Hidden U(1)s in String Compactifications

Based on 0803.1449, 0909.0017, 0909.0515, 0912.4206, 1002.1840 and to appear; variously with S. Abel, K. Benakli, J. Jaeckel, V. Khoze, Saúl Ramos-Sánchez, J. Redondo and A. Ringwald

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Overview

- Why we should look for hidden $U(1)$s
- How we can look for them
- How they can be found in string theory:
- Heterotic models
- R-R U(1)s
- D-branes in the LARGE Volume scenario

Top down motivation

Global string compactifications must have many fields we do not see, with masses below the string scale:

- Moduli; after stabilisation, masses $\sim M_{3/2}$. Couple gravitationally.
- Axion-like particles $\frac{a}{M} F \wedge F$: imaginary component of moduli; tree level decay constant typically $M \sim M_s$ or zero!
- Type II: $U(1)$s from $R - R$ four-form $C_4 = U_\alpha \wedge \beta^\alpha$ counted by $h_+^{2,1}$

In addition there may be

- Open-string moduli, masses $> TeV$
- Exotic matter, masses $> TeV$
- Hidden matter
- Hidden gauge groups

Can we detect any of these? Would learn about global structure, rather than local.

Bottom up: Shining a light on the hidden sector

Exist renormalisable operators:

$$\mathcal{L} \supset \frac{\chi_{ab}}{2} F_{a\,\mu\nu} F_b^{\mu\nu} - \frac{\theta^M}{8\pi^2} F_{a\,\mu\nu} \tilde{F}_b^{\mu\nu} + (i\tilde{\chi}_{ab}\lambda_a \sigma^\mu \partial_\mu \bar{\lambda}_b + h.c.)$$

When $F_{a\,\mu\nu}$ is the photon, and $F_b^{\mu\nu}$ is a hidden $U(1)$, exist many possible values for χ, hidden photon mass and hidden gaugino mass that are phenomenologically interesting:

1. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-6}, 0.2\,\mathrm{meV}, \ll \mathrm{GeV})$, "Hidden CMB" explains apparent excess of neutrino species
2. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-12}, 0.1\mathrm{MeV}, < \mathrm{GeV})$, Lukewarm DM
3. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-4}, 0, 100\,\mathrm{GeV})$, Hidden gaugino at LHC
4. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-11}, 0, 100\,\mathrm{GeV})$, Hidden Photino DM
5. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-23}, 0, 100\,\mathrm{GeV})$, Decaying dark matter
6. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-3}, \mathrm{TeV}, \mathrm{TeV})$, $Z' \rightarrow$ may be first new physics LHC sees...
7. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-7}, \mathrm{meV}, \mathrm{N/A})$, **Light shining through walls (e.g. ALPS)**
8. $(\chi, m_{\gamma'}, m_{\lambda'}) \sim (10^{-4}, \mathrm{GeV}, \mathrm{GeV})$, **"Dark Forces" - PAMELA, ATIC,... and beam dump experiments (e.g. at DESY, JLAB)**

Or magnetic mixing...

Magnetic Mixing

Explanation for DAMA using NaI detector seeing signal, taken from S. Chang, N. Weiner and I. Yavin, "Magnetic Inelastic Dark Matter," arXiv:1007.4200 [hep-ph].

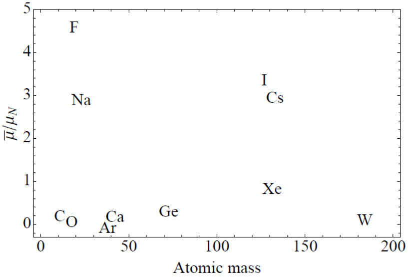
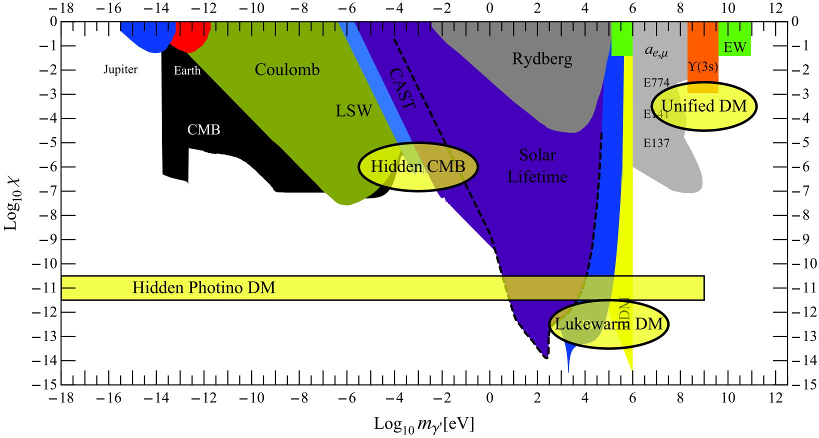


FIG. 1: The weighted-atomic mass and weighted-magnetic dipole moment (Eq. (2) in units of the nuclear magneton μ_N of various dark matter search targets. (C,O and Ca,Ar have been shifted slightly so as not to overlay each other.)

Where to look



Z' models

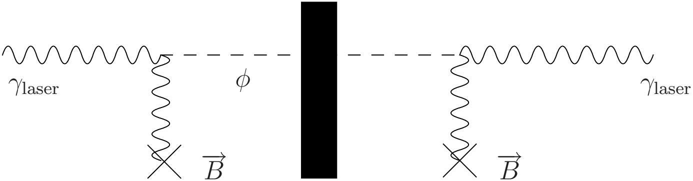
Abundance of models with extra abelian gauge symmetry under which SM fields are charged, e.g.

- Extra dimension and string D-brane models (see [Antoniadis' Talk] and later...)
- $U(1)'$ NMSSM, e.g. $W \supset \lambda N H_u H_d + \tilde{\lambda} N E \tilde{E}$
- E6 GUT
- Hyperweak brane (more later)
- Also useful for Z' (or $Z'+$ anomaly mediation...)

However I will focus on hidden $U(1)$s, but more to come in future work!

Light Shining Through Walls

- PVLAS, BFRT, ALPS searching for axion-like-particles or hidden photons:



Kinetic Mixing in SUSY Theories

- For supersymmetric configurations, kinetic mixing is a holomorphic quantity:

$$\mathcal{L} \supset \int d^2\theta \left\{ \frac{1}{4(g_a^h)^2} W_a W_a + \frac{1}{4(g_b^h)^2} W_b W_b - \frac{1}{2}\chi_{ab}^h W_a W_b \right\}$$

- Runs/is generated only at one loop
- SUSY operator contains mixing of gauge bosons, gauginos and D-terms:

$$\int d^2\theta - \frac{1}{2}\chi_{ab}^h W_a W_b + c.c. \supset -\frac{\chi_{ab}}{2} F_{a\,\mu\nu} F_b^{\mu\nu} + (i\tilde{\chi}_{ab}\lambda_a \sigma^\mu \partial_\mu \overline{\lambda}_b + h.c.) - \chi_{ab} D_a D_b$$

Kinetic Mixing in SUSY Theories II

- Can show that physical mixing obeys a Kaplunovsky-Louis type formula

$$\frac{\chi_{ab}}{g_a g_b} = \Re(\chi^h_{ab}) + \frac{1}{8\pi^2}\mathrm{tr}\Big(Q_a Q_b \log Z\Big) - \frac{1}{16\pi^2}\kappa^2 K \sum_r n_r Q_a Q_b(r)$$

- Only Kähler potentials from light fields charged under both contribute $\rightarrow$ does not run below messenger scale (except for gauge running)
- "Natural" size given by one-loop formula, assuming $\mathrm{tr}(Q_a Q_b) = 0$:

$$\chi^h_{ab} = \frac{1}{8\pi^2}\mathrm{tr}\Big(Q_a Q_b \log \mathcal{M}/\Lambda\Big)$$
$$\rightarrow \chi_{ab} = \frac{g_a g_b}{16\pi^2}\mathrm{tr}\Big(Q_a Q_b \log |\mathcal{M}|^2\Big) \sim \frac{g_a g_b}{16\pi^2}$$

- Depends only on the holomorphic quantities!
- D-term coupling can give Higgs portal terms $\chi_{ab} H_u H_d H_+ H_-$.
- Magnetic mixing given by $8\pi^2 \mathrm{Im}(\chi)_{ab}$.

Dirac Gauginos

see talk by K. Benakli

- Kinetic mixing can be used to calculate leading gaugino masses in field theory (even if kinetic mixing vanishes or have non-abelian groups!)
- From F-terms (not the case in LARGE volume scenario where complex structure moduli do not develop vevs):

$$-\frac{1}{2}\int d^2\theta \chi(S) W^\alpha W'_\alpha \rightarrow -\frac{1}{2}\lambda^\alpha \lambda'_\alpha (\partial_S \chi(S)) F_S$$

- Otherwise need adjoints; relevant term from gravity mediation and high-mass gauge mediation is D-term:

$$\int d^2\theta W'^\alpha W^a_\alpha X^a \partial_{X^a}\chi(X^a) = \int d^2\theta 2 W'^\alpha \mathrm{tr}(W_\alpha X)\partial_{X^a}\chi(X^a)$$

- Advantage: can calculate in the SUSY limit. E.g. intersecting $D6$-brane model on tori, parallel branes of length L separated by distance l in one torus, intersect I_{ab} times at angles $(\phi, -\phi)$ in other two

$$\chi_{ab} = \frac{1}{4\pi^2} I_{ab}\left[\log\left|\frac{\theta_1(\frac{ilL}{4\pi^2\alpha'}, \frac{iT_2}{\alpha'})}{\eta(\frac{iT_2}{\alpha'})}\right|^2 - \frac{l^2}{8\pi^3\alpha'}\frac{L^2}{T_2}\right]$$

- Induce D-term by shifting angles to $(\phi+\epsilon, -\phi)$, calculate mass to be

$$m_D = \epsilon\frac{m_s}{2}\frac{1}{4\pi^2}\frac{L}{l_s} I_{ab}\left[i\frac{\theta'_1(\frac{ilL}{4\pi^2\alpha'}, \frac{iT_2}{\alpha'})}{\theta_1(\frac{ilL}{4\pi^2\alpha'}, \frac{iT_2}{\alpha'})} - \frac{lL}{2\pi T_2}\right]$$

GeV Hidden Bosons

- [Arkani-Hamed, Finkbeiner, Slatyer and Weiner, 08]: Possibility to explain excess of e^+ detected by PAMELA but no protons; excess of 511 keV γ-rays from INTEGRAL as decay or annihilation of dark matter into hidden boson with mass $\mathcal{O}$(GeV) and kinetic mixing $\chi \sim 10^{-4}$ (can also explain DAMA signal ...)
- These values appear naturally if there is hidden matter:
- In MSSM hypercharge has a D-term from Higgs:

$$D_Y = -\frac{1}{2} g_Y v^2 \cos 2\beta$$

- Induces hidden D-term via mixing

$$-\int d^2\theta \chi \frac{1}{2} W_Y W_h + c.c. \supset -\chi D_Y D_h$$

GeV Hidden Bosons II

- Generates potential for hidden matter:

$$V \approx \frac{g_h^2}{2}\Big(\sum_i q_i|\phi_i|^2 + \frac{\chi}{g_h} D_Y\Big)^2$$

- $m_{\gamma_h} = \sqrt{2} g_h \langle\phi_i\rangle \sim v\left(\frac{\chi g_h g_Y \cos 2\beta}{q_i}\right)^{1/2} \sim$ GeV for $g_h \sim g_Y$
- Actually require a slightly more complicated hidden sector since naive FI mechanism gives massless hidden Higgs → minicharges

Hidden Sector Models

- Nice example, very simple dark matter model with hidden sector [Morrissey, Poland and Zurek 09]

$$W \supset \lambda_S S H_+ H_-$$

- With soft terms have potential

$$V = |\lambda_S|^2(|SH_+|^2 + |SH_-|^2 + |H_+H_-|^2) + \frac{g^2}{2}(|H_+|^2 - |H_-|^2 - \xi)^2$$
$$+ m_+^2|H_+|^2 + m_-^2|H_-|^2 + m_S^2|S|^2 + (\lambda_S A_S S H_+ H_- + c.c.)$$

- Assumed gauge mediation to obtain small hidden sector masses from little gauge mediation etc
- Large masses (e.g. from gravity) expected to prevent breaking of $U(1)'$
- Can this be compatible with string theory?

Dark Forces and Gravity Mediation

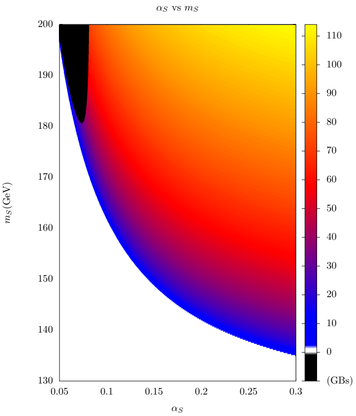
- In IIB, could have sequestering of hidden sector relative to visible sector
- However, if both are at singularities, say, or in heterotic orbifolds need another mechanism
- Provided λ_S is large enough ($\approx N = 2$ value) RGEs can drive the masses small:

$$\frac{dm_S^2}{dt} = \frac{1}{4\pi}[2\alpha_S(m_S^2 + m_+^2 + m_-^2 + A_S^2)]$$

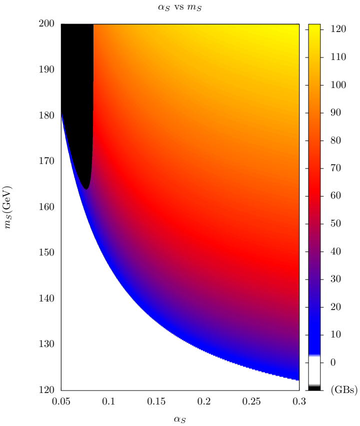
$$\frac{dm_\pm^2}{dt} = \frac{1}{4\pi}[2\alpha_S(m_S^2 + m_+^2 + m_-^2 + A_S^2) - 8M_\lambda^2\alpha \pm 2\alpha(m_+^2 - m_-^2)]$$

- If $\lambda_S^2 \gtrsim 2g^2$ at low scale and $m_{H_\pm}^2 < 0$ can have massive dark gauge bosons, no goldstone modes

Dark Forces and Gravity Mediation II



$m_H = A_S = 100$ GeV, $\alpha_S = 0.0417$
$M_0 = 71$ GeV



$m_H = A_S = 100$ GeV, $\alpha_S = 0.0417$
$M_0 = 50$ GeV

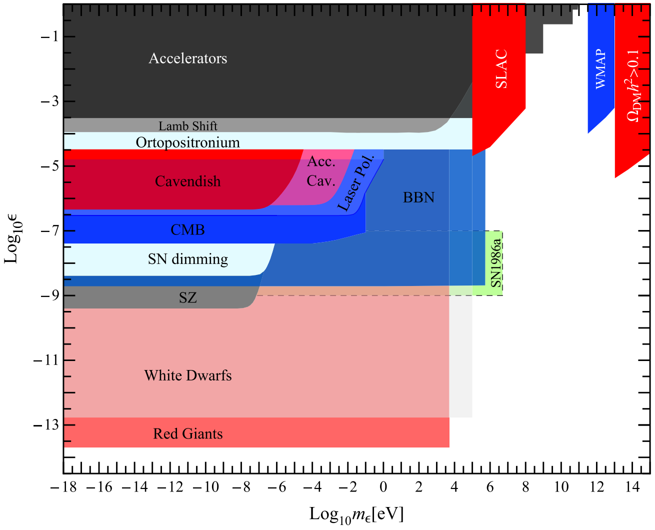
Minicharged Particles

- Kinetic mixing opens possibility of minicharged particles:

$$
\begin{aligned}
&-\frac{1}{4}F_{a\,\mu\nu}F_a^{\mu\nu}-\frac{1}{4}F_{a\,\mu\nu}F_b^{\mu\nu}+\frac{\chi}{2}F_{b\,\mu\nu}F_b^{\mu\nu}-eA_a^{\mu}j_{v\,\mu}-g_hA_b^{\mu}j_{h\,\mu}\\
\rightarrow&-\frac{1}{4}F_{v\,\mu\nu}F_v^{\mu\nu}-\frac{1}{4}F_{h\,\mu\nu}F_h^{\mu\nu}\\
&-eA_v^{\mu}-g_hA_h^{\mu}j_{h\,\mu}-\chi g_hA_v^{\mu}j_{h,\mu}-\chi g_vA_h^{\mu}j_{v,\mu}+\mathcal{O}(\chi^2)
\end{aligned}
$$

- NB $F_a \rightarrow F_a + \mathcal{O}(\chi^2)$, $F_b \rightarrow F_b - \chi F_a + \mathcal{O}(\chi^2)$
- Particles with fractional electric charge $\epsilon \sim \chi g_h/e$
- May be detected e.g. in laser polarisation experiments
- Strong bounds from astrophysics: $\epsilon < 10^{-14}$ for masses < 5 MeV

Minicharges



Hidden Photini

- Gauginos of the hidden $U(1)$ do not interact with it
- However they may mix with the Bino:

$$\mathcal{L} \supset - i(\lambda_h^\dagger \lambda_Y^\dagger) \begin{pmatrix} 1 & \chi \\ \chi & 1 \end{pmatrix} \bar{\sigma}^\mu \partial_\mu \begin{pmatrix} \lambda_h \\ \lambda_Y \end{pmatrix} - \frac{1}{2}(\lambda_h \lambda_Y) \begin{pmatrix} M_{hh} & M_{hY} \\ M_{hY} & M_{YY} \end{pmatrix} \begin{pmatrix} \lambda_h \\ \lambda_Y \end{pmatrix} + c.c.$$

$$\approx - i\tilde{\lambda}_h^\dagger \bar{\sigma}^\mu \partial_\mu \tilde{\lambda}_h - i\tilde{\lambda}_Y^\dagger \bar{\sigma}^\mu \partial_\mu \tilde{\lambda}_Y$$

$$- \frac{1}{2}(\lambda_h \lambda_Y) \begin{pmatrix} M_{hh} & M_{hY} - \chi M_{hh} \\ M_{hY} - \chi M_{hh} & M_{YY} \end{pmatrix} \begin{pmatrix} \lambda_h \\ \lambda_Y \end{pmatrix} + c.c.$$

- If hidden photino is LSP, strong bounds from dark matter overproduction on χ vs mass: for $m \gtrsim \mathrm{GeV}$, $\chi < 10^{-10}$ unless there is hidden matter for its decay ([Ibarra, Ringwald and Weniger, 08])
- If photino is LSP, $\chi \gtrsim 10^{-3}$ may detect at LHC! This is ok if mass < MeV. [Arvanitaki, Craig, Dimopoulos, Dubovsky and March-Russell,2009]

Heterotic Models

- Consider unwarped heterotic models, string scale is set $\sim 10^{17}$ GeV, all gauge groups derive from breaking $E_8 \times E_8$ or $\mathrm{Spin}(32)/\mathbb{Z}_2 \rightarrow$ generically have hidden gauge groups (e.g. for gaugino condensation to stabilise moduli and break SUSY)
- Plausible that there may be hidden $U(1)$ factors!
- [Lukas and Stelle, 99], [Blumenhagen, Honecker and Weigand, 05] showed for smooth compactification manifolds kinetic mixing is possible when there are $U(1)$ bundles by dimensionally reducing the anomaly term $S_{GS} = \frac{1}{48(2\pi)^5\alpha'} \int B \wedge X_8$:

$$
\begin{aligned}
f_{ab} =& \delta_{ab} S + f_{kab} T^k \\
f_{kab} =& \frac{1}{16} \mathrm{tr}_{E_8}(Q_m^2) \mathrm{tr}_{E_8}(Q_n^2) \sum_{ij} d_{ijk} \bar{f}_i^m \bar{f}_j^n
\end{aligned}
$$

- Expect to obtain generic value $\mathcal{O}(10^{-3})$ (or zero!) (but may be exceptions...)
- Masses of $U(1)$s given by

$$
M_{mk} = \begin{cases} \frac{1}{2} \mathrm{tr}_{E_8}(Q_m{}^2) \bar{f}_k^m & k \in \{1 \ldots h_{1,1}(\mathcal{M})\} \\ \frac{1}{64\pi^2} \mathrm{tr}_{E_8}(Q_m{}^2) \int \bar{f}^m \wedge (\mathrm{tr}\bar{F}_1{}^2 - \frac{1}{2}\mathrm{tr}\bar{R}^2) & k = 0 \end{cases}
$$

- Obtain massless $U(1)$s when some subset of fluxes are in linear dependent combinations of subset of $H^{1,1}$.

Heterotic Orbifolds

[Dienes, Kolda and March-Russell, 97] considered mixing on heterotic orbifolds:

$$\frac{\chi_{ab}}{g_a g_b} = \frac{b_{ab}}{16\pi^2} \log \frac{M_{GUT}^2}{\mu^2} + \int \frac{d^2\tau}{\mathrm{Im}\tau}[B_{ab}(\tau) - b_{ab}]$$

where

$$b_{ab} \equiv -\mathrm{Str}_{massless}(\overline{Q}_H^2 Q_a Q_b)$$

with $\overline{Q}_H$ the helicity operator, $\mathrm{Str}_{massless}$ being a supertrace over massless states; and

$$B_{ab}(\tau) \equiv -\mathrm{Str}(\overline{Q}_H^2 Q_a Q_b e^{\alpha' M_R^2 2\pi i \overline{\tau}} e^{\alpha' M_L^2 2\pi i \tau})$$

Tried some examples (Antoniadis, Leontaris and Rizos, 90], [Faraggi, 92 and 93]) and found zero mixing in each case.

Heterotic Orbifolds II

Work with S. Ramos-Sanchez and A. Ringwald

- Modern orbifold models in 'fertile patch' of mini-landscape involve $Z_6 - II$ orbifold of $E_8 \times E_8$ with two or three Wilson lines
- NMSSM model of [Lebedev and Ramos-Sanchez, 09] has hidden gauge group $SU(6) \times U(1)$
- Gauge shift in "standard embedding" $(1/6, -1/3, -1/2, 0^5)(0^8)$, three Wilson lines
- Messengers:

#	Irrep
1	$(\mathbf{3}, \mathbf{1}, \mathbf{1})_{1/6} + (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})_{-1/6}$
1	$(\mathbf{1}, \mathbf{1}, \mathbf{6})_{-1/2} + (\mathbf{1}, \mathbf{1}, \bar{\mathbf{6}})_{1/2}$
9	$(\mathbf{1}, \mathbf{1}, \mathbf{1})_{1/2} + (\mathbf{1}, \mathbf{1}, \mathbf{1})_{-1/2}$

- Despite presence of messengers, find stringy kinetic mixing is zero! (Apparently agrees with earlier orbifolds)
- Once gauge singlets acquire vevs due to anomalous $U(1)$ D-term (different $U(1)$...) find <u>non-zero</u> mixing of typical size 10^{-3}

R-R $U(1)$s

- Arvanitaki, Craig, Dimopoulos, Dubovsky and March-Russell [2009]: $h^{2,1}$ $R-R$ $U(1)$s $V^\alpha \wedge \alpha_\alpha$ which may mix with the hypercharge

$$S_{\rm YM} \supset -\int_4 2\pi \frac{1}{2}\mathrm{Im}(\mathcal{M})_{\alpha\beta} dV^\alpha \wedge \star_4 dV^\beta - \frac{1}{\pi} C_{\alpha\beta}\left((a^\beta + \bar{a}^\beta) dV^\alpha \wedge \star_4 F\right)$$

- Gauge couplings $\mathcal{O}(g_s)$, mixing determined by moduli vevs a^β
- No charged fundamental matter (adjoints possible when three-cycles shrink to zero volume and group enhanced to $SU(2)$), no masses/axions (unless non-Kähler compactification, [Grimm and Klemm, 08])
- If moduli a stabilised at string-size vev, get usual 10^{-3} mixing
- If via field theory (e.g. a is singlet of NMSSM) get $\mathcal{O}(10^{-15})$
- Gauge couplings do not depend on Kähler moduli, no matter couplings $\rightarrow$ very light photinos; for 10^{-3} mixing must be $\lesssim$ MeV to avoid astrophysical bounds - but this may be what we expect!

The LARGE Volume Scenario

- Type IIB string theory, Complex structure moduli stabilised at SUSY value by three-form fluxes, gives superpotential W_0
- Volume of Calabi-Yau in "swiss-cheese" form

$$\mathcal{V} = \tau_b^{3/2} - h(\tau_i)$$

- Or $K3$-fibration:

$$\mathcal{V} = \tau_{b'}^{1/2} \tau_b - h(\tau_i)$$

- Need small cycle $\tau_s > 1$
- $\rightarrow$ Instanton/gaugino condensate generate contribution to superpotential $W \supset A e^{-a\tau_s}$
- Kähler potential with α' corrections $K \supset -2 \log \left[\Re(\tau_b)^{3/2} + \xi/2 \right]$, needs $h^{2,1} > h^{1,1}$
- Volume, τ_b stabilised at exponentially large value: $\mathcal{V} \sim 10^6$ for GUT, $\sim 10^{14}$ for intermediate scale strings, $\sim 10^{30}$ for TeV strings
- AdS vacuum with $\not{SUSY}$, small uplift required to dS by anti-branes, D-terms, F-terms,...
- (MS)SM realised on $D7$ branes on collapsed cycles $\tau_a \sim 0$ (Quiver locus) or $\gtrsim 1$ (Geometric regime)

U(1)s

- R-R $U(1)$s
- D-branes carry $U(N) = SU(N) \times U(1)$ gauge group
- Several stacks of D-branes to realise (MS)SM

$\rightarrow$Generically several $U(1)$s (most anomalous)

- Some non-anomalous $U(1)$s massive via Stückelberg mechanism
- May have hidden branes for global consistency of model
- τ_b provides potential hyperweak U(1) with $g \sim g_{YM}\mathcal{V}^{-1/3}$ [Burgess, Conlon, Hung, Kom, Maharana, Quevedo 2008] or possibly even weaker for $K3$ fibrations, up to $g \sim g_{YM}\mathcal{V}^{-1/2}$
- May have hidden anti-$D3$ branes for uplifting to dS, or uplifting by hidden D-term
- $\rightarrow$ hidden $U(1)$s

What are the masses and mixings?

Fermion Condensates

- Dynamical scale

$$\Lambda = M_s \mathcal{V}^{1/6} e^{-\frac{4\pi\tau}{b}}$$

- or at quiver locus: $g^2 \sim 2\pi g_s \rightarrow \Lambda \sim M_s \mathcal{V}^{1/6} e^{-\frac{4\pi}{b g_s}}$
- Essentially arbitrary, unless broken by standard model: $\Lambda \sim 100\mathrm{MeV} \rightarrow m_{\gamma'} \sim 10KeV$ for hyperweak intersecting standard model branes
- Can probe to minimum $U(1)$ mass $\sim g \times 5\mathrm{MeV}$ from minicharge bounds; $\sim 100\mathrm{eV}$ for GUTs, $\sim 0.1\mathrm{eV}$ for intermediate strings

Hidden Higgs

- For a hidden Higgs, $m_{\gamma'} = \sqrt{2} g_h \langle H_h \rangle$
- Hidden Higgs behaves like minicharged particle; need $m_H > 5$ MeV
- Naively, for hyperweak gauge group, can have $m_{\gamma'} \ll m_H$
- BUT quartic coupling $\propto g_h^2 \to m_{\gamma'} \sim m_H$
- Couple to another gauge group $g' \sim e \to$ leaves one combination massless
- One solution: give second $U(1)$ a Stückelberg mass

Hidden Higgs II

- Consider moduli $X = x_i + ia_i$ with Kähler potential

$$K \supset \frac{1}{4} K_{ij}(X_i + \overline{X}_i + 2\Pi_{ik} g_k V_k)(X_j + \overline{X}_j + 2\Pi_{jl} g_l V_l)$$

- Gives contribution to Hidden Higgs scalar potential

$$\Delta V = \frac{1}{2} K_{ii} m_x^2 x_i^2 + \frac{1}{2} \tilde{g}_h^2 (K_{ii} \Pi_i M_s x_i + k_{H\overline{H}}(|H_1|^2 - |H_2|^2))^2$$

- Integrate out x, gives correction to quartic term

$$\begin{aligned} \tilde{V} =& m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_3^2 (H_1 H_2 + c.c) \\ &+ \frac{1}{2} \left[g_{\mathrm{h}}^2 + \tilde{g}_{\mathrm{h}}^2 \left(\frac{m_x^2}{m_x^2 + m_{\gamma''}^2} \right) \right] (|H_1|^2 - |H_2|^2)^2 \end{aligned}$$

- Find in LARGE volume scenario with modulus τ_α, $m_{\gamma'} \gtrsim \frac{MeV}{|W_0|}$

Stückelberg Mechanism

- Massless modes of axions generate $U(1)$ masses:

$$\begin{aligned}\mathcal{L} &\supset -\int d^4x K_{ij}\frac{1}{2}\partial_\mu a^i \partial^\nu a^j + M_{ij}\partial^\mu a^i A^j_\mu \\ &\to -\int d^4x \frac{1}{2}(K^{kl}M_{ki}M_{lj})A^i_\mu A^{j\,\mu}\end{aligned}$$

- Sensitive only to Kähler moduli
- KK modes of axions generate kinetic mixing. Couplings and masses depend on complex structure moduli (including brane positions):

$$\begin{aligned}\mathcal{L} &\supset -\int d^4x \frac{1}{2}dC_2 \wedge \star dC_2 + M_a(z)C_2 \wedge F_a + M_b(z)C_2 \wedge F_b + \frac{1}{2}m^2(z)C_2 \wedge \star C_2 \\ &\to -\int d^4x \frac{M_a M_b}{m^2}(z)F_a \wedge \star F_b + \ldots\end{aligned}$$

Stückelberg Mechanism II

- Masses from integrating out closed string spacetime two-forms
- In NS sector, gauge fields only couple to “universal axion” via $F \wedge \star B_2$ - zero mode is projected out
- In R sector, have couplings from *WZ* terms $F \wedge C_2$

Zero modes not projected out are:

- $\tilde{D}_s^\alpha \wedge \omega_\alpha \in H_+^{1,1}(Y)$, couples to gauge flux $F \in H_+^{1,1}(Y)$
- $\tilde{c}_a^2 \wedge \tilde{\omega}^a \in H_-^{2,2}(Y)$, needs brane not invariant under orientifold projection.

Mass:

$$
\begin{aligned}
m^2_{\mathrm{St}\ ab} &= \frac{g_a g_b}{4\pi} M_s^2 \\
&\times \left[G_{cd} \tilde{\Pi}^{cD_1} \tilde{\Pi}^{dD_2} r_{aD_1} r_{bD_2} + G^{\alpha\beta} \Pi_\alpha^{D_1 A} \Pi_\beta^{D_2 B} (p_{aD_1 A} - r_{aD_1} b_{D_1 A})(p_{bD_2 B} - r_{bD_2} b_{D_2 B}) \right]
\end{aligned}
$$

- $G_{cd} \sim \mathcal{V}^{1/3}$, $G^{\alpha\beta} \sim \mathcal{V}^{-1/3}$ for swiss cheese, potentially $G^{\alpha\beta} \sim \mathcal{V}^{-1}$ for $K3$ fibration.
- Metrics and gauge couplings determine size of $U(1)$ masses, suppression relative to string scale
- $1\mathrm{meV}$ possible for TeV scale strings
- GUT scale strings give phenomenologically unappealing values
- To avoid Stückelberg masses, generically require no (global) gauge flux and $[D_h] = [D_h']$
- If $D_h \neq D_h'$ pointwise may have kinetic mixing

Kinetic Mixing vs Massless Photon

Kinetic mixing arises from loop diagram (in open string channel). How can we extract the modulus dependence?

- No contributions from stringy oscillators (enter Kähler potential): only KK and winding modes of closed strings
- Can analyse by inspecting which forms couple:

$$\frac{M_s^2}{g_s \pi}\Big[\int_{\mathrm{D7_{vis}}} F \wedge \star_4 B_2 \wedge \frac{1}{2}\left(J \wedge J - c_1(\mathcal{L})^2\right) + \int_{\mathrm{D7_{vis}}} F \wedge C_2^{(2)} \wedge c_1(\mathcal{L})^2 + \int_{\mathrm{D7_{vis}}} F \wedge D_2^{(4)} \wedge Z_2 \wedge c_1(\mathcal{L}) + \int_{\mathrm{D7_{vis}}} F \wedge E_2^{(6)} \wedge Z_4\Big]$$

- For GUT model and SUSY mixing, only flux dependent parts on visible brane do not cancel; KK modes must "feel" the flux:

$$\int_{D7} Z_2 \wedge c_1(\mathcal{L}) = \int_{\partial\alpha} Z_2 = \int_{\alpha} dZ_2 \neq 0$$

- May be B_2 and $C_2^{(2)}$ couplings to flux on hidden SUSY brane
- Leaves B_2 coupling to $J \wedge J$ on hidden brane, and Z_2

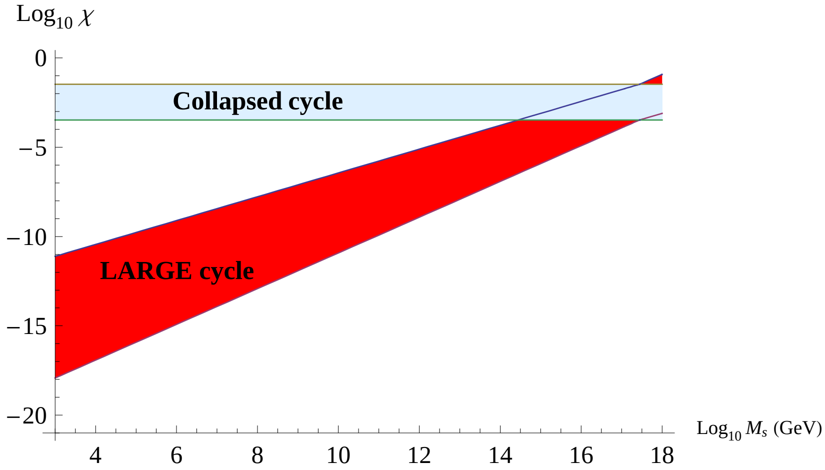
Kinetic Mixing and LARGE Volumes

- Holomorphic kinetic mixing parameter depends only on complex structure and open moduli:

$$\chi^h_{ab} = \chi^{\mathrm{1-loop}}_{ab}(z_i, y_i) + \chi^{\mathrm{non-perturbative}}_{ab}(z_i, e^{-T_j}, y_i)$$

- For separated branes, no light states $\rightarrow$ no volume dependence from Kähler potential
- Fluxes do not break supersymmetry
- Complex structure moduli typically $\mathcal{O}(1)$, or small in warped throats
- Expect typical $\chi^h_{ab} \sim \mathcal{O}(1/16\pi^2)$
- Find $\chi_{ab} \sim g_a g_b/16\pi^2$
- Hyperweak brane leads to mixing $\chi_{ab} \sim 10^{-3}\mathcal{V}^{-1/3}$ (swiss cheese) or $\chi_{ab} \sim 10^{-3}\mathcal{V}^{-1/2}$ ($K3$ fibre)

Kinetic Mixing vs String Scale



Kinetic Mixing with Antibranes

- $\overline{D3}$ branes may be introduced to uplift to dS vacuum
- Support massless $U(1)$s (unless there is a hidden higgs) since relevant axions are projected out by orientifold
- Will mix kinetically with hypercharge, with volume suppression (no longer protection by SUSY)
- Mixing with bulk branes

$$\chi \sim \frac{g_a g_b}{(16\pi^2)}$$

- Mixing with collapsed or D3 branes:

$$\chi \sim \frac{g_a g_b}{(16\pi^2)} \frac{f(t^i)}{\mathcal{V}}$$

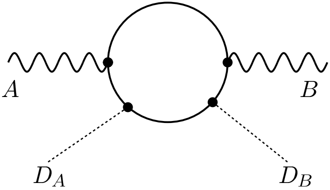
- $f(t^i) \propto t^i$ as $t^i \to \infty$, depends which KK modes of B_2, C_2 couple to $\overline{D3}$
- B_2, C_2 couple with same sign for antibranes
- Mixing with $U(1)$ from GUT brane not pointwise invariant under orientifold will always be present, since flux $\int c_1(\mathcal{L})^2$ is globally felt

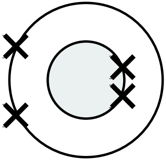
Kinetic Mixing with ~~SUSY~~

- If mixing cancels, may still be induced by SUSY breaking effects
- Look for operators at one loop:

$$\Delta\mathcal{L} \supset \int d^4\theta\, W^a W^b \left(\frac{\Xi + \overline{\Xi}}{M^2} + \frac{D^2(\overline{\Xi} + \Xi)^2}{M^4} c.c. \right) + W^a W^b \frac{\overline{W^c}\,\overline{W^c}}{M^4},$$

- Can show that first and second are zero if SUSY kinetic mixing cancels
- Second has different gauge structure, but non-zero only for hypercharge D term $W^3 W'$
- Find (from toroidal calculation) $M^{-4} \approx (4\pi^5 M_s^4)^{-1}\mathcal{V}^{-2/3} \sim (M_s R)^{-4}$:

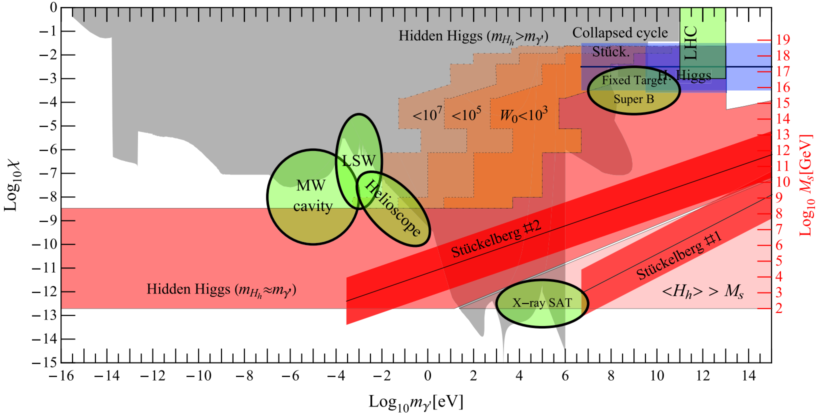




$$\chi_{Y\gamma'} \sim \frac{g_Y^2}{4} \frac{f(t^i)}{\mathcal{V}} \frac{g_{\gamma'} g_Y}{4\pi^5} \left(\frac{v}{M_s}\right)^4 \cos^2 2\beta$$

- $M_s \sim 10^{15} GeV$ have $\chi \sim \chi \sim 10^{-59}$, $M_s \sim 1 TeV$ find 10^{-27}.
- Mixing with hidden D-term 10^{-33}, 10^{-25} respectively $\rightarrow$ maybe good dark matter candidate

Predictions



Hidden KK Modes

- For large hidden dimensions may detect KK modes of hidden gauge boson in beam dump experiments $\rightarrow$ effectively have massive hidden gauge bosons even though gauge group unbroken!
- Visible sector wraps small cycle $\rightarrow$ does not have KK modes
- In swiss cheese model, TeV strings ($\mathcal{V} \sim 10^{30}$) give masses $\mathcal{O}(10)\,\mathrm{MeV}$ and mixing $\chi \sim 10^{-12}$
- Beam dumps sensitive up to $\mathcal{O}(100)\,\mathrm{MeV}$ at $\chi \sim 10^{-7}$, but now have lots of KK modes!
- $\chi_{eff} \propto \chi \times \sqrt{N_K K}$
- For swiss cheese with TeV strings, $\chi_{eff} \sim 10^{-10} \rightarrow$ may be accessible with increased luminosity
- Actually can get much more realistic values if we allow for one large dimension...

Calculating Mixing in Warped Compactifications

- Consider $\langle A^a_\mu A^b_\nu \rangle$ in 10d SUGRA
- $D3$ mixing, only $B^{(4)}_{\mu\nu}$, $C^{(4)}_{\mu\nu}$ components contribute
- Vertices $2\pi\alpha' \mu_p g_p p_\alpha \lambda_\mu \delta(\Sigma_p)$ for B
- Propagator

$$G(y_0, y_1) = \frac{2\kappa_{10}^2}{V_6} \sum_{p_6} \frac{\exp\left[i p_6 \cdot (y_1 - y_0)\right]}{|p_4|^2 + |p_6|^2}$$

- obtain

$$\frac{1}{\alpha'} \frac{(2\pi\alpha')^3}{V_6} (2\pi\alpha')^{p-3} V_{Dp_a} V_{Dp_b} A^a_\mu A^{b\,\mu}$$
$$+ F^{(a)}_{\mu\nu} F^{(b)\mu\nu} \int dy_0^{p_a} dy_1^{p_b} \frac{(2\pi\alpha')^3}{V_6} (2\pi\alpha')^{p-3} \sum_{p_6 \neq 0} \frac{\exp\left[i p_6 \cdot (y_1 - y_0)\right]}{|p_6|^2}$$

Dimensional Reduction

Consider vevs for flux components $B^{(6)}_{\mu\nu}, C^{(6)}_{\mu\nu}$:

$$S \supset -\frac{1}{4\kappa_{10}^2}\int d^{10}x(-\det G)^{1/2}\left(|F_1|^2 + |\tilde{F}_3|^2 + \frac{1}{2}|\tilde{F}_5|^2\right) - \frac{1}{4\kappa_{10}^2}\int d^{10}x(-\det G)^{1/2}e^{-2\Phi}|H_3|^2$$

Term $|\tilde{F}_5|^2 = |F_5 - \frac{1}{2}C_2 \wedge H_3 + \frac{1}{2}B_2 \wedge F_3|^2$ generates mass for $B^{(4)}_{\mu\nu}, C^{(4)}_{\mu\nu}$!
$\rightarrow$ suggests we model as a massive scalar

Flux Masses

- Effective action for component of $C^{(6)}_{\mu\nu}$:

$$\mathcal{L} = \frac{e^{-2A}\sqrt{g}}{2\kappa_{10}^2}\left[g^{mn}\partial_m\phi\partial_n\phi + \frac{1}{8}|B_2^{(6)} \wedge d^{(6)}\phi|^2 + \frac{1}{8}|H_3^{(6)}|^2\phi^2\right],$$

- Estimate

$$H_3, F_3 \sim n l_s^2 / V_3,$$

- Probe distances $\mathcal{O}(V_3/n l_s^2)$

Randall-Sundrum Models

Metric

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu + \mathrm{d}y^2$$

Propose "string inspired" Lagrangian

$$\mathcal{L}_{\mathrm{bulk}} = \frac{M_5^3}{2g^4}\int \frac{-1}{2}\mathrm{d}B \wedge *_5 \mathrm{d}B + \frac{1}{2}m^2 B \wedge *_5 B$$

and

$$\mathcal{L}_{\mathrm{D3}} = \frac{1}{4g^2}\int_{\mathrm{D3}} \frac{1}{2\pi\alpha'}F \wedge *_4 B + \frac{1}{(2\pi\alpha')^2}B \wedge *_4 B$$

EOMs:

$$\left[e^{2k|y|}\eta^{\alpha\beta}\partial_\alpha\partial_\beta + \partial_5\partial_5 - m^2\right]B^{(4)}_{\mu\nu} = 0$$

Boundary conditions:

$$\partial_y B^{(4)}_{\mu\nu} - \frac{M_s^4}{M_5^3}B^{(4)}_{\mu\nu}|_{y=0,\pi R} = 0$$

Green Functions

Green functions for various types of fields calculated in [Gherghetta, Pomerol, 2000]

$$
\begin{aligned}
G_p(z,z') \quad &= \quad i\frac{\pi}{2}k^{s-1}(zz')^{s/2}\left[\frac{\widetilde{J}_\alpha(ipe^{\pi kR}/k)H_\alpha^{(1)}(ipz_>)-\widetilde{H}_\alpha^{(1)}(ipe^{\pi kR}/k)J_\alpha(ipz_>)}{\widetilde{J}_\alpha(ipe^{\pi kR}/k)\widetilde{H}_\alpha^{(1)}(ip/k)-\widetilde{H}_\alpha^{(1)}(ipe^{\pi kR}/k)\widetilde{J}_\alpha(ip/k)}\right] \\
&\times\left[\widetilde{J}_\alpha(ip/k)H_\alpha^{(1)}(ipz_<)-\widetilde{H}_\alpha^{(1)}(ip/k)J_\alpha(ipz_<)\right] \ ,
\end{aligned}
$$

Have a simplified version: for branes at y_0, y_1 with equation

$$\partial_y(f(y)\partial_y G(y,y')) - h(y)G(y,y') = k(y)\delta(y-y')$$

obtain

$$G(y_0,y_1) = \frac{k}{2f}(y_1)\frac{\tilde{G}_<(y_0)}{\tilde{G}'_<(y_1) - \frac{M_s^4}{M_5^3}\tilde{G}_<(y_1)}$$

Independent of choice of initial conditions!

Green Functions II

- For Randall-Sundrum B-field, get kinetic mixing

$$\chi = g_a g_b \frac{32 M_s^4}{M_5^3 m} \frac{1}{\sinh m\pi R} \frac{1}{\left(1 - \frac{M_s^8}{M_5^6 m^2}\right)}.$$

- Tempting to identify M_5 with M from RS, where $e^{-k\pi R} = M_{SUSY}/M_{Plank}$, $M_{pl}^2 \approx M^3/k$. Take $M_s = \sqrt{M_{\rm SUSY} M_{\rm Pl}}$. Get

$$\chi \approx g_a g_b \frac{32}{37} \times \frac{M_{\rm SUSY}^2 \pi R}{m} \frac{1}{\sinh \pi m R}$$

- $$\chi \sim g_a g_b \times \frac{M_{\rm SUSY}^2}{m^2}.$$

- Need $m \sim 10^4 M_{\rm SUSY} \rightarrow$ flux wrapping cycles $\mathcal{O}(10^2 l_s)$

Klebanov-Tseytlin Throat

- In KKLT Scenario, have throat regions with branes at end
- KT throat is toy model of this
- Metric is a cone

$$ds^2 = h^{-1/2}(r)\eta_{\mu\nu}dx^\mu dx^\nu + h^{1/2}(r)(dr^2 + r^2 ds_M^2)$$

$$\begin{aligned} h(r) &= \frac{81(g_s M\alpha')^2 \log r/r_s}{8r^4} \\ &= \frac{27(\alpha')^2(2g_s N + 3(g_s M)^2 \log(r/r_0) + 3(g_s M)^2/4)}{8r^4}, \end{aligned}$$

- and

$$ds_M^2 = ds_{T^{1,1}}^2 = \frac{1}{9}\left(d\psi + \sum_{i=1}^{2}\cos\theta_i d\phi_i\right)^2 + \frac{1}{6}\sum_{i=1}^{2}\left(d\theta_i^2 + \sin\theta_i d\phi_i^2\right)$$

Kinetic Mixing and the Klebanov-Tseytlin Throat II

- Integrate out radial modes: one-dimensional Problem

$$S = \frac{1}{4 g_s \kappa_{10}^2} \int d^4 x \partial_r \phi \partial_r \phi (|dr|^2 + \frac{1}{8} |B_2^{(6)} \wedge dr|^2) + \frac{1}{8} \phi^2 |H_3^{(6)}|^2 .$$

- Using the variable $y = \log r/r_s$, we then have

$$S = \frac{3\pi^3 (M\alpha')^2 g_s}{4\kappa_{10}^2} \int d^4 x dy \; \partial_y \phi \partial_y \phi (2y + (y - y_0)^2) + \phi^2.$$

- Very similar to RS action with

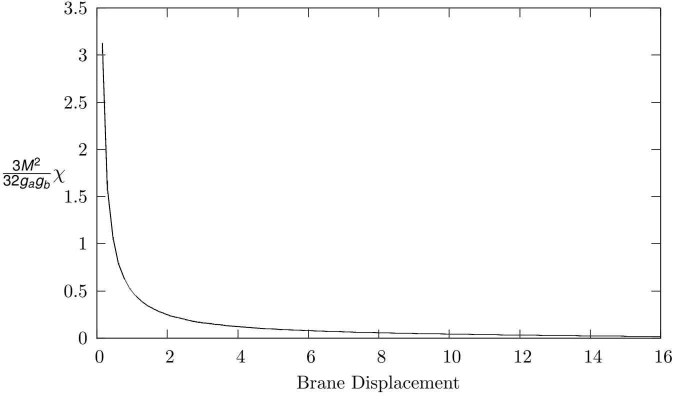
$$\frac{M_5^3}{g^2} = \frac{3\pi^3 (M\alpha')^2 g_s}{\kappa_{10}^2} y_0^{-2}$$

Numerical Solution

Find

$$\chi_{ab} = g_a g_b \frac{32}{3M^2} \frac{1}{4y_1 + 2(y_1 - y_0)^2} \frac{\tilde{G}_<(y_s)}{\tilde{G}'_<(y_1)}$$

Solve numerically:



Conclusions

- Hidden $U(1)$s can arise in different ways in different corners of string theory
- String models do make predictions for the values of kinetic mixing, gauge boson mass and hidden gaugino mass!
- May learn about hidden sector of string theory not just at LHC, but also low energy experiments such as at DESY!

Future Work

- Lots of possible model building!
- Can we see the R-R U(1)s?
- Extend to F-theory
- Calculation of holomorphic kinetic mixing in D-brane models