Theory and phenomenology of hidden U(1)s from string compactifications

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- Mainly based on:
  - S. A. Abel, J. Jaeckel, V. V. Khoze, AR,
    "Illuminating the hidden sector of string theory by shining light through a magnetic field,"
    Phys. Lett. B **666** (2008) 66 [arXiv:hep-ph/0608248]
  - S. A. Abel, M. D. Goodsell, J. Jaeckel, V. V. Khoze, AR,
    "Kinetic Mixing of the Photon with Hidden U(1)s in String Phenomenology,"
    JHEP **0807** (2008) 124 [arXiv:0803.1449 [hep-ph]]
  - M. Goodsell, J. Jaeckel, J. Redondo, AR,
    "Naturally Light Hidden Photons in LARGE Volume String Compactifications,"
    arXiv:0909.0515 [hep-ph]

Table of Content:

1. Introduction

- Embeddings of the standard model in string theory typically contain several hidden sector U(1) gauge factors, e.g. ⇒ e.g. lectures by [Antoniadis; Dudas; Lüst]
  - in orbifold compactifications of heterotic string theory:

    ⇒ e.g. talks by [Ramos-Sanchez; Vaudrevange]

    e.g.

$$\mathrm{E}_8 \times \mathrm{E}_8 \to \mathrm{G}_{\mathrm{SM}} \times \mathrm{U}(1)^4 \times \left[\mathrm{SU}(4) \times \mathrm{SU}(2) \times \mathrm{U}(1)^4\right]$$

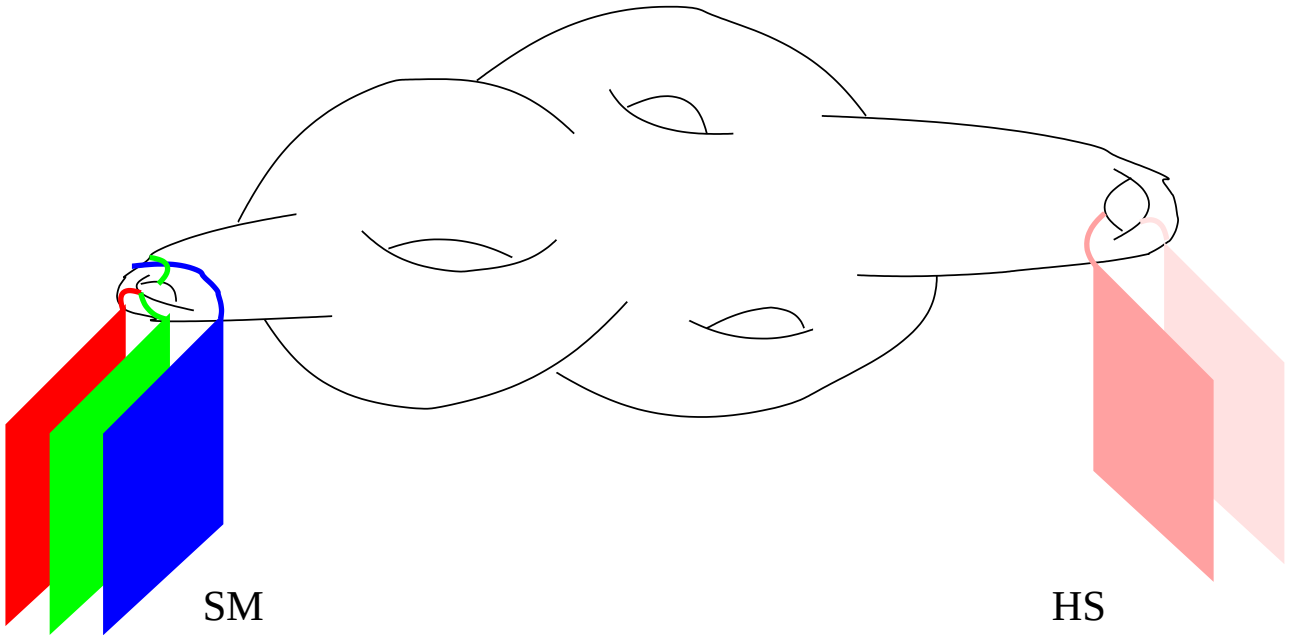
    or

$$\mathrm{E}_8 \times \mathrm{E}_8 \to \mathrm{G}_{\mathrm{SM}} \times \mathrm{U}(1)^4 \times \left[\mathrm{SO}(8) \times \mathrm{SU}(2) \times \mathrm{U}(1)^3\right]$$

1. Introduction

- Embeddings of the standard model in string theory typically contain several hidden sector U(1) gauge factors, e.g. ⇒ e.g. lectures by [Antoniadis; Dudas; Lüst]
  - in type II string theory with branes:

⇒ e.g. lecture by [Bachas]



- Generically mix with visible U(1), i.e. low energy effective Lagrangian

$$\mathcal{L} \supset -\frac{1}{4g_a^2}F^{(a)}_{\mu\nu}F^{\mu\nu}_{(a)} - \frac{1}{4g_b^2}F^{(b)}_{\mu\nu}F^{\mu\nu}_{(b)} + \frac{\chi_{ab}}{2g_a g_b}F^{(a)}_{\mu\nu}F^{(b)\mu\nu} + \frac{m^2_{ab}}{g_a g_b}A^{(a)}_{\mu}A^{(b)\mu}$$

- Kinetic and mass mixing terms, χ_{ab} and m^2_{ab}, provide a unique window to hidden sectors

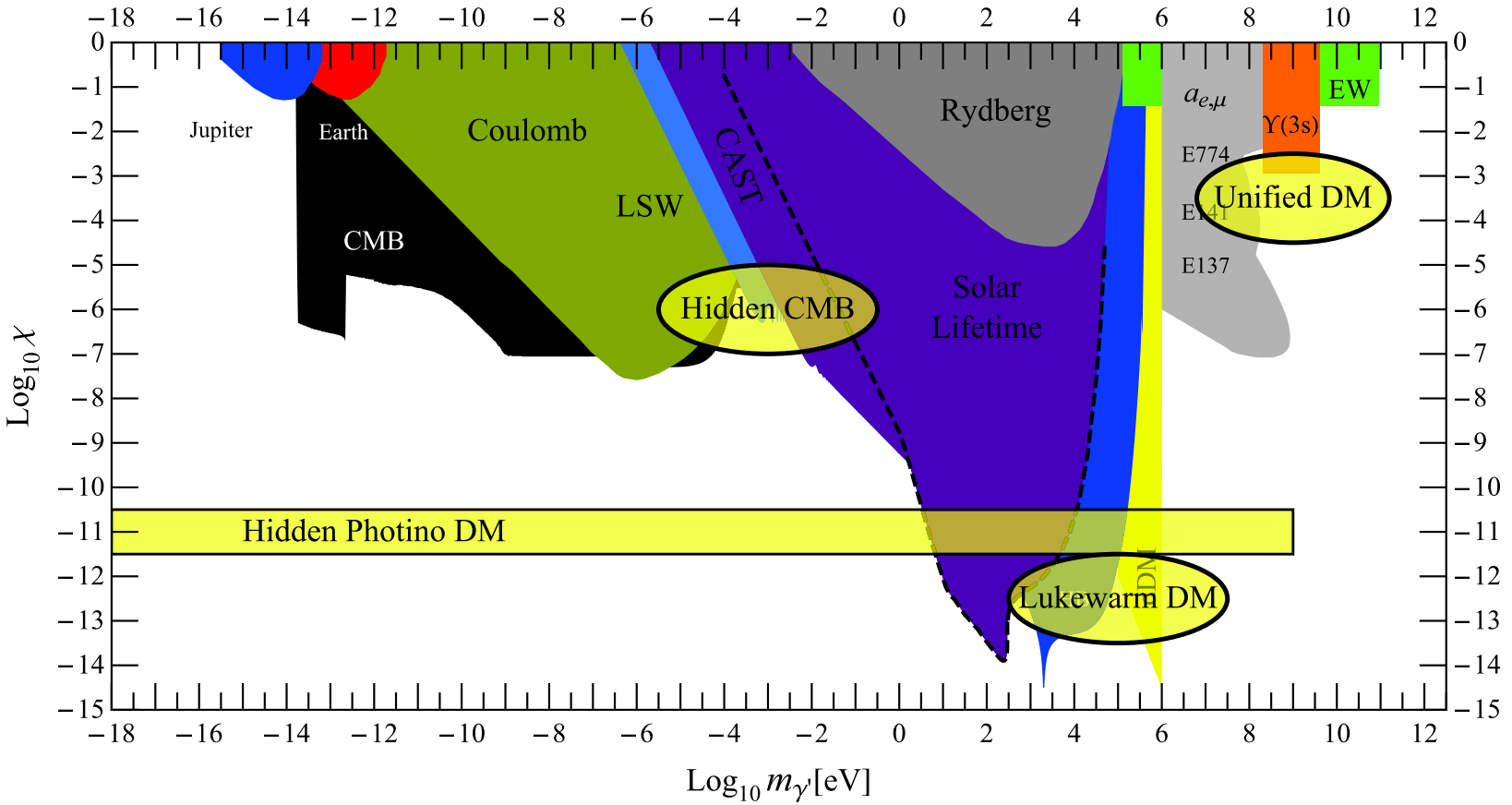
- Phenomenology (very strong limits on photon mass) requires structure:

$$\chi = \begin{pmatrix} 0 & \chi \\ \chi & 0 \end{pmatrix}; \qquad m^2 \approx \begin{pmatrix} 0 & 0 \\ 0 & m^2_{\gamma'} \end{pmatrix}$$

$\Rightarrow$ Massless photon and massive U(1) (hidden photon), with mass squared $m^2_{\gamma'}/\sqrt{1-\chi^2}$

- Rich phenomenology of hidden photons:

[Bartlett,..'88; Kumar,..'06; Coriano,...'07; Ahlers,..'07; Jaeckel,..'07; Redondo,..'08; ...; Bjorken,.. '09, ...]



- meV scale hidden photon results in hidden CMB; may explain $N_\nu^{\rm eff} > 3$, as favored from some analyses of CMB + large scale structure if Ly-α data is included; can be checked in light-shining-through-wall experiments

  [Jaeckel,Redondo,AR '08]

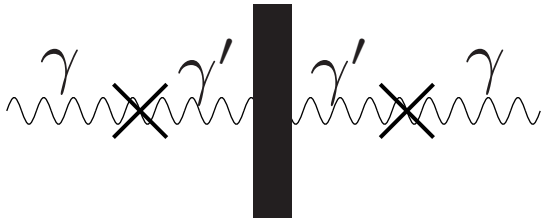
- For $(\chi, m_{\gamma'}) \sim (10^{-12}, 0.1\ {\rm MeV})$ the hidden photon is a lukewarm dark matter candidate [Pospelov,Ritz,Voloshin '07; Redondo,Postma '08]

- EW scale hidden photino of light hidden U(1) may be cold dark matter if $\chi \sim 10^{-11}$ [Ibarra,AR,Weniger '09]
  If $\chi \sim 10^{-23}$, TeV scale hidden photino is candidate for decaying dark matter. May explain cosmic ray positron excess observed by PAMELA

  [...; Shirai,Takahashi,Yanagida; Ibarra,AR,Tran,Weniger '09]

- Region $(\chi, m_{\gamma'}) \sim (10^{-4}, {\rm GeV})$ favored by Unified Dark Matter scenario: unified description of PAMELA excess and annual modulation signal seen by direct DM search experiment DAMA ... Hidden sector dark matter; hidden U(1) mediates Dark Force [Arkani-Hamed *et al.* '08;...]

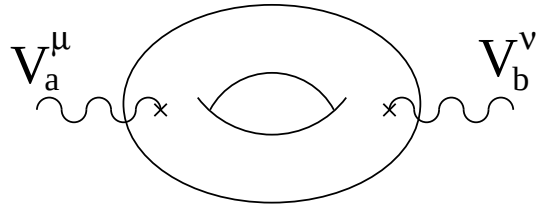
Light Shining through a Wall (LSW):



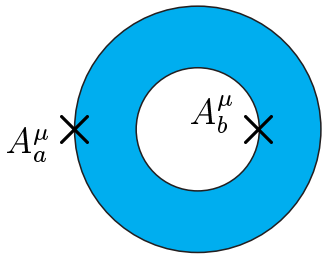
Any **L**ight **P**article **S**earch **(ALPS)** at DESY:

2. Hidden U(1)s in LARGE volume string compactifications

- First studies of kinetic mixing in string compactifications:
  - Heterotic string: [Dienes,Kolda,March-Russell '97; Lukas,Stelle '99; Blumenhagen,Honecker,Weigand '05]



  - Type II strings with D-branes: [Lüst,Stieberger '03; Abel,Schofield '03; Berg,Haack,Körs '04]



- First studies of mass mixing in type I/II strings with D-branes:

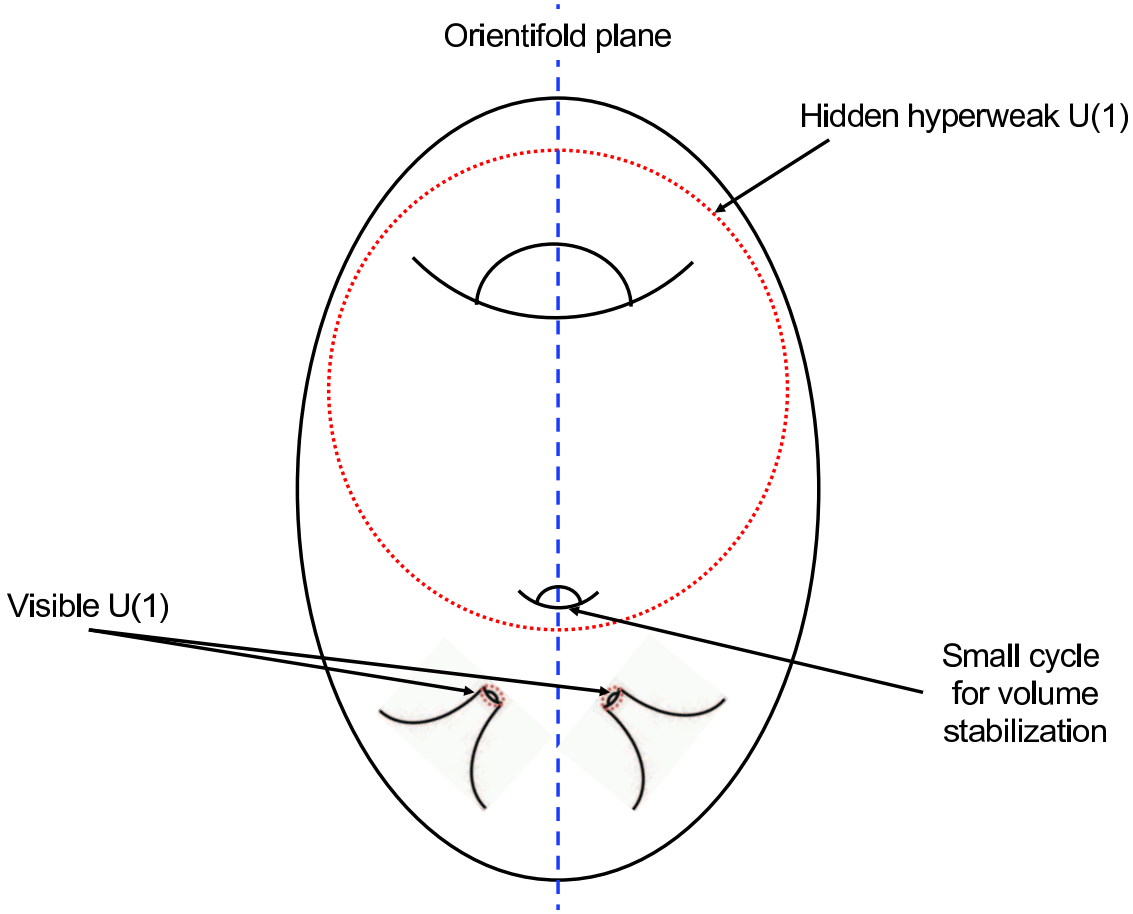
  [Antoniadis,Kiritsis,Rizos '02; Ghilencea,Ibanez,Irges,Quevedo '02; ...; Buican,Malyshev,Morrison,Verlinde,Wijnholt '06]

LARGE volumes and hyperweak interactions

- Based on IIB strings with D3 and D7 branes
  - Visible sector on stack of space-time filling D-branes wrapping collapsed cycles
  - Gravity propagates in bulk of volume $V/l_s^6 \equiv \mathcal{V}$

$$M_P^2 = \frac{4\pi}{g_s^2}\mathcal{V}M_s^2$$

$M_s = 10^{16}\,\text{GeV}$, for $\mathcal{V} \sim 100$
$M_s = 10^{10}\,\text{GeV}$, for $\mathcal{V} \sim 10^{14}$
$M_s = 10^{3}\,\text{GeV}$, for $\mathcal{V} \sim 10^{28}$



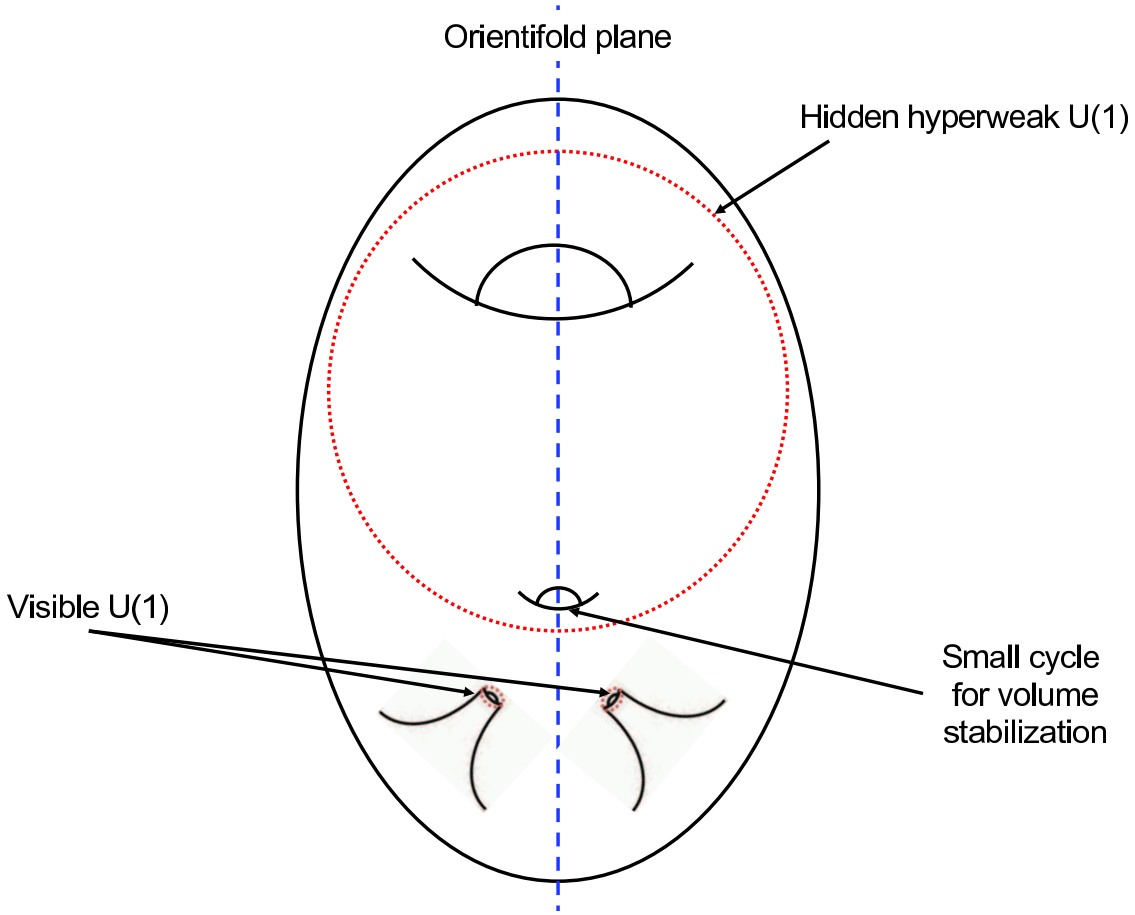
[...;Conlon,Maharana,Quevedo '08;...]

LARGE volumes and hyperweak interactions

- Visible sector on stack of space-time filling D-branes wrapping collapsed cycles

- Hidden U(1)s: located on space-time filling D-branes not intersecting with visible branes

  1. D7 wraps LARGE cycle



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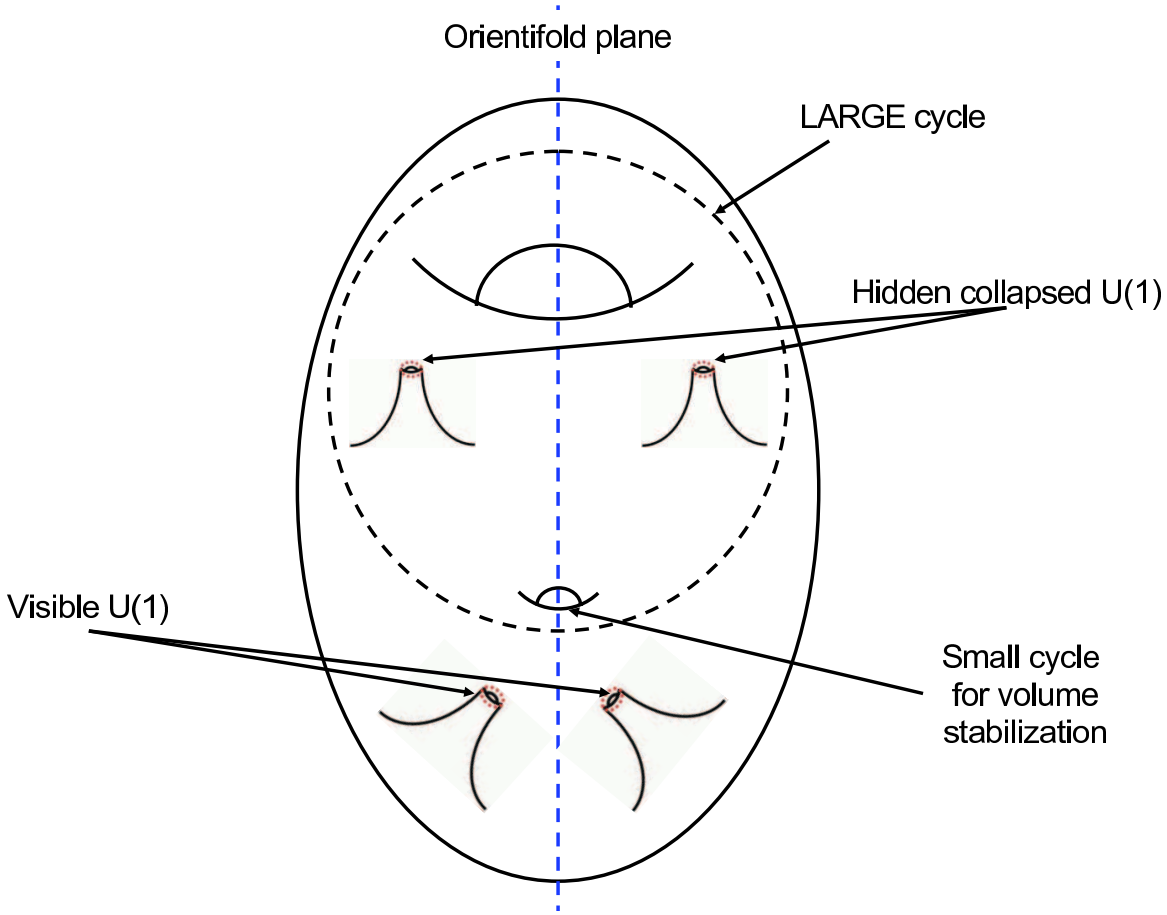

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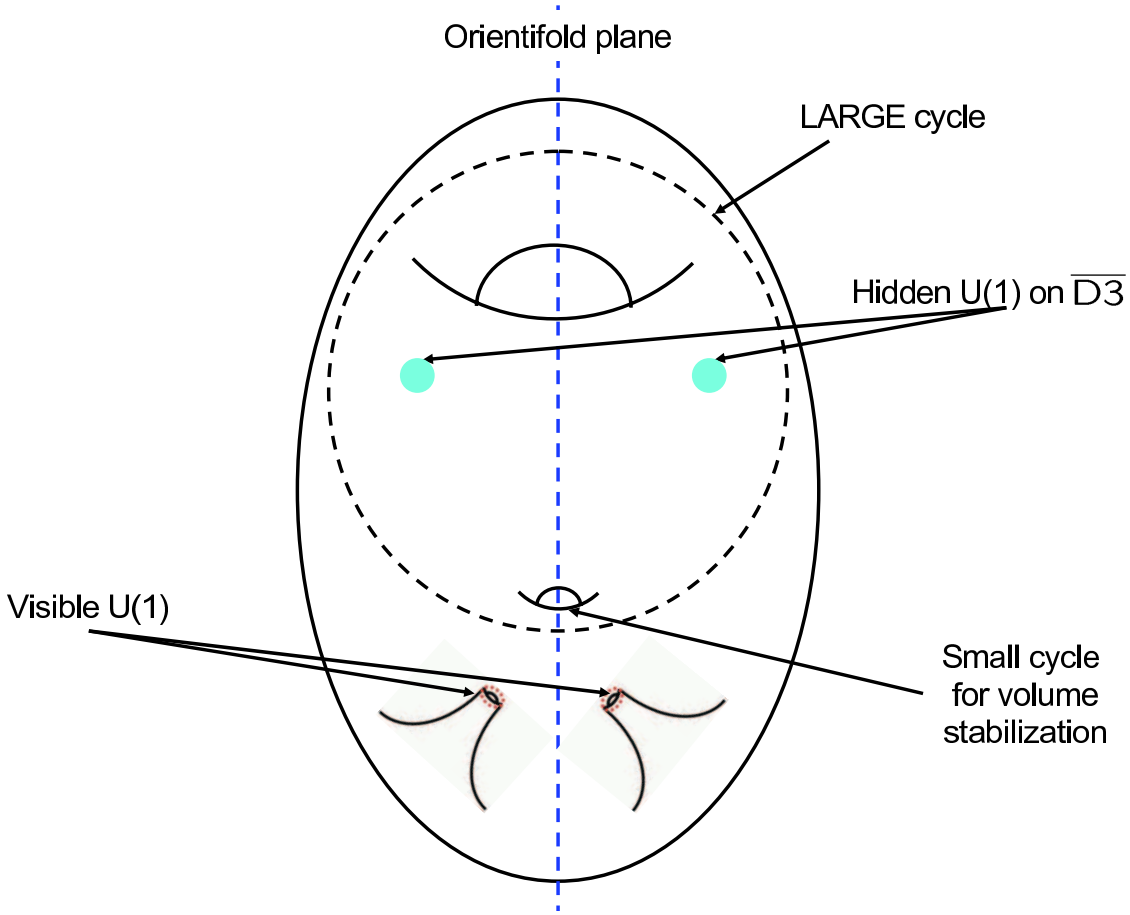
  2. D7 wraps collapsed cycle
  3. anti D3



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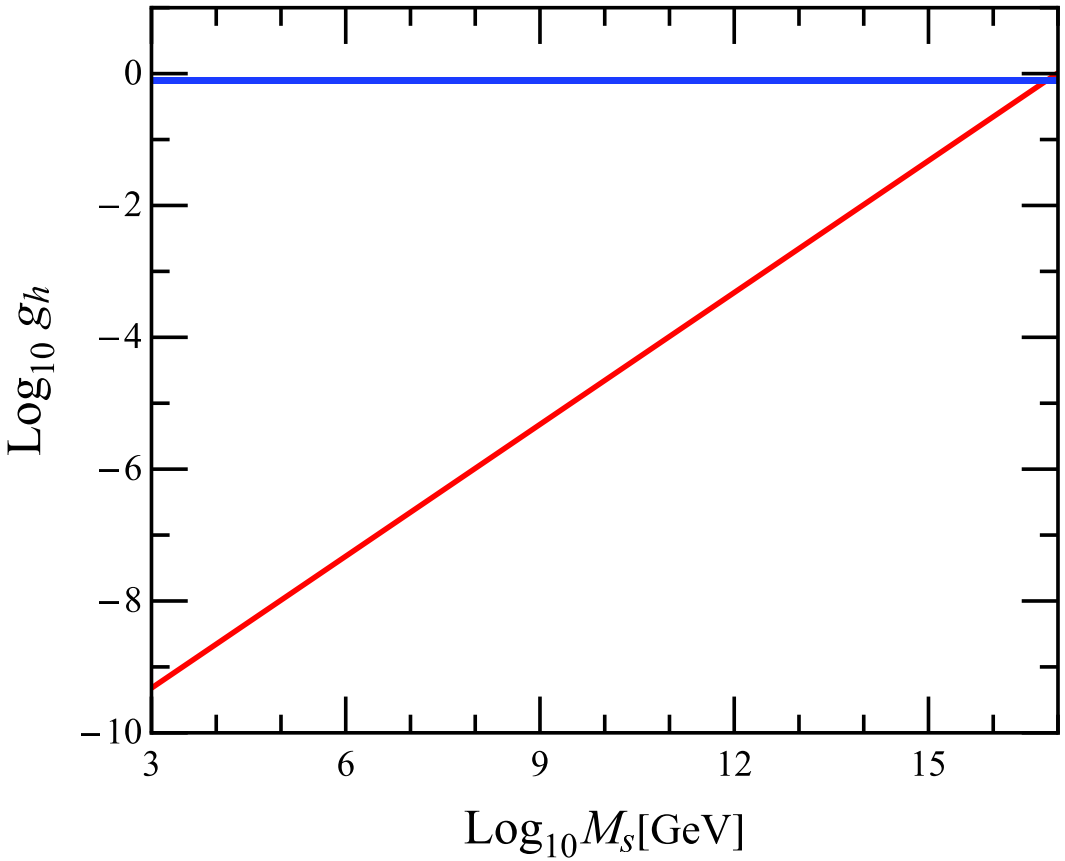
  2. D7 wraps collapsed cycle
  3. anti D3

  D$(3+q)$-brane:

$$g^2_{(q)} = \frac{2\pi g_s}{|Z|} \approx \frac{2\pi g_s}{\mathcal{V}_q}$$



LARGE volumes and hyperweak interactions

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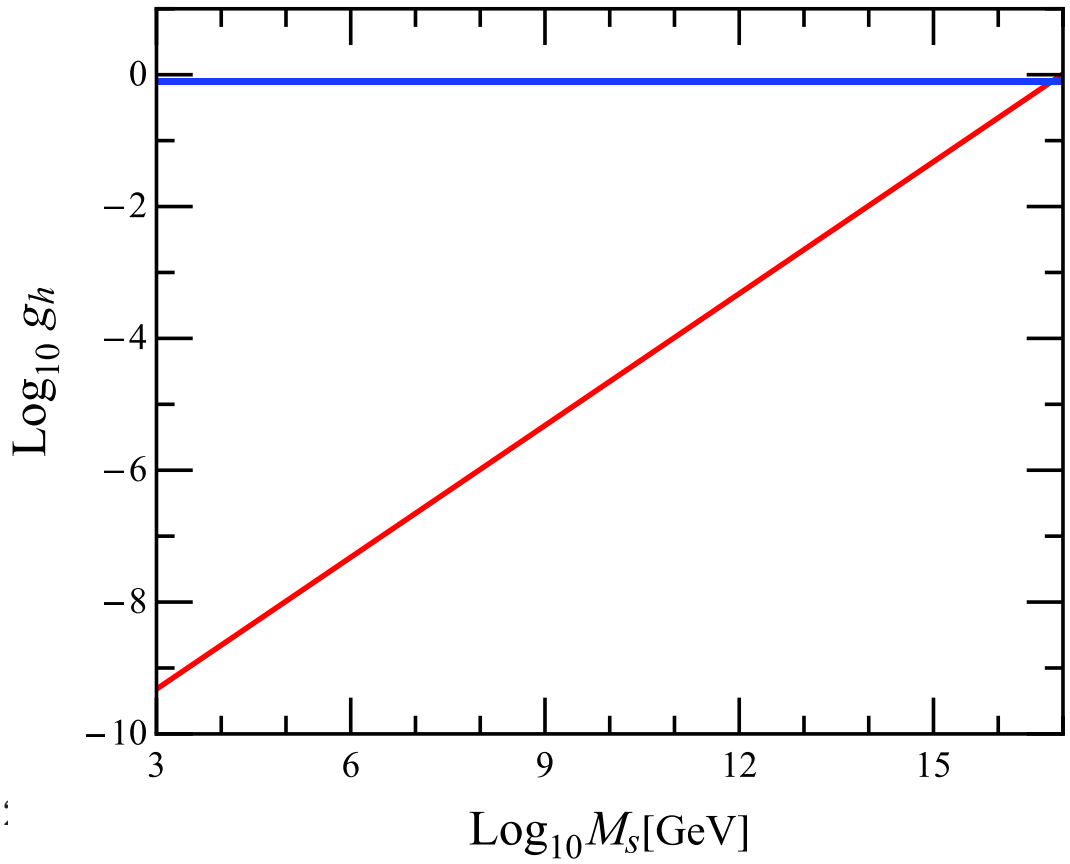
  2. D7 wraps collapsed cycle
  3. anti D3

  1. $\Rightarrow$ hyperweak interactions

[Burgess,Conlon,Hung,Kom,Maharana,Quevedo '08]

$$g_{(4)}^2 \approx \frac{2\pi g_s}{(\mathcal{V})^{2/3}} = 2\pi g_s \left(\frac{4\pi}{g_s^2}\frac{M_s^2}{M_P^2}\right)$$



3. Kinetic mixing between visible U(1) and hidden U(1)

- Before ~~SUSY~~, kinetic mixing appears as holomorphic quantity in SUGRA:

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

  g_a^h, g_b^h and χ_{ab}^h must run only at one loop

- Physical and holomorphic couplings related by generalisation of [Kaplunovsky,Louis '94,95]

$$g_a^{-2} = \mathrm{Re}\left[(g_a^h)^{-2} \right] - \sum_r \frac{Q_a^2(r)}{8\pi^2} \log\det Z^{(r)} - \sum_r \frac{n_r Q_a^2(r)}{16\pi^2} \frac{K}{M_P^2}$$

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

- In analogy to structure of holomorphic gauge kinetic function

cf. e.g. [Akerblom,Blumenhagen,Lüst,Schmidt-Sommerfeldt '07]

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

complex structure moduli z^k, Kähler moduli T_j, open string moduli y_i

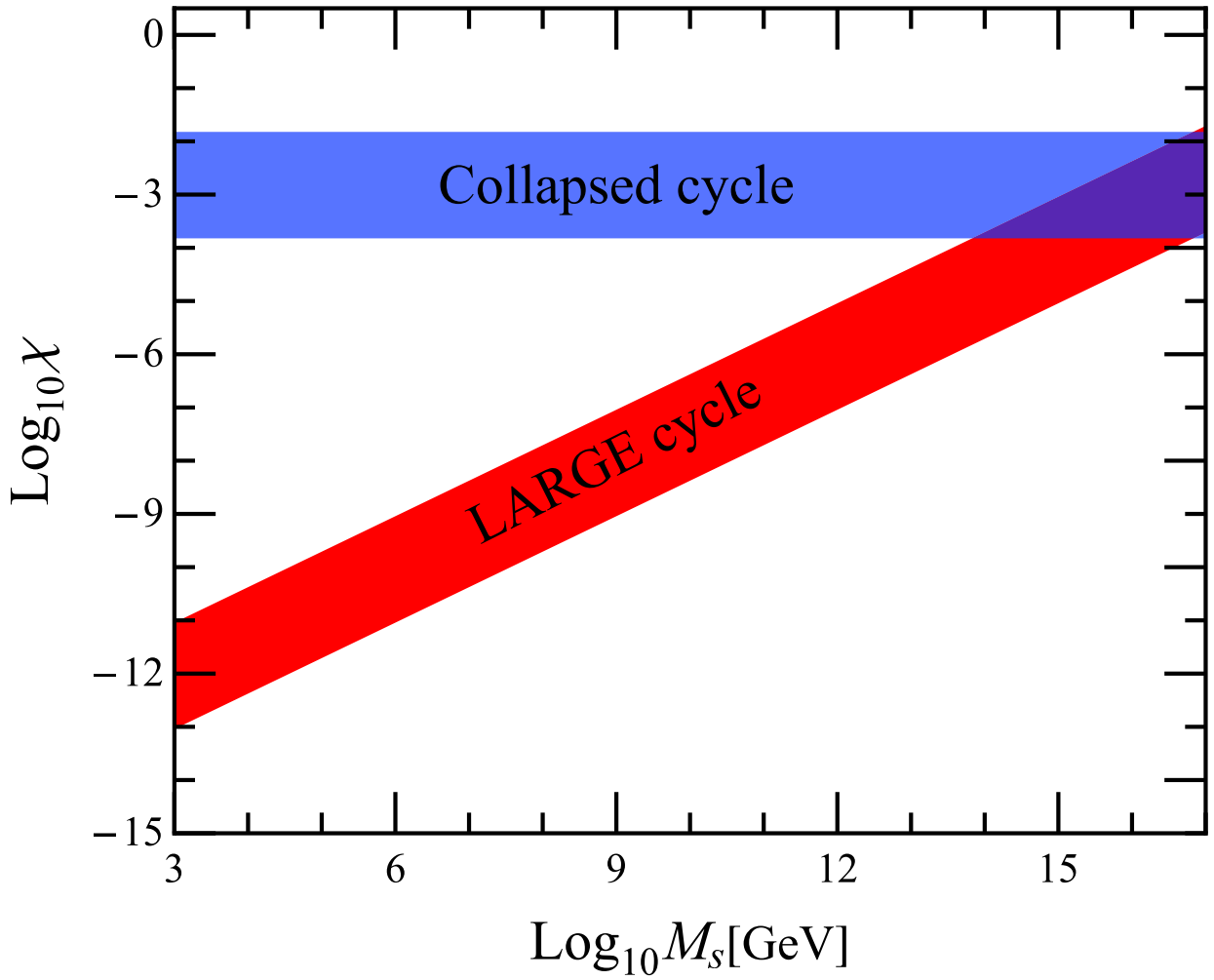
- T_j have shift symmetries $\Rightarrow$ may only appear as exponentials
- T_j depend on g_s^{-1} $\Rightarrow$ cannot enter at 1-loop

- Generically,

$$\chi^h_{ab} \simeq \chi^{1-\mathrm{loop}}_{ab}(z^k, y_i) \simeq \frac{1}{16\pi^2} \times \mathcal{O}(1)$$

$\Rightarrow$ Therefore,

$$\chi_{ab} \simeq \frac{g_a g_b}{16\pi^2} \times \mathcal{O}(1)$$


0
−3
−6
−9
−12
−15
3
6
9
12
15
Collapsed cycle
LARGE cycle
$\mathrm{Log}_{10}\chi$
$\mathrm{Log}_{10}M_s[\mathrm{GeV}]$

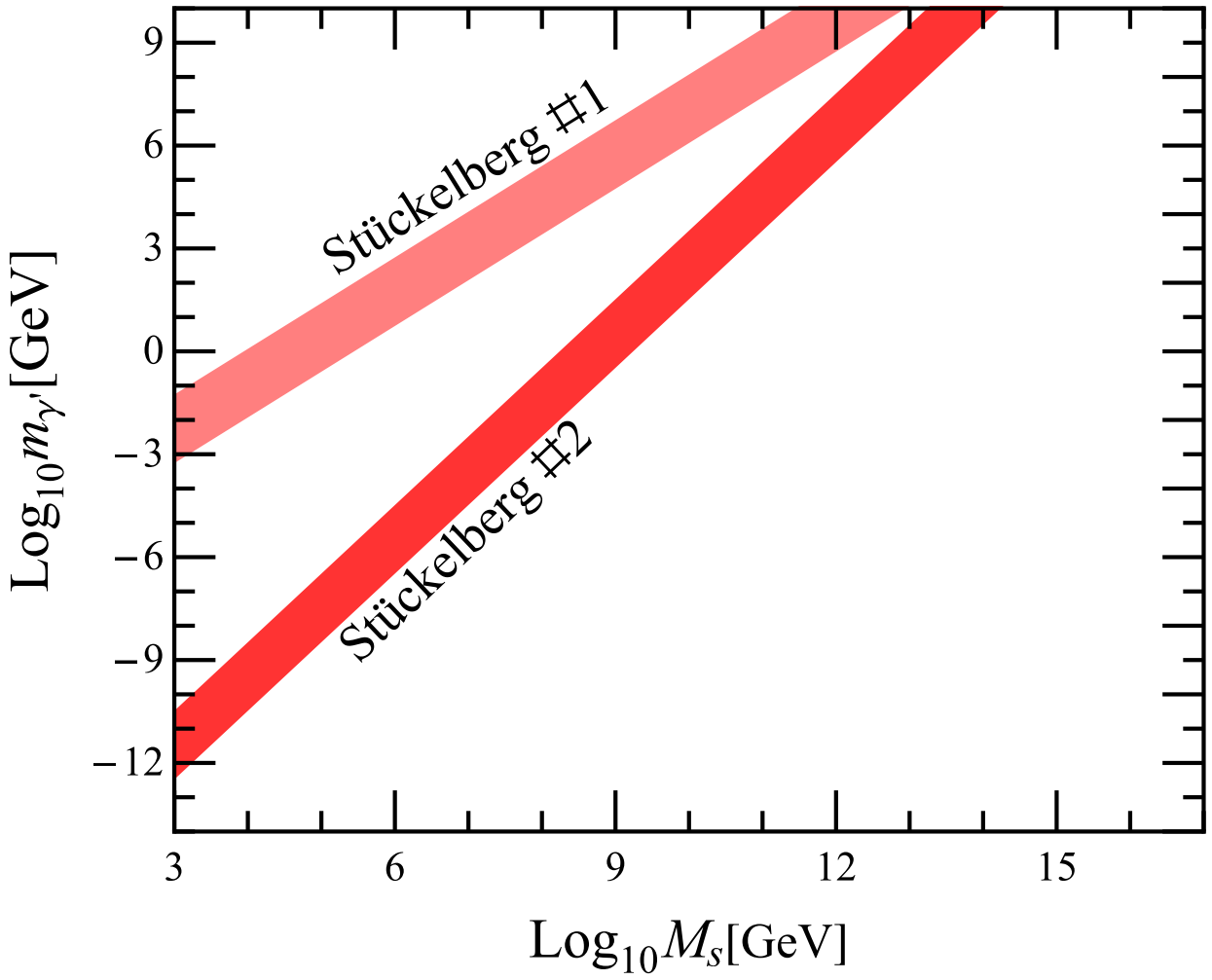
4. Mass of hidden U(1)

- **Stückelberg masses:** [Buican,Malyshev,Morrison,Verlinde,Wijnholt '06; Conlon,Maharana,Quevedo '08; ...]

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

  - $\mathcal{O}(1)$ factors: overlaps $\tilde{\Pi}^{cD_1}$, $\Pi_\alpha^{D_1 A}$; D7 brane charges r_{aD_1}; fluxes $p_{aD_1 A}$ and $b_{D_1 A}$
  - Size determined by metric G_{cd} and $G^{\alpha\beta}$ on space of harmonic forms
    - For anomalous U(1)s, dual cycles vanishing $\Rightarrow G \sim 1$
    - For bulk cycles, corresponding to non-anomalous U(1)s,

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


Stückelberg #1
Stückelberg #2
$\mathrm{Log}_{10} m_{\gamma'}$[GeV]
$\mathrm{Log}_{10} M_s$[GeV]
9
6
3
0
−3
−6
−9
−12
3
6
9
12
15

- **Masses from hidden Higgs mechanism:**
  - Expect generically $m_{\gamma'} \sim m_{H_{\rm h}} \sim m_{\rm soft}^{\rm hid}$
  - In gauge mediation, for example,

$$m_{\rm soft}^{\rm vis} \sim \frac{g_{\rm vis}^2}{16\pi^2}\frac{M_{\not{\rm SUSY}}^2}{M_{\rm mess}}$$

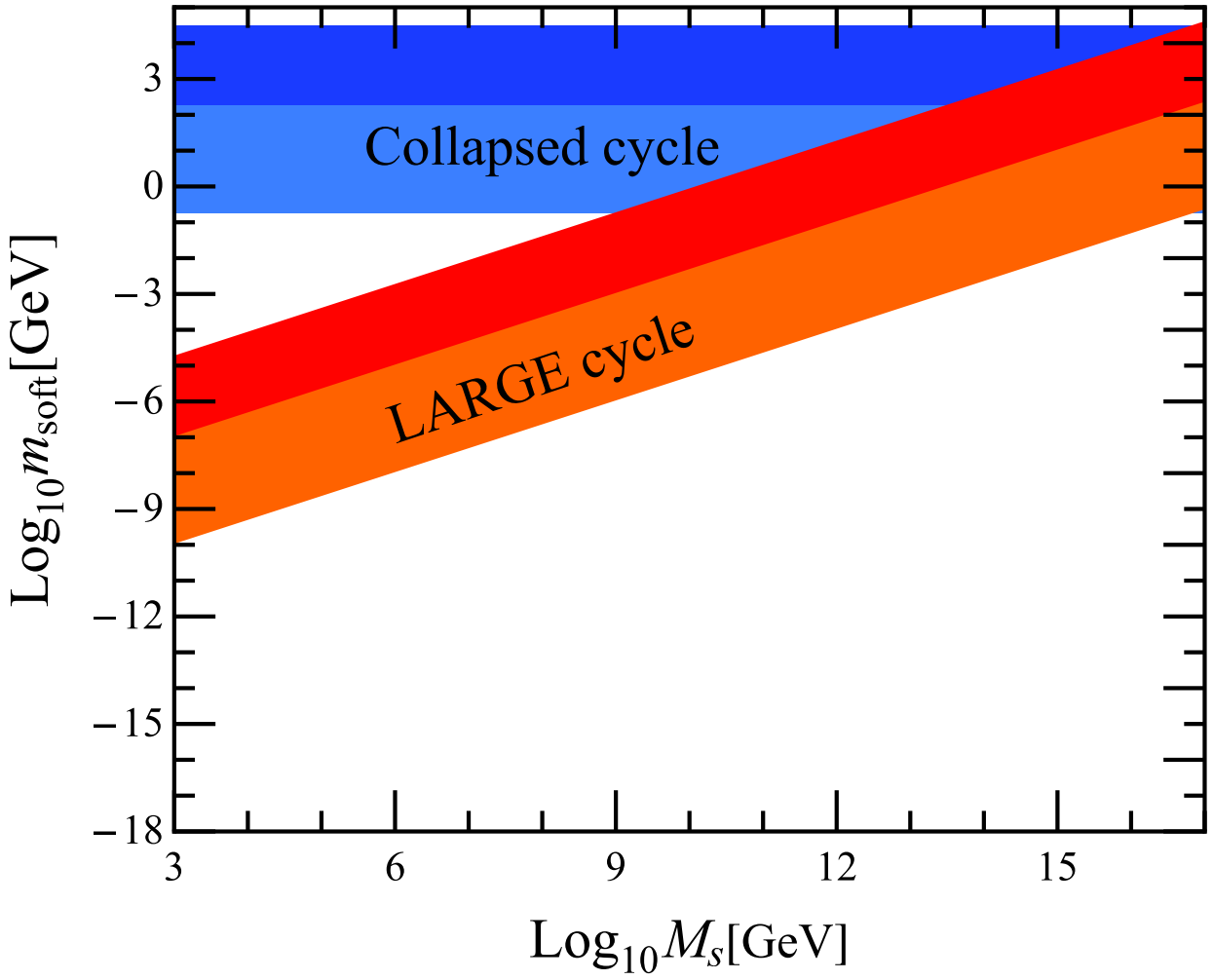
    * If hidden sector couples directly to sequestered $\not{\rm SUSY}$ sector,

$$m_{\rm soft}^{\rm hid} \sim \frac{g_{\rm h}^2}{16\pi^2}\frac{M_{\not{\rm SUSY}}^2}{M_{\rm mess}} \sim \frac{g_{\rm h}}{g_{\rm vis}} m_{\rm soft}^{\rm vis}$$

    * If hidden sector couples only indirectly via kinetic mixing to it,

[Dienes,Kolda,March-Russell '96;..;Suematsu '06;...;Morrissey,Poland,Zurek '09;...]

$$(m_{\rm soft}^{\rm hid})^2 = Q_{\rm h} g_{\rm h} \chi \langle D_Y \rangle = Q_{\rm h} g_{\rm h} g_Y \chi \frac{1}{8} v^2 \cos 2\beta \ll \left(m_{\rm soft}^{\rm vis}\right)^2$$


Collapsed cycle
LARGE cycle
3
0
−3
−6
−9
−12
−15
−18
3
6
9
12
15
$\mathrm{Log}_{10} m_{\mathrm{soft}}[\mathrm{GeV}]$
$\mathrm{Log}_{10} M_s[\mathrm{GeV}]$

5. Discussion and outlook

- Extra U(1) gauge bosons kinetically mixing with the electromagnetic (or hypercharge) U(1) may provide us with a unique window into hidden sector physics

- Moreover, they could play a role in a number of observed phenomena possibly connected to dark matter

- LARGE volume scenarios allow for a variety of different extra, hidden U(1) gauge bosons $\Rightarrow$ a variety of possibilities, some of which overlapping with the phenomenologically interesting regions

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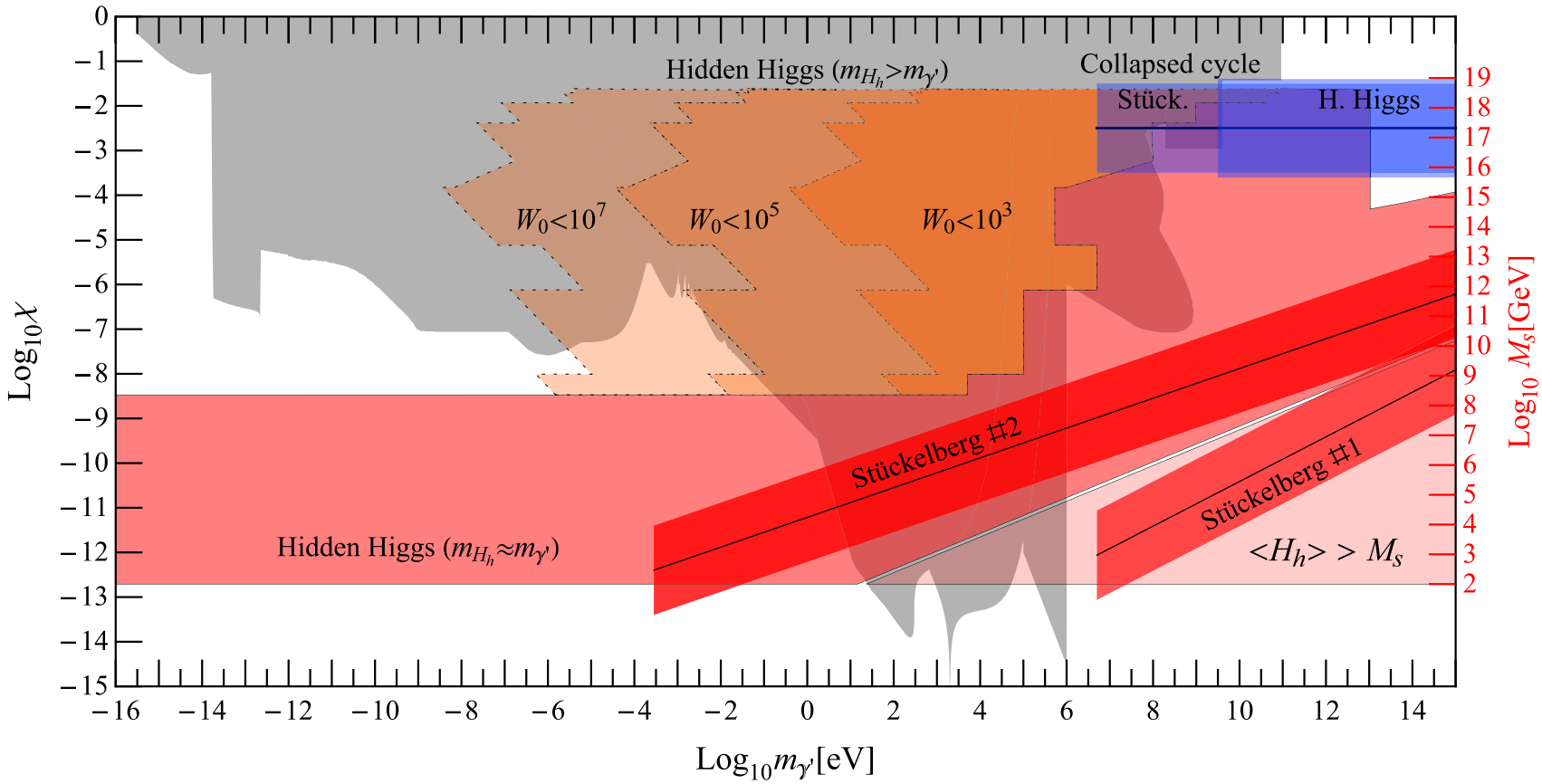

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- Near future astrophysical observations and laboratory experiments can test a variety of possible scenarios and an impressive range of string scales

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