U(1) portals into hidden sectors

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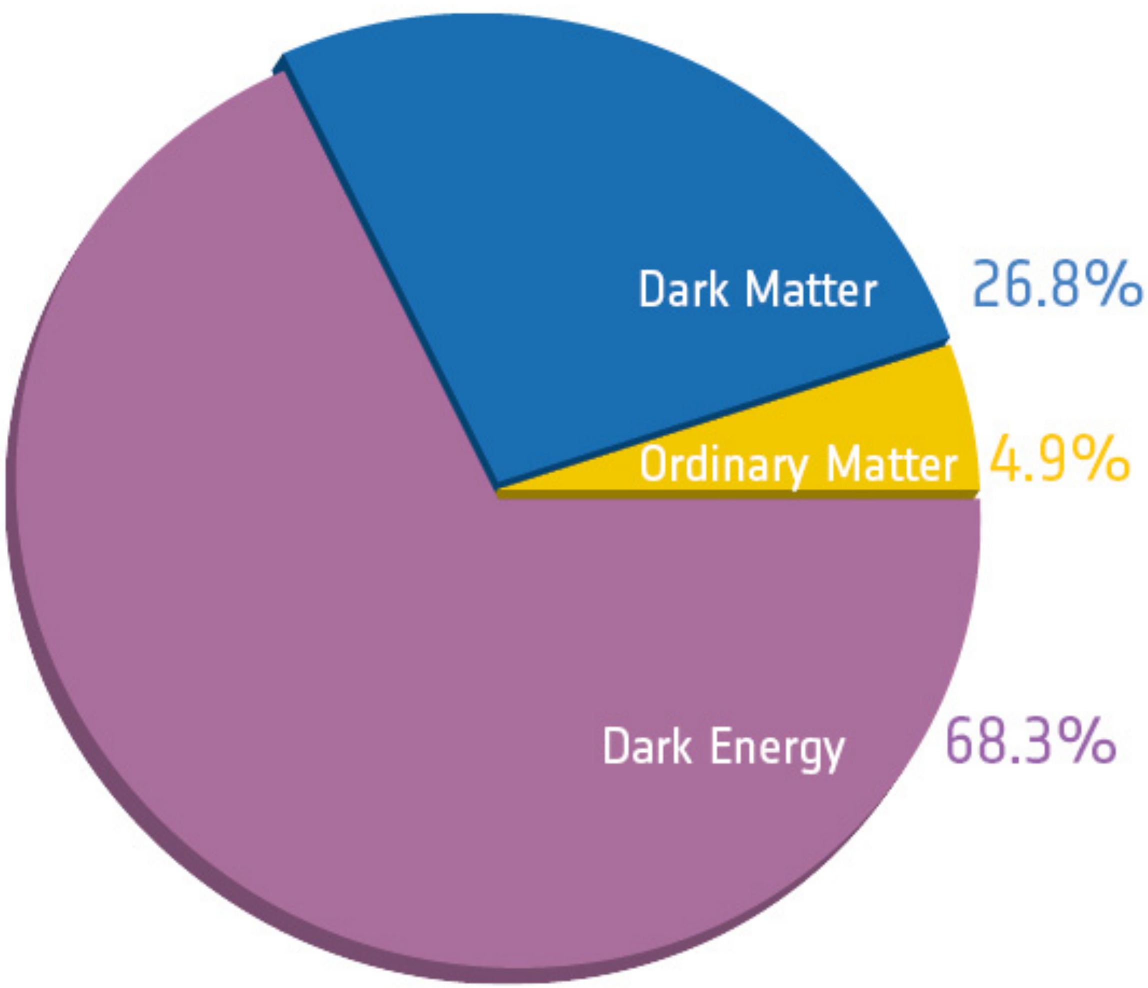
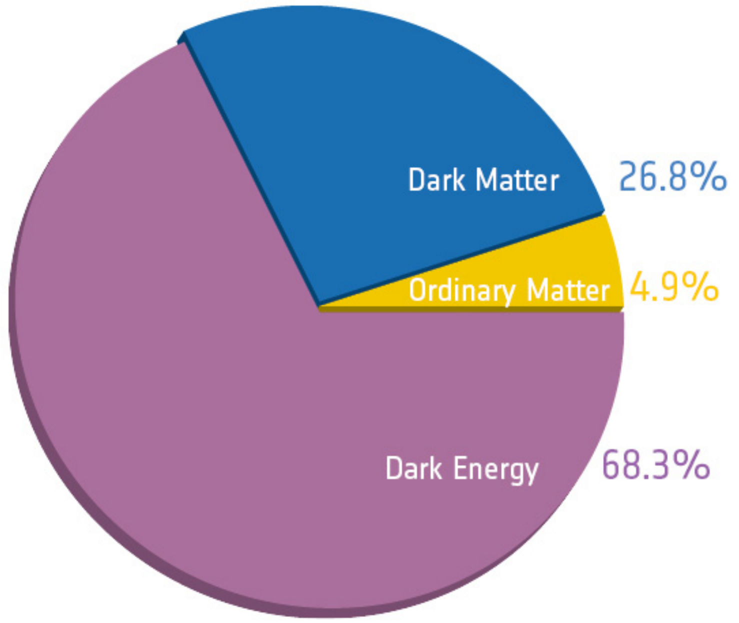
Motivation

- What is Dark Matter?



Motivation



- What is Dark Matter?

- Simple proposal: "Hidden Sector" scenario

$$\underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\Psi_{\rm v}} \quad \times \quad \underbrace{G_{\rm h}}_{\Psi_{\rm h}}$$

- Does DM interact with us (non-gravitationally)?

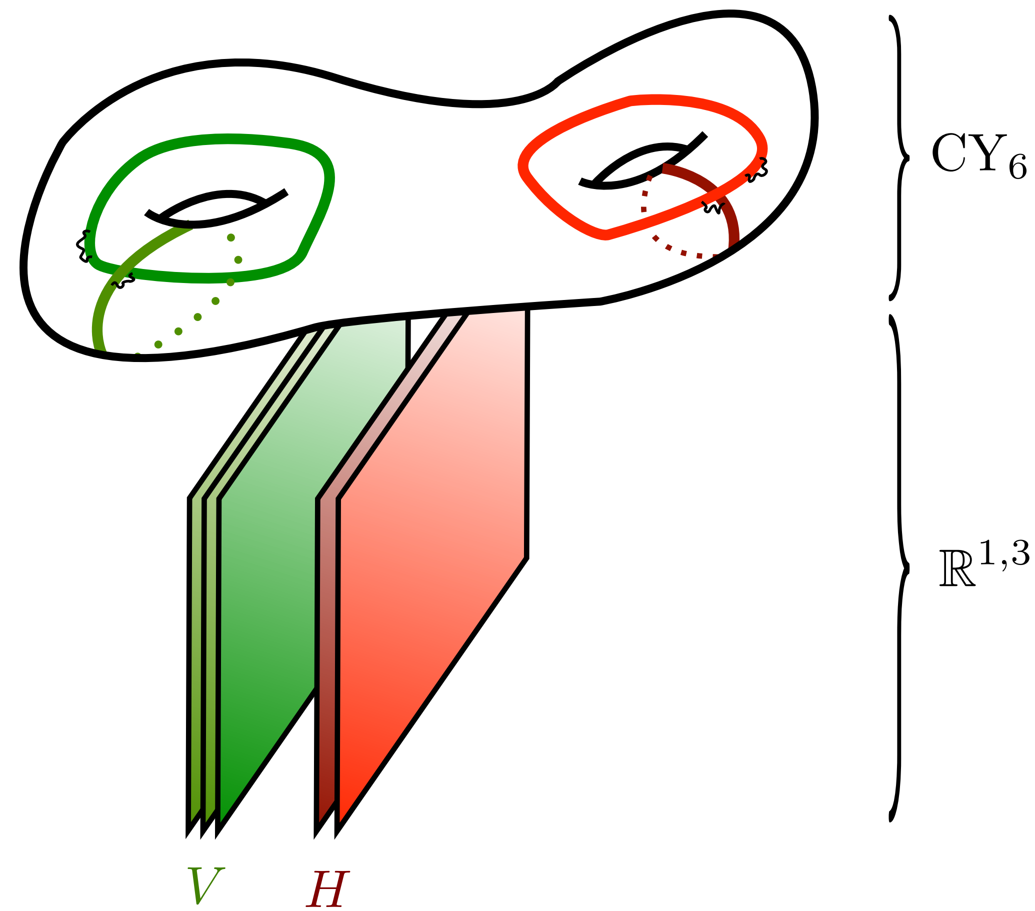
  "Portals": Higgs, axion, dilaton, hidden photons, Z',...

- Here we study the role played by U(1)'s as portals.

Motivation

- A simple setup: intersecting D-branes

$$\underbrace{\mathrm{SM}'}_{\Psi_\mathrm{v}} \times \underbrace{G'_\mathrm{h}}_{\Psi_\mathrm{h}}$$



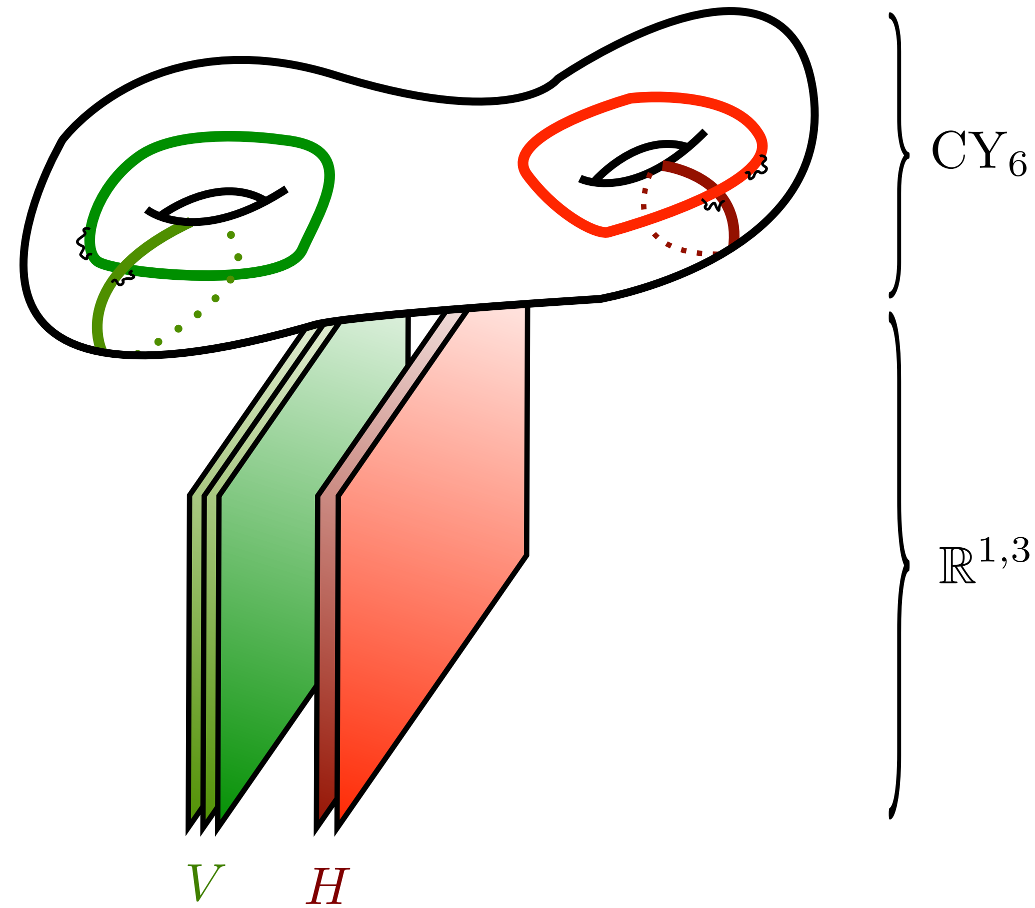
Motivation

- A simple setup: intersecting D-branes

$$\underbrace{\mathrm{SM}'}_{\Psi_{\mathrm{v}}} \times \underbrace{G'_{\mathrm{h}}}_{\Psi_{\mathrm{h}}}$$

- Gauge groups from stack of N-branes

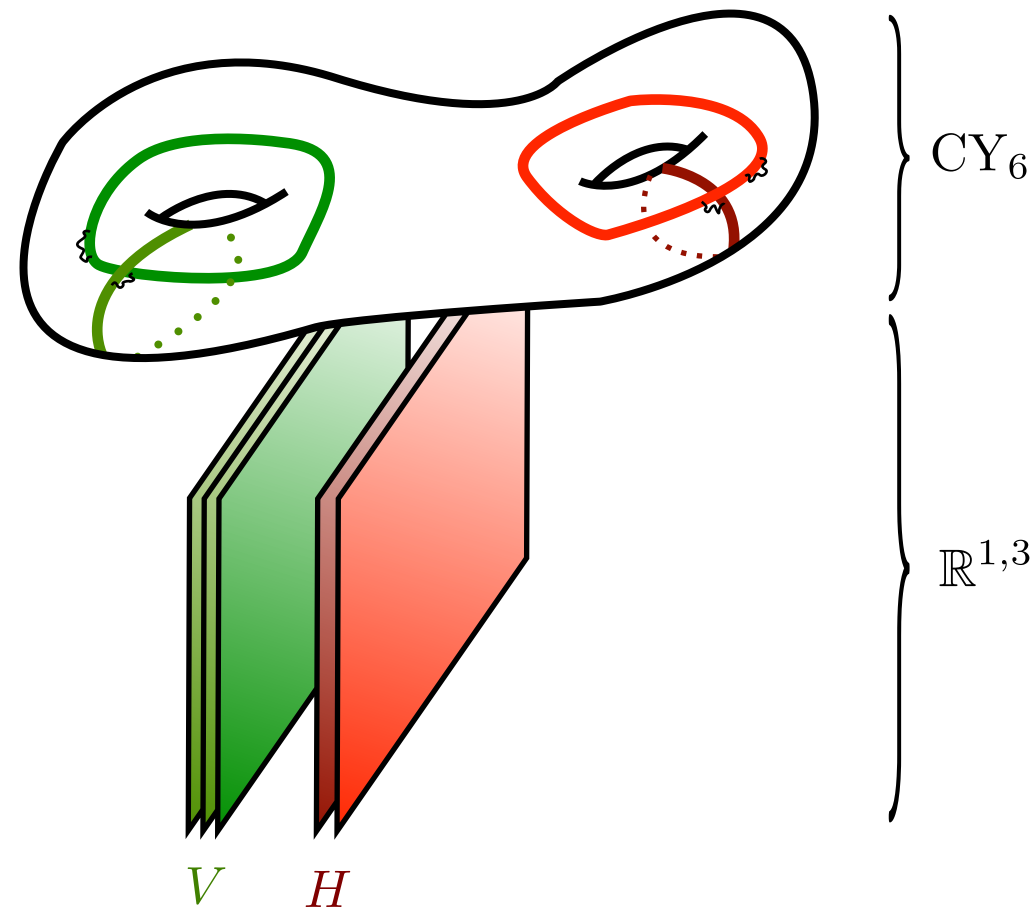
$$U(N) = SU(N) \times U(1)$$



Motivation

- A simple setup: intersecting D-branes

$$\underbrace{\mathrm{SM}'}_{\Psi_{\mathrm{v}}} \times \underbrace{G'_{\mathrm{h}}}_{\Psi_{\mathrm{h}}}$$



- Gauge groups from stack of N-branes

$$U(N) = SU(N) \times U(1)$$

- In (semi)-realistic D-brane models, what we get is

$$\underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)^n_{\mathrm{v}}}_{\Psi_{\mathrm{v}}} \times \underbrace{U(1)^m_{\mathrm{h}} \times G_{\mathrm{h}}}_{\Psi_{\mathrm{h}}}$$

Goal: study the role played by U(1)s as portals.

Overview

- Motivation.
- Milli-charged Dark Matter scenarios.
    - Field theory construction
    - Constraints from Quantum Gravity
    - Charge quantization and millicharges
- Stueckelberg portal via massive Z'.
- Conclusions

Milli-charged DM scenarios

Can DM carry a tiny electric charge?

Millicharged DM in field theory

$$\underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\Psi_{\rm v}} \times \underbrace{U(1)_{\rm h}}_{\Psi_{\rm h}}$$

- Charged massive states generate effective kinetic mixing: $\delta \ll 1$

$$\mathcal{L} = -\frac{1}{4} F_\gamma \cdot F_\gamma - \frac{1}{4} F_{\rm h} \cdot F_{\rm h} - \frac{\delta}{2} F_\gamma \cdot F_{\rm h} + A_\gamma \cdot J_{\rm e.m.} + A_{\rm h} \cdot J_{\rm h}$$

- Diagonalize kinetic term by: $A_\gamma \to \hat{A}_\gamma \qquad A_{\rm h} \to \hat{A}_h - \delta \hat{A}_\gamma$

$$\mathcal{L} = -\frac{1}{4} \hat{F}_\gamma \cdot \hat{F}_\gamma - \frac{1}{4} \hat{F}_{\rm h} \cdot \hat{F}_{\rm h} + \hat{A}_\gamma \cdot (J_{\rm e.m.} - \underline{\delta\, J_{\rm h}}) + \hat{A}_{\rm h} \cdot J_{\rm h} + \mathcal{O}(\delta^2)$$

- DM particles in $J_{\rm h}$ acquire a small **non-quantized** electric charge with respect to the visible (e.g. electron) charges.

$$\frac{q_{\rm h}}{q_{\rm e.m.}} \propto \delta \notin \mathbb{Q}$$

B. Holdom '86

Millicharged DM in field theory

- Add a mass matrix (of rank 1) to the previous model:

$$\mathcal{L}_{\text{Mass}} = -\frac{1}{2} \begin{pmatrix} A_\gamma & A_{\text{h}} \end{pmatrix} \begin{pmatrix} M_1^2 & M_1 M_2 \\ M_1 M_2 & M_2^2 \end{pmatrix} \begin{pmatrix} A_\gamma \\ A_{\text{h}} \end{pmatrix}$$

consider the case $\epsilon \equiv M_1/M_2 \ll 1$

- Diagonalize kinetic & mass terms:

$$\begin{cases} A_\gamma & \to \hat{A}_\gamma + (\epsilon - \delta)\hat{A}_M \\ A_{\text{h}} & \to \hat{A}_M - \epsilon\,\hat{A}_\gamma \end{cases}$$

$$\mathcal{L} \approx -\frac{1}{4}\hat{F}_\gamma^2 - \frac{1}{4}\hat{F}_M^2 - \frac{1}{2}M_2^2\hat{A}_M^2 + \hat{A}_\gamma\,(J_{\text{e.m.}} - \underline{\epsilon\,J_{\text{h}}}) + \hat{A}_M\,(J_{\text{h}} + (\epsilon - \delta)\,J_{\text{e.m.}})$$

- Again, DM carries a small (non-quantized) electric charge:

$$\frac{q_{\text{h}}}{q_{\text{e.m.}}} \propto \epsilon \notin \mathbb{Q}$$

B. Körs, P. Nath ’04

$\bullet \in \mathbb{Z}$

Millicharged DM in field theory

- General setup, multiple U(1)'s: $\vec{A}^T = (A_1 \; A_2 \; \ldots \; A_N)$

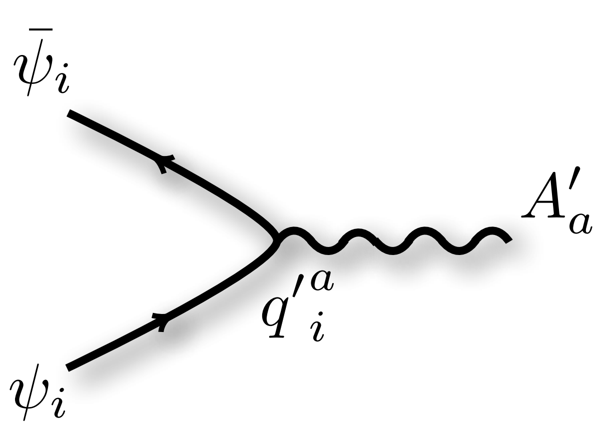
$$\mathcal{L} = -\frac{1}{4}\vec{F}^T \cdot f \cdot \vec{F} - \frac{1}{2}\vec{A}^T \cdot M^2 \cdot \vec{A} + \sum_i (\vec{q}_i^{\,T} \cdot \vec{A}) \; J^{(i)}$$

- Need canonical kinetic and diagonal mass terms:

$$\vec{A} \equiv \mathcal{T} \cdot \vec{A}' \qquad \text{s.t.} \quad \mathcal{T}^T \cdot f \cdot \mathcal{T} = 1 \,, \qquad \mathcal{T}^T \cdot M^2 \cdot \mathcal{T} = \mathrm{diag}(m_1^2, \cdots, m_n^2)$$

$$\mathcal{L} = -\frac{1}{4}(F_a')^2 - \frac{1}{2}m_a^2 (A_a')^2 + \sum_i (\vec{q}_i^{\,T} \cdot \mathcal{T} \cdot \vec{A}') \; J^{(i)}$$

- Physical 'charges':



$$(q')_i^a \equiv q_i^b \cdot \mathcal{T}_b{}^a \qquad \Longrightarrow \qquad \frac{(q')_i^a}{(q')_j^a} \notin \mathbb{Q}$$

Quantization???

Quantum gravity constraints

$$U(1) \quad \text{or} \quad \mathbb{R} \quad ???$$

- Non-quantized charges signal non-compact groups.
- Field theories with non-compact gauge groups cannot be consistently coupled to quantum gravity.
- Take a theory with elementary charges 1 and $\sqrt{2}$. Construct a black hole with charge

$$q_{\rm bh} = n \cdot 1 + m \cdot \sqrt{2}$$

By appropriate choices of (n, m) one can make $q_{\rm bh}$ arbitrarily small. For infinite choices of (n, m) the corresponding microstates are indistinguishable. This implies a violation of the Covariant Entropy Bound.

T. Banks, N. Seiberg ' 10

Charge quantization:

Millicharge DM scenarios in
quantum gravity

Millicharges & Quantization

$\bullet \in \mathbb{Z}$

- U(1) masses from Stueckelberg or Higgs mechanisms:

$$\mathcal{L}_M = -\frac{1}{2} G_{ij} (\partial \phi^i + k^i_a A^a)(\partial \phi^j + k^j_b A^b)$$

  - Gauge bosons absorb periodic axions: $\phi^i \sim \phi^i + 1$
  - Gauge transformations read

$$A^a \to A^a + d\Lambda^a \ , \qquad \phi^i \to \phi^i - k^i_a \Lambda^a \ , \qquad \psi_\alpha \to e^{2\pi i q^\alpha_a \Lambda^a} \psi_\alpha$$

  - **Compactness** of U(1), requires (in appropriate normalization)

$$\Lambda^a \sim \Lambda^a + 1 \qquad \Longrightarrow \qquad k^i_a,\, q^\alpha_a \in \mathbb{Z}$$

$$M^2 = K^T \cdot G \cdot K$$

$G_{ij} \in \mathbb{R}$ — Axion metric: Positive definite

$K^i_a \in \mathbb{Z}$

$\bullet \in \mathbb{Z}$

Millicharges & Quantization

- Diagonalization revisited:

$$\mathcal{L} = -\frac{1}{4}\vec{F}^T \cdot f \cdot \vec{F} - \frac{1}{2}\vec{A}^T \cdot (K^T G K) \cdot \vec{A} + \sum_i (\vec{q}_i^T \cdot \vec{A})\ J^{(i)}$$

- G and f positive-definite, zero-mass eigenstates determined by:

$$K \cdot \vec{w} = 0$$

- Assume a single massless boson ($\vec{w}$ is unique).
  After diagonalization:

$$A_\gamma^{\text{phys}} = e\ \vec{w}^T \cdot f \cdot \vec{A}$$

$$q_i^{\text{phys}} = e\ (\vec{q}_i^T \cdot \vec{w}) \quad \Longrightarrow \quad \frac{q_i^{\text{phys}}}{q_j^{\text{phys}}} \in \mathbb{Q}$$

Charges are quantized
"No millicharges"

Millicharges & Quantization

- Diagonalization revisited:

$$\mathcal{L} = -\frac{1}{4}\vec{F}^{\,T}\cdot f\cdot\vec{F} - \frac{1}{2}\vec{A}^{T}\cdot(K^{\,T}\,G\,K)\cdot\vec{A} + \sum_i(\vec{q}_i^{\,T}\cdot\vec{A})\;J^{(i)}$$

- G and f positive-definite, zero-mass eigenstates determined by:

$$K\cdot\vec{w} = 0$$

- Assume <u>two massless bosons</u>: $K\cdot\vec{w}_{1,2} = 0$

- However $\vec{w}_1^{\,T}\cdot\vec{w}_2 \neq 0$. Need to project, e.g. $\vec{w}_2$ onto subspace orthogonal to $\vec{w}_1$. After diagonalization physical ‘charges’ read:

$$q_i^{(1)} = g_1\,(\vec{q}_i^{\,T}\cdot\vec{w}_1)\,; \qquad q_i^{(2)} = g_2\,\vec{q}_i^{\,T}\cdot(\vec{w}_2 - \delta\,\vec{w}_1)$$

$$\delta \equiv g_1^2\,(\vec{w}_2^{\,T}\cdot f\cdot\vec{w}_1)$$

Millicharges & Quantization

$$q_i^{(1)} = g_1 \left(\vec{q}_i^{\,T} \cdot \vec{w}_1\right) ; \qquad q_i^{(2)} = g_2 \, \vec{q}_i^{\,T} \cdot \left(\vec{w}_2 - \delta \, \vec{w}_1\right)$$

$$\delta \equiv g_1^2 \left(\vec{w}_2^{\,T} \cdot f \cdot \vec{w}_1\right)$$

Millicharges & Quantization

$$q_i^{(1)} = g_1 \left(\vec{q}_i^{\,T} \cdot \vec{w}_1 \right); \qquad q_i^{(2)} = g_2 \, \vec{q}_i^{\,T} \cdot \left(\vec{w}_2 - \delta \, \vec{w}_1 \right)$$

$$\delta \equiv g_1^2 \left(\vec{w}_2^{\,T} \cdot f \cdot \vec{w}_1 \right)$$

- Non-quantized $q^{(2)}$ (milli)charges via kinetic mixing of **massless** U(1)'s

$$\frac{q_i^{(2)}}{q_j^{(2)}} \propto \delta \notin \mathbb{Q}$$

- Massive bosons don't play any role.

- No problems with quantum gravity, charged objects are always distinguishable. **Gauge group still compact.**

Massive U(1)'s:

The Stueckelberg portal

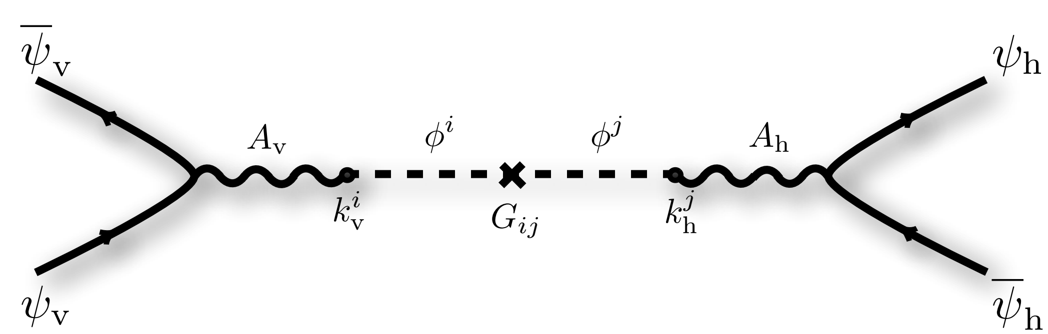
Stueckelberg Z’ portal

$$\underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathbf{U(1)^n_v}}_{\Psi_{SM}} \times \underbrace{\mathbf{U(1)^m_h} \times G_h}_{\chi_{DM}}$$

- U(1) mass terms read:

$$\mathcal{L}_M = -\frac{1}{2} G_{ij} (\partial\phi^i + k^i_a A^a)(\partial\phi^j + k^j_b A^b) \implies M^2 = K^T \cdot G \cdot K$$

- Non-diagonal mass terms mix visible and hidden U(1)s
  - From non-diagonal metric G.
  - From an axion ϕ^i coupled to different U(1)s.



- Mass mixing from axionic charges k^i_a is generically large:
  - Tree-level effect controlled by integers

Stueckelberg Z' portal

- Toy model with two massive U(1)s: $(U(1)_{\rm v} \;\; U(1)_{\rm h})$
- Two axions with generic 'charges': $K = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$
- Assume for simplicity: $G = \begin{pmatrix} M^2 & 0 \\ 0 & m^2 \end{pmatrix} = M^2 \begin{pmatrix} 1 & 0 \\ 0 & \epsilon^2 \end{pmatrix}, \quad \epsilon \ll 1$
- Set U(1) canonical kinetic term and diagonalize mass matrix:
  - Eigenstates:
    $$Z'_m \approx g_{\rm h}\, b\, A_{\rm v} - g_{\rm v}\, a\, A_{\rm h} \qquad {\rm Mass}(Z'_m) \propto m$$
    $$Z'_M \approx g_{\rm v}\, a\, A_{\rm v} + g_{\rm h}\, b\, A_{\rm h} \qquad {\rm Mass}(Z'_M) \propto M$$
  - Interactions:
    $$\mathcal{L}_{\rm int} = g_{\rm v} A_{\rm v} J_{\rm v} + g_{\rm h} A_{\rm h} J_{\rm h}$$
    $$\approx g_m Z'_m (b\, J_{\rm v} - a\, J_{\rm h}) + g_M Z'_M (a\, J_{\rm v} + \chi^2 b\, J_{\rm h})$$
- Physical Z's communicate visible and hidden sectors.

Conclusions

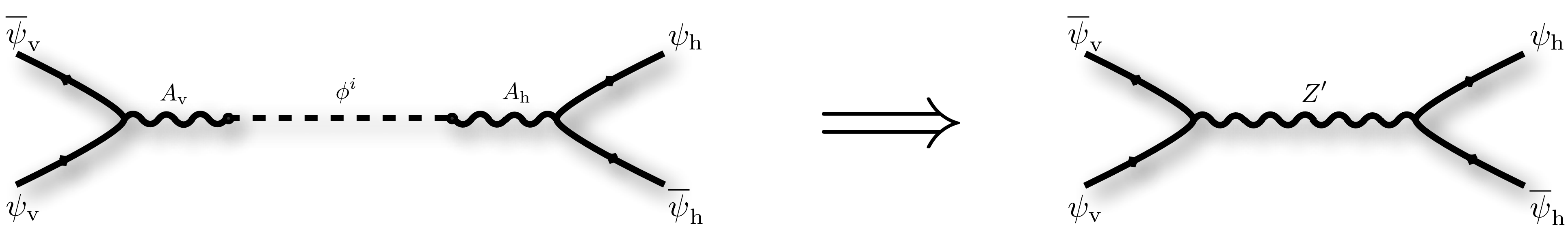
Conclusions

- Hidden sectors are natural scenarios in string theory models

$$\underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{\rm v}^n}_{\Psi_{\rm v}} \times \underbrace{U(1)_{\rm h}^m \times G_{\rm h}}_{\Psi_{\rm h}}$$

- Hypercharge can naturally mix with hidden U(1)'s
  - Kinetic mixing: mini-charged DM ✔
  - Mass mixing: fractional charges ✘

- Mass mixing of extra U(1)'s is possible and interesting



  - Tree-level mixing generates Z' mediation: DM and ~~SUSY~~
  - Simple explicit implementation in D-brane realistic models

Thank you