Fake Split Supersymmetry

Mark D. Goodsell

LPTHE

Dudas, MDG, Heurtier, Tziveloglou, Nucl. Phys. B **884** (2014) 632 [1312.2011]

Benakli, Darmé, MDG, Slavich, JHEP **1405** (2014) 113 [1312.5220]

Introduction

- Motivation: high supersymmetry-breaking scales, inflation, axions and the Higgs mass
- The scenario and its predictions
- Two variants of the scenario
- Their relevance for string models

Hints of an intermediate scale

- If the results of BICEP2 are confirmed, then there is a stability problem for inflationary models with $m_{3/2} < H_I \simeq 10^{14}$ GeV.
- It would also stongly suggest an axion in the classical window of $10^9 - 10^{12}$ GeV; although it could otherwise extend higher.
- In addition, there is the X-ray hint of ALPs from the Coma cluster (talks by Angus, Conlon, Marsh, Rummel, ...)

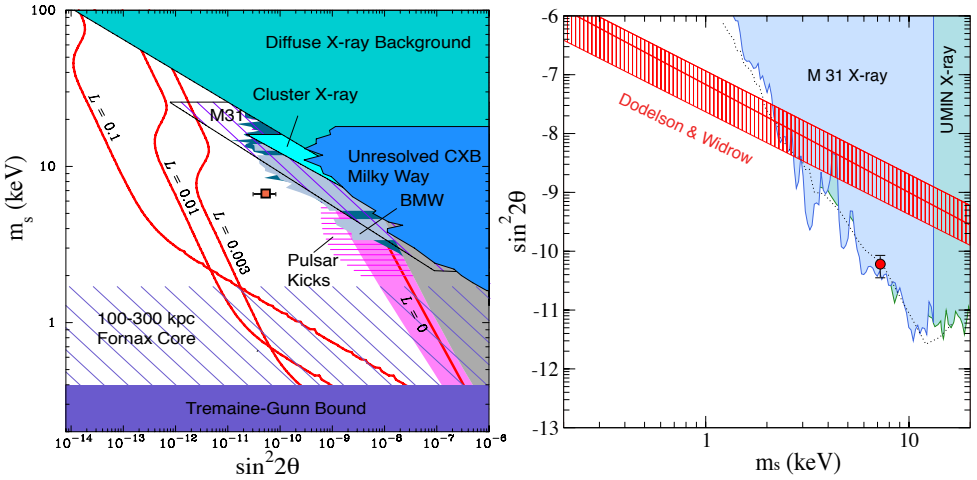
$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{4}\frac{\alpha_{em}}{2\pi}\frac{C_{a\gamma}}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g_{a\gamma} \gtrsim 10^{-13}\text{GeV}^{-1}\sqrt{0.5/\Delta N_{eff}}$$
$$\rightarrow 10^8\,\text{GeV} \lesssim \frac{f_a}{C_{a\gamma}} \lesssim 10^{10}\text{GeV}\sqrt{\Delta N_{eff}/0.5}$$

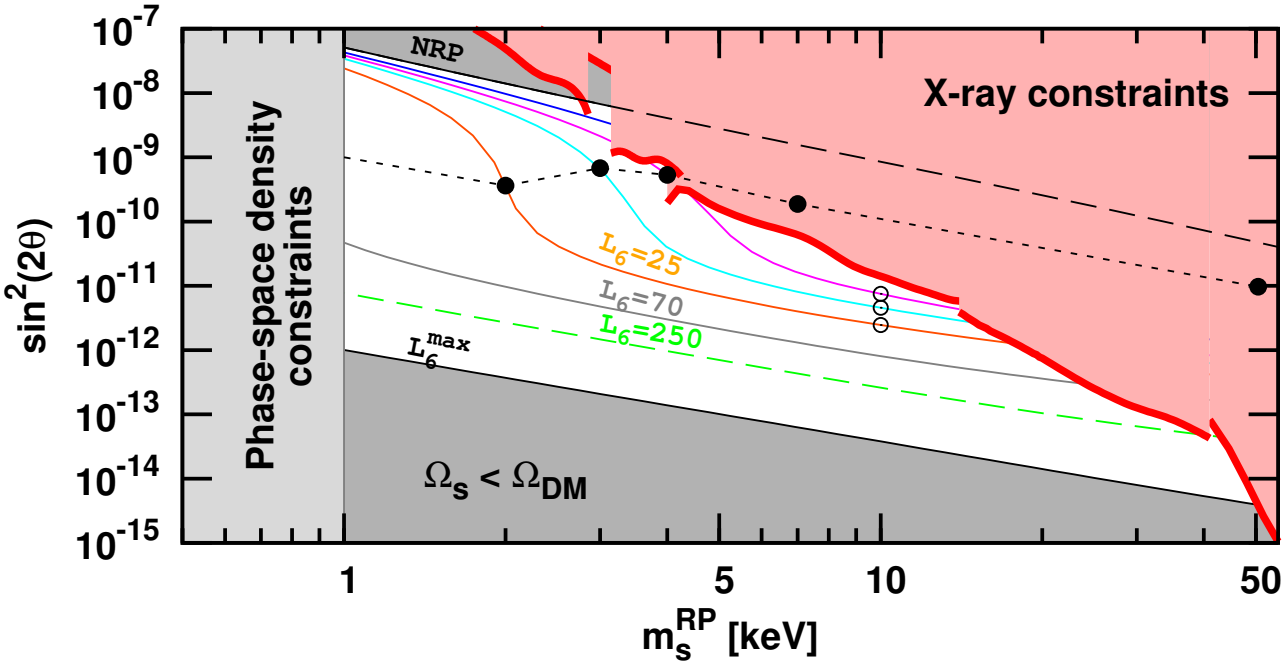
- And the anomalous transparency of the universe – $\frac{f_a}{C_{a\gamma}} \lesssim 10^9$GeV

Sterile neutrinos

Furthermore, there is the hint from [Bulbul et al, 1402.2301]:



c.f. from [Boyarsky, Lesgourgues, Ruchayskiy, Viel 0812.3256]:



Sterile neutrinos and ALPs

- Corresponds very well with galaxy simulations which suggest fermionic Warm Dark Matter (they have been predicting $1-2$ keV for several years! E.g. [de Vega, Sanchez 1304.0759] as one example).
- Idea of [Cicoli, Conlon, Marsh, Rummel]: dark matter decays to an ALP.
- So they suggest a sterile neutrino with coupling to an ALP:

$$\mathcal{L} \supset \frac{\partial_\mu a}{\Lambda}\overline{N}\gamma^\mu\gamma_5\nu \leftrightarrow \frac{m_N}{\Lambda}a\overline{N}\gamma_5\nu, \qquad \Lambda \simeq 10^{17}\text{GeV}$$

- In LVS, for direct couplings, we have (see [Cicoli, MDG, Ringwald '12])

$$\Lambda \simeq \begin{cases} M_s/g^2 & \text{SM in geometric regime} \\ \gg M_P & \text{Sequestered} \end{cases}$$

- This does not seem to fit well; however, we can instead couple via the Majorana mass:

$$\mathcal{L} \supset -e^{-T}NN \to -m_N\frac{a}{f_a}\overline{N}\gamma_5 N \to -m_N\frac{\sin\theta_N}{f_a}a\overline{N}\gamma_5\nu$$

- This implies $\sin\theta_N \sim f_a/10^{17}$GeV but we also have $\theta_N \gtrsim 10^{-6}$ to generate enough dark matter through resonant prouction $\to$ we are right at the border of this, but corresponds well!

Two possibilities

ALPs are closed strings $\rightarrow$ intermediate string scale:

- Natural scale for axions and TeV SUSY
- Brane on the large cycle in the LVS may lead to a hidden photon with mass greater than $\mathcal{O}(\text{GeV})$.
- Problems with unification, inflation and cosmological moduli.

ALPs are open strings:

- Some new physics at the intermediate scale to break the approximate global symmetries.
- If we allow unification of gauge couplings, and take $\mathcal{V} \lesssim 10^8$ in string units, have high gravitino mass $\gtrsim 10^{10}$ GeV.
- Either need complete sequestering of masses, high scale SUSY, or something else.

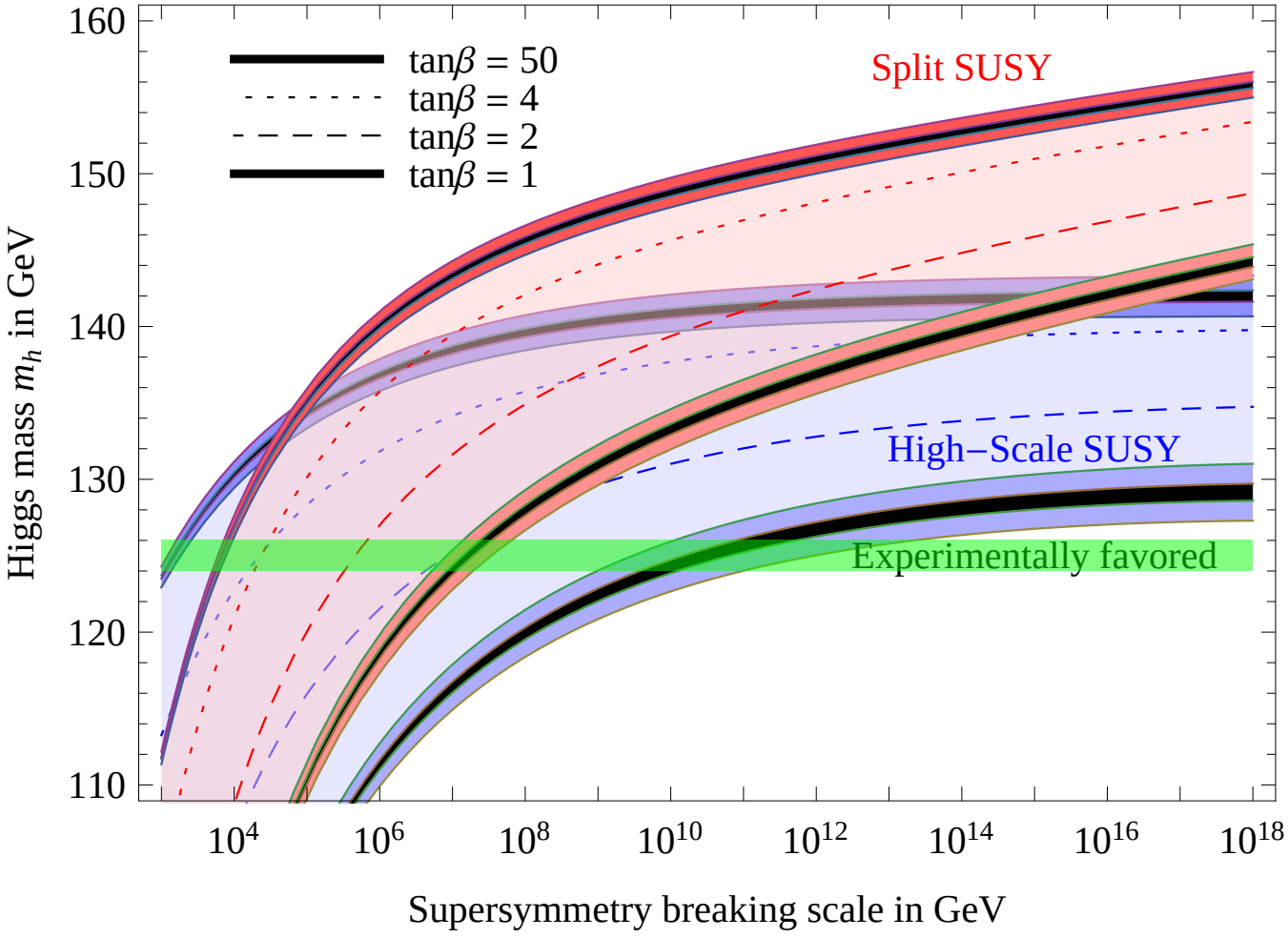
Split SUSY recap

- Many people at this conference have considered explicitly or implicitly abandoning the hierarchy problem†.
- After all, we mostly accept the anthropic explanation for the cosmological constant, and a similar argument can be made for the weak scale; but string theory still needs SUSY at some scale.
- If we take all scalar superpartners to be at a high mass (M_S), we lift complete $SU(5)$ generations (except for heavy Higgs) and so do not affect unification at one loop. We can tune one Higgs to be light.
- Need a symmetry to preserve the hierarchy betweent the gauginos and scalars: this must be an approximate R-symmetry in the effective globally SUSY theory.
- This also preserves $B\mu \gg \mu \rightarrow$ light higgsinos, as required for unification.

† *I am hedging my bets here.*

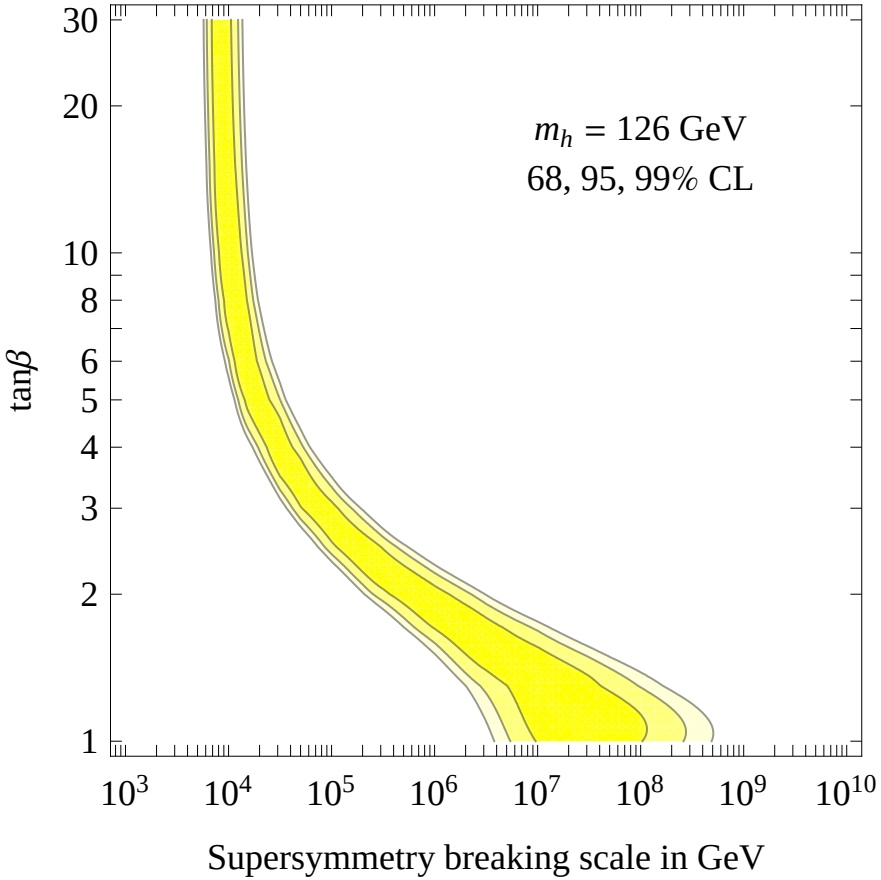
Split SUSY and the Higgs mass

Taken from [Giudice, Strumia, 1108.6077]:
Predicted range for the Higgs mass



Taken from [Giudice, Strumia, 1108.6077]:

Split supersymmetry



Difficult to reconcile with any higher scale, e.g. BICEP, axion(s), ...

Fake Split SUSY

The main idea:

- Split SUSY does not have to descend from the MSSM with split boundary conditions.
- We could consider different UV completions with the same IR matter content and retain all the same motivating features (unification, etc).
- Some couplings may change and affect the phenomenology – Higgs mass, cosmology, etc.

Low energy theory

- If we only preserve the field content and not the UV boundary conditions, the theory has SM + adjoints of $SU(2)$ and $SU(3)$, plus a singlet fermion, and a vector-like pair of fermions.
- Other than the gauge couplings, the only other couplings for the non-SM fields we can write down are the Higgs-'higgsino'-'gaugino' couplings:

$$\mathcal{L}_{\text{eff}} \supset -\frac{H^\dagger}{\sqrt{2}}(\tilde{g}_{2u}\,\sigma^a\,\tilde{W}'^a + \tilde{g}_{1u}\,\tilde{B}')\,\tilde{H}'_u - \frac{H^T i\sigma^2}{\sqrt{2}}(-\tilde{g}_{2d}\,\sigma^a\,\tilde{W}'^a + \tilde{g}_{1d}\,\tilde{B}')\,\tilde{H}'_d\,.$$

- For the purposes of this talk, let us define the IR FSSM to have

$$\tilde{g}_{2u} \sim \tilde{g}_{1u} \sim \tilde{g}_{2d} \sim \tilde{g}_{1d} \sim \varepsilon^2.$$

- In addition we take the boundary condition of the Higgs quartic coupling λ to be

$$\lambda(M_S) = \frac{1}{4}\left[g_2^2(M_S) + \frac{3}{5}\,g_1^2(M_S)\right]\cos^2 2\beta + \mathcal{O}(\varepsilon^2)\,,$$

- This is a more robust prediction of SUSY than the above couplings, although it, too, can be varied by adding fields and couplings to the high-energy theory.
- As a choice, impose unified gaugino masses at M_S:

$$m_{\tilde{B}'}(M_S) = \left[\frac{g_1(M_S)}{g_3(M_S)}\right]^2 m_{\tilde{g}'}(M_S)\,,\quad m_{\tilde{W}'}(M_S) = \left[\frac{g_2(M_S)}{g_3(M_S)}\right]^2 m_{\tilde{g}'}(M_S)\,.$$

Consequences for the Higgs mass

Have done a state-of-the-art analysis:

- Two-loop RGEs (we added those for the gaugino/higgsino masses)
- Two-loop QCD including gluino and one-loop electroweak threshold corrections to top mass

$$m_t(M_Z) = \frac{M_t}{1 + \frac{g_3^2}{(4\pi)^2} C_1 + \frac{g_3^4}{(4\pi)^4}\left(C_2^{SM} + C_2^{\tilde{g}'}\right)} + \Sigma_t(m_t)^{EW},$$

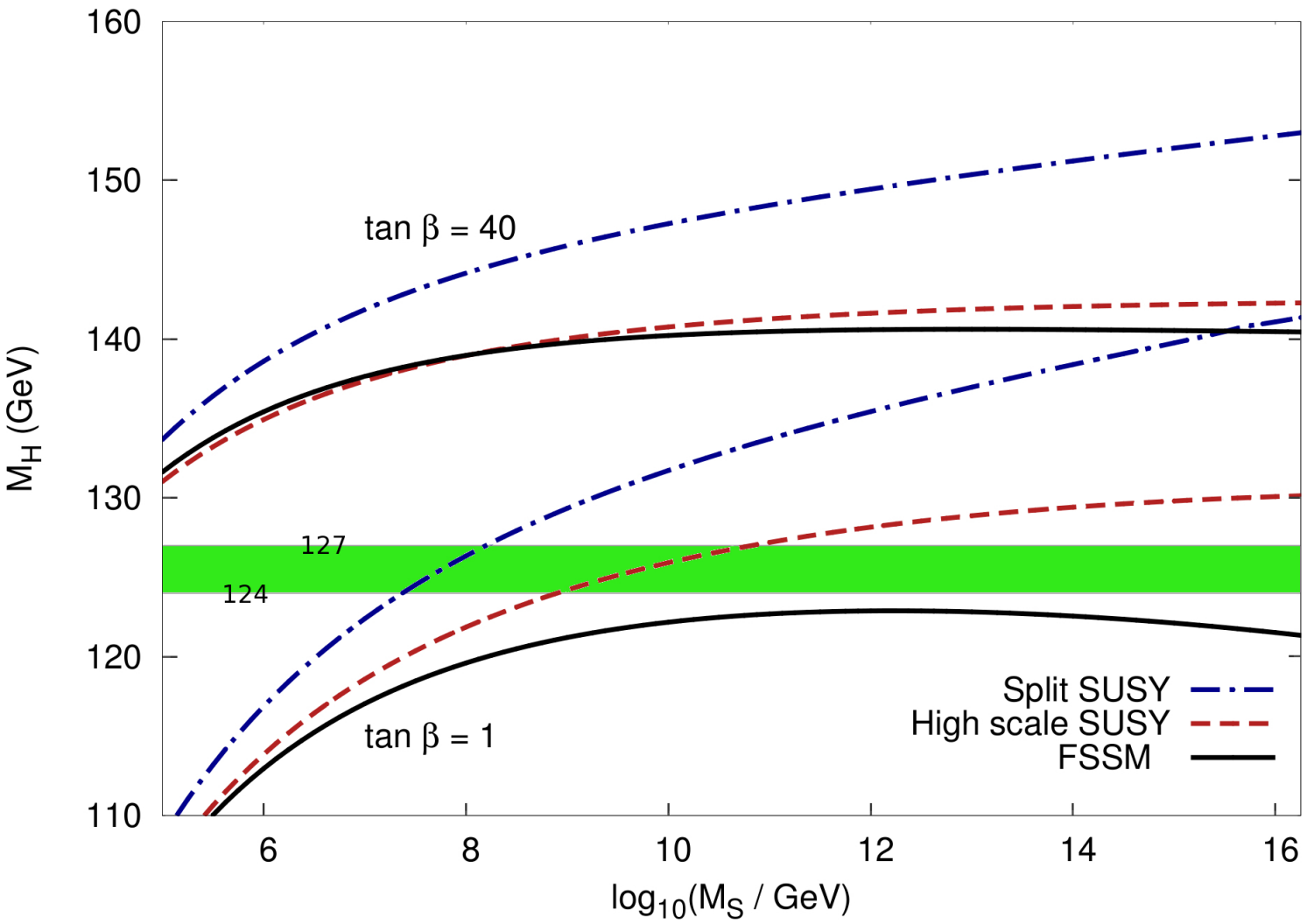
$$C_2^{\tilde{g}'} = \frac{89}{9} + 4 \ln \frac{m_{\tilde{g}'}^2}{M_Z^2}\left(\frac{13}{3} + \ln \frac{m_{\tilde{g}'}^2}{M_Z^2} - 2 \ln \frac{M_t^2}{M_Z^2}\right).$$

- Higgs pole mass:

$$\begin{aligned} M_H^2 &= \frac{\lambda(Q_W)}{\sqrt{2}\, G_F}\left[1 - \delta^{1\ell}(Q_W)\right] \\ &+ \frac{g_t^4 v^2}{128\,\pi^4}\left[16\, g_3^2\,(3\,\ell_t^2 + \ell_t) - 3\, g_t^2\left(9\,\ell_t^2 - 3\,\ell_t + 2 + \frac{\pi^2}{3}\right)\right] \\ &+ \frac{g_3^4\, g_t^4\, v^2}{64\,\pi^6} \ln^3 \frac{m_{\tilde{g}'}^2}{Q_W^2}, \end{aligned}$$

- One-loop $\delta^{1\ell}(Q_W)$, two-loop corrections proportional to $g_3^2 g_t^4$ and to g_t^6; leading-logarithmic correction arising from three-loop diagrams involving F-gluinos.

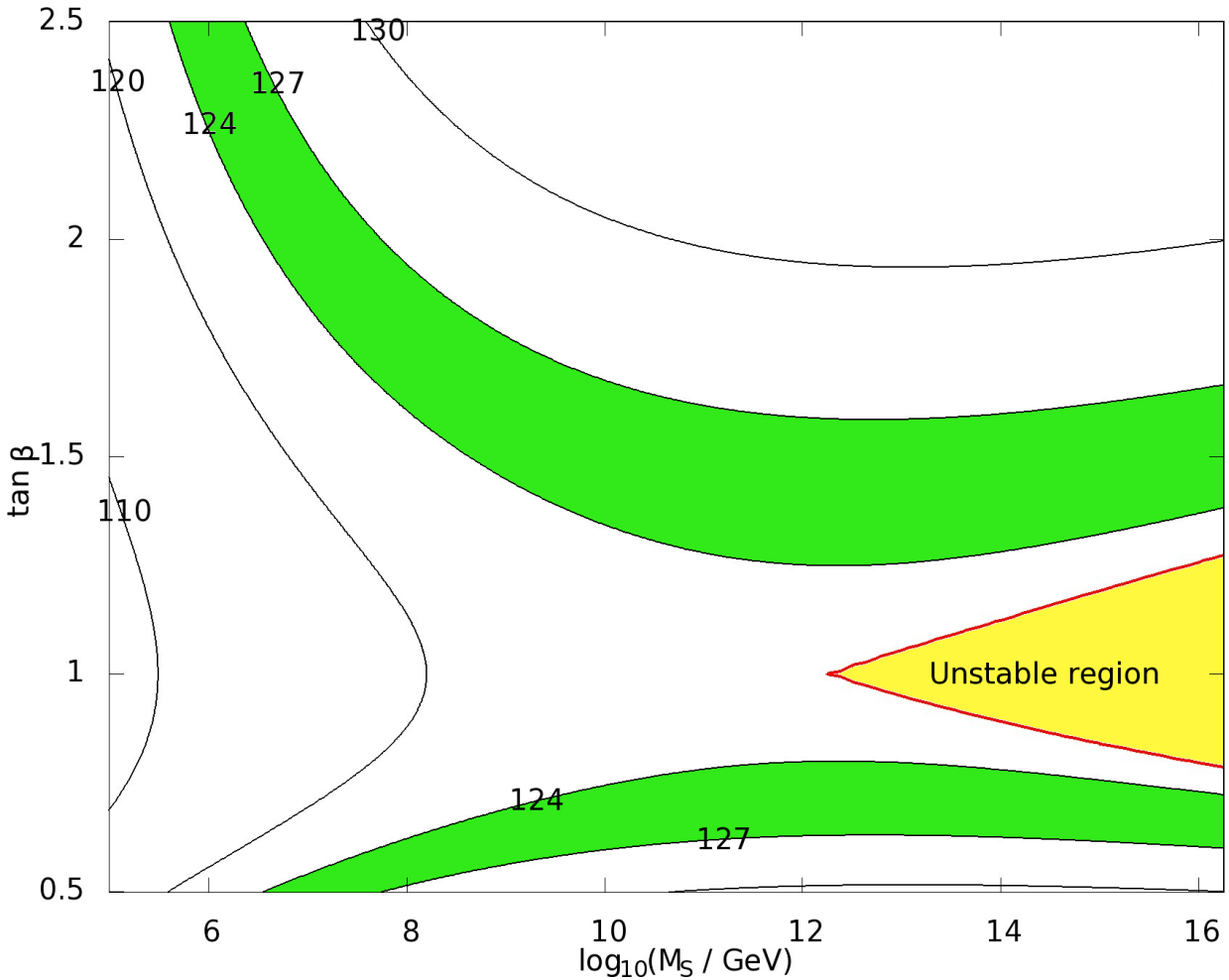
Higgs mass predictions:



No upper bound to the SUSY-breaking scale!

Stability

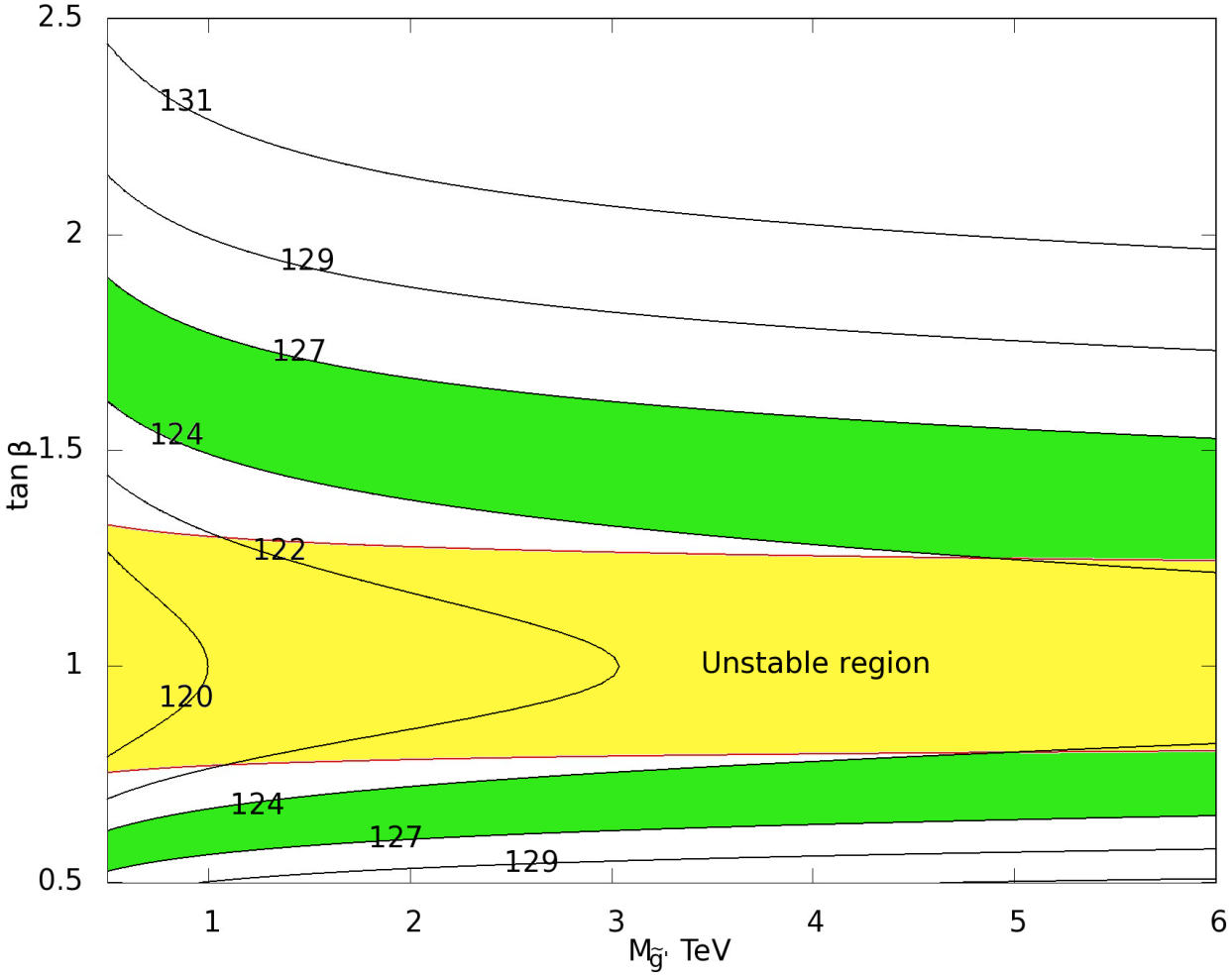
Model is generically absolutely stable:



$$\mu = m_{\tilde{g}'} = 2\text{TeV}$$

Stability 2

... except when the gluino becomes too massive



$\mu = 2\text{TeV}$

Two ways to Fake Split SUSY

I'll describe two ways to Fake It:

1. Faking all of the new particles.
2. Faking only the Higgsinos.

(Both give the same results for the Higgs mass)

Then I'll discuss the consequences and possible connections with strings.

Totally Fake SUSY

What if the 'gauginos' are not gauginos, just adjoint fermions? Add in the UV:

1. F-gauginos: fermions χ_Σ in the adjoint representation of each gauge group, having scalar partner Σ. Consist of: a singlet $\mathbf{S} = S + \sqrt{2}\theta\chi_S + \ldots$; an $SU(2)$ triplet $\mathbf{T}$; an $SU(3)$ octet $\mathbf{O}$.
2. F-Higgs doublets $\mathbf{H'_u}$ and $\mathbf{H'_d}$
3. Two pairs of vector-like electron superfields $\hat{E}$, $\hat{\bar{E}}$ (i.e. two pairs of superfields with charges ± 1 under $U(1)_Y$) with a supersymmetric (or GM) mass M_s.

With this field content we automatically have gauge coupling unification independently of M_s.

Instead of split MSSM this is split MDGSSM. NB different to 'Split Extended SUSY' of [Antoniadis et al, 05]

Protected masses

- To explain the spectrum we need to protect the mass of the F-gauginos and F-higgsinos.
- This we do with an approximate $U(1)_F$:

	$U(1)_F$
MSSM Fields	0
$\mathbf{S}, \mathbf{T}, \mathbf{O}, \mathbf{H_u'}, \mathbf{H_d'}$	1
$\hat{E} \times \hat{\bar{E}}$	0

- Breaking of $U(1)_F$ paramtrised by $\varepsilon \sim v_F/\Lambda$.
- Write the superpotential

$$
\begin{aligned}
W \quad = \quad & \mu_0\, \mathbf{H_u} \cdot \mathbf{H_d} + Y_u\, \mathbf{U^c}\, \mathbf{Q} \cdot \mathbf{H_u} - Y_d\, \mathbf{D^c}\, \mathbf{Q} \cdot \mathbf{H_d} - Y_e\, \mathbf{E^c}\, \mathbf{L} \cdot \mathbf{H_d} \\
+ \quad & \varepsilon\, \left(\hat{\mu}'_d\, \mathbf{H_u} \cdot \mathbf{H_d'} + \hat{\mu}'_u\, \mathbf{H_u'} \cdot \mathbf{H_d} + \hat{Y}'_u\, \mathbf{U^c}\, \mathbf{Q} \cdot \mathbf{H_u'} - \hat{Y}'_d\, \mathbf{D^c}\, \mathbf{Q} \cdot \mathbf{H_d'} - \hat{Y}'_e\, \mathbf{E^c}\, \mathbf{L} \cdot \mathbf{H_d'}\right) \\
+ \quad & \varepsilon\, \left(\hat{\lambda}_S\, \mathbf{S}\, \mathbf{H_u} \cdot \mathbf{H_d} + 2\, \hat{\lambda}_T\, \mathbf{H_d} \cdot \mathbf{T}\, \mathbf{H_u}\right) \\
+ \quad & \varepsilon^2\, \left(\hat{\lambda}'_{Sd}\, \mathbf{S}\, \mathbf{H_u} \cdot \mathbf{H_d'} + \hat{\lambda}'_{Su}\, \mathbf{S}\, \mathbf{H_u'} \cdot \mathbf{H_d} + 2\, \hat{\lambda}'_{Tu}\, \mathbf{H_d} \cdot \mathbf{T}\, \mathbf{H_u'} + 2\, \hat{\lambda}'_{Td}\, \mathbf{H_d'} \cdot \mathbf{T}\, \mathbf{H_u}\right) \\
+ \quad & \varepsilon^2\, \hat{\mu}''\, \mathbf{H_u'} \cdot \mathbf{H_d'} \; + \; \varepsilon^2 \left[\frac{1}{2}\, \hat{M}_S\, \mathbf{S}^2 + \hat{M}_T\, \mathrm{Tr}(\mathbf{TT}) + \hat{M}_O\, \mathrm{Tr}(\mathbf{OO})\right] ,
\end{aligned}
$$

Spectrum

- We can write the masses for the gauginos λ and the adjoint fermions χ as

$$-\Delta\mathcal{L}_{\text{gauginos}} = M_s \left[\frac{1}{2}\lambda\lambda + \mathcal{O}(\varepsilon)\lambda\chi + \mathcal{O}(\varepsilon^2)\chi\chi + \text{h.c.}\right]$$

- So $\varepsilon^2 = \frac{\text{TeV}}{M_s}$; similarly the F-higgsino mass is $\sim$ TeV.
- The light eigenstate $\lambda_1 \sim \chi + \mathcal{O}(\varepsilon)\lambda$, although the 'true' gaugino component may be even more suppressed since the mixing relies on Dirac gaugino masses.
- Adjoint scalar masses are under control:

$$-\Delta\mathcal{L}_{\text{adjoint scalars}} = M_s^2 \left[|\Sigma|^2 + \mathcal{O}(\varepsilon^2)(\frac{1}{2}\Sigma^2 + \frac{1}{2}\Sigma^{*\,2})\right]$$

Higgs mixing

- The Higgs soft terms, and thence the Higgs mass matrix, can be written as a matrix in terms of the four-vector $v_H \equiv (H_u, H_d{}^*, H'_u, H'^*_d)$

$$-\frac{1}{M_S^2}\mathcal{L}_{soft} \supset v_H^\dagger \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(\varepsilon) & \mathcal{O}(\varepsilon) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(\varepsilon) & \mathcal{O}(\varepsilon) \\ \mathcal{O}(\varepsilon) & \mathcal{O}(\varepsilon) & \mathcal{O}(1) & \mathcal{O}(\varepsilon^2) \\ \mathcal{O}(\varepsilon) & \mathcal{O}(\varepsilon) & \mathcal{O}(\varepsilon^2) & \mathcal{O}(1) \end{pmatrix} v_H.$$

- This structure allows tuning between the H_u, H_d fields to get a small SM-higgs mass:

$$H_u \approx \sin\beta\, H + \dots, \qquad H_d \approx \cos\beta\, i\sigma^2 H^* + \dots,$$

- There is also a small mixing with the F-higgs fields:

$$H'_u \approx \varepsilon H + \dots, \qquad H'_d \approx \varepsilon\, i\sigma^2 H^* + \dots,$$

Realisation of FSSM

- To realise the FSSM, we need to consider the Higgs–F-higgsino–F-gaugino couplings.
- These come from both the gauge current and the superpotential. To illustrate:

$$\mathcal{L}_{\text{gauge current}} \supset -\frac{H_u^\dagger}{\sqrt{2}}\left(g\,\sigma^a\lambda_2^a + g'\,\lambda_Y\right)\tilde{H}_u - \frac{H_d^\dagger}{\sqrt{2}}\left(g\,\sigma^a\lambda_2^a - g'\,\lambda_Y\right)\tilde{H}_d$$
$$-\frac{H_u'^\dagger}{\sqrt{2}}\left(g\,\sigma^a\lambda_2^a + g'\,\lambda_Y\right)\tilde{H}_u' - \frac{H_d'^\dagger}{\sqrt{2}}\left(g\,\sigma^a\lambda_2^a - g'\,\lambda_Y\right)\tilde{H}_d'$$

- When we integrate out the heavy fields, we find a double suppression:

$$\tilde{g}_{1u} \sim \tilde{g}_{1d} \sim \tilde{g}_{2u} \sim \tilde{g}_{2d} \sim \varepsilon^2.$$

- The SUSY prediction for the Higgs quartic coupling at tree-level is preserved, up to one-loop corrections (including proportional to $|A_t - \mu_0^* \cot\beta|^2/M_S^2$)

Electroweakinos

- Chargino mass matrix

$$\begin{pmatrix} m_{\tilde{W}'} & \varepsilon^2 M_W \\ \varepsilon^2 M_W & \mu \end{pmatrix}$$

- The F-neutralino mass matrix in basis $(\tilde{B}', \tilde{W}'^0, \tilde{H}_d'^0, \tilde{H}_u'^0)$ is

$$\mathcal{M}_{\chi^0} = \begin{pmatrix} m_{\tilde{B}'} & 0 & \varepsilon^2 M_Z & \varepsilon^2 M_Z \\ 0 & m_{\tilde{W}'} & \varepsilon^2 M_Z & \varepsilon^2 M_Z \\ \varepsilon^2 M_Z & \varepsilon^2 M_Z & 0 & -\mu \\ \varepsilon^2 M_Z & \varepsilon^2 M_Z & -\mu & 0 \end{pmatrix}$$

- Quasi-Dirac higgsinos: mass splitting is

$$\delta m_{\tilde{h}'} \sim \left(\frac{\text{TeV}}{M_S}\right)^2 \frac{M_Z^2}{\mu}$$

Cosmology

- F-gluino has longer life:

$$\tau_{\tilde{g}'} \simeq \frac{4\ \text{sec}}{\varepsilon^4} \times \left(\frac{M_S}{10^9\text{GeV}}\right)^4 \times \left(\frac{1\ \text{TeV}}{m_{\tilde{g}'}}\right)^5$$
$$\sim \text{sec} \times \left(\frac{M_S}{10^7\text{GeV}}\right)^6 \times \left(\frac{1\ \text{TeV}}{m_{\tilde{g}'}}\right)^7$$

- Safer to restrict to $M_S \lesssim 10^7$ GeV if BICEP is confirmed
- Otherwise this constraint may be removed by appropriate late dilution etc.
- Decays of heavy neutralinos suppressed by $\varepsilon^4 \rightarrow$ no problem cosmologically since no heavy particle exchange in the decay:

$$\Gamma(\chi_2 \rightarrow h\chi_1) \sim \varepsilon^4 \frac{M_Z^2}{\text{TeV}}$$
$$\tau_{\chi_2} \lesssim \text{sec} \times \left(\frac{M_S}{10^{14}\text{GeV}}\right)^2$$

- Can have a component of inelastic dark matter $\delta m \sim 100$ keV for higgsino LSP if $M_S \sim 10^3$ TeV $\rightarrow$ this is novel compared to usual split SUSY.

Fake Higgsinos

Another realisation to consider: just replace the Higgsinos!

- We just add <u>two pairs</u> of extra doublets, H'_u, H'_d and R_d, R_u.
- The relevant symmetry is now an approximate R-symmetry:

	Q_R
H_u, H_d	0
R_u, R_d	2
$\mathbf{H'_u, H'_d}$	± 1

$$\begin{aligned}\mathcal{W} \supset\ & \mu_u H_u R_u + \mu_d H_d R_d \\ & + \varepsilon \tilde{\mu}'_u H'_u H_d + \varepsilon \tilde{\mu}'_d H_u H'_d + \varepsilon \mu'_u H'_u R_u + \mu'_d H'_d R_d \\ & + \mathcal{O}(\varepsilon^2)\end{aligned}$$

- To preserve unification of gauge couplings above M_S we can add two pairs in representations $(\mathbf{3},\mathbf{1})_{1/3} \oplus (\bar{\mathbf{3}},\mathbf{1})_{-1/3}$ (i.e. in total we have just added a vector-like pair of $\mathbf{5} + \bar{\mathbf{5}}$ of $SU(5)$, c.f. messengers).

Phenomenology

- Higgs mixing looks similar to the FSSM.
- Smaller suppression of Higgsino couplings:

$$\tilde{g}_{1u} \sim \tilde{g}_{1d} \sim \tilde{g}_{2u} \sim \tilde{g}_{2d} \sim \varepsilon.$$

- $\rightarrow$ almost identical predictions for Higgs mass.
- Gluino lifetime is the same as in Split SUSY $\rightarrow$ can reach $M_s = 10^9$ GeV without cosmological problems.
- $\rightarrow$ still have pseudo-Dirac higgsino, but larger mass splitting.
- However, for $M_s = 10^9$ GeV, DM is the bino, axion/ALP or sterile neutrino.

$\rightarrow$ best of both worlds!

Stringy perspectives I

- This scenario could in principle even allow us to break SUSY at the string level while still preserving some vestiges and having the correct Higgs mass.
- To find the totally fake FSSM, require adjoints charged linearly under an approximate $U(1)$.
- Adjoints are abundant in string theory, e.g. position/Wilson line moduli.
- For a continuous symmetry this is difficult to imagine (typically find they tranform with a shift symmetry).
- However, a discrete symmetry is very reasonable. We could easily imagine that the model is localised on a cycle invariant under an approximate $\mathbb{Z}_N$ which is not preserved by the bulk (see e.g. [Maharana '11]) and then a volume factor controls ε.

Stringy perspectives 2

- Any attempt to derive Split SUSY in string theory can also apply to the F-Higgsino FSSM; see e.g. [Antoniadis and Dimopoulos '04].
- Could equally consider that the gauginos/F-higgsinos are sequestered and the matter fields/Higgs are not, as we may expect when we have flavour branes.
- Then $m_{1/2} \sim \mu \sim g_s m_{3/2}/\mathcal{V}$, $m_0 \sim m_{3/2} \sim M_P/\mathcal{V}$.
- Volume modulus decay can dilute dark matter density (c.f. talk by Dutta).
- If we do have some sequestering of the scalars and have $M_s < m_{\tau_b}$ then, since the two UV completions of the FSSM have extra vector-like fields which may have Giudice-Masiero terms, we may have no problem with dark radiation.

Conclusions

- Have proposed a new bottom-up framework which removes some problems of split SUSY and has some interesting new features.
- Suggests looking for modest extensions of the MSSM in model building.
- Many avenues can be explored for the string embedding.

Corrections to Yukawa couplings and soft terms

[Blumenhagen, Conlon, Krippendorff, Moster, Quevedo '09], talk by Krippendorf

- Consider "matter" fields ϕ_α which do not obtain a vev having Kähler metric Z_α; usual supergravity formula gives

$$m_\alpha^2 = m_{3/2}^2 + V_0^F - F^m F^{\overline{n}} \partial_m \partial_{\overline{n}} \log Z_\alpha$$

- <u>if</u> we have F-term uplifting, then $V_0^F \simeq 0$.
- If $Z_\alpha = e^{K/3}$ then

$$m_\alpha^2 = \frac{2}{3} V_0^F = 0.$$

- (if we have D-term uplifting, then $V_0^F < 0 \sim \mathcal{V}^{-3}$ and thus $m_\alpha^2 \sim M_P^2/\mathcal{V}^3$ and may be tachyonic)
- Note that physical Yukawa couplings are given by

$$Y_{\alpha\beta\gamma}^{phys} = \frac{e^{K/2}}{\sqrt{Z_\alpha Z_\beta Z_\gamma}} Y_{\alpha\beta\gamma}^{holomorphic} \tag{1}$$

- Putting $Z_\alpha = e^{K/3}$ gives us physical Yukawas that are independent of the moduli
- $\rightarrow$ computing corrections to the modulus dependence of Yukawa couplings gives us corrections to soft masses.

Corrections to matter metrics

- Suppose that we compute corrections to matter metrics so that we can write

$$Z_\alpha \equiv e^{K/3}(1+Z^1_\alpha)$$
$$Z^1_\alpha \equiv z S^{-\epsilon_S} \tau_b^{-\epsilon_b} \tau_s^{-\epsilon_s}$$

- We have

$$F^S \sim \frac{W_0}{\mathcal{V}^2} + \ldots$$
$$F^b = 2\tau_b m_{3/2}\left(1+\mathcal{O}(\mathcal{V}^{-1})\right)$$
$$F^s = F^b\left(\frac{\tau_s}{\tau_b}\right)\left(1+\mathcal{O}(\mathcal{V}^{-1})\right) \tag{2}$$

- For generic ϵ_b, ϵ_s we have

$$m^2_\alpha \sim \frac{M_P^2}{\mathcal{V}^2} Z^1_\alpha$$

- For Z^1_α a homogeneous function of (τ_s/τ_b) we have the subleading term

$$m^2_\alpha \sim \frac{M_P^2}{\mathcal{V}^3}$$

- For cancelling contributions from τ_s, τ_b we have the contribution from the dilaton F-term:

$$m^2_\alpha \sim \frac{M_P^2}{\mathcal{V}^4}$$

Gaugino masses

Similar story holds for gaugino masses. Recall leading gaugino mass contibution is $\frac{1}{2}F^m\partial_m \log f$:

- In sequestered scenario, gauge kinetic function $f = S + s_i T_i$ and is exact.
- In ultra-local models, the s_i are zero.
- For all local models, have $s_{\tau_b} = 0$, and should have $s_{\tau_s} = 0$ provided small cycle does not intersect the standard model. Then only local blow-ups τ_a can contribute at leading order - and these are usually assumed to be blown down.
- Hence minimum mass set by dilaton F-term, giving $m_{1/2} \gtrsim g_s m_{3/2}/\mathcal{V}$.
- Recall higher-order gaugino mass given by

$$m_{1/2} = -\frac{g^2}{16\pi^2} \times \left[(3T_G - T_R)\, m_{3/2} - (T_G - T_R)\, K_i F^i - \frac{2T_R}{d_R} F^i \partial_i \left(\ln \det Z\right) + 2T_G F^I \partial_I \ln f \right] \xrightarrow[\text{ultralocal}]{} -\frac{b_1 g^2}{16\pi^2}\left[m_{3/2} - \frac{1}{3} F^m K_m \right] \tag{3}$$

What do we already know?

- Consider a four-point function of complex scalars

$$\langle \Phi_i(z_1)\overline{\Phi}_i(z_2)\Phi_j(z_3)\overline{\Phi}_j(z_4)\rangle = N^4 C_{disk} f(\alpha' s, \alpha' t)$$

- Note: here (unlike other string cases) f indep of internal volumes!
- We can take limiting values:

$$\langle \Phi_i(z_1)\overline{\Phi}_i(z_2)\Phi_j(z_3)\overline{\Phi}_j(z_4)\rangle \xrightarrow{k_1\cdot k_4\to 0} 2g^2 Z_i Z_j$$

$$\langle \Phi_i(z_1)\overline{\Phi}_i(z_2)\Phi_j(z_3)\overline{\Phi}_j(z_4)\rangle \xrightarrow{k_1\cdot k_3\to 0} e^K |Y|^2 (Z_k)^{-1} + 2g^2 Z_i Z_j$$

Gives us lots of information:

- Physical Yukawas given by gauge coupling: $Y^{phys} = \sqrt{2} g_s = \sqrt{2} g_s = \sqrt{2}/\mathrm{Re}(S)$
- $Z_\alpha = S^{1/3} e^{K/3}$
- Also normalisation of vertex operators, $V^{-1}_{\Phi_i}(z) \sim (\alpha')^{1/2} g_s^{1/2} Z_\alpha^{1/2} \lambda_i e^{-\phi(z)} e^{ik\cdot X(z)} e^{iH_i(z)}$.

Importantly, CFT calculations on orbifolds are exact in α', so recall

$$Z_\alpha = \frac{k}{\mathcal{V}^{2/3}} S^{1/3} \left[1 - \delta \frac{\mathrm{Re}(S)^{3/2}}{\mathcal{V}} + \delta^{(1)} \frac{1}{\mathrm{Re}(S)} \left(\frac{\mathrm{Re}(S)}{\mathcal{V}^{2/3}} \right)^{n/2} + \sum_{n,m} g_s^m \epsilon^{m,n} \tau_a^n + \ldots \right]$$

$$e^{K/3} = \exp[-\frac{2}{3} \log \mathcal{V} + \frac{\xi}{2 g_s^{3/2} \mathcal{V}}]$$

$$= \frac{1}{\mathcal{V}^{2/3}} \exp[1 - \frac{\xi}{3 g_s^{3/2} \mathcal{V}}]$$

- The presence of $S^{1/3}$ ensures that there is a minimum mass coming from the dilaton F-term.
- We must have $\delta = \frac{\xi}{3}$, and can write corrections to all orders in α'
- Note that $\mathcal{V} = g_s^{-3/2} V_s$ where V_s is the volume in the string frame.
- Does this all apply for τ_s? **No**: since τ_s is a blow-up mode (even if it is large). Strictly this implies only the corrections for τ_b.
- To understand the corrections from F^s we must calculate the corrections for τ_s.