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U(1) portals into dark sectors

Gary Shiu

Based on:

- Millicharged Dark Matter in Quantum Gravity and String Theory

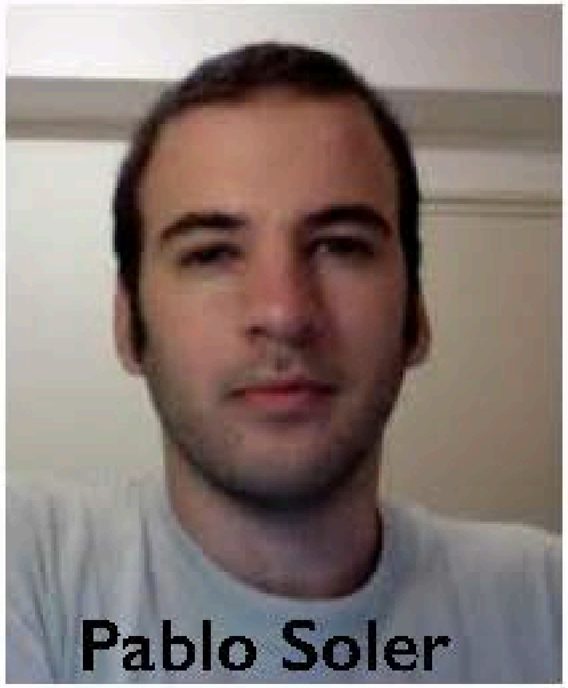
  GS, P. Soler, F. Ye, Phys. Rev. Lett. **110**, 241304 (2013)

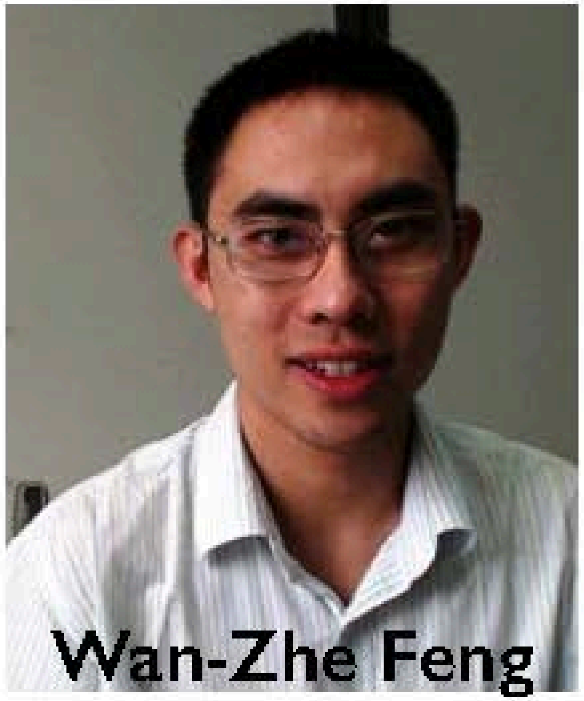
- Stueckelberg Portal into Dark Sectors

  W.-Z. Feng, GS, P. Soler, F. Ye, arXiv:1401.5880 [hep-ph]

- Building a Stueckelberg Portal

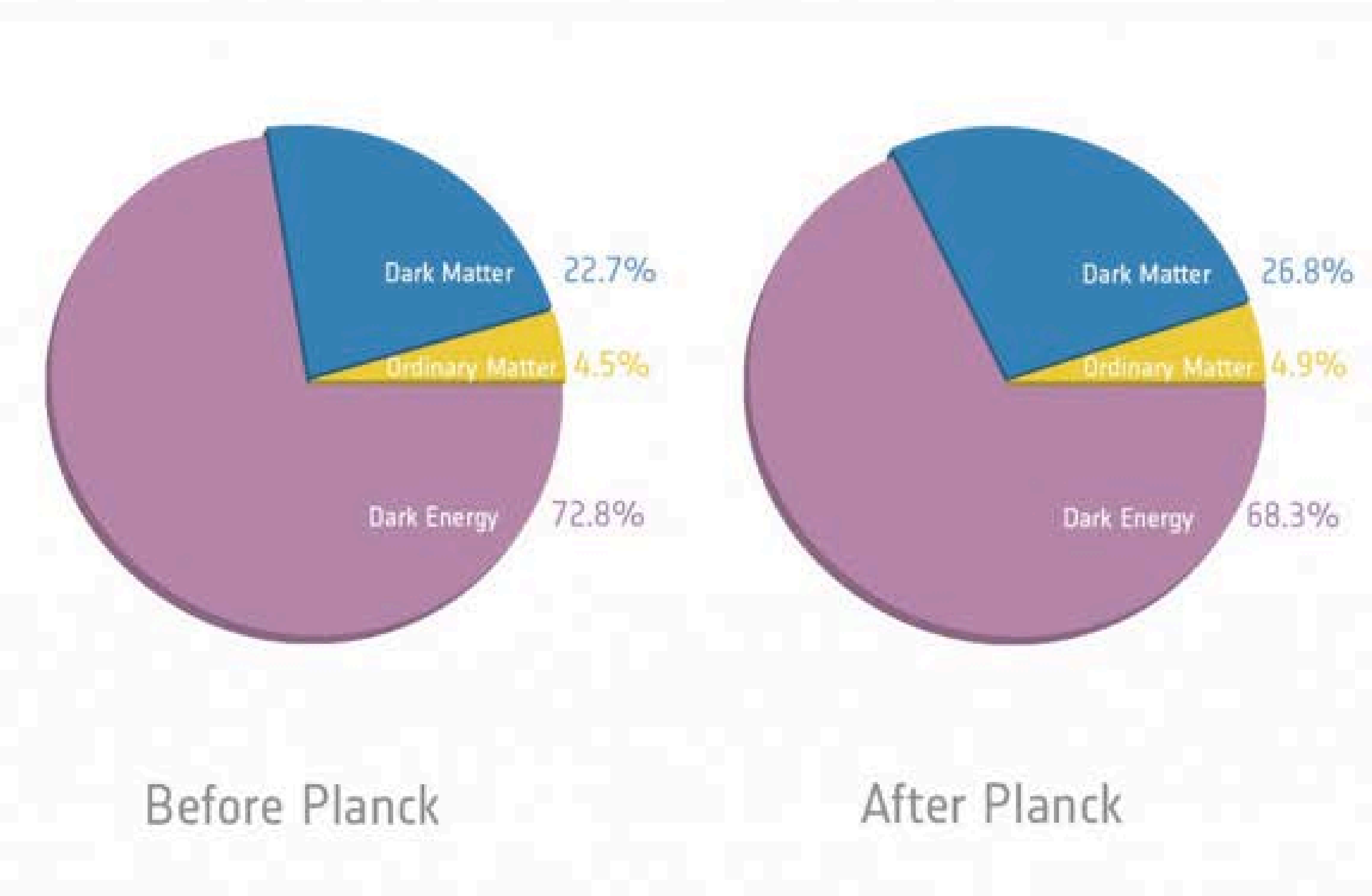
  W.-Z. Feng, GS, P. Soler, F. Ye, arXiv:1401.5890 [hep-ph]





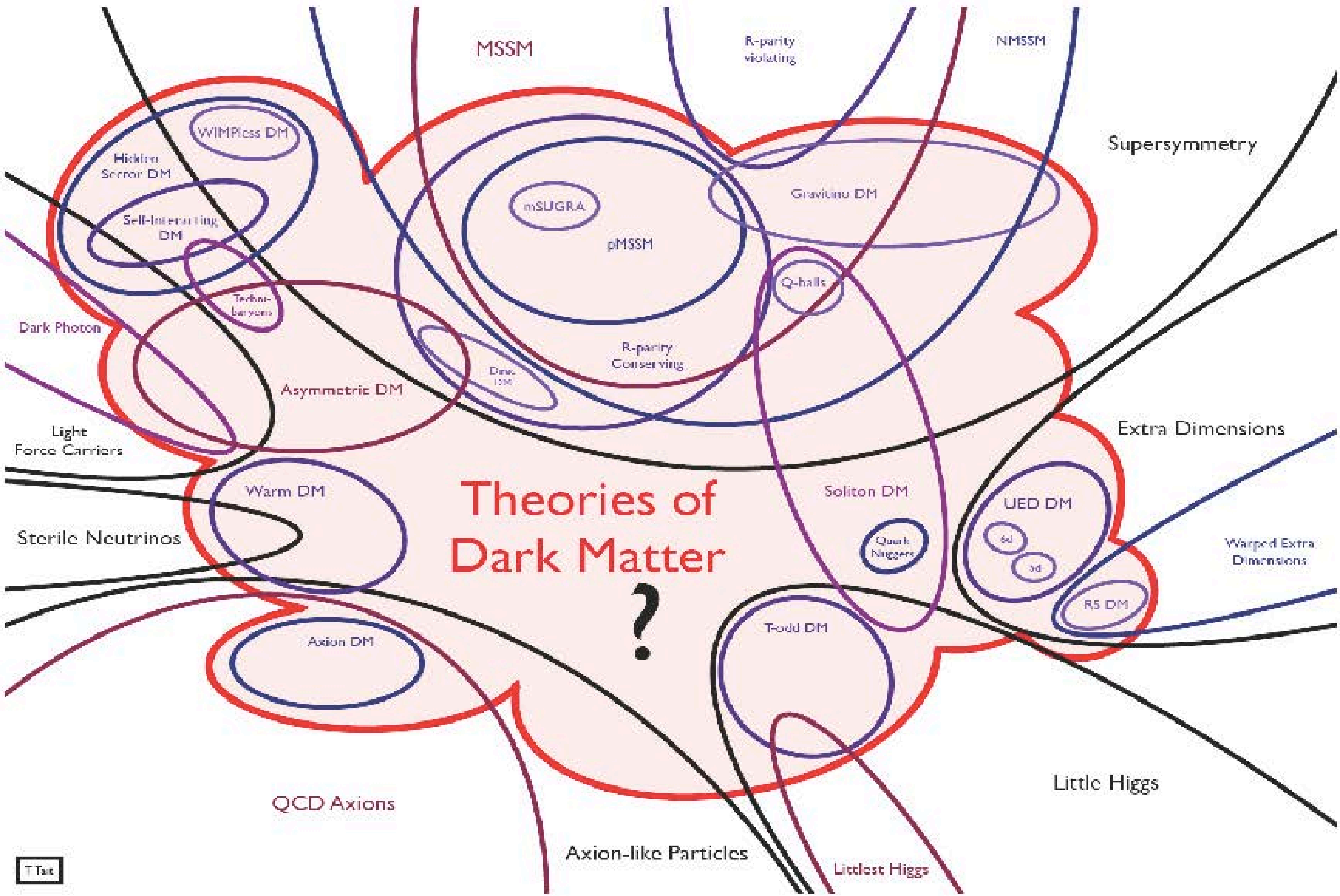
Motivation

- There is now overwhelming evidence that normal (atomic) matter is not all the matter in the Universe:



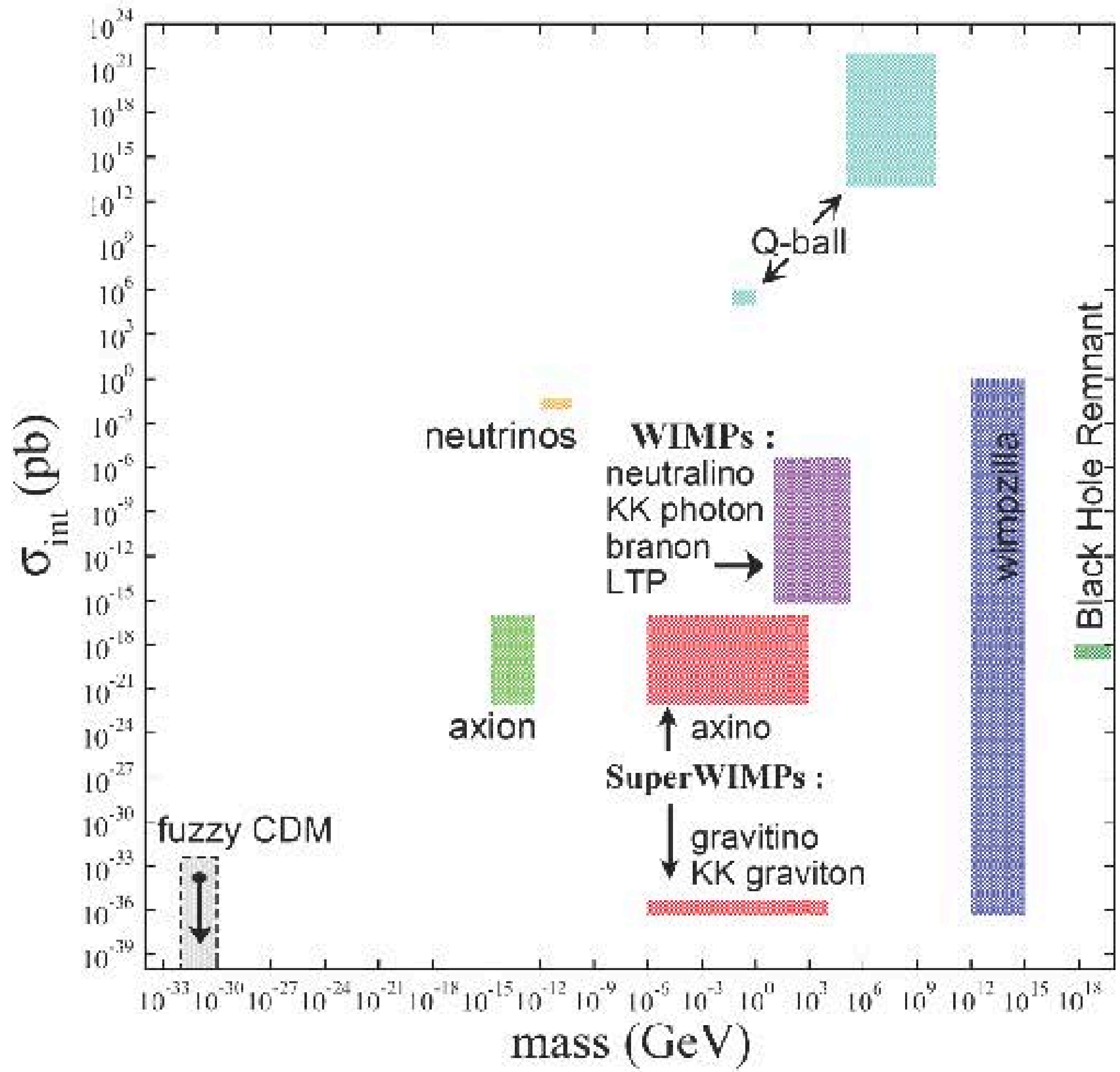
- Realizing dark energy in string theory (work with various linear combinations of Danielsson, Haque, Koerber, Underwood, Van Riet, Wrase, Chen, Sumitomo, Tye) is a subject of a different talk.

Dark Matter Candidates



Dark Matter Candidates

- Unfortunately, we don't know what its other properties are, and there are many possibilities.
- Masses & interaction strengths span ***many, many orders of magnitude***.
- Some candidates are better motivated than others?



HEPAP/AAAC DMSAG Subpanel (2007)

Motivation

- Does Dark Matter interact with the SM (non-gravitationally)?
    - Via weak direct interactions? (e.g. milli-charged DM)
    - Via heavy intermediate states? (“hidden valley” scenarios)
- Numerous experimental efforts into (in)direct detection of DM candidates; different scenarios suggest different search strategies.
- How well theoretically motivated are different scenarios?
    - Can they be embedded into string theory?

Motivation

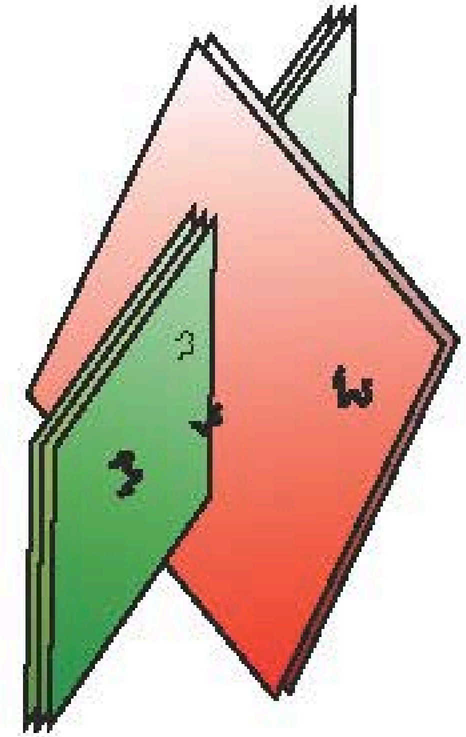
- We focus on scenarios with 'hidden sectors' that host DM:

$$\underbrace{SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}}_{\Psi_{\mathrm{SM}}} \times \underbrace{U(1)_{\mathrm{h}}^{m} \times G_{\mathrm{h}}}_{\chi_{\mathrm{DM}}}$$

- Several portals have been proposed to communicate both sectors
  - Higgs boson, axion, gravity, dilaton, hidden photons, Z',…
- Here we focus on the role played by U(1)s as portals:
  - Milli-charged Dark Matter scenarios
  - Stueckelberg portals
  - Hidden photons

Motivation

- D-brane implementation (intersecting branes)



  - The gauge theory on a stack of N_i D-branes:

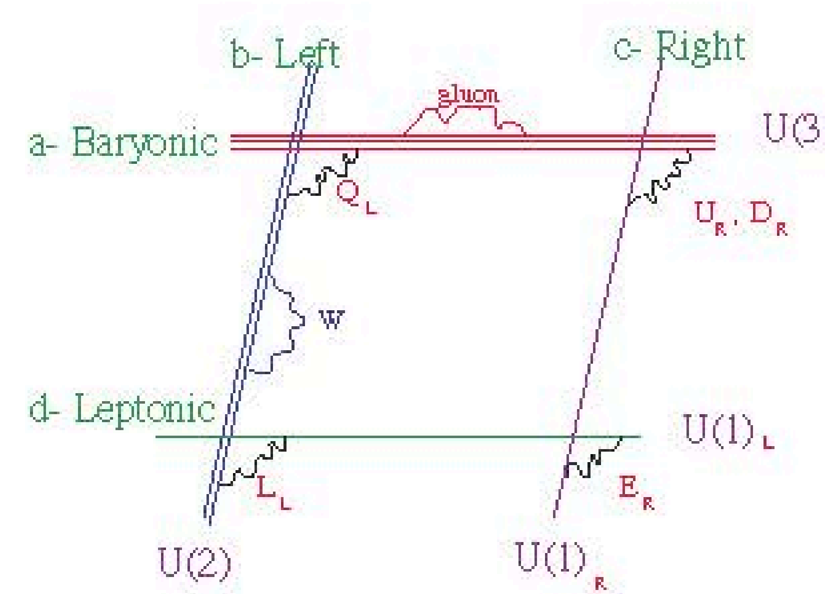
$$U(N_i) \cong SU(N_i) \times \underline{\mathbf{U(1)}}$$

  - Charged chiral matter from intersections

$$\Psi_{ab} : \qquad (\overline{\mathbf{N}}_{\mathbf{a}}, \mathbf{N}_{\mathbf{b}})_{(-1,+1)}$$

- Simple models can reproduce the SM with extra (massive) U(1)s:

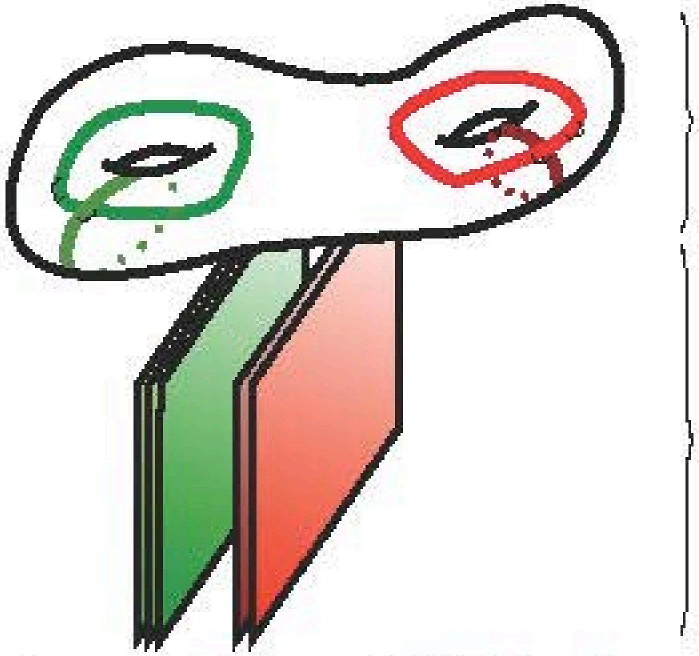
$$\text{`SM'} \cong SU(3) \times SU(2) \times \underline{\mathbf{U(1)^m}}$$



For review, see e.g., [Blumenhagen, Cvetic, Langacker, GS]

Motivation

- We can construct different gauge sectors with stacks of branes separated in the internal space



- Our models will consist of the 'SM' plus a 'hidden sector'

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

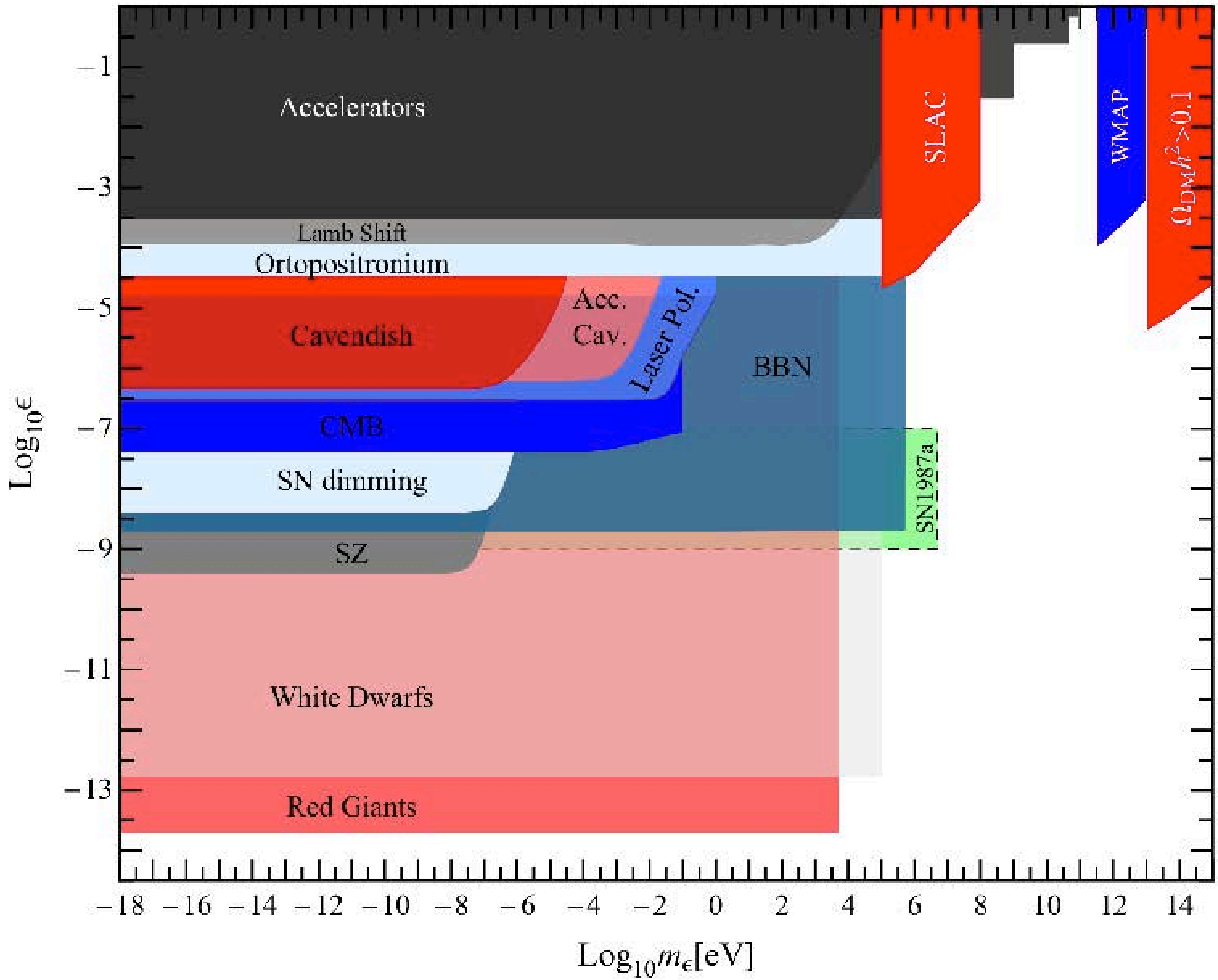
  - 1st **global** intersecting brane models which extend the **SM** with a ***genuine* hidden sector**; 2 sectors connect only via ***U(1) mixings***.
  - String theory realizations of **Z' mediation** & **hidden valley** scenarios.

Overview

- Mini-charged Dark Matter scenarios:
  - Field theory construction
  - Constraints from Quantum Gravity
  - Charge quantization and millicharges
- Stueckelberg portal
  - Massive U(1)'s and their mass mixing
  - Explicit string constructions
  - Phenomenological features
- Conclusions

Mini-charged DM scenarios

Can DM carry a tiny electric charge?



Goodsell, Jaeckel, Redondo & Ringwald 2009

Minicharged DM in field theory

- Consider two massless U(1)s from different sectors $(U(1)_\gamma\ ,\ U(1)_{\rm h})$ with small 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 tiny electric charge **not quantized** 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

Minicharged 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:

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

$$\mathcal{L} \approx -\frac{1}{4}\hat{F}_\gamma^2 - \frac{1}{4}\hat{F}_M^2 - \frac{1}{2}M_1^2\hat{A}_M^2 + \hat{A}_\gamma\,(J_\text{e.m.} - \underline{\epsilon\,J_\text{h}}) + \hat{A}_M\,(J_\text{h} + (\epsilon - \delta)\,J_\text{e.m.})$$

- 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

- DM/LHC connection [e.g., Cheung and Yuan '07]

Minicharged DM in field theory

$\bullet \in \mathbb{Z}$

- 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:

1. Canonical kinetic: $\vec{A} \to \mathcal{T} \cdot \vec{A} \quad \text{s.t.} \quad \mathcal{T}^T \cdot f \cdot \mathcal{T} = 1$

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

2. Diagonalize $\tilde{M}^2$, i.e. find orthonormal eigenvectors: $\tilde{M}^2 \cdot \vec{v}_a = m_a^2 \, \vec{v}_a$

- Physical basis: $\hat{A}_a = \vec{v}_a^T \cdot \mathcal{T}^{-1} \cdot \vec{A}$

$$\hat{q}_i^a = \vec{q}_i^T \cdot \mathcal{T} \cdot \vec{v}_a \quad \Longrightarrow \quad \frac{\hat{q}_i^a}{\hat{q}_j^a} \notin \mathbb{Q}$$

Quantization???

Quantum gravity constraints

- Field theories with non-compact gauge groups cannot be consistently coupled to quantum gravity.
- Non-quantized charges signal non-compact groups.
- 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 $q_{\rm bh}$ as close to zero as desired. 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

Are minicharge scenarios consistent with Quantum Gravity?

Charge quantization:

Minicharge DM scenarios in
quantum gravity

$\bullet \in \mathbb{Z}$

Minicharges & Quantization

- U(1) masses come from Stueckelberg or BEH mechanisms:

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

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

$$A^a \to A^a + d\Lambda^a \ , \quad \phi^i \to \phi^i - k_a^i \Lambda^a \ , \quad \psi_\alpha \to e^{2\pi i q_a^\alpha \Lambda^a} \psi_\alpha$$

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

$$\Lambda^a \sim \Lambda^a + 1 \quad \Longrightarrow \quad k_a^i, \, q_a^\alpha \in \mathbb{Z}$$

$$\boxed{M^2 = K^T \cdot G \cdot K}$$

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

$K_a^i \in \mathbb{Z}$

$\bullet \in \mathbb{Z}$

Minicharges & Quantization

- Diagonalization revisited:

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

Minicharges & Quantization

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

- Set canonical kinetic term

$$\vec{A} = \mathcal{T} \cdot \vec{A}' \quad \text{s.t.} \quad \mathcal{T}^T \cdot f \cdot \mathcal{T} = 1$$

Minicharges & Quantization

$\bullet \in \mathbb{Z}$

- Diagonalization revisited:

$$\mathcal{L} = -\frac{1}{4}\vec{F}'^{T} \cdot \vec{F}' - \frac{1}{2}\vec{A}'^{T} \cdot \underbrace{(\mathcal{T}^{T} K^{T} G K \mathcal{T})}_{\tilde{M}^2} \cdot \vec{A}' + \sum_i (\vec{q}_i^{\,T} \cdot \mathcal{T} \cdot \vec{A}')\, J^{(i)}$$

- Set canonical kinetic term

$$\vec{A} = \mathcal{T} \cdot \vec{A}' \quad \text{s.t.} \quad \mathcal{T}^{T} \cdot f \cdot \mathcal{T} = 1$$

Minicharges & Quantization

$\bullet \in \mathbb{Z}$

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- Set canonical kinetic term

$$\vec{A} = \mathcal{T} \cdot \vec{A}' \quad \text{s.t.} \quad \mathcal{T}^{T} \cdot f \cdot \mathcal{T} = 1$$

- Diagonalize resulting mass matrix $\tilde{M}^2$
  - Equivalently, find its eigenvectors.

$$\tilde{M}^2 \cdot \vec{v}_a = m_a^2\, \vec{v}_a$$

Minicharges & Quantization

- Diagonalization revisited:

$$\mathcal{L} = -\frac{1}{4}\vec{F}'^{\,T}\cdot\vec{F}' - \frac{1}{2}\vec{A}'^{\,T}\cdot\underbrace{(\mathcal{T}^T K^T G K \mathcal{T})}_{\tilde{M}^2}\cdot\vec{A}' + \sum_i (\vec{q}_i^{\,T}\cdot\mathcal{T}\cdot\vec{A}')\,J^{(i)}$$

$\bullet \in \mathbb{Z}$

Minicharges & Quantization

- Diagonalization revisited:

$$\mathcal{L} = -\frac{1}{4}\vec{F}'^{T} \cdot \vec{F}' - \frac{1}{2}\vec{A}'^{T} \cdot \underbrace{(\mathcal{T}^{T} K^{T} G K \mathcal{T})}_{\tilde{M}^2} \cdot \vec{A}' + \sum_i (\vec{q}_i^{\,T} \cdot \mathcal{T} \cdot \vec{A}')\, J^{(i)}$$

- Assume only one massless boson:
  - Find the eigenvector $K \cdot \vec{w} = 0$ $\quad \tilde{M}^2 \cdot \vec{w} \neq 0$
  - Physical eigenvector $\vec{v} \equiv \mathcal{T}^{-1} \cdot \vec{w}$ $\quad \tilde{M}^2 \cdot \vec{v} = 0$

$$A_\gamma^{\rm phys} = \frac{1}{|\vec{v}|}\vec{v}^{\,T} \cdot \vec{A}' = \frac{1}{|\vec{v}|}\vec{w}^{\,T} \cdot f \cdot \vec{A}$$

$$q_i^{\rm phys} = \frac{1}{|\vec{v}|}\vec{q}_i^{\,T} \cdot \mathcal{T} \cdot \vec{v} = \frac{1}{|\vec{v}|}\vec{q}_i^{\,T} \cdot \vec{w} \quad \Longrightarrow \quad \frac{q_i^{\rm phys}}{q_j^{\rm phys}} \in \mathbb{Q}$$

Charges are quantized

"No minicharges"

$\bullet \in \mathbb{Z}$

Minicharges & Quantization

- Diagonalization revisited:

$$\mathcal{L} = -\frac{1}{4}\vec{F}'^{\,T}\cdot\vec{F}' - \frac{1}{2}\vec{A}'^{\,T}\cdot\underbrace{(\mathcal{T}^T K^T G K \mathcal{T})}_{\tilde{M}^2}\cdot\vec{A}' + \sum_i (\vec{q}_i^{\,T}\cdot\mathcal{T}\cdot\vec{A}')\, J^{(i)}$$

- Assume two massless boson (easily generalizable):
  - Find two eigenvectors $\quad K\cdot\vec{w}_{1,2} = 0 \qquad \tilde{M}^2\cdot\vec{w}_{1,2} \neq 0$
  - Physical eigenvectors $\quad \vec{v}_{1,2} \equiv \mathcal{T}^{-1}\cdot\vec{w}_{1,2} \qquad \vec{v}_1^{\,T}\cdot\vec{v}_2 \neq 0$
  - Project $\vec{v}_2$ to subspace orthogonal to $\vec{v}_1$:

$$\vec{v}'_2 \equiv \vec{v}_2 - \frac{(\vec{v}_2^{\,T}\cdot\vec{v}_1)}{|\vec{v}_1|^2}\cdot\vec{v}_1 = \mathcal{T}^{-1}\left[\vec{w}_2 - \frac{\overbrace{(\vec{w}_2^{\,T}\cdot f\cdot\vec{w}_1)}^{\equiv\delta}}{|\vec{v}_1|^2}\cdot\vec{w}_1\right]$$

$$q_i^{(1)} = \frac{1}{|\vec{v}_1|}\,\vec{q}_i^{\,T}\cdot\vec{w}_1\,; \qquad q_i^{(2)} = \frac{1}{|\vec{v}'_2|}\,\vec{q}_i^{\,T}\cdot(\vec{w}_2 - \delta\,\vec{w}_1)$$

Minicharges & Quantization

$\bullet \in \mathbb{Z}$

$$q_i^{(1)} = \frac{1}{|\vec{v}_1|} \vec{q}_i^{\,T} \cdot \vec{w}_1 \, ; \qquad q_i^{(2)} = \frac{1}{|\vec{v}\,'_2|} \vec{q}_i^{\,T} \cdot (\vec{w}_2 - \delta \, \vec{w}_1)$$

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

$\bullet \in \mathbb{Z}$

Minicharges & Quantization

$$q_i^{(1)} = \frac{1}{|\vec{v}_1|}\,\vec{q}_i^{\,T} \cdot \vec{w}_1\,; \qquad q_i^{(2)} = \frac{1}{|\vec{v}\,'_2|}\,\vec{q}_i^{\,T} \cdot (\vec{w}_2 - \delta\,\vec{w}_1)$$

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

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

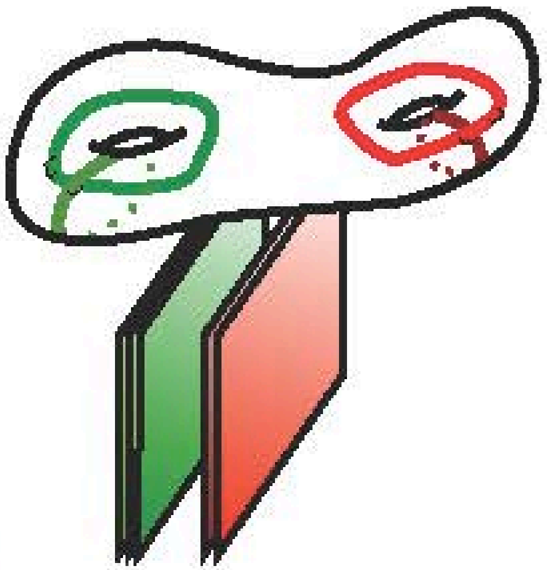
$$\frac{q_i^{(2)}}{q_j^{(2)}} \notin \mathbb{Q}$$

- Massive bosons don't play any role.
- No problems with quantum gravity, charged objects are always distinguishable. Gauge group still compact.
- Extra massless U(1) also key for hidden sector monopole DM scenario [Baek, Ko, Park].

Massive U(1)'s

The 'Stueckelberg' portal
from intersecting branes

Massive U(1)'s



- Take our usual scenario

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

- Hypercharge can mix <u>kinetically</u> (loop-suppressed):
  - With a massless hidden $U(1)_h$: mini-charged DM.
  - With a massive $U(1)_h$: 'hidden photon' models.

- Massive visible U(1)s can have <u>mass mixing</u> (at tree-level) with massive hidden photons
  - We discuss now these Z'-portals
  - Very interesting phenomenologically if Z' are light enough

Massive U(1)'s

- Recall: U(1) mass terms read:

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

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

- Non-diagonal mass terms mixing visible and hidden U(1)s
  - From non-diagonal metric G. $k^i_{a_\text{v}} \neq 0$
  - From an axion ϕ^i coupled to different U(1)'s, i.e. $k^i_{a_\text{h}} \neq 0$
- Mass mixing from axionic charges k_a^i are generically large:
  - Tree-level effect controlled by integers.
  - We neglect sub-leading kinetic mixing effects

Massive U(1)'s

- 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 canonical kinetic term and diagonalize M:
  - 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.

D-brane implementation

Motivating the Stueckelberg portal

Massive U(1)'s

- Orientifold type IIA compactification with D6-branes wrapping 3-cycles of the internal space $\mathbf{X}_6$:
  - Basis $\{[\alpha^i], [\beta_i]\}$ of $H_3^{\pm}(\mathbf{X}_6)$ with intersections $[\alpha^i] \cdot [\beta_j] = \delta^i_j$
  - Each stack of D6-branes wraps $[\Pi_a] = s_{ai}[\alpha^i] + r_a^j[\beta_j]$

- $U(1)_a \subset U(N_a)$ gauge boson have Stueckelberg couplings

$$\mathcal{L}_M = -\frac{1}{2} G_{ij}(\partial\phi^i + N_a r_a^i A^a)(\partial\phi^j + N_b r_b^j A^b)$$

  - ϕ^i are closed string RR axions: $\phi^i = \int_{\alpha^i} C_3$
  - G_{ij} is the complex structure moduli space metric.
  - r_a^i are integer topological intersections $r_a^i = [\alpha^i] \cdot [\Pi_a]$

Massive U(1)'s

- U(1)s mass matrix then reads:

$$M^2 = (NR)^T \cdot G \cdot NR$$

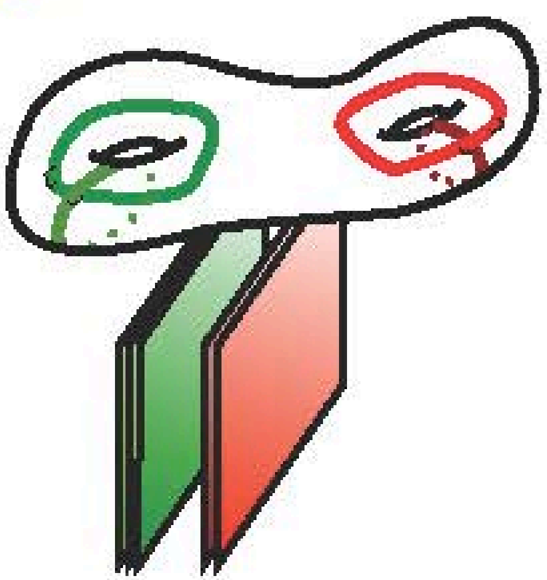
- On the other hand, chiral matter charged under $U(N_a) \times U(N_b)$ comes from intersections

$$[\Pi_a] \cdot [\Pi_b] = s_{ai}\, r_b^i - r_a^i\, s_{bi} = (SR - RS)_{ab}$$

  - With appropriate R and S, one can construct scenarios with non-intersecting sectors communicated by axions

$$\phi$$

$$\underbrace{SM \times \mathbf{U(1)^n_v}}_{\Psi_{\rm SM}} \quad \times \quad \underbrace{\mathbf{U(1)^m_h} \times G_{\rm h}}_{\chi_{\rm DM}}$$



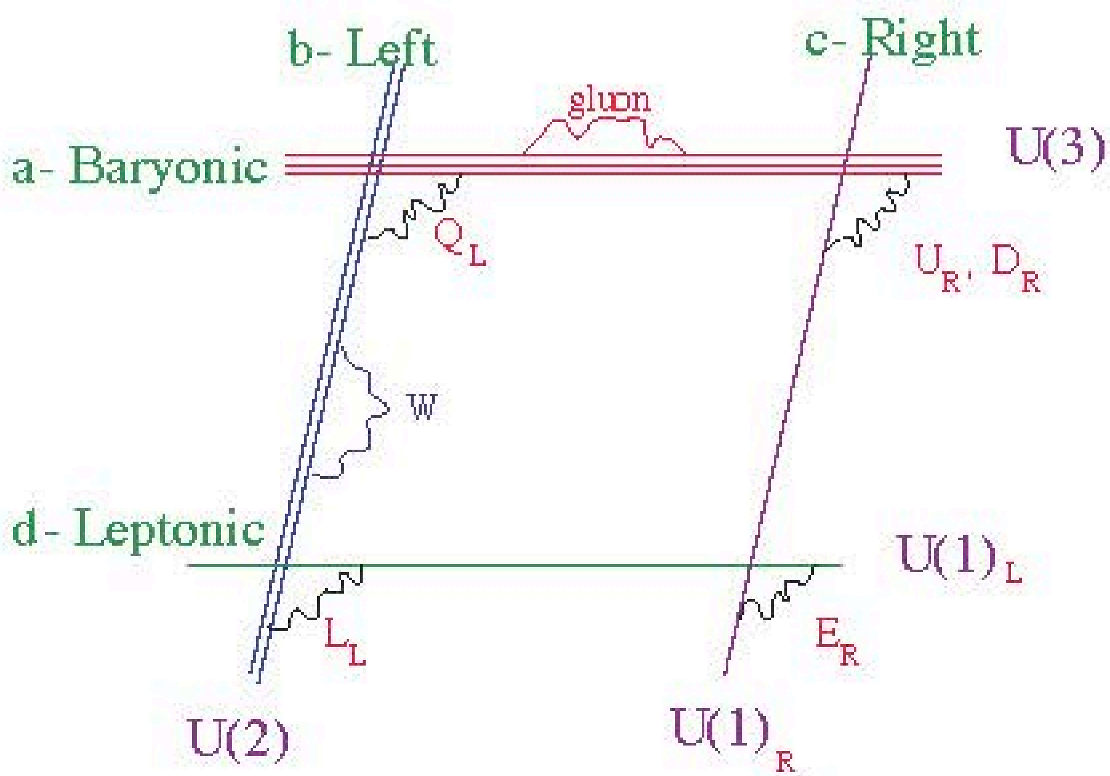
  - Off-diagonal U(1) mass matrix

Massive U(1)'s

- Stueckelberg or Higgs?
  - Stueckelberg mechanism arises naturally from **closed** string RR axions that propagate in the bulk.
  - Higgs fields come from **open** strings and do not naturally communicate separated sectors of branes.
- RR axions involved in Green-Schwarz mechanism for anomaly cancellation (automatic in tadpole-free compactifications)
  - Massive U(1)s need not be anomaly-free, nor we need exotic matter. We are not restricted to B-L in the visible sector.
- Explicit semi-realistic constructions extending known SM-like models can be implemented even in simple toroidal compactifications

Explicit String Models

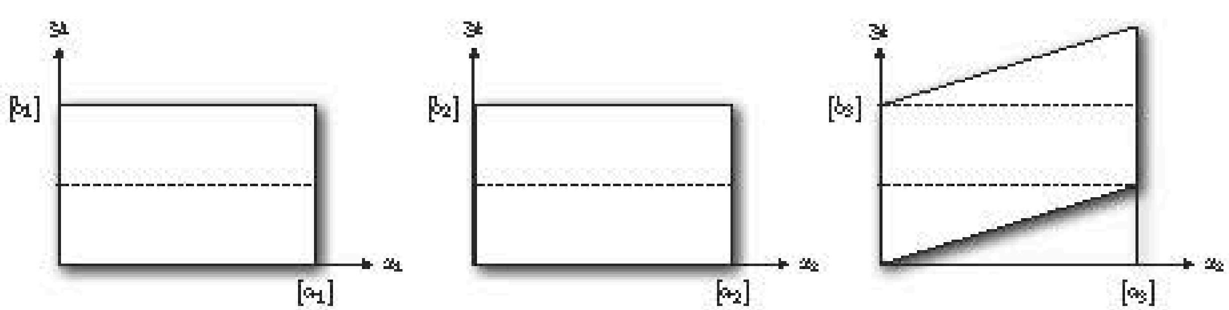
- Extending the (MS)SM Quiver in a toroidal compactification (can in principle be realized in more general CY compactifications):



$$[\Pi_a^{(v)}] = [\alpha^0] + \frac{1}{2}[\alpha^1] + [\beta_2] + \frac{1}{2}[\beta_3],$$
$$[\Pi_b^{(v)}] = -\frac{3}{2}[\alpha^2] - [\beta_1],$$
$$[\Pi_c^{(v)}] = 3[\alpha^2] - 4[\beta_3],$$
$$[\Pi_d^{(v)}] = -3[\alpha^0] - \frac{3}{2}[\alpha^1] - [\beta_2] - \frac{9}{2}[\beta_3],$$

$$[\Pi^{(h)}] = n_h[\alpha^0] - p_h[\beta_0] + 2p_h[\beta_1] + m_h[\beta_3] \,.$$

- A basis of 3-cycles for a toroidal model:



$$[\alpha^0] = [a_1][a_2][a_3], \quad [\beta_0] = [b_1][b_2][b_3],$$
$$[\alpha^1] = [a_1][b_2][b_3], \quad [\beta_1] = [b_1][a_2][a_3],$$
$$[\alpha^2] = [b_1][a_2][b_3], \quad [\beta_2] = [a_1][b_2][a_3],$$
$$[\alpha^3] = [b_1][b_2][a_3], \quad [\beta_3] = [a_1][a_2][b_3],$$

Some Phenomenological Comments

& Relations to Other Scenarios

Phenomenological Features

- Z' phenomenology has been vastly studied but our scenario has several distinctive features.
- Since GS mechanism is in force, there are many more choices of U(1)'s without the need of introducing exotic matter.

  [Anomaly cancellation: B-L or Y if family-independent & without exotics]

- Stueckelberg Z' is not broken by scalar vev but non-pert. effects

  ⇒ U(1) symmetry remain unbroken at a perturbative level in EFT

  ⇒ protects certain operators, e.g., μ-term, Dirac neutrino mass, ...

- Due to integrality of axion charges, Z' couples with significant strengths to visible sector yet can evade Z-Z' mixing constraints.
- Z' searches (LEP II & LHC), g-2, precision EW constraints can be satisfied with $m_{Z'} \gtrsim 2$ TeV.

Dark Matter Stability and Relic Density

- $U(1)_h$ symmetries (broken only non-perturbatively by instanton effects) help protect DM stability.
- In our explicit string models: $U(1)_h \rightarrow Z_s$ where s=g.c.d (n_h, p_h).
- No exotic matter is introduced, but dark matter can annihilate through:

$$\bar{\psi}_h + \psi_h \rightarrow Z' \rightarrow \bar{\psi}_v + \psi_v$$

- Efficient enough to reduce the hidden primordial particle density and achieve the current DM relic density.

SUSY Mediation and Hidden Valley

- Z' mediation of ~~SUSY~~: differ from earlier proposal of Langacker, Paz, Wang, Yavin in several respects, e.g., no exotics yet strong mixings between visible & hidden sector (more pronounced signatures).
- Differ from higher form of mediation (Verlinde, Wang, Wijnholt, Yavin) as mixing is with massive U(1), thus no exotic coupling with SM.
- Visible sector sfermions couple directly to Z' messenger while gauging masses are generated only a higher loop (like split SUSY).
- String theory realization of "hidden valley":
  - U(1) mass mixings leads to a concrete and minimal scenario.
  - barrier energy scale set by lightest Z' mass
  - broader U(1) choices (not just B-L & Y) [c.f. Han, Si, Strassler, Zurek]

Hidden Photon Scenarios

- "Hidden photon" usually introduced via kinetic mixing with $U(1)_Y$:

$$\mathcal{L} = -\frac{1}{4g_Y^2}F_Y^2 - \frac{1}{4g_h^2}F_h^2 - \frac{\delta}{2}F_Y F_h - \frac{1}{2}m_h^2 A_h^2 + A_Y J_Y + A_h J_h$$

- If the axion moduli space metric is slightly off-diagonal:

$$G = \begin{pmatrix} m_v^2 & \epsilon \\ \epsilon & m_h^2 \end{pmatrix}$$

there is small mass mixings

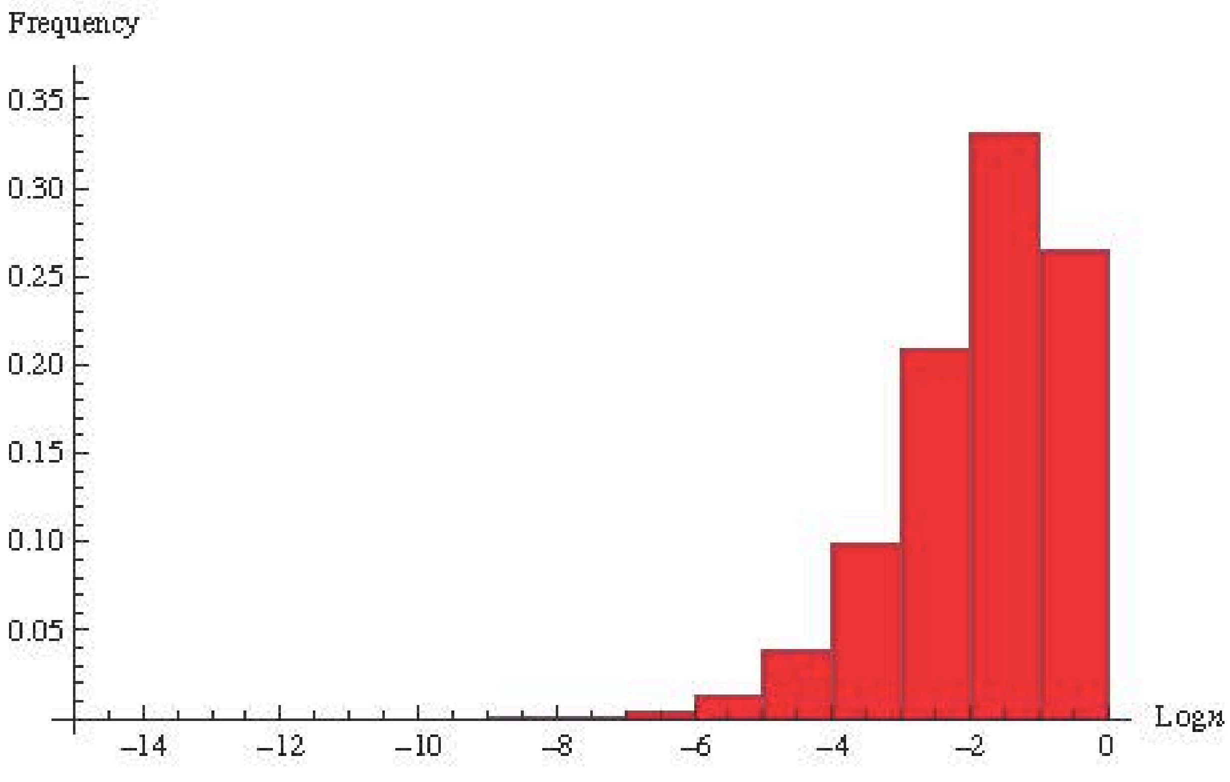
$$\mathcal{L} = -\frac{1}{4g_v^2}F_v^2 - \frac{1}{4g_h^2}F_h^2 - \frac{1}{2}m_v^2 A_v^2 - \frac{1}{2}m_h^2 A_h^2 - \epsilon A_v A_h + A_v J_v + A_h J_h\,,$$

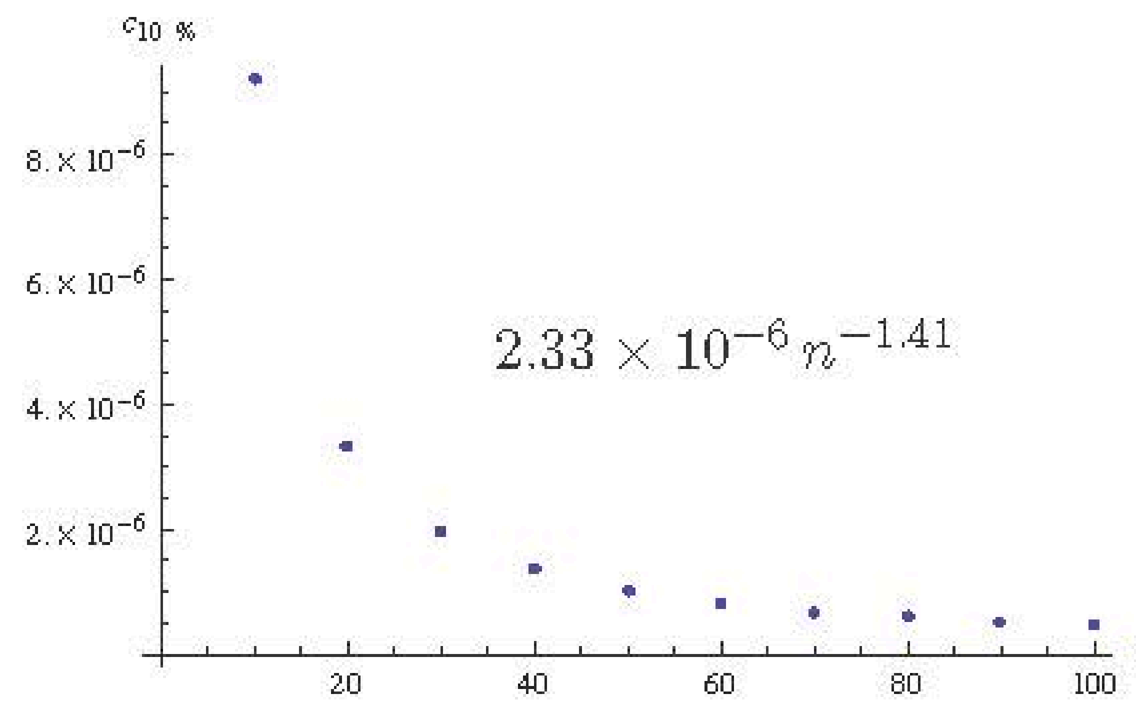
also lead to a hidden photon coupled weakly with visible matter.

- Main difference: coupling to hidden photon is not proportional to charges under $U(1)_Y$ but $U(1)_h$.

Light Z' from Large Hidden Sectors

- Stueckelberg mass matrix: $\tilde{M}^2_{ab} = \sum_{ij} g_a g_b K^i_a K^j_b G_{ij} \sim \mathcal{O}(g^2 M_s^2)$,
- Lower the Z' mass by eigenvalue repulsion (large hidden sector).
- Randomize $K^i{}_a \in [-10,10]$; $g_a \in [10^{-3}, 1]$





Conclusions

Conclusions

- U(1) bosons provide natural portals into hidden sectors, well motivated from string theory.
- Quantum gravity imposes important constraints on mass matrix
  - Mini-charged DM arises exclusively from kinetic mixing w/ hypercharge
  - Heavy (Stueckelberg) Z' may naturally mix hidden and visible sectors at tree-level.
  - Light (massive) dark photons may also mass-mix with heavy visible Z'
- D-brane models provide a natural framework for these scenarios
- Details of explicit string constructions and phenomenology (DM, collider, SUSY mediation,...) in 1401.5880 and 1401.5890.

Thank you