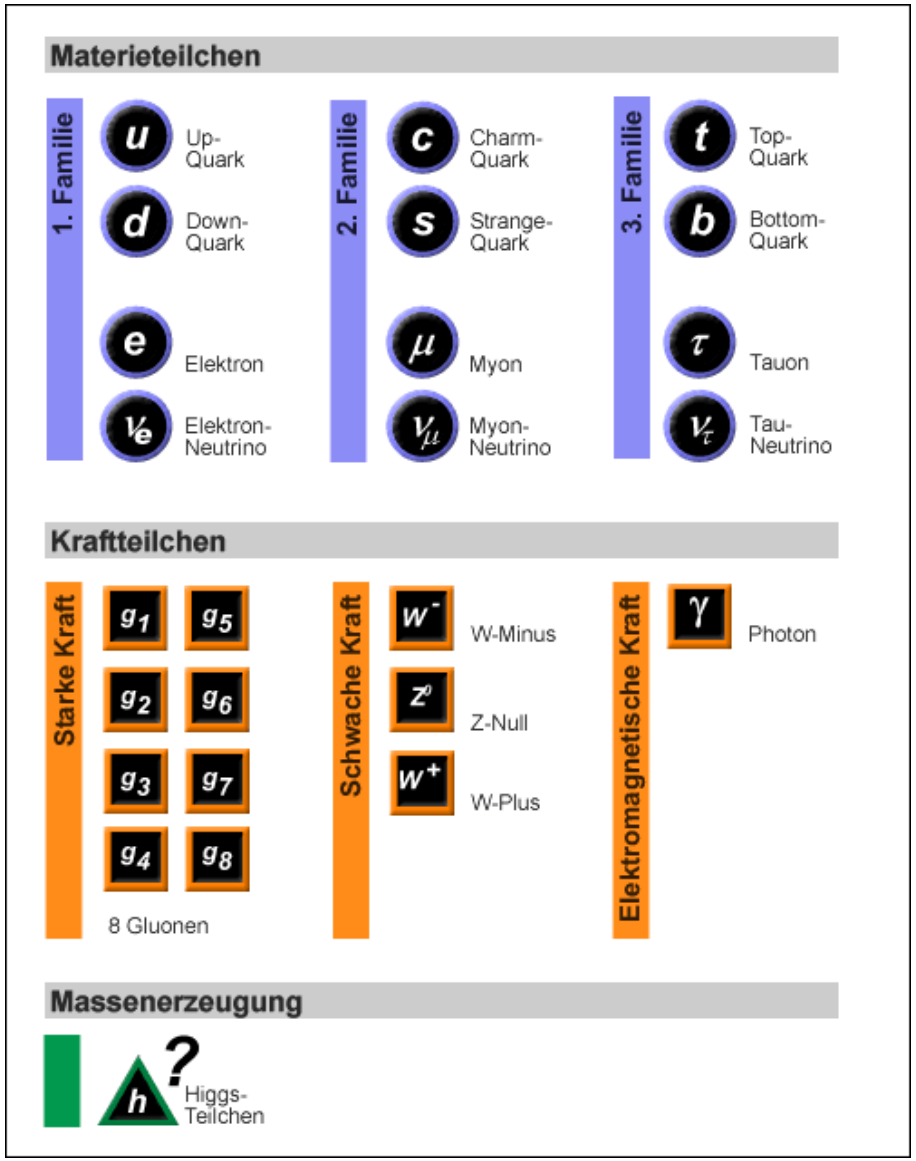
Light Paraphotons and Minicharged Particles in Realistic Extensions of the Standard Model

Andreas Ringwald

3rd ILIAS-CERN-DESY Axion-WIMP Workshop
June 23, 2007
Patras, GR

1. Introduction

- Most successful theory of all times: standard model



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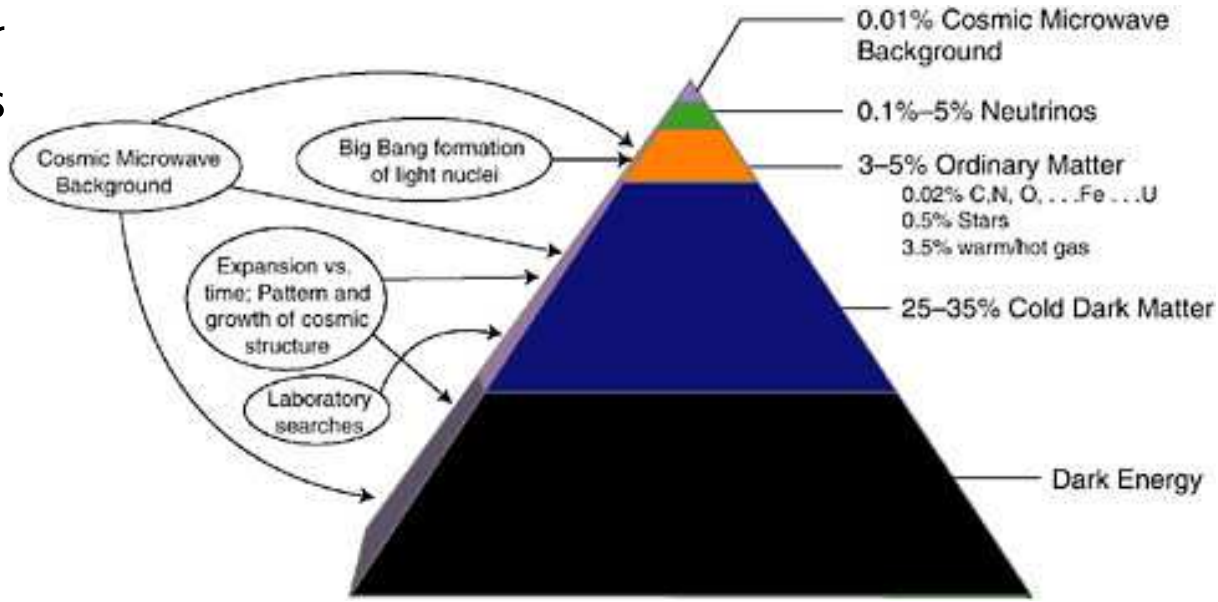
- Circumstantial evidence for existence of new particles beyond the standard model:
  – Dark matter



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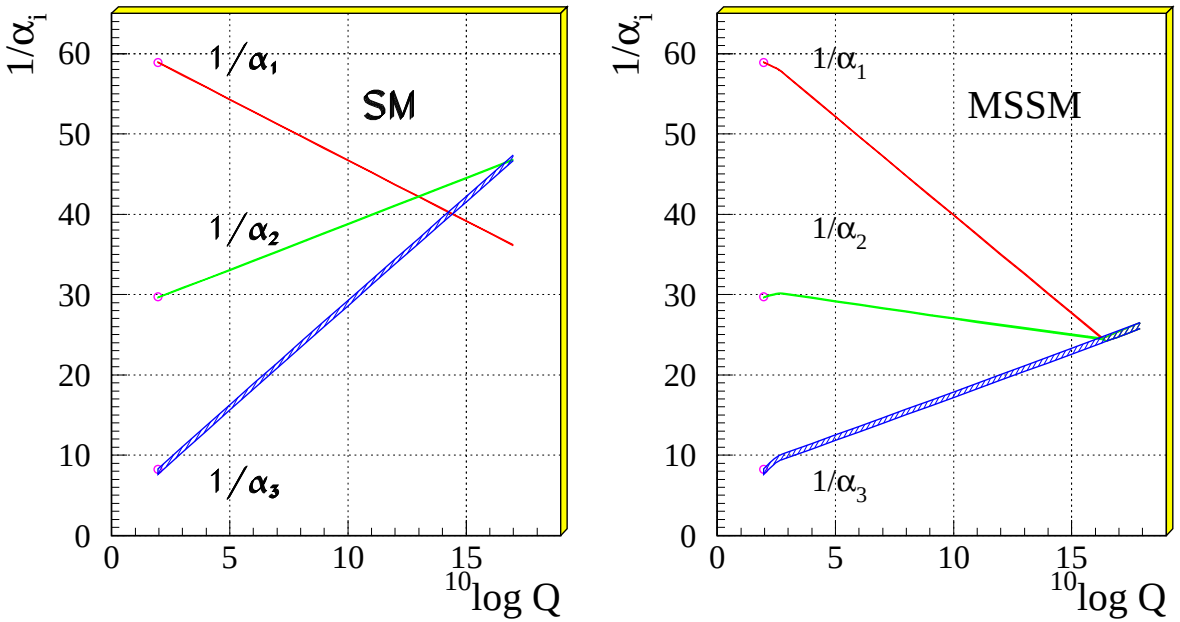
  - Unification of forces

Unification of the Coupling Constants in the SM and the minimal MSSM



[Amaldi, de Boer, Fürstenau '91]

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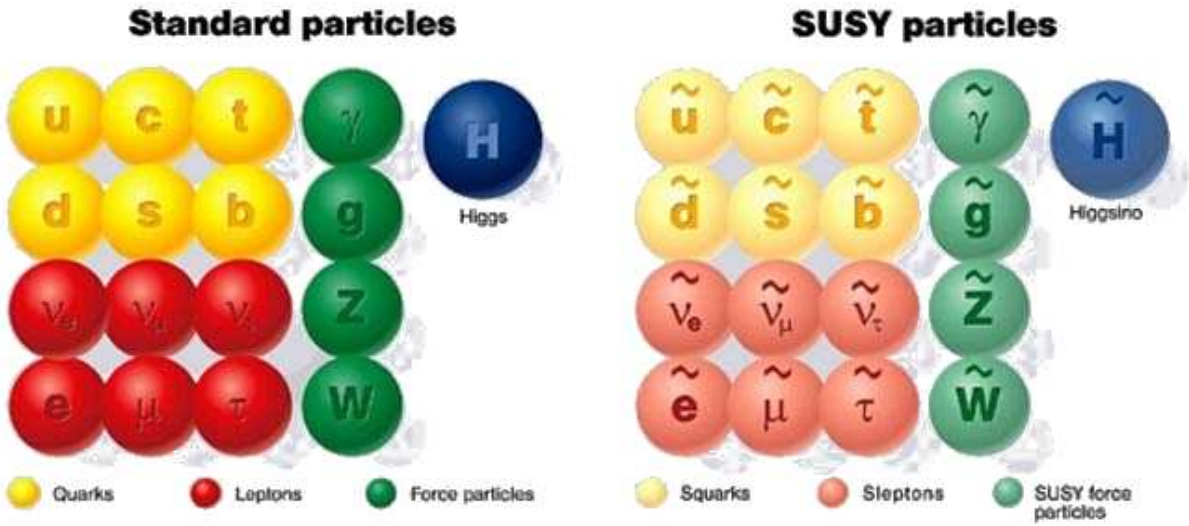
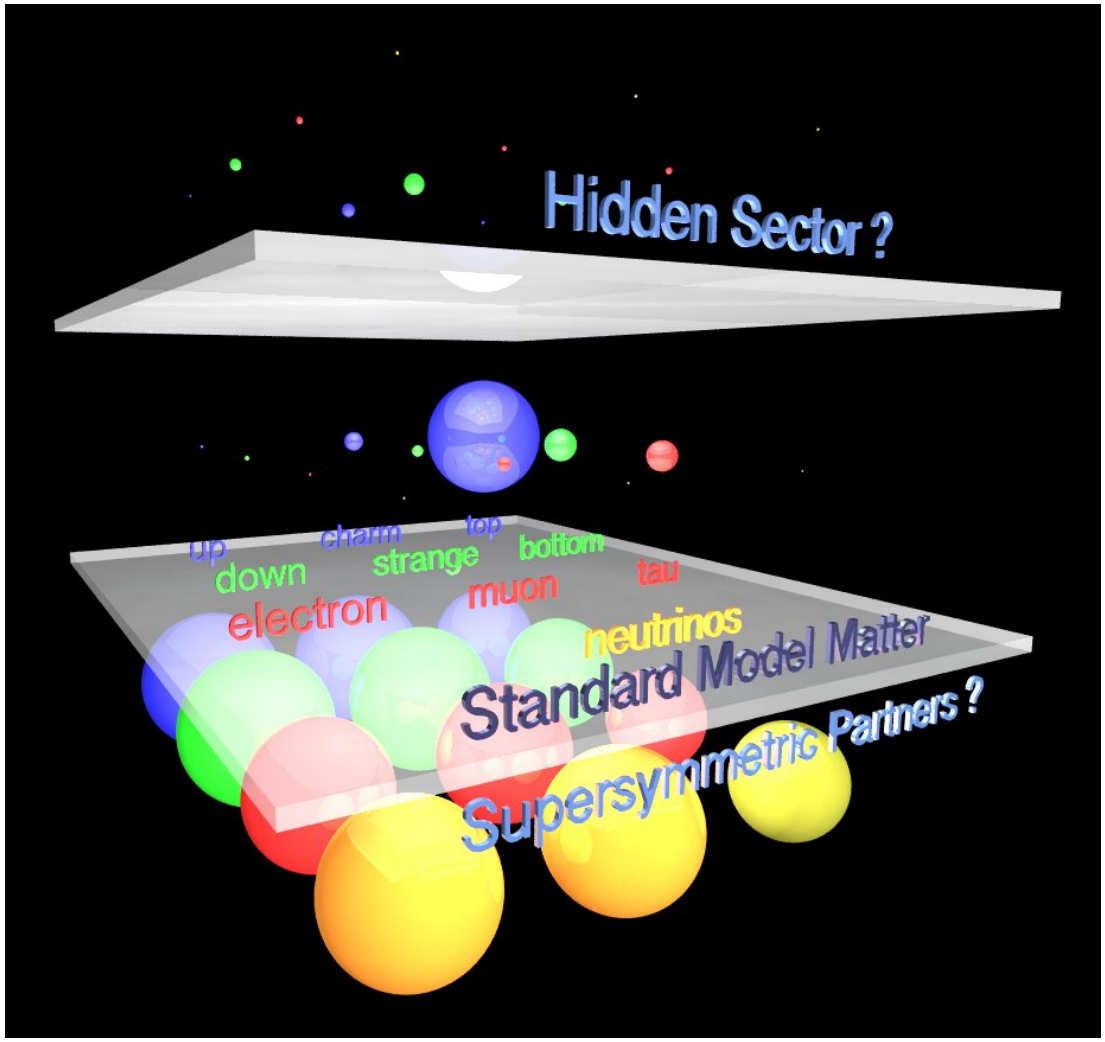


1. Introduction

- Most successful theory of all times: standard model
- Circumstantial evidence for existence of new particles beyond the standard model:
  - Dark matter
  - Unification of forces
  - Neutrino masses
- Many extensions of the standard model predict not only very massive, often very short-lived new particles, but also very light and very long-lived ones

$\Rightarrow$ A keyhole to hidden sectors of nature



[Ahlers (unpubl.)]

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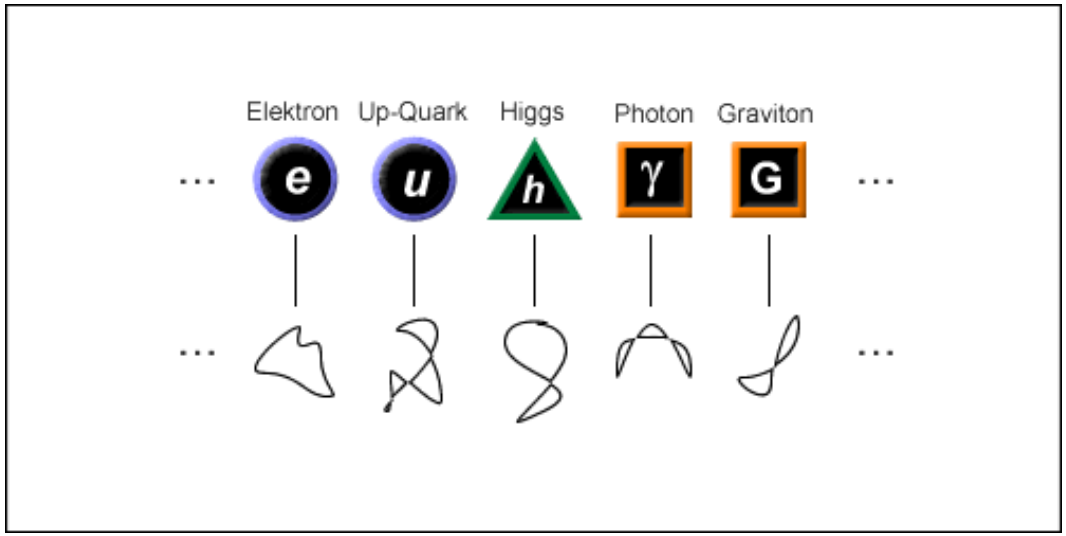
- Theoretically best motivated extensions of the standard model are based on string theory $\Leftrightarrow$ small strings in (9+1)-dimensional space-time are basic building blocks



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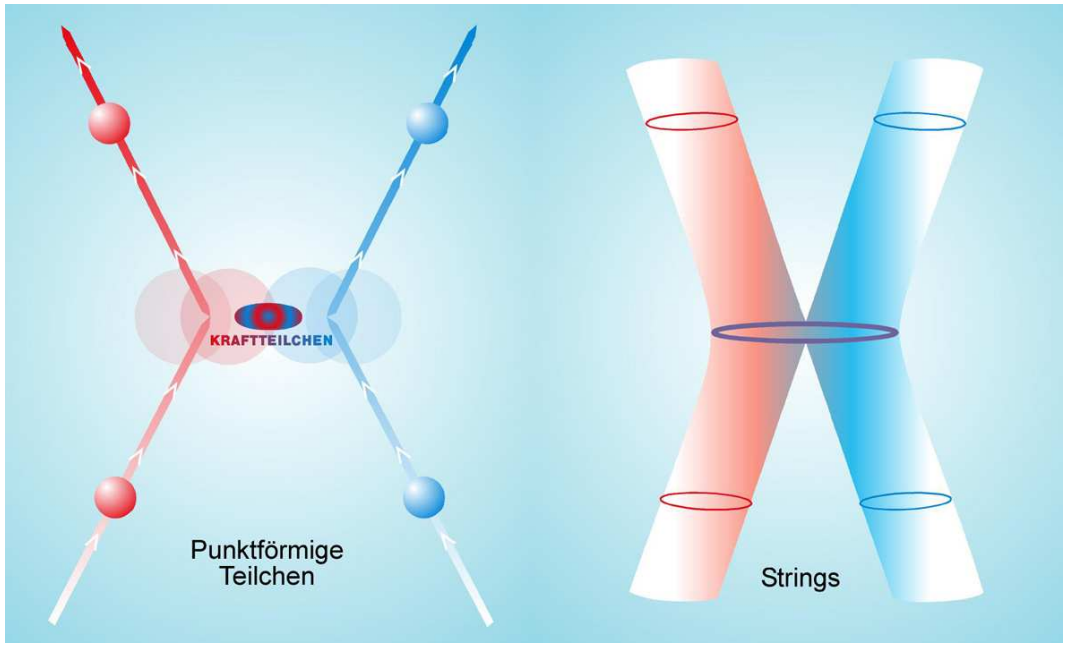

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  - Axion + Dilaton $(S = a + \mathrm{i}\mathrm{e}^{\phi})$

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	$C_{(1)}, C_{(3)}$

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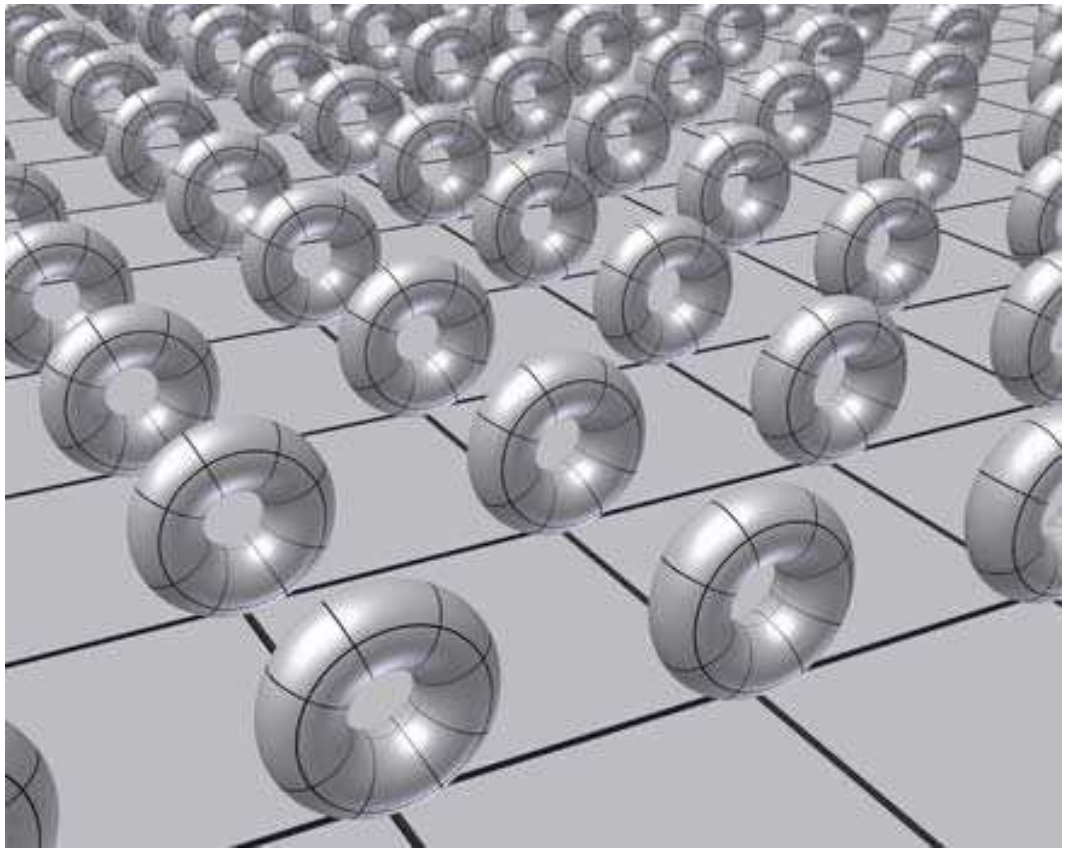
  - Low-energy description in (3+1) dimensions:



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  - Unification of all forces, including gravitation
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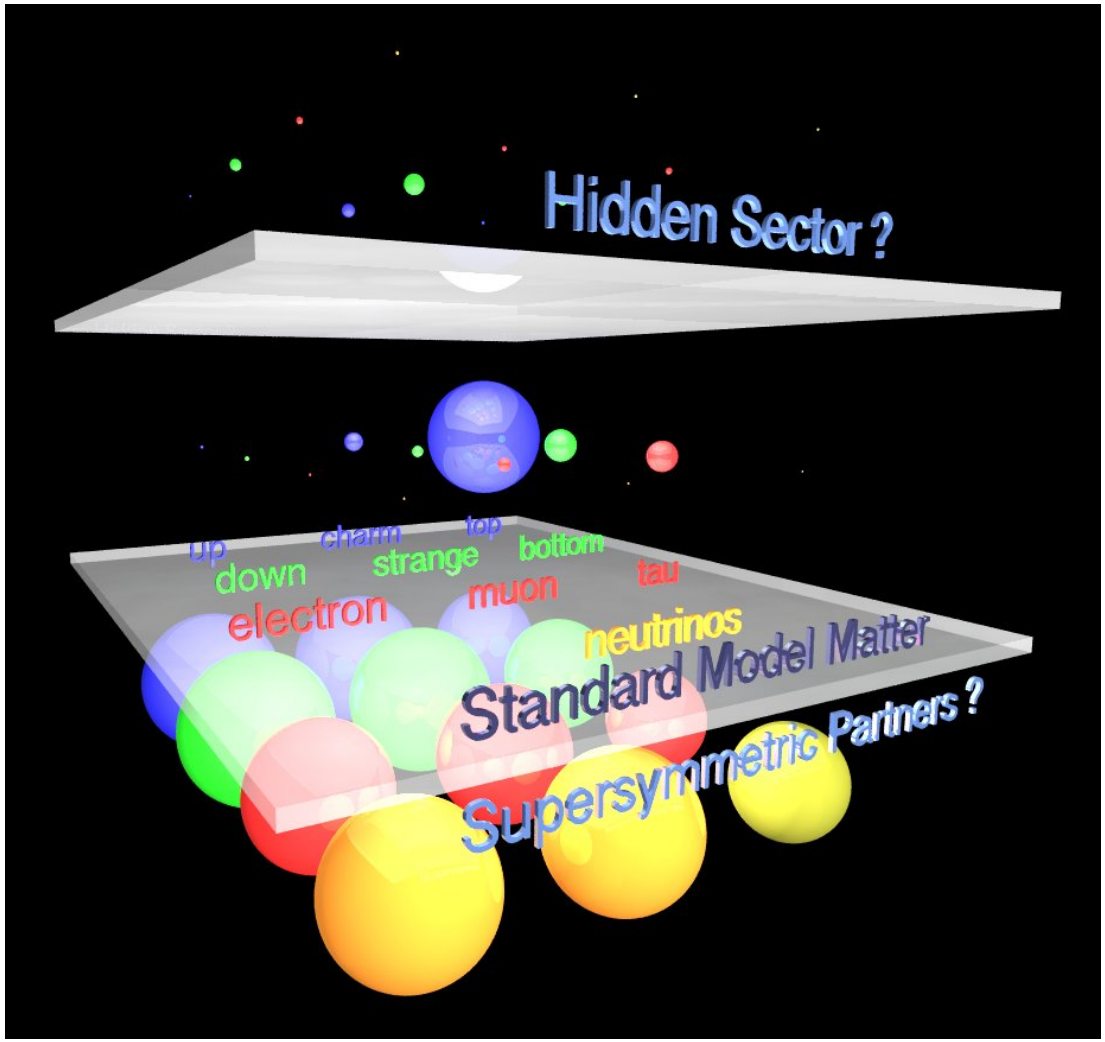
  - Low-energy description in (3+1) dimensions:
    - Particles of standard model + superpartners
    - "Hidden sector" particles: light(?) paraphotons, para-(s)electrons, ...



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Outline:

2. Paraphotons and Minicharged Particles

Small mixing of "hidden sector" extra U(1) gauge bosons with the photon naturally leads to small "visible" electromagnetic charges of "hidden sector" extra particles

3. Gauge Kinetic Mixing in String Theory

Extra U(1) gauge bosons and hidden sector extra particles occur naturally in embeddings of the standard model into string theory.

4. Summary

2. Paraphotons and Minicharged Particles

Minicharged particles arise very naturally in models with extra U(1) gauge bosons (paraphotons) [Okun '82; Holdom '85]

- Simplest model:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\mathrm{U}(1)_{\mathrm{em}}} \underbrace{-\frac{1}{4}B^{\mu\nu}B_{\mu\nu}}_{\mathrm{U}(1)_{\mathrm{hidden}}} \underbrace{-\frac{1}{2}\chi\, F^{\mu\nu}B_{\mu\nu}}_{\mathrm{mixing}}$$

- Dimensionless mixing parameter χ
  - $\chi = 0$ at high-energy scale
  - $\chi \neq 0$ generated by quantum fluctuations below this scale ($\Rightarrow$ later)

- Diagonalization of kinetic term:

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

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

- Hidden sector charged (e_h) particle gets induced electric charge:

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

$$\Rightarrow \quad Q_h \equiv \epsilon e = -\chi e_h$$

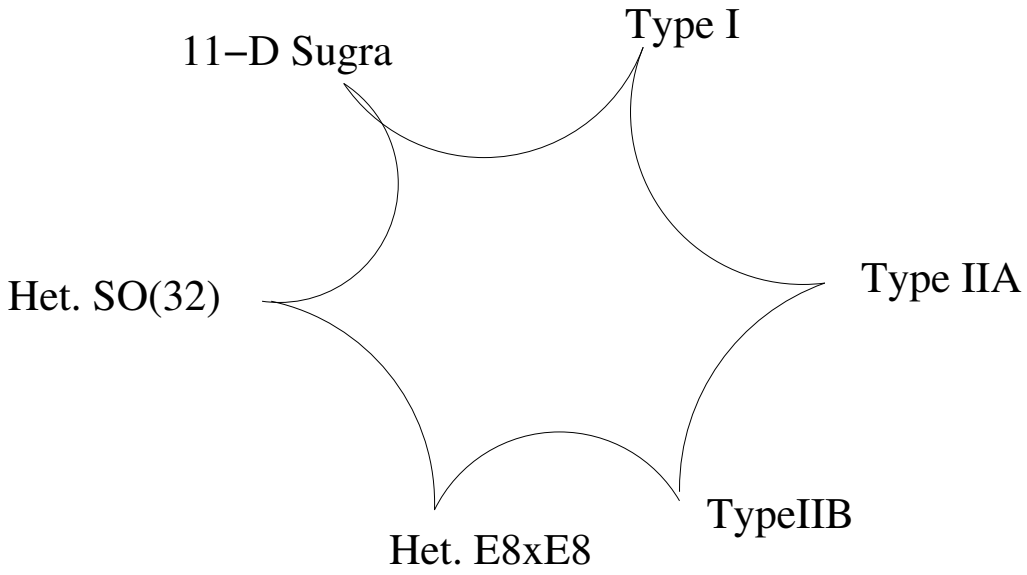
  – may be fractional
  – may be tiny, if $\chi \ll 1$: minicharged particle

- Value of χ in well-motivated extensions of standard model?

3. Gauge Kinetic Mixing in String Theory

[Abel,Jaeckel,Khoze,AR '06]

- Most standard model extensions based on string theory predict additional U(1) factors
- Expected size of χ in particular string theory setting can be investigated by performing a one-loop calculation



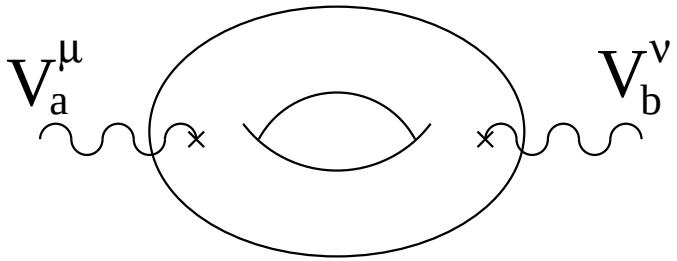
[Abel,Santiago '04]

3. Gauge Kinetic Mixing in String Theory

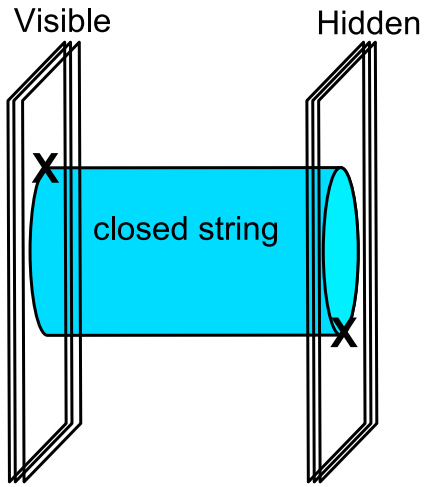
[Abel,Jaeckel,Khoze,AR '06]

- Most standard model extensions based on string theory predict additional U(1) factors
- Expected size of χ in particular string theory setting can be investigated by performing a one-loop calculation
  - Weakly coupled heterotic closed string models [Dienes,Kolda,March-Russell '97]
  - Open string models involving stacks of Dirichlet branes and antibranes [Abel,Schofield '04]

Heterotic string models:

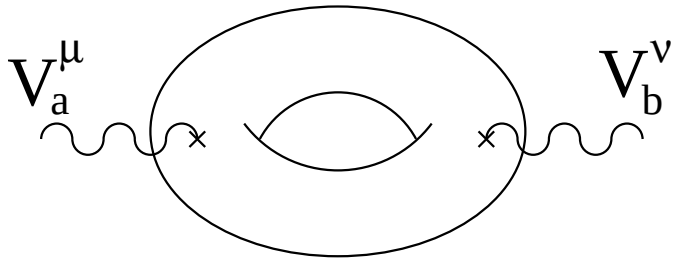


IIA/IIB string models:



Heterotic string models:

[Dienes,Kolda,March-Russell '97]

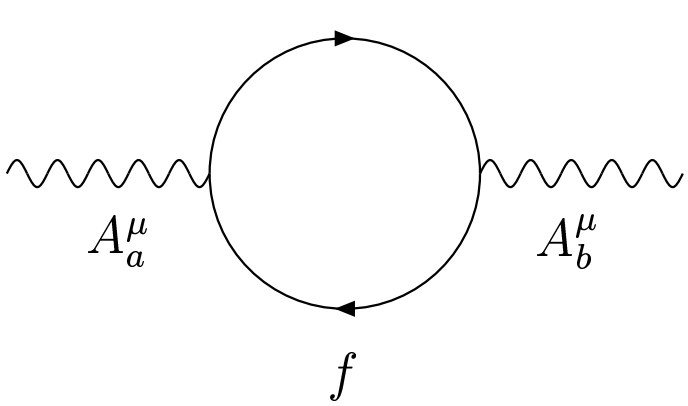


- Kinetic mixing can be avoided by choosing vacua in which additional U(1)s are embedded into non-abelian structure

- Otherwise, nevertheless "memory" of original underlying non-abelian structure $\Rightarrow$ small, but nonzero χ
  - Above string scale: kinetic mixing vanishes at LO
  - Below string scale: kinetic mixing appears due to splitting of relevant matter multiplets, cf. contribution from two chiral superfields,

(e, e_h) and $(e, -e_h)$, with masses m and m':

$$\chi \simeq \frac{e e_h}{16\pi^2} \log\left(\frac{m^2}{m'^2}\right)$$

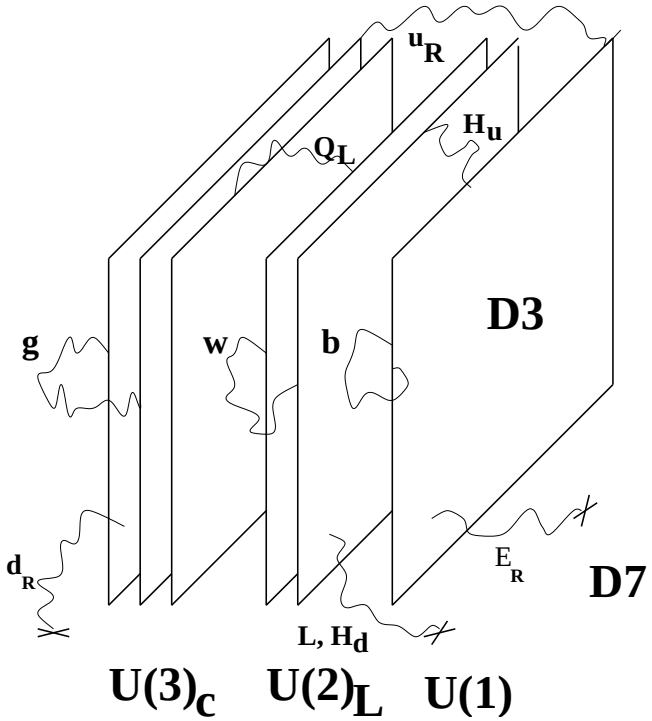


– Mass splittings $\Delta m \sim M_{\rm SUSY}^{\text{hidden sector}} \sim (\underbrace{10^4}_{\rm GM} \div \underbrace{10^{11}}_{\rm SUGRA})$ GeV $\Rightarrow$

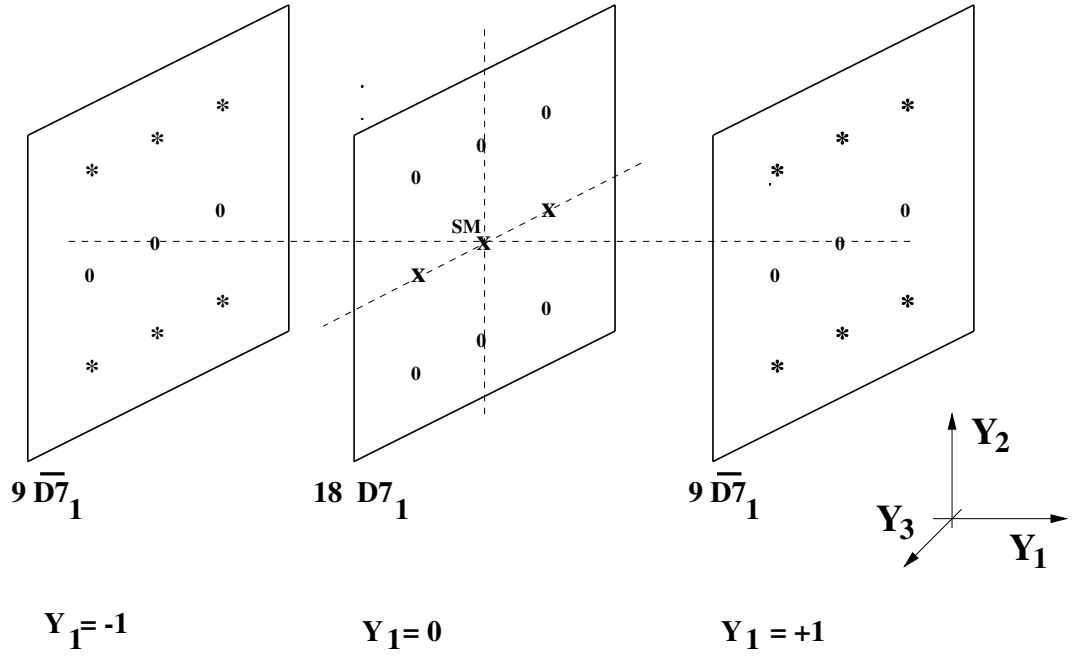
$$\chi \sim (\underbrace{\mathbf{10^{-16}}}_{\mathbf{GM}} \div \underbrace{\mathbf{10^{-9}}}_{\mathbf{SUGRA}})\ e_h\ \underbrace{C}_{\mathbf{10 \div 100}} \sim (10^{-15} \div 10^{-7})\ e_h$$

Open string models with D- and $\overline{\mathrm{D}}$-branes:

- IIB string models: [...;Aldazabal,Ibanez,Quevedo,Uranga '00;...]
  - Visible sector: stack of D3-branes at orbifold fixed point in internal space:



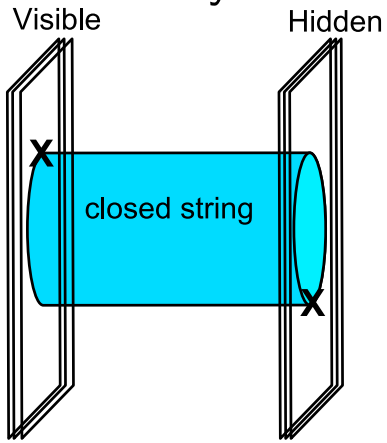
– Hidden sector: $\overline{\mathrm{D3}}$-branes at other fixed points in the bulk:



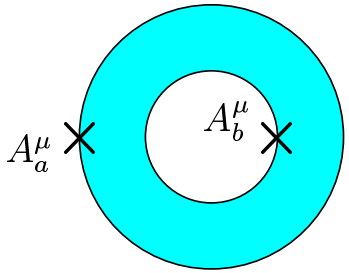
- IIA string models: [...;Blumenhagen,Görlich,Körs,Lüst '00;...]

  – Visible sector: D6-branes intersecting at non-trivial angles
  – Hidden sector: $\overline{\mathrm{D6}}$-branes in the bulk

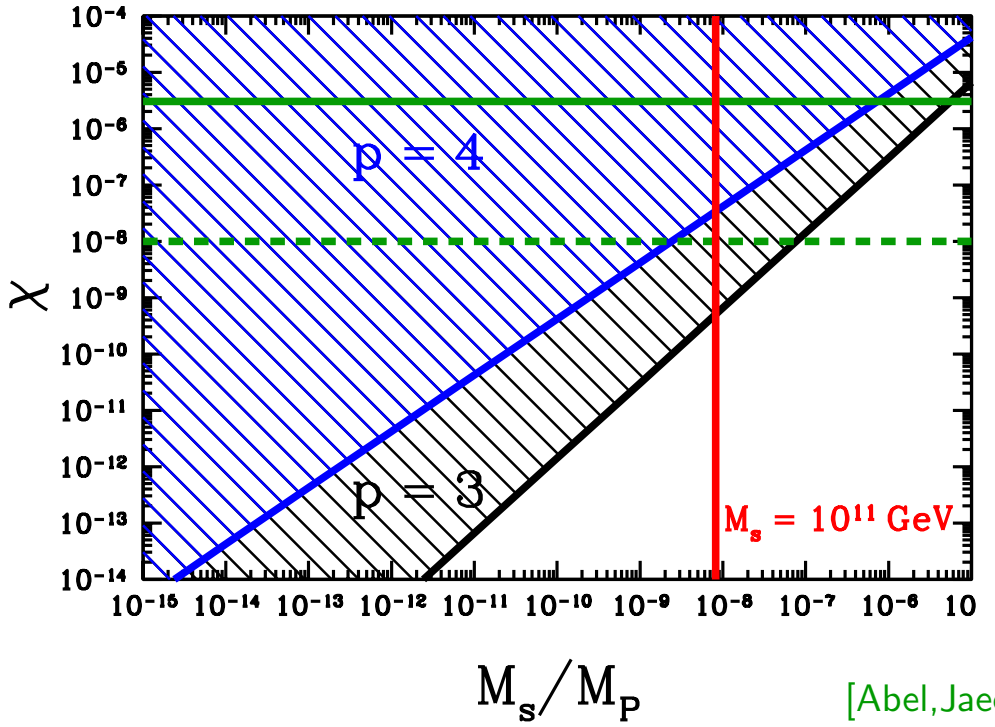
- Brane antibrane kinetic mixing: [Abel,Schofield '04]
  - Stack of hidden sector antibranes carry U(1) factors
  - Interact with visible sector branes by exchanging closed string modes:



  - Cylinder diagram in closed string channel $\Leftrightarrow$ kinetic mixing diagram in open string channel:



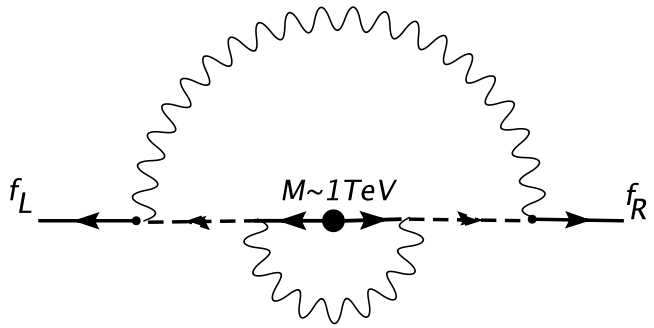
$$\chi \sim e\, e_h \frac{V_{\rm NN}}{V_{\rm DD,small}} (M_s R)^{p-d-7} \sim e\, e_h \left(\frac{2^{(8-p)/2}}{\alpha_p} \frac{M_s}{M_P} \right)^{\frac{2(5-p)}{6-p}} \left(\frac{R}{r} \right)^{\frac{d-p+3}{6-p}}$$



[Abel,Jaeckel,Khoze,AR '06]

- Hidden sector spectrum:
  - "Anomalous" hidden sector U(1) gauge bosons have mass $\sim M_s$
  - "Non-anomalous" hidden sector U(1) gauge bosons may be massless or light
  - Hidden sector charged matter multiplets may have sub-eV mass,

$$m_{\rm hidden} = \alpha_p^{-4} \frac{M_s^6}{M_P^4 \, \mu} \sim \alpha_p^{-4} \frac{M_W^2}{M_P}, \quad \text{for } M_s = \sqrt{M_W M_P} \sim 10^{11}\,\text{GeV}$$



⇒ Paraphotons and para(s)electrons are well motivated Weakly Interacting Sub-eV Particles (WISPs)

4. Summary

- In many realistic extensions of the standard model there are extra hidden sector U(1) gauge bosons, weakly mixing with the photon

- Hidden sector charged particles get a small electric charge $Q_h = \epsilon e = \chi e_h$

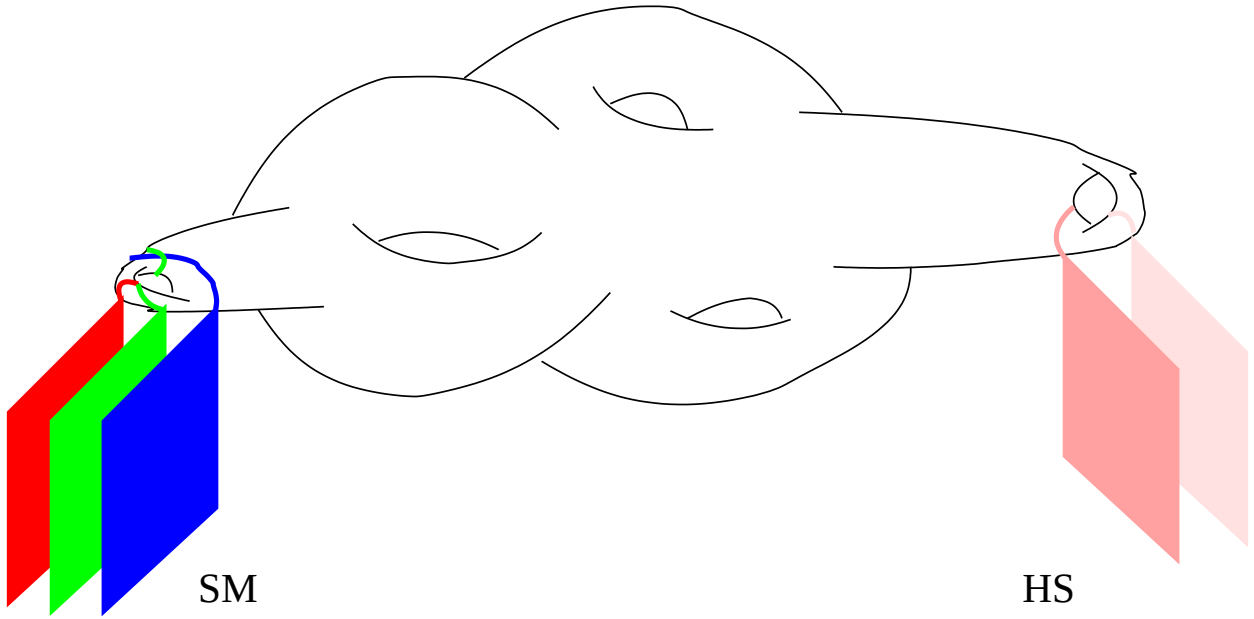
- Mixing parameter in many models expected to be in the range

$$\chi \sim 10^{-15} \div 10^{-7}$$

  Its size reflects parameters of the underlying high-energy theory (mass splittings, size of extra dimensions,..)

- Hidden sector U(1) gauge bosons as well as hidden sector charged particles may be light

- Searches for the effects of kinetic mixing, in particular for paraphotons and mini-charged particles, offer one of the few opportunities to explore the global structure of string compactifications:



[Blumenhagen,Braun,Körs,Lüst '02]

⇒ **Low energy photons shed light on the bulk and the hidden sector**