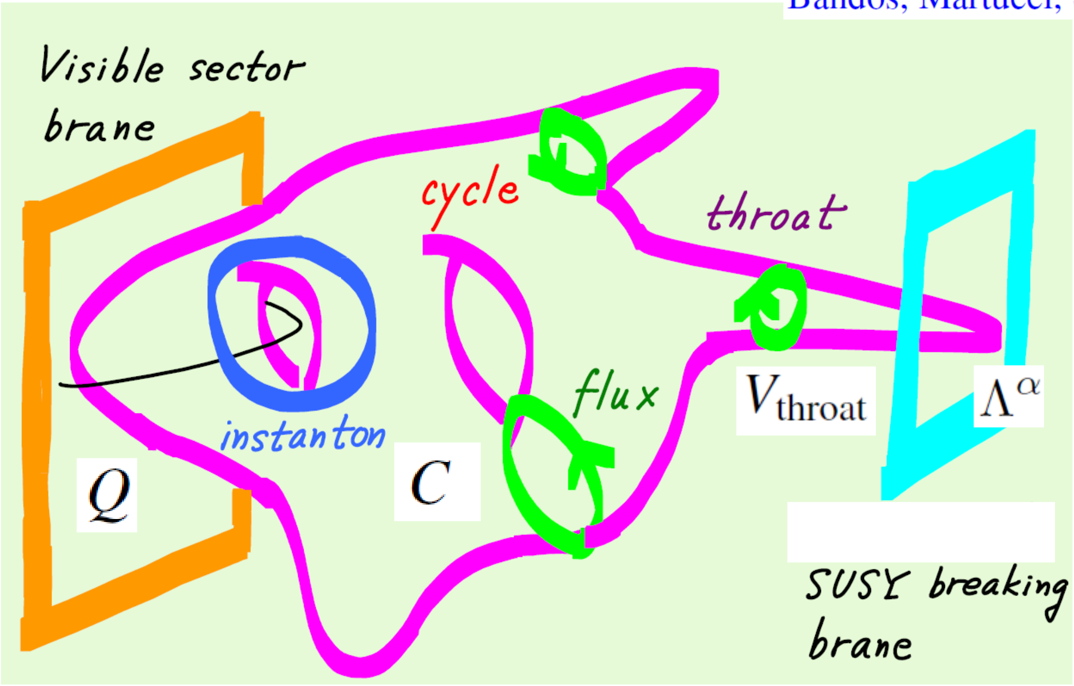
SUSY breaking (anti)brane described by the warped Volkov-Akulov term:

$$\int d^4\theta\, e^{-4A} C^2 C^{*2} \Lambda^2 \bar{\Lambda}^2 \Big(\beta_0 + \beta_1 Q^* Q + \ldots\Big) + \ldots$$

$$\left(\Lambda^\alpha = \frac{\lambda^\alpha}{M_*^2} + \theta^\alpha + \ldots = \text{Goldstino superfield}\right)$$

Equivalent description in terms of nilpotent superfield?

Bandos, Martucci, Sorokin & Tonin, 2015



i) Makes the anomaly mediation to work by uplifting AdS to dS (Minkowski):

Gripaios, Kim, Rattazzi, Redi & Scrucca, 2008

$$\frac{F^C}{C_0} \simeq m_{3/2}$$

ii) Small shift of moduli VEV to generate moduli F-components:

$$\frac{F^{T_i}}{T_i + T_i^*} \simeq \frac{\ell_0}{\ell_0 - \ell_i} \frac{m_{3/2}}{\ln(M_{\rm Planck}/m_{3/2})} \sim \frac{m_{3/2}^2}{m_{T_i}} \quad \left(m_{T_i} \sim m_{3/2} \ln(M_{\rm Planck}/m_{3/2}) \right)$$

The SUSY configuration $D_\alpha W_{\rm mod} = (\partial_\alpha K_{\rm mod}) W_{\rm mod} = 0$ is a stationary point of both $V_F = e^{K_{\rm mod}} K^{I\bar{J}}_{\rm mod} D_I W_{\rm mod} (D_J W_{\rm mod})^*$ and $V_{\rm lift} \simeq e^{-4A} \beta_0 e^{2K_{\rm mod}/3}$.

As a result, nonzero F^{T_α} is induced by the Kähler mixing between T_α and T_i:

KC & Jeong, 2006

$$F^{T_\alpha} \sim (K_{\rm mod})_{i\bar{\alpha}} F^i = \mathcal{O}\left(\frac{m_{3/2}}{\ln(M_{\rm Planck}/m_{3/2})} \right) \quad \left(m_{T_\alpha} \sim m_{3/2} \right)$$

Negligible F components of flux-stabilized superheavy moduli:

$$F^{S,U} \sim \frac{m_{3/2}^2}{m_{S,T}} \ll F^T$$

iii) If there exists light vector multiplet $V_{\rm throat}$ propagating along the throat with a mass

Brümmer, Hebecker & Trapletti, 2006

$$M_V \lesssim \frac{1}{\text{throat length}},$$

$V_{\rm throat}$ can transmit the SUSY breaking at the end of throat to the visible matter in bulk CY, generating an effective Goldstino-matter interaction as

$$\beta_1 e^{-4A}\Lambda^2\bar{\Lambda}^2 Q^* Q \quad \text{with} \quad \beta_1 e^{-4A} \sim D_V \sim \beta_1 m_{3/2}^2.$$

The size of such D-term is highly model-dependent, particularly on how the throat isometry is broken by the bulk CY: Kachru, McAllister & Sundrum, 2007

$$\beta_1 = \mathcal{O}(1) - \mathcal{O}(e^{-\xi A}) \quad \left(\xi = \mathcal{O}(1)\right)$$

An interesting specific example:

$$\ell_i = 0 \quad \left(W_{\rm np} = \sum_i A_i e^{-8\pi^2 (k_i T_i + \ell_i S)} \right)$$

No-scale Kähler potential: $\quad K^{I\bar{J}}_{\rm mod} \partial_{\bar{J}} K_{\rm mod} = -(T_I + T_I^*)$

KC & Jeong, 2006

$$\Rightarrow \quad \frac{T_i}{T_i + T_i^*} = \frac{T_\alpha}{T_\alpha + T_\alpha^*} = \frac{m_{3/2}}{\ln(M_{\rm Planck}/m_{3/2})}$$

(up to corrections suppressed by $1/\ln(M_{\rm Planck}/m_{3/2}) \sim 1/4\pi^2$)

KS throat with $SO(4)$ isometry, broken down to $SO(3)$ by anti-D_3 brane at the tip of throat:

Kachru, McAllister & Sundrum, 2007

$$\beta_1 \sim e^{-\sqrt{28}A}$$

Soft SUSY breaking in KKLT compactification

Mixed moduli-anomaly-throat vector mediation (Mirage mediation):

$$\frac{F^T}{T+T^*} \sim \frac{1}{8\pi^2}\frac{F^C}{C} \sim \frac{m_{3/2}}{\ln(M_{\text{Planck}}/m_{3/2})} \quad , \qquad D_V \sim \beta_1 m_{3/2}^2$$

Two key parameters for soft SUSY breaking:

$$i) \quad \alpha = \frac{\text{anomaly mediation}}{\text{moduli mediation}} \equiv \frac{m_{3/2}}{M_0 \ln(M_{\text{Planck}}/m_{3/2})} = \mathcal{O}(1)$$

$$\begin{aligned} M_0 &= \text{moduli-mediated gaugino mass at } M_{\text{GUT}} \\ &= F^I\partial_I(\text{Re}(f_a)) = k_a g_{\text{GUT}}^2 F^{T_{\text{vis}}} = \mathcal{O}\left(\frac{m_{3/2}}{\ln(M_{\text{Planck}}/m_{3/2})}\right) \quad (f_a = k_a T_{\text{vis}} + \ell_a S) \end{aligned}$$

If the visible sector lives on $D3$, then $f_a = S$, yielding $\alpha \gg 1$ (anomaly domination).

(This might be less interesting as $\text{Im}(f_a)$ can not contain a QCD axion .)

$$ii) \quad \beta_1 = \mathcal{O}(1) - \mathcal{O}(e^{-\xi A}) \quad \left(\xi = \mathcal{O}(1)\right)$$

Pattern of superpartner masses in KKLT compactification

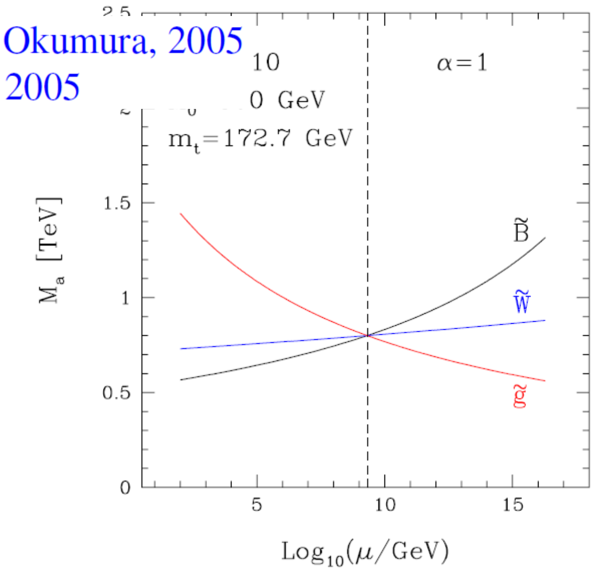
Mirage-unified gaugino masses:

KC, Jeong & Okumura, 2005
KC & Nilles, 2005

$$M_a(\mu) = \mathcal{O}(F^T) + \mathcal{O}\left(\frac{F^C}{8\pi^2}\right)$$

$$= M_0\left[1 - \frac{1}{8\pi^2} b_a g_a^2(\mu) \ln\left(\frac{M_{\rm mirage}}{\mu}\right)\right]$$

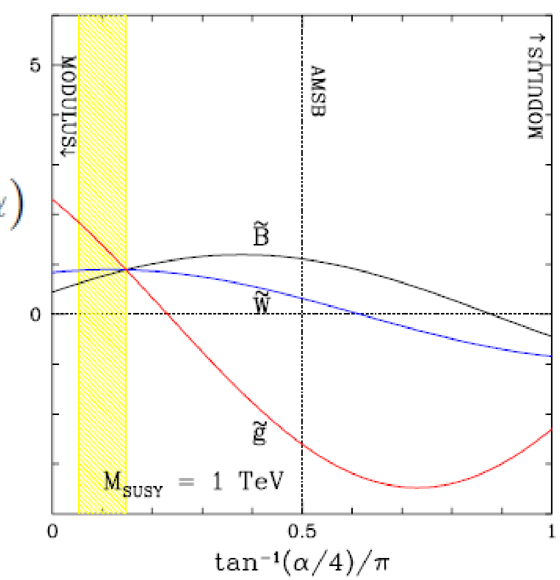
$$M_{\rm mirage} = \frac{M_{GUT}}{(M_{\rm Planck}/m_{3/2})^{\alpha/2}}$$



Pattern of gaugino masses around the TeV scale:

$$M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} \simeq (1 + 0.66\alpha) : (2 + 0.2\alpha) : (6 - 1.8\alpha)$$

Gaugino masses at TeV are nearly degenerate
when $\alpha \simeq 2$. $\Rightarrow$ Compressed SUSY



$$A_{ijk} = \mathcal{O}(F^T) + \mathcal{O}\left(\frac{F^C}{8\pi^2}\right) = \mathcal{O}(M_a)$$

$$m_{\tilde{Q}}^2 = \beta_1 m_{3/2}^2 + \mathcal{O}\left(|F^T|^2, \frac{|F^C|^2}{(8\pi^2)^2}, \frac{F^T F^{C*}}{8\pi^2}\right) = \mathcal{O}(M_a^2) - \mathcal{O}((8\pi^2 M_a)^2)$$

Lightest modulus mass

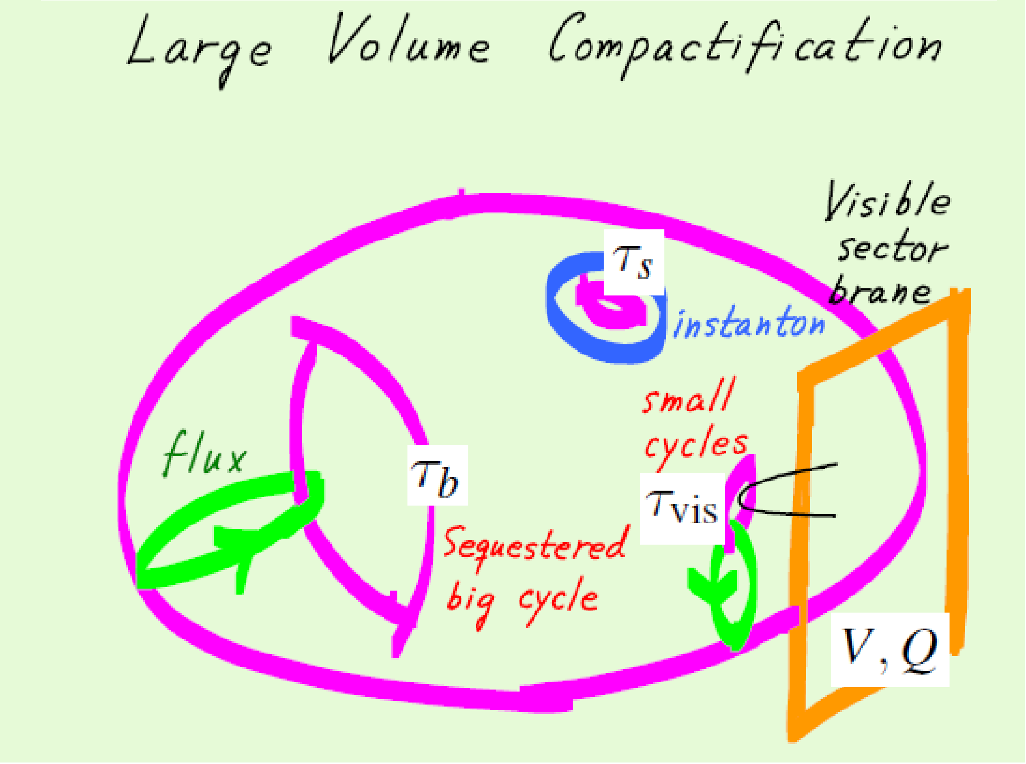
$$\Rightarrow \quad m_{\tilde{Q}} : M_a : A_Q : m_{3/2} : m_T \sim (1 - 8\pi^2) : 1 : 1 : 8\pi^2 : (8\pi^2)^2 \text{ (or } 8\pi^2)$$

Uncertainties in throat vector mediation

Large volume scenario

- Flux stabilization of all moduli except for the Kähler moduli $\{T\}$
- Stabilization of the bulk volume $\mathcal{V}$ at an exponentially large value through the competition between the α' correction of $\mathcal{O}(1/\mathcal{V})$ and an exponentially small non-perturbative effects.

Balasubramanian, Beglund, Conlon & Quevedo, 2005
Blumenhagen, Conlon, Krippendorf, Moster & Quevedo, 2009



Relevant degrees of freedom:

S, U = dilaton and complex structure moduli

$\{T_b, T_s, T_{\text{vis}}, \ldots\}$ = Kähler moduli

$\tau_b = \text{Re}(T_b)$ = bulk 4-cycle volume $(\mathcal{V} \sim \tau_b^{3/2})$

$\tau_s = \text{Re}(T_s)$ = volume of small 4-cycle supporting a nonperturbative dynamics to generate $W_{\text{np}} = Ae^{-8\pi^2 k_s T_s}$

$\tau_{\text{vis}} = \text{Re}(T_{\text{vis}})$ = volume of another small 4-cycle supporting the visible sector

V, Q = visible gauge and matter superfields

After integrating out the flux-stabilized S and U, the effective theory of the bulk volume modulus T_b takes the form of **no-scale SUGRA** at leading order in the large radius expansion:

$$\int d^4\theta \left[-3CC^* (T_b + T_b^*) \right] + \left(\int d^2\theta \, W_0 + \text{h.c} \right)$$

$$\left(K = -3 \ln(T_b + T_b^*) \right)$$

SUSY breaking Minkowski vacuum with identically vanishing moduli potenial:

$$V(\tau_b) = 0 \qquad \left(\tau_b = \text{Re}(T_b) \right)$$

$$\frac{F^{T_b}}{T_b + T_b^*} = m_{3/2} = \frac{W_0}{(T_b + T_b^*)^{3/2}}, \qquad F^C = 0$$

Include the small cycle sector supporting hidden non-perturbative dynamics, together with the volume-suppressed α' corrections:

Balasubramanian, Beglund, Conlon & Quevedo, 2005
Blumenhagen, Conlon, Krippendorf, Moster & Quevedo, 2009

$$K_{\rm mod} = -3\ln\tau_b - \frac{\xi_{\alpha'}}{\tau_b^{3/2}} + \frac{\tau_s^{3/2}}{\tau_b^{3/2}} + \mathcal{O}\left(\frac{1}{t_b^3}\right) \quad \left(\mathcal{V} \sim \tau_b^{3/2}\right)$$

$$W_{\rm mod} = W_0 + Ae^{-8\pi^2 k_s T_s}$$

Competition between volume-suppression and non-perturbative effect, which results in τ_b stabilized at an exponentially large value:

$$\tau_s \sim \xi_{\alpha'}^{2/3}, \qquad \frac{W_0}{\tau_b^{3/2}} \sim e^{-8\pi^2 k_s \tau_s}$$

$$m_{3/2} \sim \frac{W_0}{\tau_b^{3/2}}, \qquad m_{T_s} \sim m_{3/2}\ln(M_{\rm Planck}/m_{3/2}), \qquad m_{t_b} \sim \frac{m_{3/2}}{\tau_b^{3/4}}$$

$$\frac{F^{T_b}}{2\tau_b} \simeq m_{3/2}, \qquad \frac{F^{T_s}}{2\tau_s} \sim \frac{m_{3/2}}{\ln(M_{\rm Planck}/m_{3/2})}, \qquad \frac{F^C}{C} \sim F^{S,U} \sim \frac{m_{3/2}}{\tau_b^{3/2}}$$

(Due to the no-scale structure, F^C is suppressed by the large volume factor.)

For the visible sector living on $D7$, introduce small 4-cycle supporting the visible sector, which is described by T_{vis}:

$$K_{\text{vis}} = \frac{\Omega(\tau_{\text{vis}})}{\tau_b^{3/2}} + Z_Q Q^* e^{gV} Q + \ldots = \frac{\tau_{\text{vis}}^2}{\tau_b^{3/2}} + Z_Q Q^* e^{gV} Q + \ldots$$

$\Big(\Omega(\tau_{\text{vis}})$ is expanded around the SUSY configuration: $D_{T_{\text{vis}}} W \propto \partial_{\tau_{\text{vis}}} \Omega = 0\Big)$

$$W_{\text{vis}} = \frac{1}{2}\mu QQ + \frac{1}{6} y_Q QQQ + \ldots,$$

$$f_a = kT_{\text{vis}} + \ell S$$

For the visible sector living on $D3$, we don't need T_{vis}, so

$$f_a = S.$$

Again this is less interesting as in such case $\text{Im}(f_a)$ does not include a QCD axion.

Generically $F^{T_{\rm vis}}$ depends on how $T_{\rm vis}$ is stabilized.

Note that the no-scale SUSY breaking by F^{T_b} yields a tachyonic mass of $\tau_{\rm vis}$:

$$\delta m^2_{\tau_{\rm vis}} = -\frac{1}{2} m^2_{3/2}.$$

Unlike the KKLT case, the uplifting potential in LVS can not be useful for stabilizing $T_{\rm vis}$:

$$\left(V_{\rm lift}\right)_{\rm LVS} \sim \frac{m^2_{3/2} M^2_{\rm Planck}}{\tau_b^{3/2}} \qquad \left(\left(V_{\rm lift}\right)_{\rm KKLT} \sim m^2_{3/2} M^2_{\rm Planck}\right)$$

$T_{\rm vis}$ might be stabilized by $W_{\rm np} \propto e^{-8\pi^2 k T_{\rm vis}}$, which would yield

$$F^{T_{\rm vis}} \sim \frac{m_{3/2}}{\ln(M_{\rm Planck}/m_{3/2})}.$$

Again this is less interesting as in such case ${\rm Im}(f_a)$ does not contain a QCD axion.

Furthermore, it is difficult to generate such $W_{\rm np}$ on the visible sector supporting chiral charged matter fields. Blumenhagen, Moster & Plauschinn, 2007

A more interesting scheme to stabilize $T_{\rm vis}$, while leaving a $U(1)_{\rm PQ}$ for QCD axion, is to use the D-term potential associated with an anomalous $U(1)_A$ symmetry under which

Blumenhagen, Conlon, Krippendorf, Moster & Quevedo, 2009
Aparicio, Cicoli, Krippendorf, Maharana, Munia & Quevedo, 2014

$$U(1)_A : \quad T_{\rm vis} \;\to\; T_{\rm vis} + i\delta_{\rm GS}, \quad Q \;\to\; e^{iq_Q\alpha(x)}Q$$

$$\left(\delta_{\rm GS} = \frac{1}{8\pi^2}\sum_Q q_Q {\rm Tr}(T_a^2(Q))\right)$$

In this case, $\{T_{\rm vis}, V_A\}$ form a massive vector multiplet through the Stükelberg mechanism, leaving an anomalous global PQ symmetry in the low energy world:

$$U(1)_{\rm PQ} : \quad Q \;\to\; e^{iq_Q\alpha}Q.$$

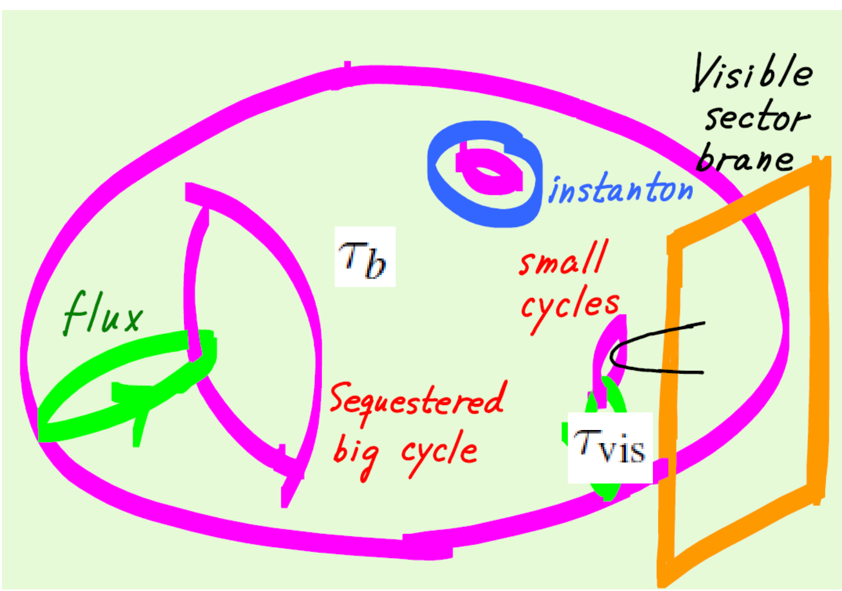
The main origin of SUSY breaking in LVS is

$$\frac{F^{T_b}}{(T_b + T_b^*)} \simeq m_{3/2},$$

and often the superpartner masses in the visible sector are determined by how F^{T_b} is transmitted to the local visible sector.

No-scale sequestering at leading order approximation:

Local physics is insensitive to the overall size of the bulk volume, i.e.



$$\frac{\partial}{\partial \tau_b}\left(g_a^2, y_Q, \ldots\right) \simeq 0$$

$$\frac{\partial}{\partial F^{T_b}}\left(M_a, m_{\tilde{Q}}^2, A_Q\right) \simeq 0.$$

Transmission of SUSY breaking by F^{T_b}

$=$ Desequestering.

Short summary of SUSY breaking soft terms in 4D SUGRA:

$$\int d^4\theta\, CC^* \left(-3e^{-K/3} \right) + \left[\int d^2\theta \left(\frac{1}{4} f_a\, W^{a\alpha} W^a_\alpha + C^3 W \right) + \text{h.c} \right]$$

$$-3e^{-K/3} = -3e^{-K_{\text{mod}}/3} + Y_Q Q^* Q + \ldots$$

$$\left(K = K_{\text{mod}} + Z_Q Q^* Q + \ldots \quad \text{with} \quad Z_Q = e^{K_{\text{mod}}/3} Y_Q \right)$$

$$W = W_{\text{mod}} + \frac{1}{2}\mu QQ + \frac{1}{6}\lambda_Q QQQ + \ldots$$

SUSY breaking superfields with nonzero auxiliary components:

$$\left\{ C,\ \ X^m = \left(\text{moduli}, \ldots\right),\ \ V_A \right\}$$

(It is straightforward to incorporate the nonlinear SUSY sector with Λ^α)

Samuel & Wess, 1983

KC, Falkowski, Nilles & Olechowski, 2005

1PI gauge couplings:

Novikov, Shifman, Vainshtein & Zakharov, 1986
Kaplunovsky & Louis, 1994

$$\frac{1}{g_a^2(p)} = \mathrm{Re}(f_a)+\frac{b_a}{16\pi^2}\ln\left(\frac{1}{e^{-K_{\rm mod}/3}p^2}\right)-\sum_Q \frac{\mathrm{Tr}\big(T_a^2(Q)\big)}{8\pi^2}\ln Y_Q-\frac{\mathrm{Tr}\big(T_a^2(\mathrm{Adj})\big)}{8\pi^2}\ln g_a^2(p)$$

Physical Yukawa couplings: $y_Q = \dfrac{\lambda_Q}{\sqrt{Y_Q Y_Q Y_Q}}$

Soft SUSY breaking masses including the anomaly mediated contributions:

$$R\,\frac{M_a(p)}{g_a^2(p)} = F^m\partial_m \mathrm{Re}(f_a)-\sum_Q \frac{\mathrm{Tr}\big(T_a^2(Q)\big)}{8\pi^2}F^m\partial_m\ln Y_Q+\frac{\left(b_a+\sum_Q \mathrm{Tr}\big(T_a^2(Q)\big)\gamma_Q\right)}{16\pi^2}\frac{F^C}{C}$$

$$m_{\tilde{Q}}^2 = -F^m F^{n*}\partial_m\partial_{\bar{n}}\ln Y_Q-\frac{1}{2}\left(\frac{F^C}{C}F^{m*}\partial_{\bar{m}}+\mathrm{h.c}\right)\frac{d\ln Y_Q}{d\ln p}-\frac{1}{4}\left|\frac{F^C}{C}\right|^2\frac{d^2\ln Y_Q}{d(\ln p)^2}$$
$$-\frac{1}{2}D_A\frac{\partial\ln Y_Q}{\partial V_A} \qquad \left(R = 1-\frac{\mathrm{Tr}\big(T_a^2(\mathrm{Adj})\big)}{8\pi^2}g_a^2(p), \quad \gamma_Q = \frac{d\ln Y_Q}{d\ln p}\right)$$

$$A_Q = -F^m\partial_m\ln\left(\frac{\lambda_Q}{Y_Q Y_Q Y_Q}\right)-\frac{1}{2}\frac{F^C}{C}\frac{d\ln(Y_Q Y_Q Y_Q)}{d\ln p}$$

Randall & Sundrum, 1998
Giudice, Luty, Murayama & Rattazzi, 1998
Bagger & Moroi, 1999

Lesson:

It is more convenient to express observable quantities in terms of $e^{-K/3} = e^{-K_{\text{mod}}/3} + Y_Q Q^* Q + \ldots,$ rather than in terms of $K = K_{\text{mod}} + Z_Q Q^* Q + \ldots$

X is sequestered from the visible sector:

$$\frac{\partial}{\partial X}\Big(f_a,\, Y_Q,\, \lambda_Q\Big) = 0 \quad \Leftrightarrow \quad \frac{\partial}{\partial X}\Big(g_a^2,\, y_Q\Big) = \frac{\partial}{\partial F^X}\Big(M_a,\, m_{\tilde{Q}}^2,\, A_Q\Big) = 0$$

$$\frac{\partial}{\partial X}\ln Y_Q = 0 \quad \Leftrightarrow \quad \frac{\partial}{\partial X}\ln Z_Q - \frac{1}{3}\frac{\partial}{\partial X}K_{\text{mod}} = 0$$

With the holomorphy constraint on f_a and λ_Q, the desequestering is implemented mostly through higher order corrections generating

$$\frac{\partial}{\partial \tau_b} \ln Y_Q \neq 0$$

$$\Rightarrow \quad \delta m^2_{\tilde{Q}} = -|F^{T_b}|^2 \partial_{T_b} \partial_{\bar{T}_b} \ln Y_Q$$

$$\delta A_Q = -F^{T_b} \partial_{T_b} \ln \left(\frac{\lambda_Q}{Y_Q Y_Q Y_Q} \right)$$

$$\delta M_a = -\sum_Q \frac{g_a^2 \mathrm{Tr}\left(T_a^2(Q)\right)}{8\pi^2} F^{T_b} \partial_{T_b} \ln Y_Q$$

Origin of possible desequestering, generating superpartner masses in the visible sector:

i) Volume-suppressed α' corrections:

Blumenhagen, Conlon, Krippendorf, Moster & Quevedo, 2009
Aparicio, Cicoli, Krippendorf, Maharana, Munia & Quevedo, 2014
Aparicio, Quevedo & Valandro, 2016
Reece & Xue, 2016

$$Y_Q \propto \left(1 + \mathcal{O}\left(\frac{1}{\tau_b^{3/2}}\right)\right) \qquad \left(\mathcal{V} \sim \tau_b^{3/2} \sim \frac{M_{\text{Planck}}}{m_{3/2}} \ \text{ for } \ W_0 \sim 1\right)$$

Together with $F^S \sim \frac{m_{3/2}}{\tau_b^{3/2}}$ which is generated at the same order, this yields

$$\delta m^2_{\tilde{Q}} \sim \frac{m^2_{3/2}}{\tau_b^{3/2}}, \qquad \delta M_a \sim \delta A_Q \sim \frac{m_{3/2}}{\tau_b^{3/2}}$$

$$\Rightarrow \quad \delta m_{\tilde{Q}} : \delta M_a : \delta A_Q : m_{3/2} : m_{\tau_b} \sim \left(\frac{M_{\text{Planck}}}{m_{3/2}}\right)^{1/2} : 1 : 1 : \left(\frac{M_{\text{Planck}}}{m_{3/2}}\right) : \left(\frac{M_{\text{Planck}}}{m_{3/2}}\right)^{1/2}$$

In case with a visible sector on $D3$, for which $f_a = S$, this is the main origin of soft masses and determines the pattern of superparticle masses.

ii) Visible sector on $D7$ with $\tau_{\rm vis}$ stabilized by $W_{\rm np} \sim e^{-8\pi^2 k T_{\rm vis}}$:

Aparicio, Cicoli, Krippendorf, Maharana, Munia & Quevedo, 2014
Aparicio, Quevedo & Valandro, 2016

$$\frac{F^{T_{\rm vis}}}{\tau_{\rm vis}} \sim \frac{m_{3/2}}{\ln \tau_b} \sim \frac{m_{3/2}}{\ln(M_{\rm Planck}/m_{3/2})}$$

$$\Rightarrow \quad \delta m_{\tilde{Q}} \sim \delta A_Q \sim \delta M_a \sim \frac{m_{3/2}}{\ln(M_{\rm Planck}/m_{3/2})}$$

$$\Rightarrow \quad m_{\tilde{Q}} : M_a : A_Q : m_{3/2} : m_{\tau_b} \sim 1 : 1 : 1 : 8\pi^2 : (8\pi^2)^{3/2} \left(\frac{M_a}{M_{\rm Planck}}\right)^{1/2}$$

* Anomaly mediation is negligible, and therefore gaugino masses take the mSUGRA pattern.

* Volume modulus is very light, which may cause serious cosmological moduli problem.

iii) D-term stabilization of $\tau_{\rm vis}$ in the presence of radiative moduli-redefinition:

Conlon & Pedro, 2010
KC, Nilles, Shin & Trapletti, 2010

$$\tau_{\rm vis} \to \tau_{\rm vis} + \beta \ln \tau_b \qquad \left(\beta \sim \frac{1}{8\pi^2}\right)$$

$$\Rightarrow \quad \Delta K(\tau_{\rm vis}) = \frac{(\tau_{\rm vis} + \beta \ln \tau_b - \delta_{\rm GS} V_A)^2}{\tau_b^{3/2}} \quad \left(\beta \sim \delta_{\rm GS} \sim \frac{1}{8\pi^2}\right)$$

$\{V_A, T_{\rm vis}\}$ becomes supermassive through the Stükelberg mechanism.

Gauge invariant masive vector superfield: $V_A - \dfrac{\tau_{\rm vis}}{\delta_{\rm GS}} = \dfrac{\beta}{\delta_{\rm GS}} \ln \tau_b$

$$Y_Q(\tau_{\rm vis}) Q^* e^{q_Q V_A} Q \quad \to \quad Y_Q^{\rm eff} Q^* Q$$

Arkani-Hamed, Dine & Martin, 1998

$$Y_Q^{\rm eff} = \langle e^{q_Q V_A} Y_Q \rangle = \tau_b^{q_Q \beta/\delta_{\rm GS}} Y_Q(\tau_{\rm vis} = -\beta \ln \tau_b) \quad \left(\frac{\beta}{\delta_{\rm GS}} \sim 1\right)$$

$$\Rightarrow \quad \delta m_{\tilde{Q}}^2 \sim m_{3/2}^2, \qquad \delta A_Q \sim \delta M_a \sim \frac{m_{3/2}}{8\pi^2} \quad (q_i + q_j + q_k = 0 \ \text{ for } \ A_{ijk} \neq 0)$$

$$\Rightarrow \quad \delta m_{\tilde{Q}} : \delta M_a : \delta A_Q : m_{3/2} : m_{\tau_b} \sim 8\pi^2 : 1 : 1 : 8\pi^2 : (8\pi^2)^{3/2} \left(\frac{M_a}{M_{\rm Planck}}\right)^{1/2}$$

iv) D-term stabilization in the absence of radiative moduli-redefinition: $\beta = 0$

$$\Delta K(\tau_{\rm vis}) = \frac{(\tau_{\rm vis} - \delta_{\rm GS} V_A)^2}{\tau_b^{3/2}}$$

$\Rightarrow$ Mass splitting of $\{V_A, T_{\rm vis}\} = \{A_\mu, \tau_{\rm vis}, \lambda_1, \lambda_2\}$:

$$M^2_{\tau_{\rm vis}} = M_A^2 - \frac{1}{2} m^2_{3/2}, \quad M^2_{\lambda_{1,2}} = M_A^2 \pm \frac{1}{2} m_{3/2} M_A + \frac{1}{8} m^2_{3/2} \quad \left(\frac{F^{T_b}}{2\tau_b} = m_{3/2} \right)$$

$$\Rightarrow \quad \delta \ln Y_Q = \frac{g_A^2 q_Q^2}{64\pi^2} \ln \tau_b$$ Shin, 2011

$$\Rightarrow \quad \delta m^2_{\tilde{Q}} \sim \frac{m^2_{3/2}}{8\pi^2}, \quad \delta A_Q \sim \frac{m_{3/2}}{8\pi^2}, \quad \delta M_a \sim \frac{m_{3/2}}{(8\pi^2)^2}$$

$$\Rightarrow \quad \delta m_{\tilde{Q}} : \delta M_a : \delta A_Q : m_{3/2} : m_{\tau_b} \sim \left(8\pi^2\right)^{3/2} : 1 : 8\pi^2 : \left(8\pi^2\right)^2 : \left(8\pi^2\right)^3 \left(\frac{M_a}{M_{\rm Planck}} \right)^{1/2}$$

Conclusion

SUSY might exist in low energy world, so hopefully in some future we may have experimental information on superpartner masses.

An interesting framework which would allow us to compute superpartner masses starting from fundamental theory is string moduli stabilization.

There are two reasonably well-understood concrete schemes of string moduli stabilization: KKLT and LVS.

Depending on how to stabilize the moduli in the visible sector gauge kinetic function (and the matter kinetic coefficient Y_Q), a variety of interesting patterns of superpartner masses can arise from KKLT or LVS, in particular a variety of different (mini) split SUSY scenario.