From Axions to Other WISPs

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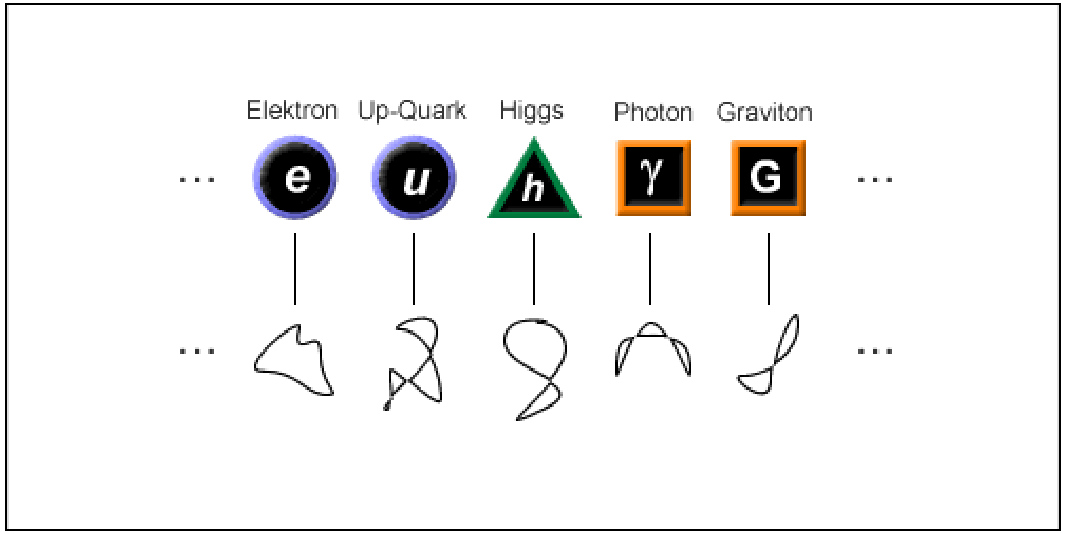
1. Introduction

- Theoretically well motivated extensions of the standard model are based on string theory ⇔ small strings in (9+1)-dimensional space-time are basic building blocks



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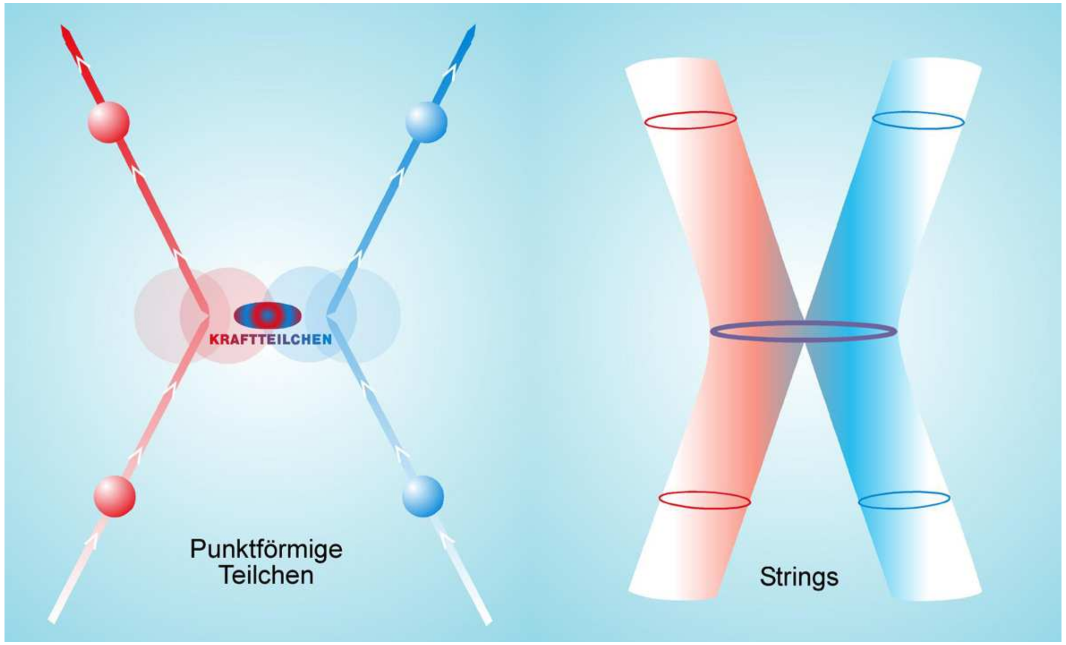
  - Unification of all forces, including gravitation



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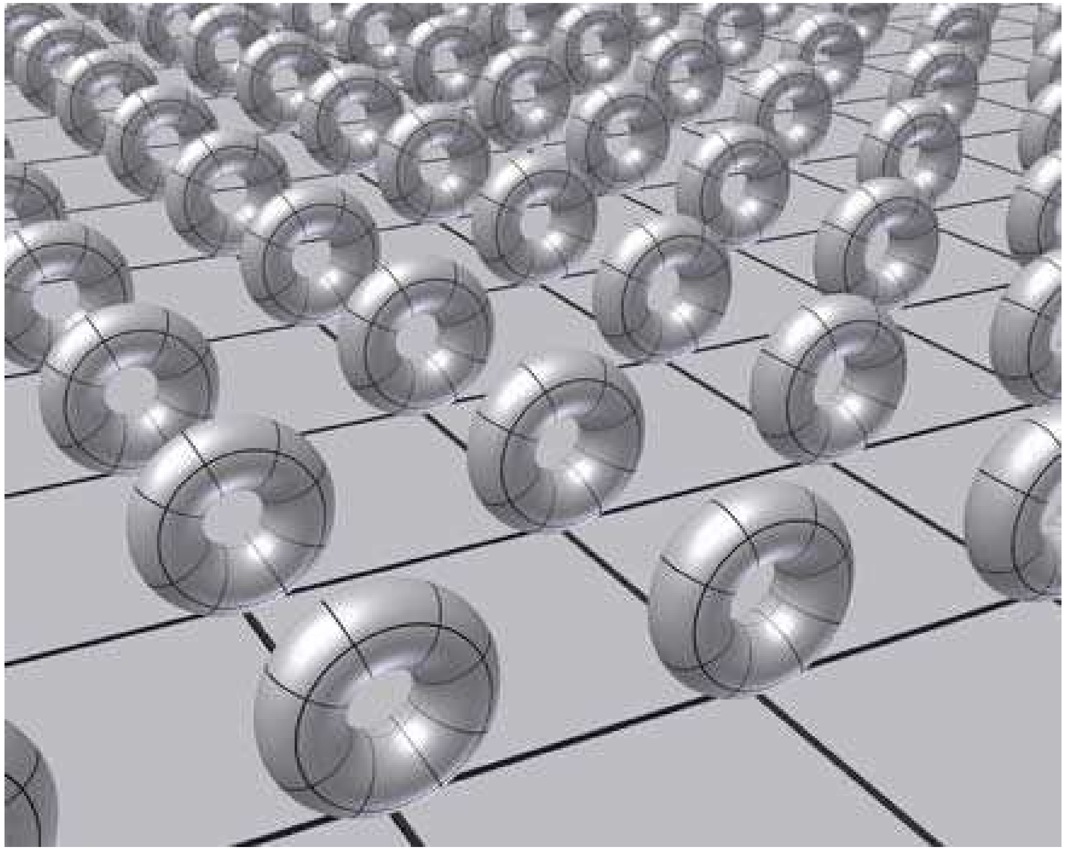
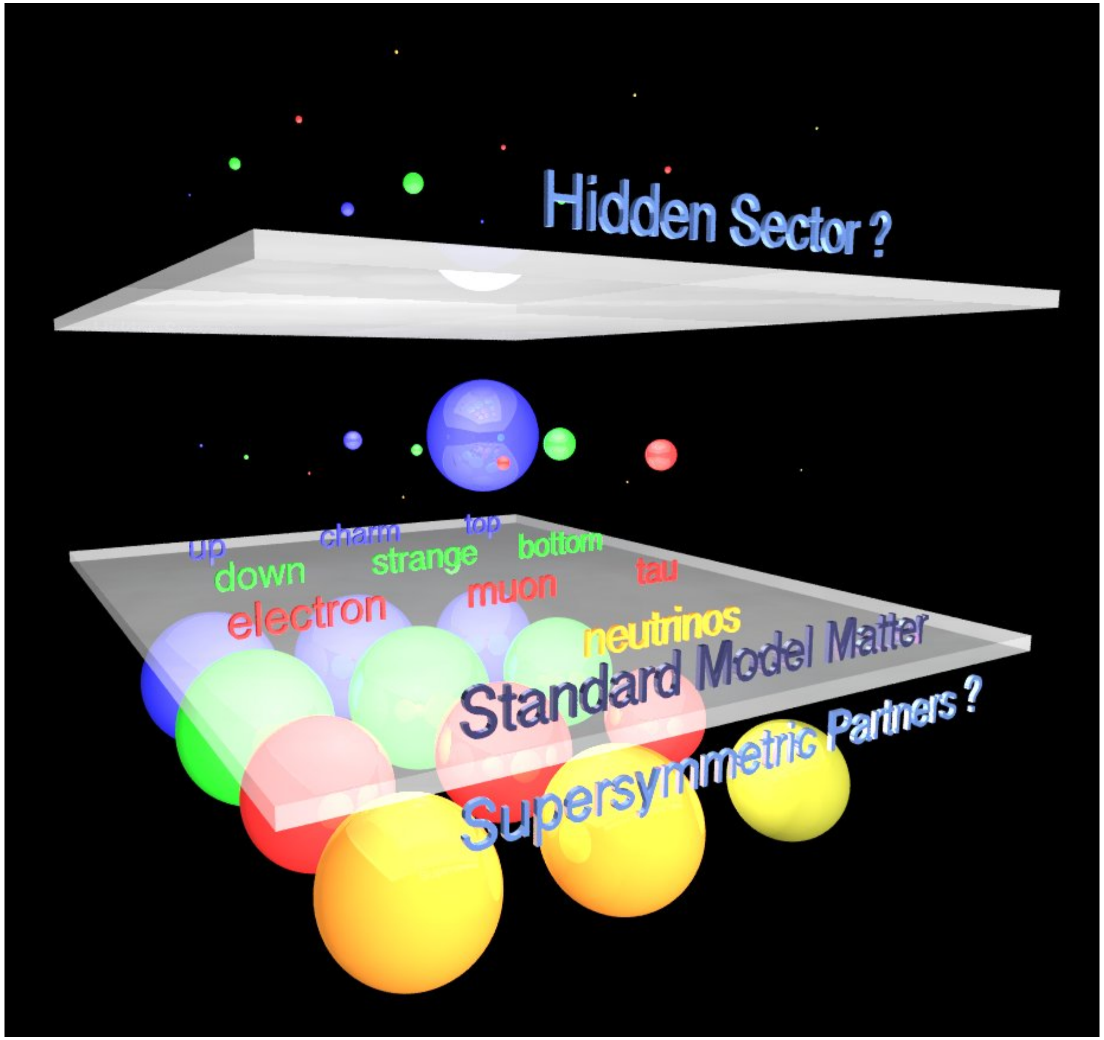
  - Low-energy description in (3+1) dimensions:



1. Introduction

- Theoretically well motivated extensions of the standard model are based on string theory ⇔ small strings in (9+1)-dimensional space-time are basic building blocks
  - Unification of all forces, including gravitation
  - Low-energy description in (3+1) dimensions:
    - ∗ Particles of standard model + heavy superpartners
    - ∗ Ultralight "invisible" axion
    - ∗ "Hidden-sector" particles: extra U(1) gauge bosons, extra U(1) charged matter



[Ahlers (unpubl.)]

• Plan:

2. **Axions from string compactifications**
3. **Other WISPs: Ultralight hidden-sector particles**
4. **Summary**

2. Axions from string compactifications

- **Strong CP problem:** Due to non-Abelian nature of QCD, additional CP-violating term in the Lagrangian,

$$\mathcal{L}_{\rm CP-viol.} = \frac{\alpha_s}{4\pi}\,\theta\,{\rm tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu} \equiv \frac{\alpha_s}{4\pi}\,\theta\,\frac{1}{2}\,\epsilon^{\mu\nu\alpha\beta}\,{\rm tr}\,G_{\mu\nu}G_{\alpha\beta}$$

  – Effective CP-violating parameter in standard model,

$$\theta \to \bar\theta = \theta + {\rm arg}\ {\rm det}\ M$$

  – Upper bound on electric dipole moment of neutron $\Rightarrow$

$$|\bar\theta| \lesssim 10^{-10}$$

  – **Unnaturally small!**

- **Peccei-Quinn solution to the strong CP problem:**
  - Introduce global anomalous chiral $U(1)_{\rm PQ}$ symmetry, spontaneously broken by the vev of a complex scalar $\langle\Phi\rangle = f_a e^{ia/f_a}$ [Peccei,Quinn '77]
  - Axion field a shifts under a $U(1)_{\rm PQ}$ transformation, $a \to a + {\rm const.}$
  - Axion field can enter in Lagrangian only through derivative terms and explicit symmetry violating terms originating from chiral anomalies,

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_a^{\rm int}\left[\frac{\partial a}{f_a};\psi\right] + \frac{r\alpha_s}{4\pi f_a}\, a\, {\rm tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{s\alpha}{8\pi f_a}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$

  - $\bar\theta$-term in $\mathcal{L}_{\rm SM}+\mathcal{L}_a$ can be eliminated by exploiting the shift symmetry, $a \to a - \bar\theta f_a/r$
  - Topological charge density $\propto \langle {\rm tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu}\rangle \neq 0$ provides nontrivial potential for axion field $\Rightarrow$ axion is pseudo-Nambu-Goldstone boson

[S.Weinberg '78; Wilczek '78]

Mass obtained via current algebra: [S.Weinberg '78]

$$m_a = \frac{r\, m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 0.6\,\mathrm{meV} \times \left(\frac{10^{10}\,\mathrm{GeV}}{f_a/r}\right)$$

– For large f_a: axion is ultralight and invisible:

[J.E. Kim '79; Shifman *et al.* '80; Dine *et al.* '81;...]

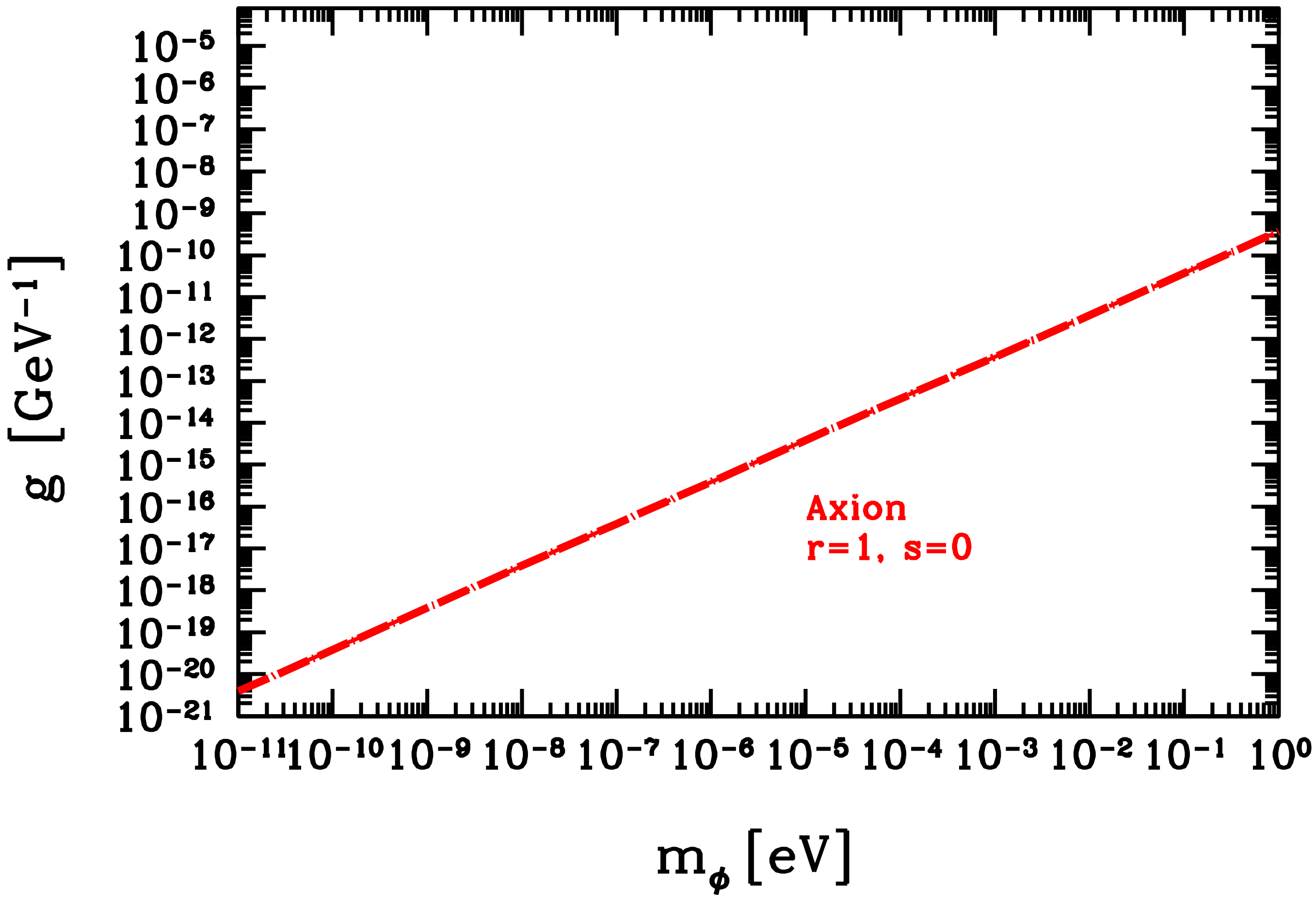
e.g. coupling to photons,

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} = g\, a\, \vec{E} \cdot \vec{B},$$

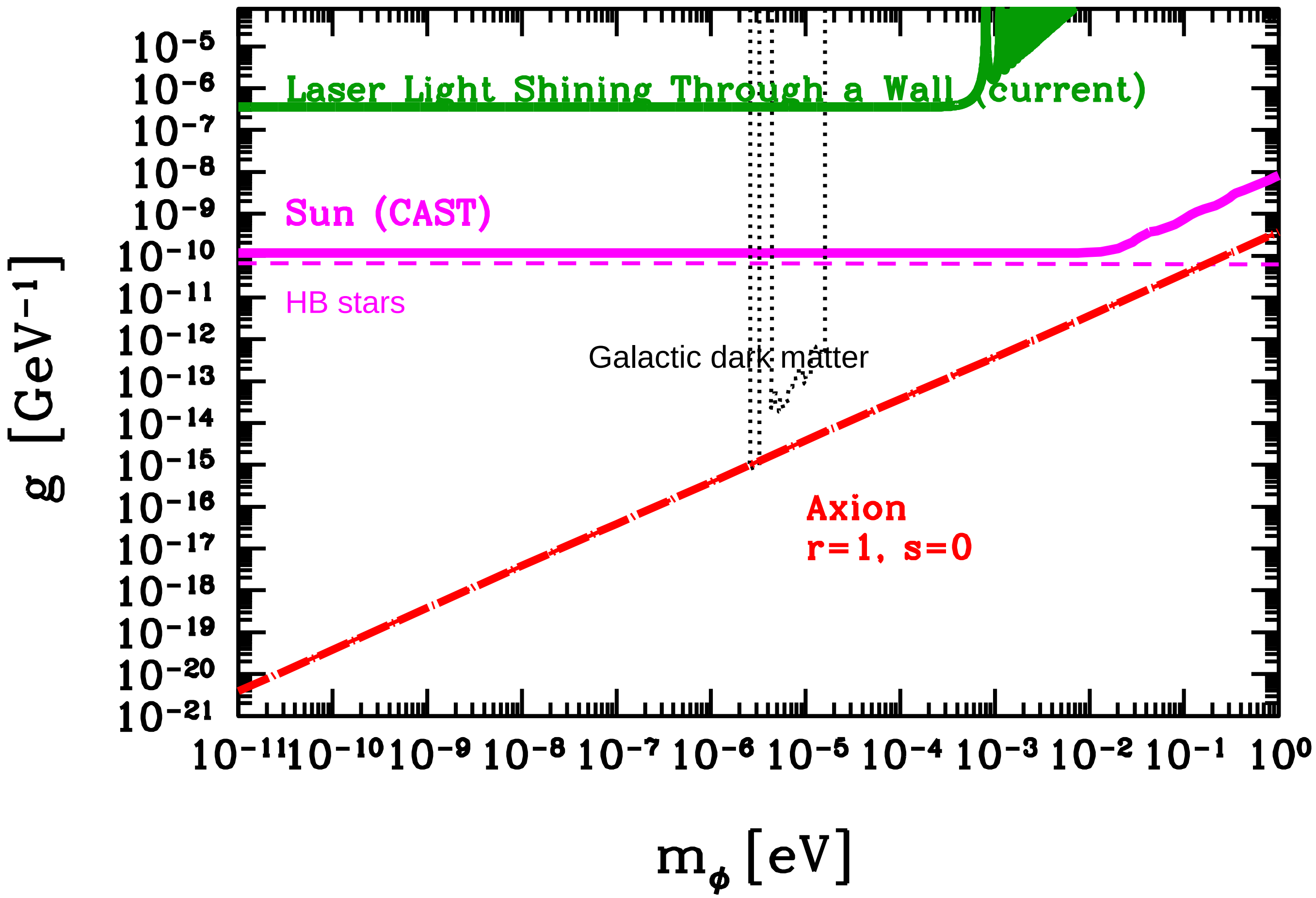
with [Bardeen,Tye '78; Kaplan '85; Srednicki '85]

$$g_{a\gamma\gamma} = \frac{r\alpha}{2\pi f_a} \left(\frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d} - \frac{s}{r}\right) \sim 10^{-13}\ \mathrm{GeV}^{-1} \left(\frac{10^{10}\,\mathrm{GeV}}{f_a/r}\right)$$

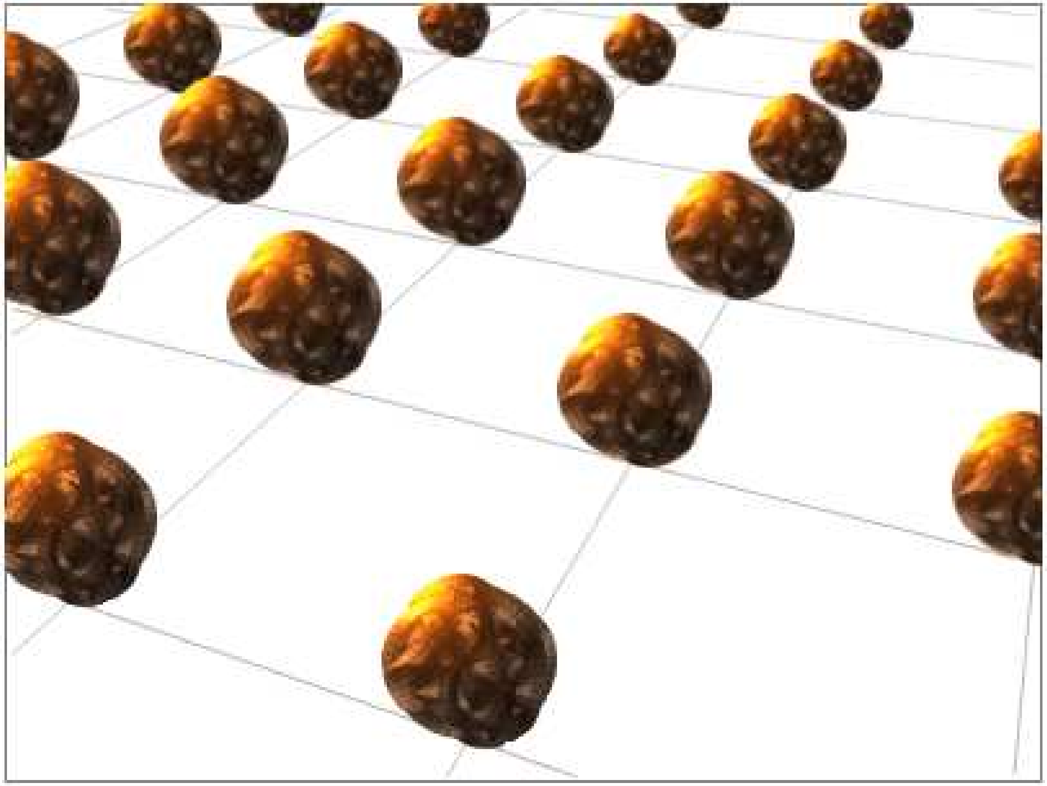
- Generic prediction for axion:



- Adding laboratory, astrophysical and cosmological constraints: ⇐this workshop



- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications



- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications
  - Model-independent axion of weakly coupled heterotic string: dual of $B_{\mu\nu}$, with μ and ν tangent to 4d Minkowski spacetime:

MASSLESS SPECTRUM OF STRING THEORIES				
THEORY	DIMENSION	SUPERCHARGES	BOSONIC SPECTRUM	
Heterotic $E_8 \times E_8$	10	16		$g_{\mu\nu}, B_{\mu\nu}, \phi$ A_μ^{ij} in adjoint representation
Heterotic $SO(32)$	10	16		$g_{\mu\nu}, B_{\mu\nu}, \phi$ A_μ^{ij} in adjoint representation
Type I $SO(32)$	10	16	NS-NS	$g_{\mu\nu}, \phi$
				A_μ^{ij} in adjoint representation
			R-R	$C_{(2)}$
Type IIB	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(0)}, C_{(2)}, C_{(4)}$
Type IIA	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(1)}, C_{(3)}$

- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications

  – Model-independent axion of weakly coupled heterotic string: dual of $B_{\mu\nu}$, with μ and ν tangent to 4d Minkowski spacetime:

$$f_a = \frac{g_s^2}{\sqrt{2\pi V_6} M_s^2} = \frac{\alpha_C M_P}{2\pi\sqrt{2}}$$

$$\simeq 10^{16}\ \mathrm{GeV}$$

- Heterotic string:

  – 10d low-energy Lagrangian:

$$\mathcal{L}_{10\mathrm{d}} = \frac{2\pi M_s^8}{g_s^2}\sqrt{-g}R - \frac{M_s^6}{2\pi g_s^2}\frac{1}{4}\mathrm{tr}F\wedge\star F - \frac{2\pi M_s^4}{g_s^2}\frac{1}{2}H\wedge\star H + \ldots$$

  – Compactify 6 extra dimensions:

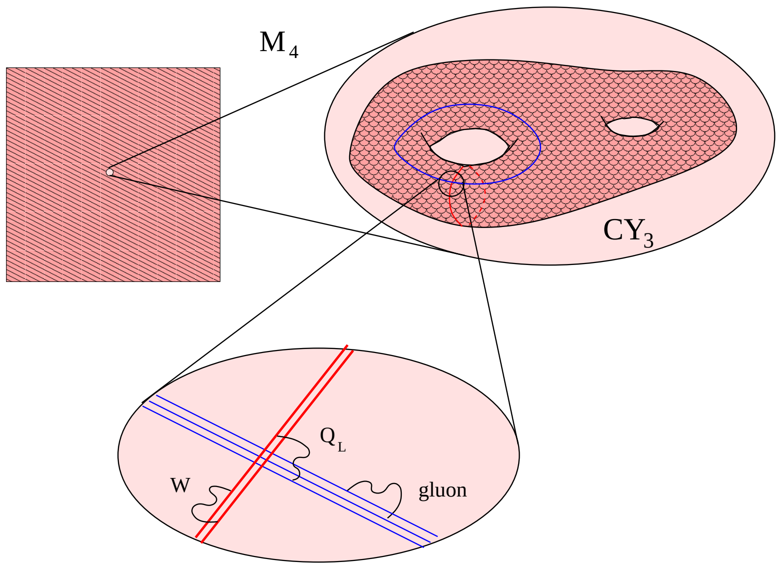
$$\mathcal{L}_{4\mathrm{d}} = \frac{M_P^2}{2}\sqrt{-g}R - \frac{1}{4g_{\mathrm{YM}}^2}\sqrt{-g}\mathrm{tr}F_{\mu\nu}F^{\mu\nu} - \frac{1}{f_a^2}\frac{1}{2}H\wedge\star H + \ldots$$

$\Rightarrow$ Read off coefficients:

$$M_P^2 = \frac{4\pi}{g_s^2}M_s^8 V_6;\quad g_{\mathrm{YM}}^2 = \frac{4\pi g_s^2}{M_s^6 V_6};\quad f_a^2 = \frac{g_s^2}{2\pi M_s^4 V_6}$$

- **Axions in string theory:**
  Axions with global anomalous PQ symmetries generic in string compactifications
  - Axions in intersecting D(3+q)-brane models in type II string theory

- Intersecting D-brane models:
  - Gauge theory lives on D$(3+q)$-branes, extending along the 4 non-compact dimensions and wrapping a q-cycle in the extra dimensions



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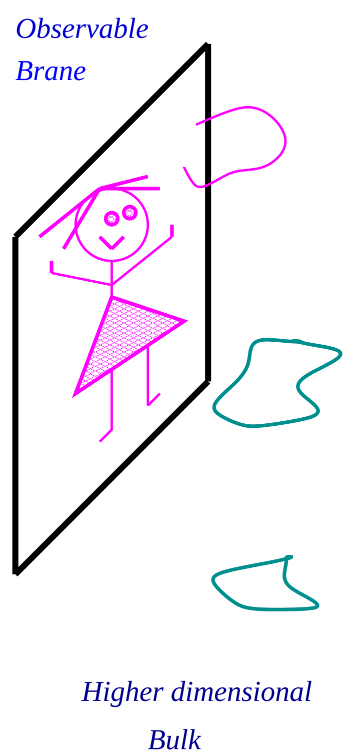
- Intersecting D-brane models:

  – Gauge theory lives on D$(3+q)$-branes, extending along the 4 non-compact dimensions and wrapping a q-cycle in the extra dimensions
  – Gravity lives in all 10 dimensions



- **Axions in string theory:**
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  – Axions in intersecting D(3+q)-brane models in type II string theory come from zero modes of the RR gauge fields C:

$$f_a \simeq \sqrt{\frac{g_s^2}{8\pi^2}}\,(M_s R)^{-q}\,M_P$$

$$\simeq 10^{16}\ \text{GeV}\ (M_s R)^{-q}$$

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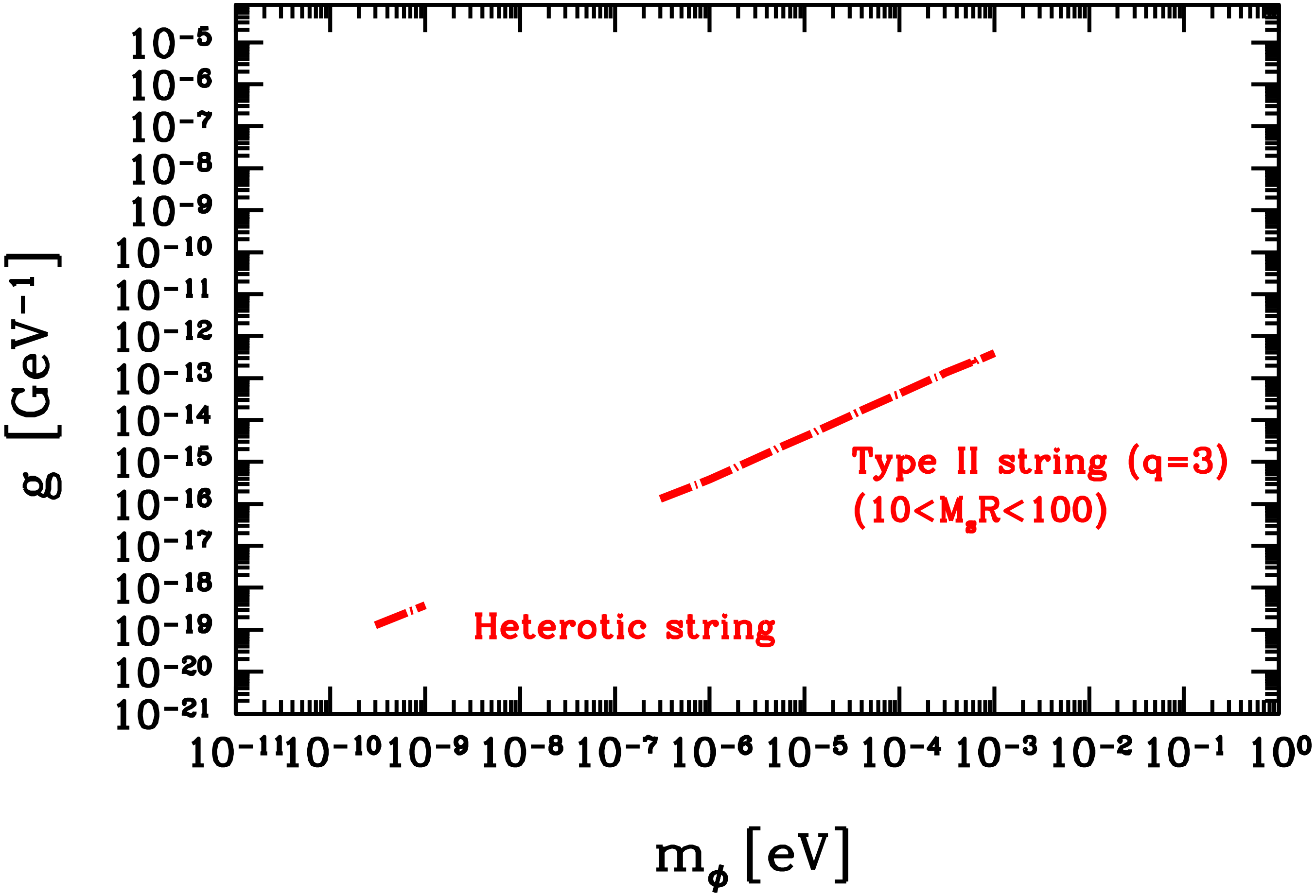
String predictions for axion:



3. Other WISPs: Ultralight hidden-sector particles

- Most extensions of standard model based on supergravity or superstrings predict "hidden sector" of particles which are very weakly coupled to the "visible sector" standard model particles
  - cf. "gravity mediation" of SUSY breaking from hidden sector to visible sector
- Gauge interactions in hidden sector generically involve U(1) factors. There are also hidden sector matter particles charged under these U(1)s.
  - Usual assumption: hidden sector particles very heavy

    $\Rightarrow$ no constraints from low-energy phenomenology
  - Here: what if hidden sector particles remain massless or light?

    $\Rightarrow$ hidden sector U(1) gauge boson ("hidden photon" γ') interacts with visible photon through gauge kinetic mixing

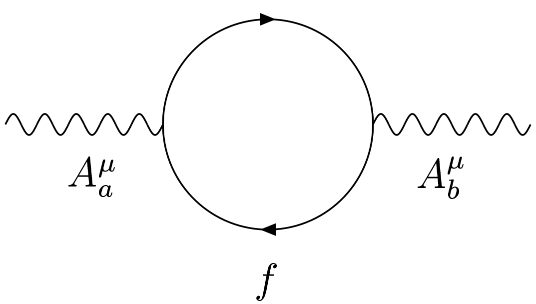
    $\Rightarrow$ hidden sector U(1) charged matter appears to have a small electric charge due to this mixing ("minicharged particle" ϵ)

- Simplest model: [Holdom ‘85]

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\mathrm{U(1)_{visible}}} \underbrace{-\frac{1}{4}B^{\mu\nu}B_{\mu\nu}}_{\mathrm{U(1)_{hidden}}} \underbrace{+\frac{1}{2}\chi\, F^{\mu\nu}B_{\mu\nu}}_{\text{kinetic mixing}} \underbrace{+\bar{v}(\mathrm{i}\partial\!\!\!/ + e A\!\!\!/)v}_{\text{visible matter}} \underbrace{+\bar{h}(\mathrm{i}\partial\!\!\!/ + e_h B\!\!\!/)h}_{\text{hidden matter}}$$

  – Dimensionless kinetic mixing parameter χ:

    * Kinetic mixing generically appears in theories with several U(1) factors (renormalizable term respecting gauge and Lorentz symmetry)
    * Integrating out heavy particles generically tends to generate $\chi \neq 0$:



$$\Rightarrow \Delta\chi = \frac{e e_h}{16\pi^2}\log(m^2/\mu^2)$$

– Diagonalization of kinetic term:

$$B^\mu \to \tilde{B}^\mu + \chi A^\mu$$

U(1)$_{\rm visible}$ unaffected, up to renormalization, $e^2 \to e^2/(1-\chi^2)$

– Hidden sector charged particle gets induced electric charge:

$$e_h \bar{h} \not{B} h \quad \to \quad e_h \bar{h} \tilde{\not{B}} h + \chi e_h \bar{h} \not{A} h$$

$$\Rightarrow \quad Q_h^{\rm vis} \equiv \epsilon e = \chi e_h$$

∗ may be fractional

∗ may be tiny, if $\chi \ll 1$: h is minicharged particle

- Possible parameter ranges in string phenomenology: [Dienes *et al.* '97;Abel *et al.* '06]

$$\chi \sim 10^{-16} \div 10^{-2}; \qquad m_{\gamma'} \sim 0 \div M_s; \qquad m_\epsilon \sim 0 \div M_s$$

- U(1) factors in hidden sectors: generic prediction of realistic string compactifications
  - $E_8 \times E_8$ heterotic closed string theory

Orbifold compactifications of heterotic string theory:
e.g. [Buchmüller *et al.* '07;. . .]

$$E_8 \times E_8 \longrightarrow$$
$$G_{SM} \times U(1)^4 \times \left[SU(4) \times SU(2) \times U(1)^4\right]$$

or [Lebedev *et al.* '07]

$$E_8 \times E_8 \longrightarrow$$
$$G_{SM} \times U(1)^4 \times \left[SO(8) \times SU(2) \times U(1)^3\right]$$

and many more

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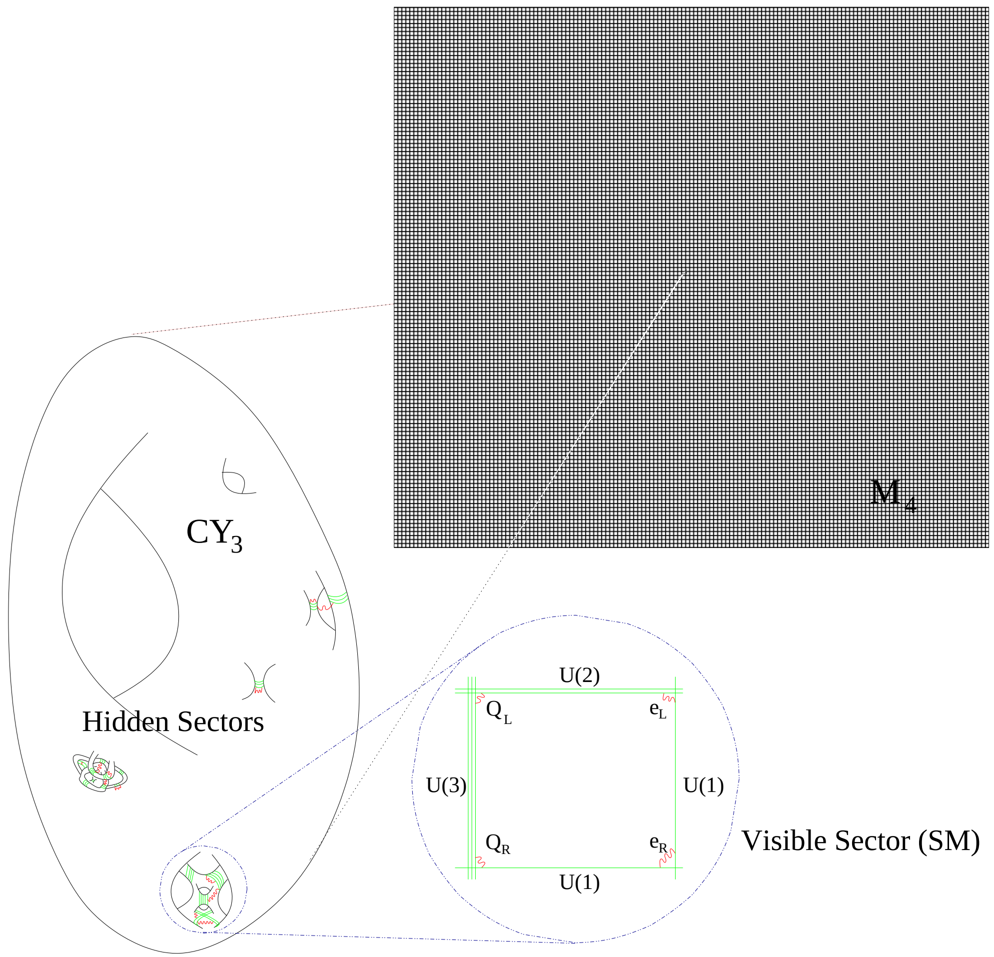
  - IIA/IIB open string theory with branes

Compactification of type II string theory:



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- Some hidden U(1) gauge bosons and hidden charged fermions may remain massless or light

Favored mass scales for hidden U(1)s: [...; Antoniadis *et al.* '02]

$$0 \lesssim \frac{M_s^2}{M_P} \lesssim m_{\gamma'} \lesssim M_s$$

In particular, for $M_s \sim$ TeV,

$$0 \lesssim \mathrm{meV} \lesssim m_{\gamma'} \lesssim \mathrm{TeV}$$

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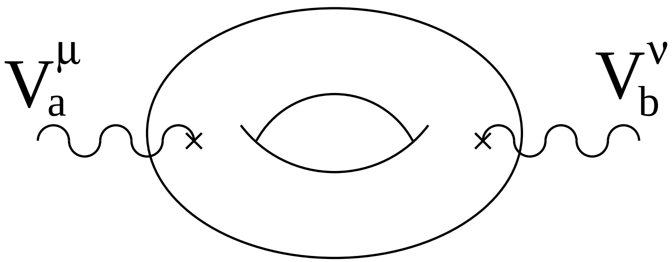
⇒ Dominant interaction with standard model: gauge kinetic mixing and minicharge

KM in heterotic string models:

[Dienes,Kolda,March-Russell '97]



$$\chi \simeq \frac{e e_h}{16\pi^2} C \frac{\Delta m_{\rm hidden}}{M_P}$$

$$\simeq e_h \underbrace{C}_{10\div 100} (\underbrace{10^{-16}}_{\rm GMSB} \div \underbrace{10^{-4}}_{\rm GUT})$$

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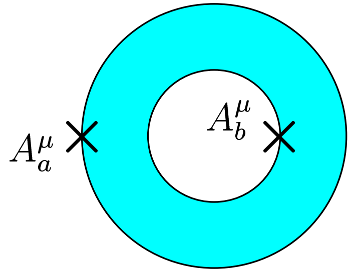
$\Rightarrow$ Dominant interaction with standard model: gauge kinetic mixing and minicharge

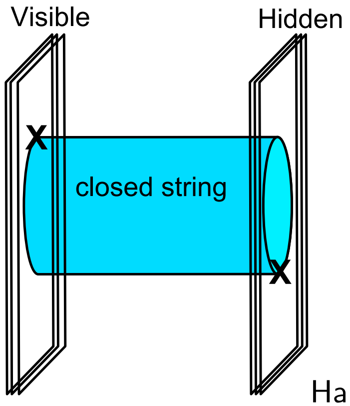
KM in IIA/IIB string models:

[Lüst,Stieberger '03;Abel,Schofield '04;Berg,Haack,Körs '05]

One-loop kinetic mixing diagram in open string channel,



$\Leftrightarrow$ tree cylinder diagram in closed string channel,



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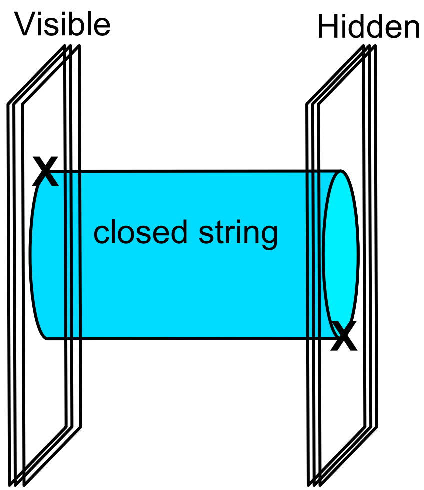

e.g. Dp brane anti-Dp brane kinetic mixing:

$$\chi \sim e\, e_h \left(\frac{2^{(8-p)/2}}{\alpha_p} \frac{M_s}{M_P} \right)^{\frac{2(5-p)}{6-p}} \left(\frac{R}{r} \right)^{\frac{d-p+3}{6-p}}$$

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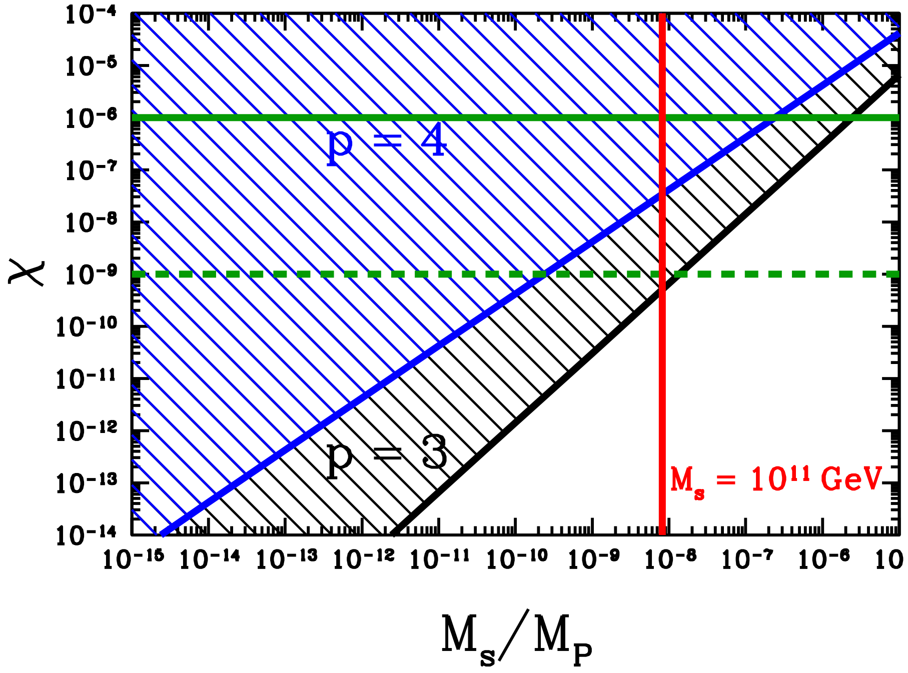
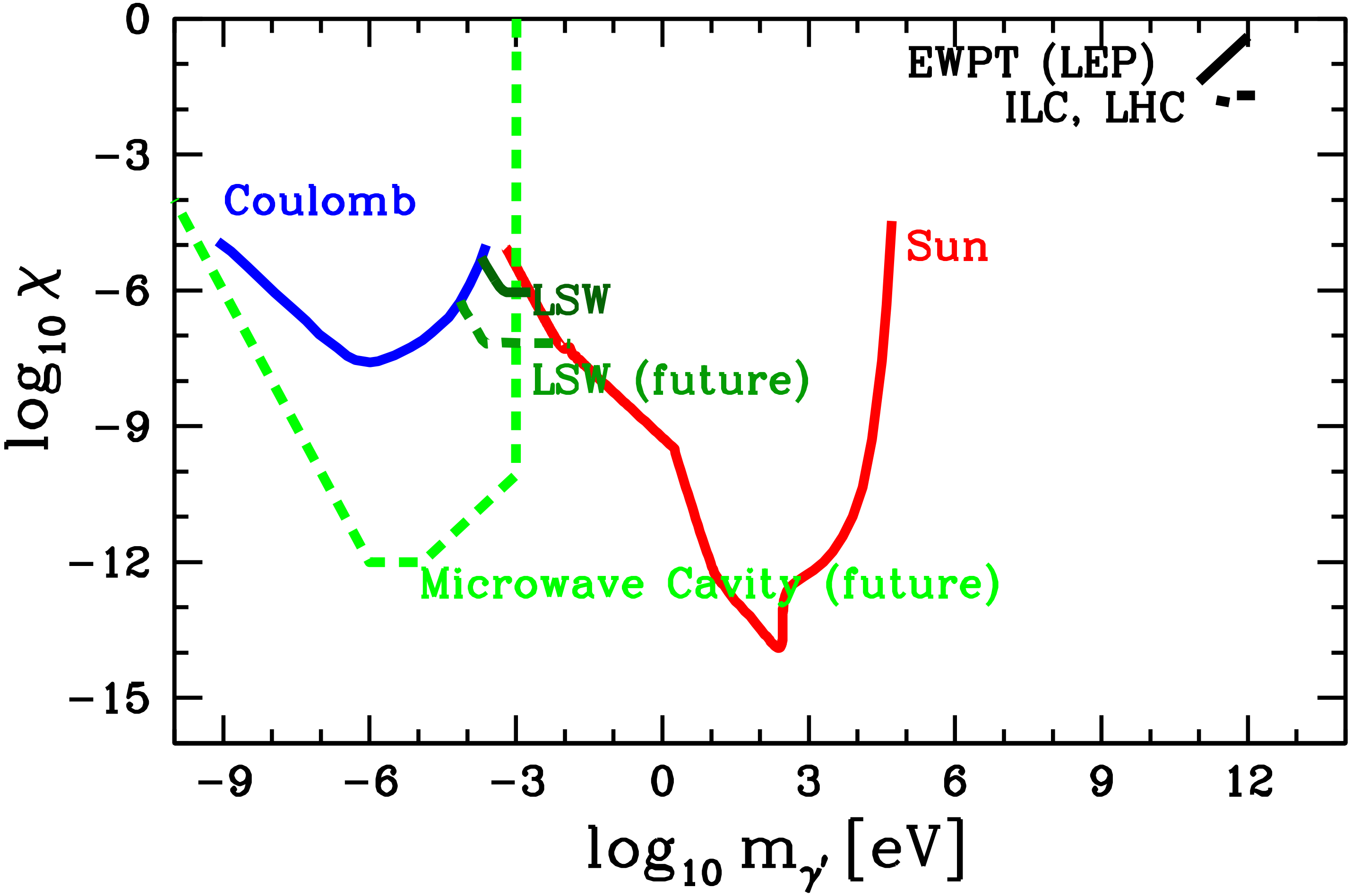
Dp-brane anti-Dp-brane kin. mix.:

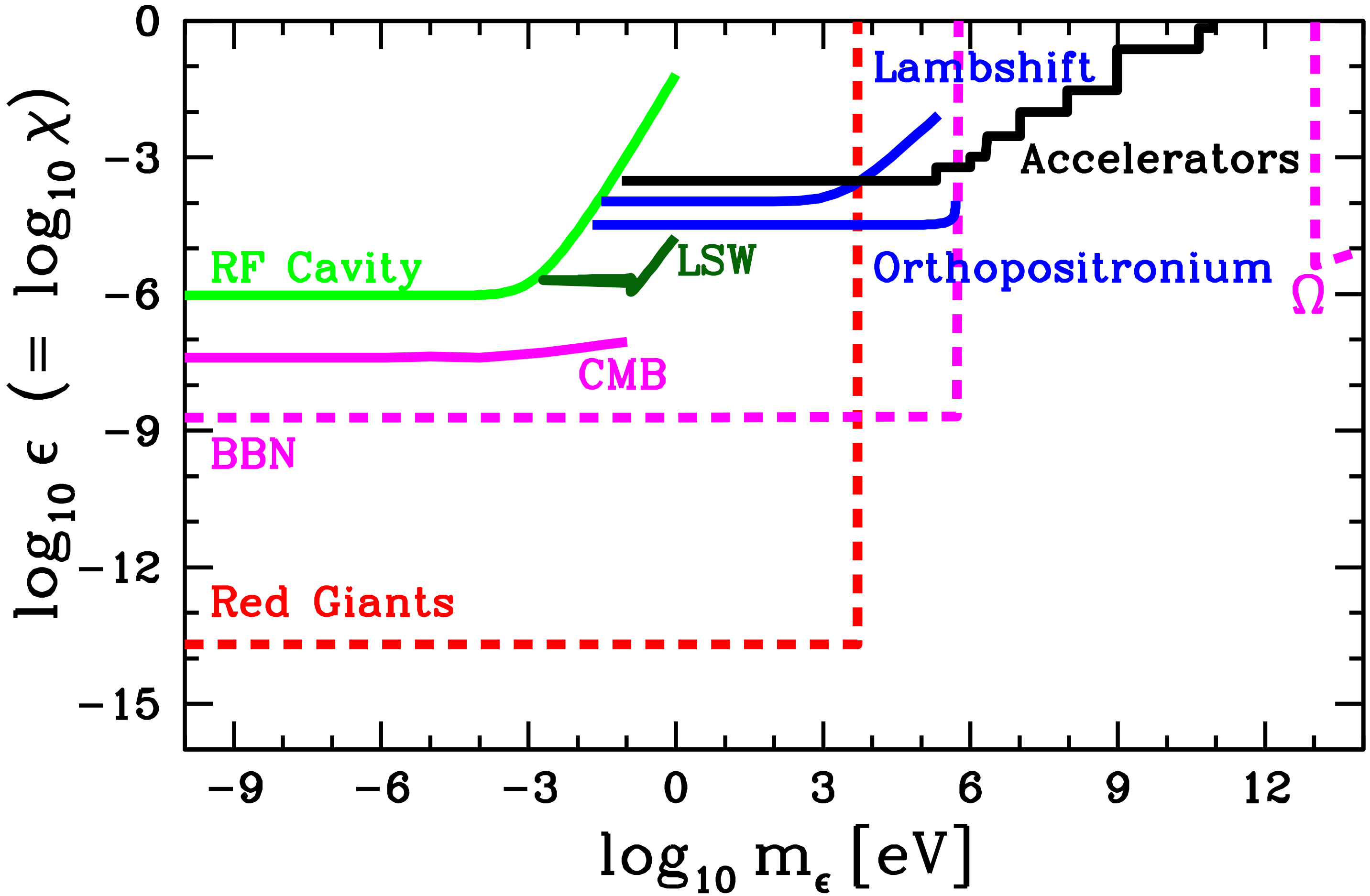


[Abel,Jaeckel,Khoze,AR '06]

- Constraints on hidden photons: ⇐ this workshop!



• Constraints on minicharged particles: ⇐ this workshop!



BBN and RG relaxed in models with several U(1)s [Masso,Redondo '06; Abel *et al.* '06]

4. Summary

- Phenomenologically viable string compactifications
  - predict ultralight invisible axion,

$$10^{-10}\ \mathrm{eV} \lesssim m_a \lesssim 10^{-3}\ \mathrm{eV}$$
$$10^{10}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{16}\ \mathrm{GeV}$$

  - may have ultralight hidden-sector U(1) gauge bosons,

$$0 \lesssim m_{\gamma'} \lesssim \mathrm{eV},$$

which generally mix kinetically with the visible-sector U(1),

$$10^{-16} \lesssim \chi \lesssim 10^{-2},$$

and ultralight hidden-sector U(1) charged fermions, with tiny electric charge

$$Q_\epsilon \simeq \chi e_h \ll e$$

- Hidden sectors carry crucial information on how the standard model is embedded in a more fundamental theory

⇒ Any experimental or observational hint extremely welcome!

- Lots of previously unexplored parameter space, which may be accessed in the near future!

- High-precision experiments at the low-energy frontier ideal complement to experiments at the high-energy frontier in the quest for the fundamental theory of space, time, and matter!