Light $U(1)$s in String Compactifications

Based on JHEP **0807** (2008) 124 [arXiv:0803.1449 [hep-ph]], in collaboration with S. Abel, J. Jaeckel, V. Khoze and A. Ringwald;
and 0907.xxxx, in collaboration with J. Jaeckel, J. Redondo and A. Ringwald.

Mark D. Goodsell

Laboratoire de Physique Théorique et Hautes Energies,
Université Paris 6

15th July, 2009

Overview

- Motivation for hidden $U(1)$s from string theory
- Kinetic and mass mixing in string D-brane models
- Results for the LARGE volume scenario
- Hidden Higgs
- Dirac gaugino masses

Motivation

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

→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
- Masses suppressed relative to M_s by volume factors

→expect to have light or massless $U(1)$

Stückelberg Mechanism

- Set of axions a^i coupling to gauge fields A^i_μ:

$$\mathcal{L} \supset -\int d^4x G_{ij} \frac{1}{2} \partial_\mu a^i \partial^\nu a^j + M_{ij} \partial^\mu a^i A^j_\mu$$

- Generates mass for $U(1)$s:

$$\mathcal{L} \supset -\int d^4x \frac{1}{2} (G^{kl} M_{ki} M_{lj}) A^i_\mu A^{j\,\mu}$$

- Axion becomes longitudinal component of gauge boson

Stückelberg Mechanism for Strings

- In string theory, axions may be from two-forms, Poincaré dual to scalars
- In NS sector, gauge fields only couple to "universal axion" B_2:

$$S_{DBI} = -\frac{1}{4}\mu_p \int d^{p+1}x e^{-\Phi}\sqrt{-g}\Big((2\pi\alpha')^2 F_{\mu\nu}F^{\mu\nu} + B_{\mu\nu}B^{\mu\nu} + \ldots + 2(2\pi\alpha')F_{\mu\nu}B^{\mu\nu}\Big)$$

- In R sector, have couplings from *WZ* terms:

$$S_{WZ} = \mu_p \int_{Dp} \sum_q C_q \wedge tr\,\exp(2\pi\alpha' F + B) \wedge \sqrt{\frac{\hat{A}(4\pi^2\alpha' R_T)}{\hat{A}(4\pi^2\alpha' R_N)}}$$

- Part responsible for mass comes from zero mode of field propagating in ten-dimensions

Stückelberg Mechanism for Strings II

- Consider $\langle A^a_\mu A^b_\nu \rangle$ in 10d SUGRA
- Vertices $2\pi\alpha' \mu_p g_p p_\alpha \lambda_\mu \delta(\Sigma_p)$ for B
- Propagator

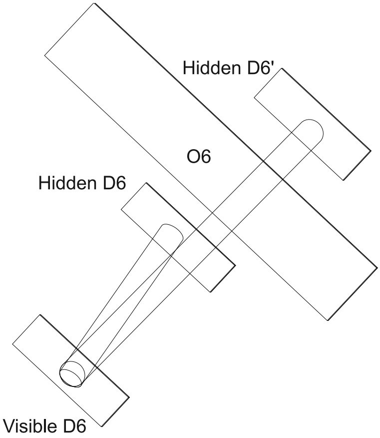
$$G(y_0, y_1) = \frac{2\kappa_{10}^2}{V_6} \sum_{p_6} \frac{\exp\left[i p_6 \cdot (y_1 - y_0)\right]}{|p_4|^2 + |p_6|^2}$$

- obtain

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

- NB zero mode of B-field is cancelled by orientifold projection
- Kinetic mixing depends on more than homology data: depends on representative of homology class of branes

Stückelberg Mechanism for Strings III



Exact Kinetic Mixing Functions

- For supersymmetric configurations, kinetic mixing is a <u>holomorphic</u> 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
- In fact, can show that it obeys a Kaplunovsky-Louis type formula

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

The LARGE Volume Scenario

→ cf Joe Conlon's talk

- In type IIB string theory, (MS)SM realised on $D7$ branes on collapsed cycles $\tau_a \sim 0$
- Complex structure moduli stabilised at SUSY value, gives superpotential contribution W_0
- Volume of Calabi-Yau in form

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

- Need small cycle $\tau_s > l_s^4$
- → Instanton/gaugino condensate generate contribution to superpotential $W \supset Ae^{a\tau_s}$
- One loop Kähler potential $K \supset -2\log\left[\Re(\tau_b)^{3/2} + \xi/2\right]$
- Volume, τ_b stabilised at exponentially large value
- τ_b provides potential hyperweak U(1) with $g \sim g_{YM}\mathcal{V}^{-1/3}$ [Burgess, Conlon, Hung, Kom, Maharana, Quevedo 2008]
- AdS vacuum with ~~SUSY~~, small uplift provided by anti-branes

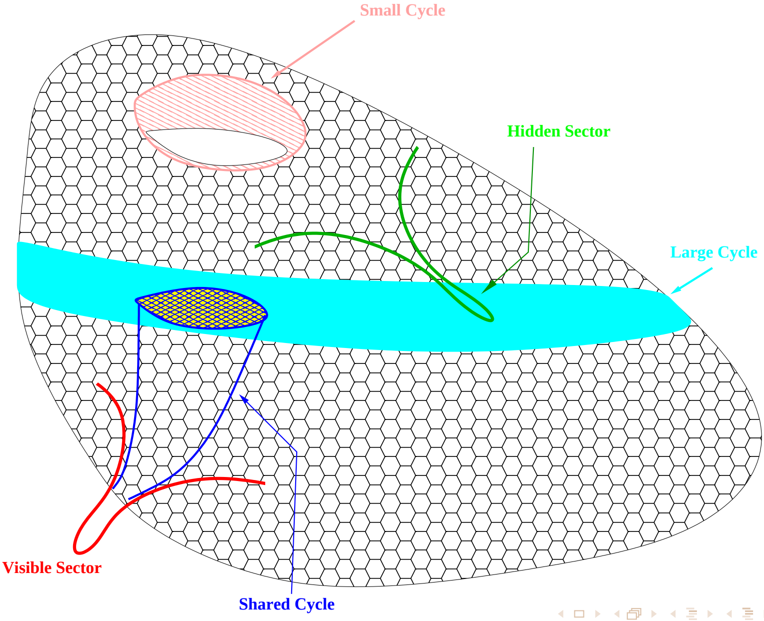
Kinetic Mixing in LARGE Volume models

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

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

- 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 $\chi_{ab} \sim g_a g_b / 16\pi^2$

Scenario


Small Cycle
Hidden Sector
Large Cycle
Visible Sector
Shared Cycle

Mass Mixing

- Coupling by *WZ* terms to two-forms on CY:

$$M_{\alpha\beta} = M_s \left[\int_{\alpha_A \subset D_1} \omega_\alpha \right] \left[\int_{\alpha_A \subset D_1} c_1(\mathcal{L}) - \int_{\alpha_A \subset D_1} B_+ \right]$$

- and four-forms:

$$M^{ab} = M_s r_c \int_{D_1} \tilde{\omega}^c$$

- Different Kähler metrics give scaling

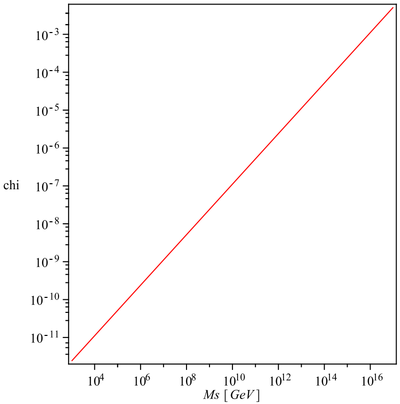
$$G^{\alpha\beta} \sim \mathcal{V}^{-1/3}, \qquad G_{ab} \sim \mathcal{V}^{1/3}$$

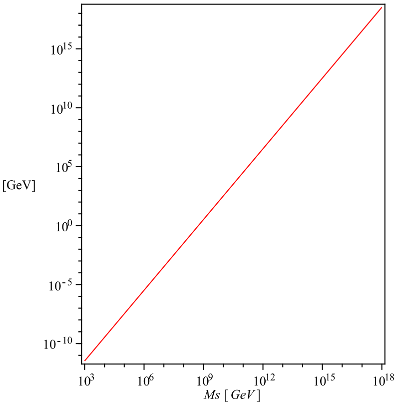
- For hyperweak gauge boson, gives

$$m_{cc}^2 \sim \frac{g_s}{2} \frac{M_s^2}{\mathcal{V}^{1/3}}, \qquad m_{\alpha\alpha}^2 \sim \frac{g_s}{2} \frac{M_s^2}{\mathcal{V}}$$

- May have masses as small as $\sim 10 meV$ for *TeV* strings!

Mixing and Mass Values





Kinetic Mixing vs Massless Photon

- If we have separated branes in same homology class, can cancel mass without cancelling kinetic mixing
- Can cancel mixing by brane on top of orientifold, invariant under orientifold action
- Alternative: local GUT model, gauge group broken by vevs of $c_1(\mathcal{L})$ on $SU(5)$ stack, e.g. $\mathrm{diag}(2,2,2,-3,-3)\times\omega_2$, or $\mathrm{diag}(1,1,1,1,1)\omega_1+\mathrm{diag}(0,0,0,1,1)\omega_2$ for ω_2 trivial on CY
- Requires base divisor not invariant under orientifold (i.e. need $b_-^{1,1}\neq 0$) or additional flux in $h_+^{1,1}$ non-trivial in CY, as need to make diagonal $U(1)$ massive
- C_6 (four-form on CY) contribution cancels due to tracelessness
- B_2 contribution actually cancels due to tracelessness and C_2 contribution
- Zero mode of C_4 (two form on CY) does not couple to flux due to triviality of cycle, but higher KK modes may

Kinetic Mixing with ~~SUSY~~

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

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

- Can show that first and third are zero if SUSY kinetic mixing cancels
- Second has different gauge structure, but non-zero only for hypercharge D term
- Find

$$\chi_{ab}(v) \sim \frac{g_a g_b}{16\pi^2} \left(\frac{v}{M_s}\right)^4 \cos^2 2\beta$$

- $M_s \sim 10^{15} GeV$ have $\chi \sim 10^{-52} \frac{g_a g_b}{16\pi^2}$
- $M_s \sim 1\, TeV$ find $\chi \sim 10^{-3} \frac{g_a g_b}{16\pi^2}$.

Hidden Higgs

Want a very light (but not massless) $U(1)$ without TeV scale strings. Either

- Fermion condensates (too large)
- Hidden Higgs

Two types:

- Vector-like pair: only charged under one gauge group. Non-local behaviour
- Chiral pair: extra gauge group necessary, local $\rightarrow$ EW scale Higgs mass

GeV Hidden Sector

- [Morrisey, Poland, Zurek 09] If we have $\chi \sim 10^{-3}, 10^{-4}$ hypercharge D term gives an FI term

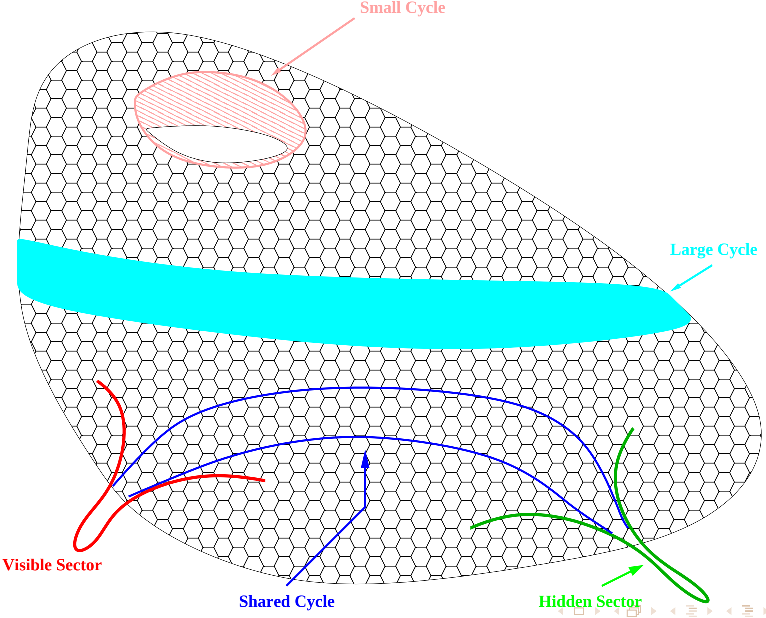
$$\xi = \chi_{ab} \frac{g_Y}{2} c_{2\beta} v^2$$

- Causes breaking of hidden gauge group, and gives

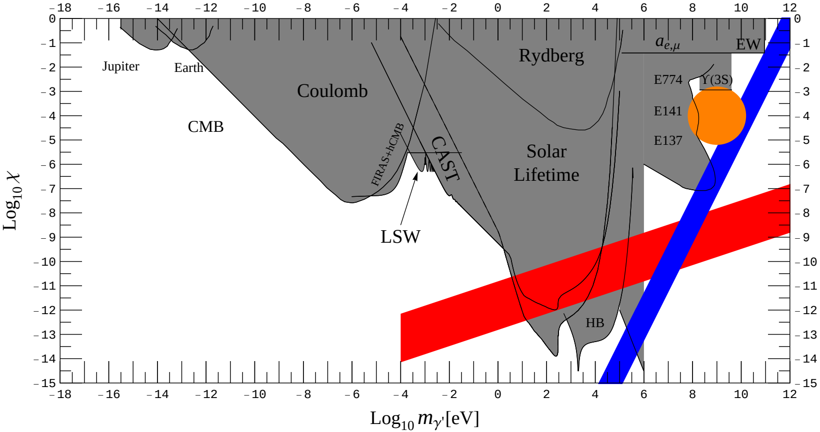
$$m_{\gamma'} \sim 1 GeV$$

- Naturally realised if $g_b \sim g_Y$ - i.e. hidden sector at collapsed cycle

GeV Hidden Sector



Predictions



Dirac Gauginos

work with K. Benakli

- Kinetic mixing can be used to calculate leading gaugino masses in field theory
- From F-terms:

$$-\frac{1}{2}\int d^2\theta W^{a\,\alpha} W^b_\alpha \partial_S \chi_h(S) F_S$$

- And D-terms:

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

- Gives a gauge mediation expression

$$m_D = \frac{D'}{\sqrt{2}}\frac{gg'}{16\pi^2}\partial_{X^I}\mathrm{tr}\left(Q' R(T^I)\log \mathcal{M}^2/\mu^2\right)\Big|_{X^I=0}$$

- If moduli develop F-terms, kinetic mixing gives Dirac gaugino masses
- Not the case in LARGE volume scenario; complex structure moduli do not develop vevs

Conclusions

- Described how to determine kinetic and mass mixing in string models with D-branes
- Kaplunovsky-Louis type formula
- Conditions for light U(1)s and small masses
- ~~*SUSY*~~ kinetic mixing terms
- Showed LARGE volume scenario is fertile territory for light U(1) mixing
- Dirac gaugino masses

Future Work

- Z' type models
- Model building
- F-theory
- Application to Dark Matter...