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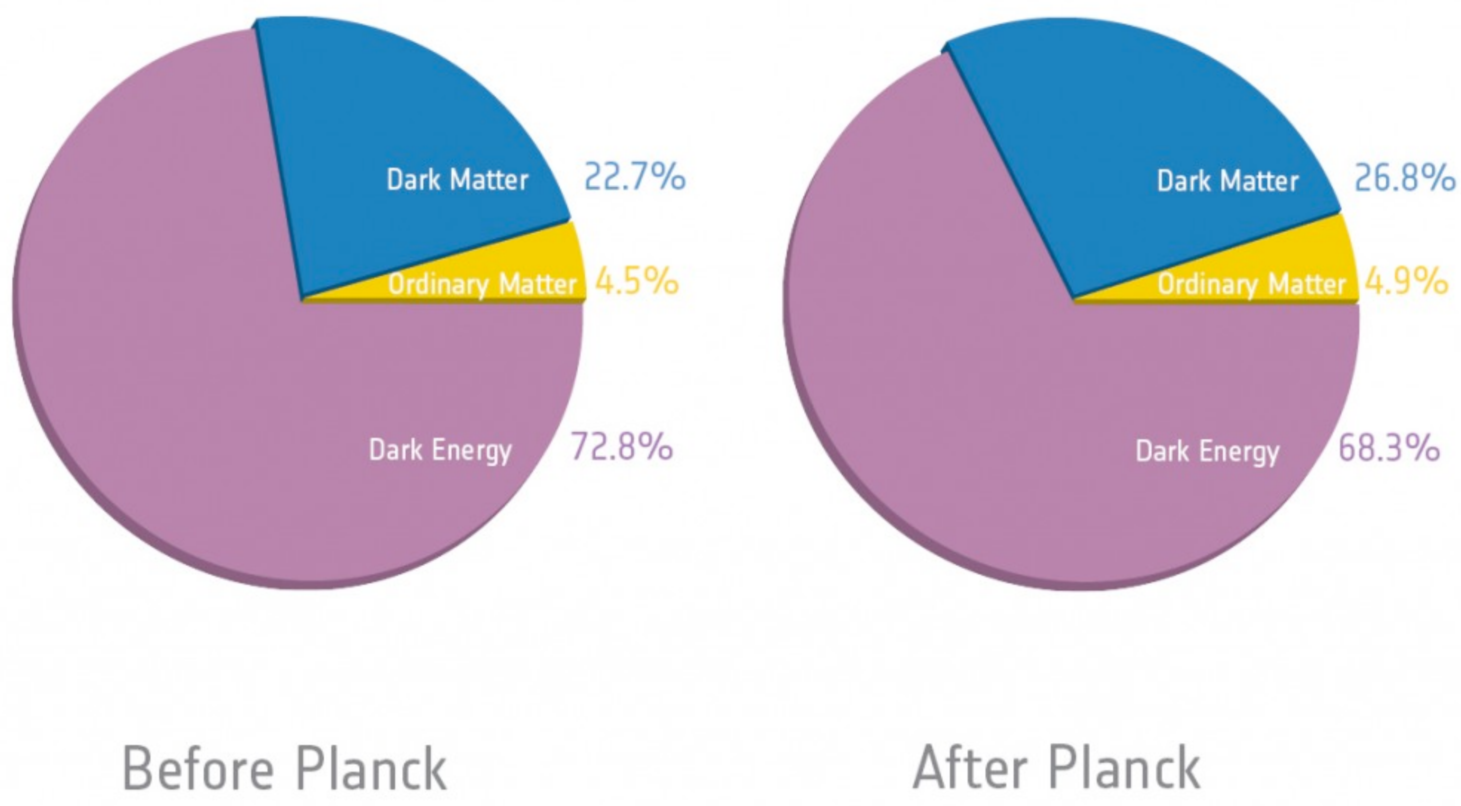
Dark Matter and Dark Energy in String Theory

Gary Shiu

Motivation

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



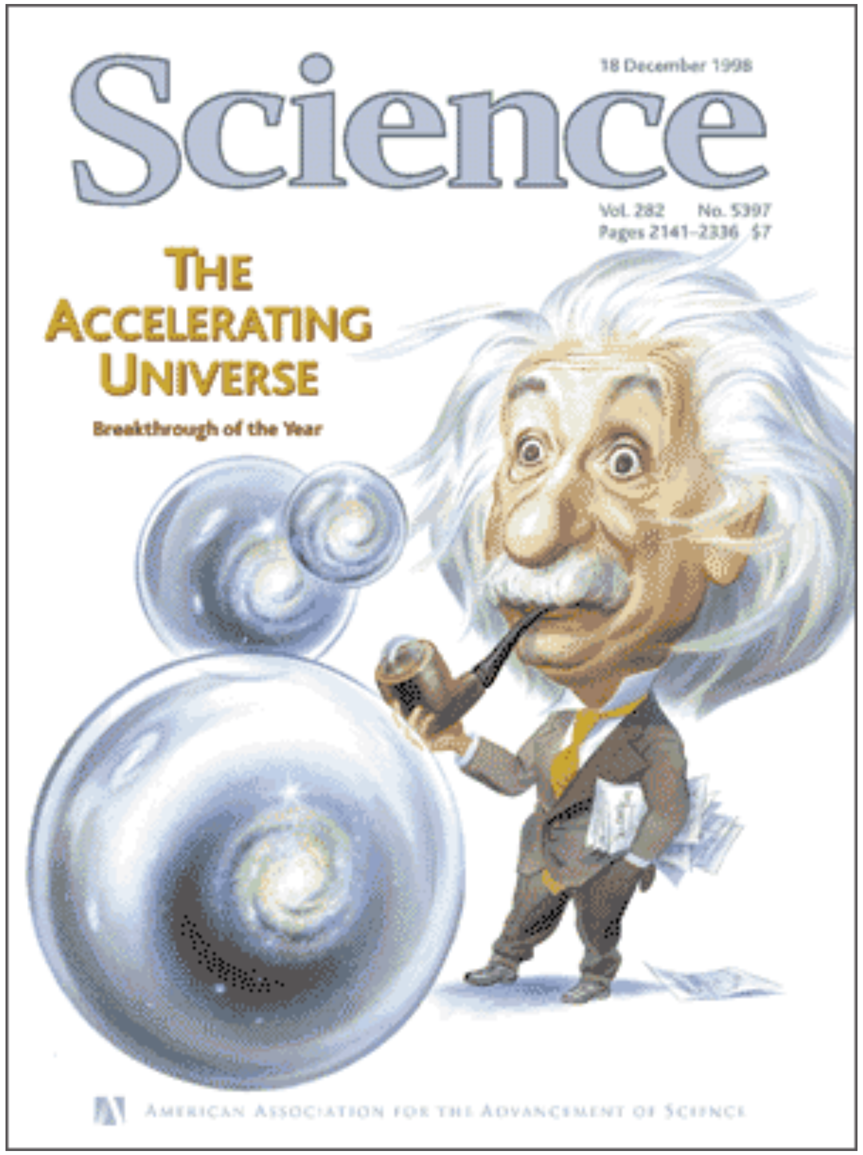
- This talk is about the other 95% through the lens of string theory.
- Focus mostly on dark matter: [GS, Pablo Soler, Fang Ye, Phys. Rev. Lett. 110, 241304 (2013)] + [Wan-Zhe Feng, GS, Pablo Soler, Fang Ye, to appear].

Dark Energy

- The simplest realization is $\Lambda > 0$.
- It is an issue for **quantum gravity!**
- In **string theory**, these challenges include:
  - **Moduli Stabilization**
  - **Lack of SUSY**
- **Uplift scenarios** have been proposed

  (e.g., KKLT, LVS, F/D-term, Kahler uplift,...)

  but <u>**explicit models**</u> are lacking.



Metastability

- Attempts to construct explicit de Sitter vacua from string theory (w/ fluxes, generalized geometries, …) so far came up empty.

  [Silverstein];[Haque,GS,Underwood,Van Riet];[Flauger,Paban,Robbins,Wrase];[Caviezel,Koerber,Lust,Wrase,Zagermann]; [de Carlos,Guarino,Moreno];[Caviezel, Wrase,Zagermann];[Danielsson,Haque,GS,Van Riet];[Danielsson,Koerber,van Riet];[Danielsson,Haque,Koerber,GS,Van Riet, Wrase];[Blåbäck,Danielsson,Dibitetto];[Dodelson,Dong, Silverstein,Torroba];…

- Large number of moduli
  - Landscape?

    $N_{crit} \sim (\text{flux quanta})^N$

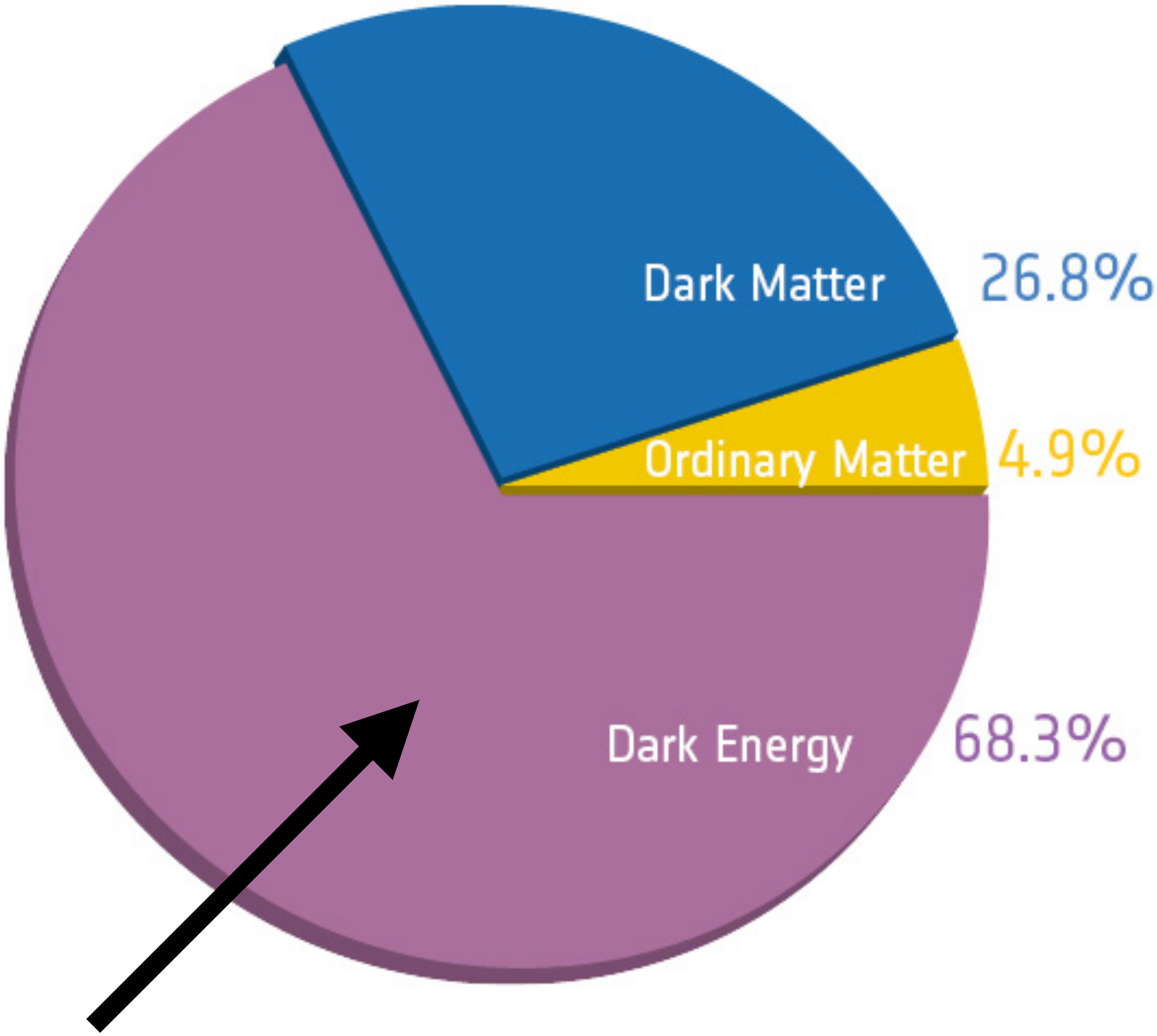
    [Bousso,Polchinski],…
  - Tachyons!

    Probability of stability

    $P(N) \sim \exp(-bN^2)$ (for N>>1)

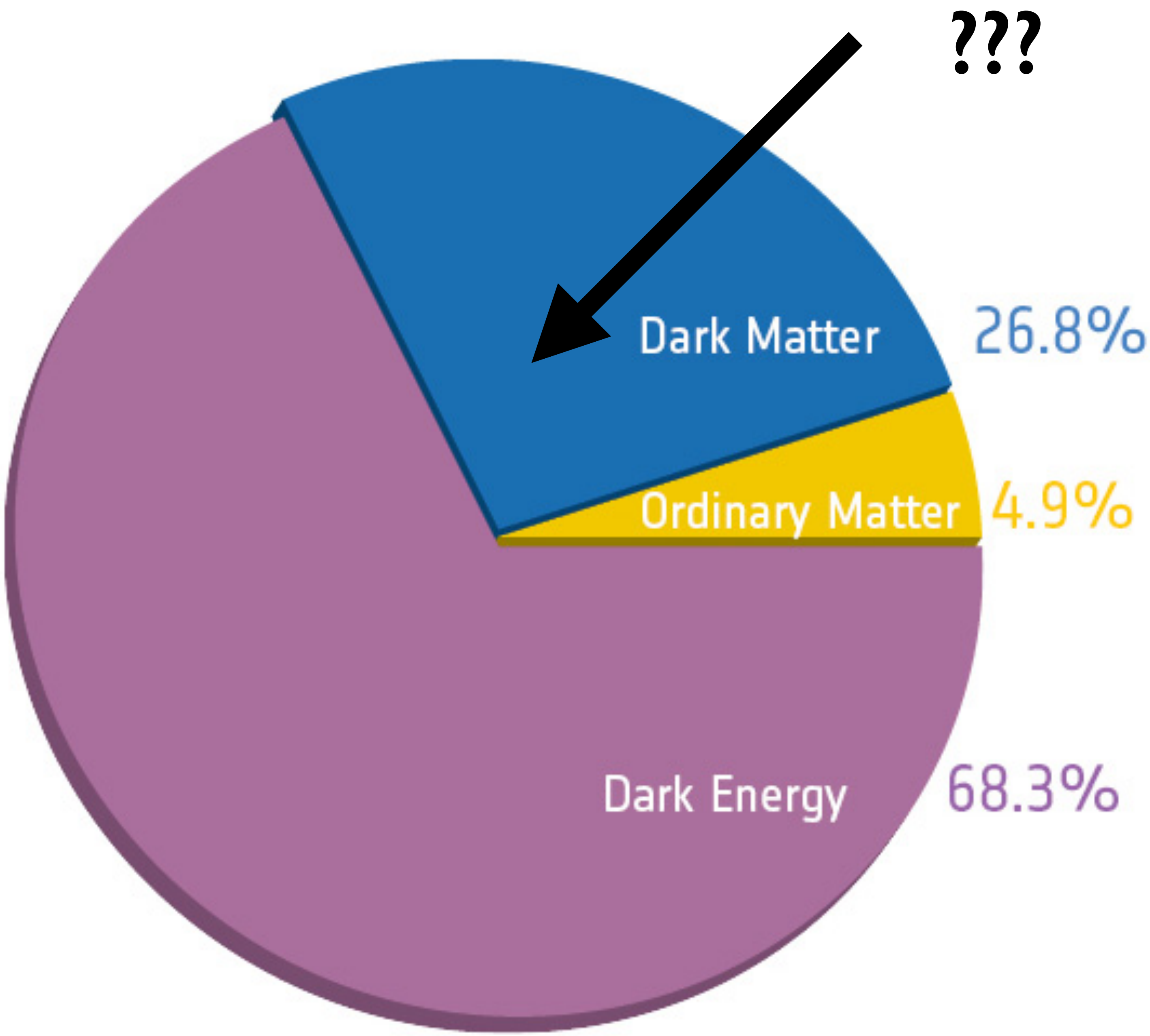
    [Chen,GS,Sumitomo,Tye];[Marsh,McAllister,Wrase]

Dark Energy

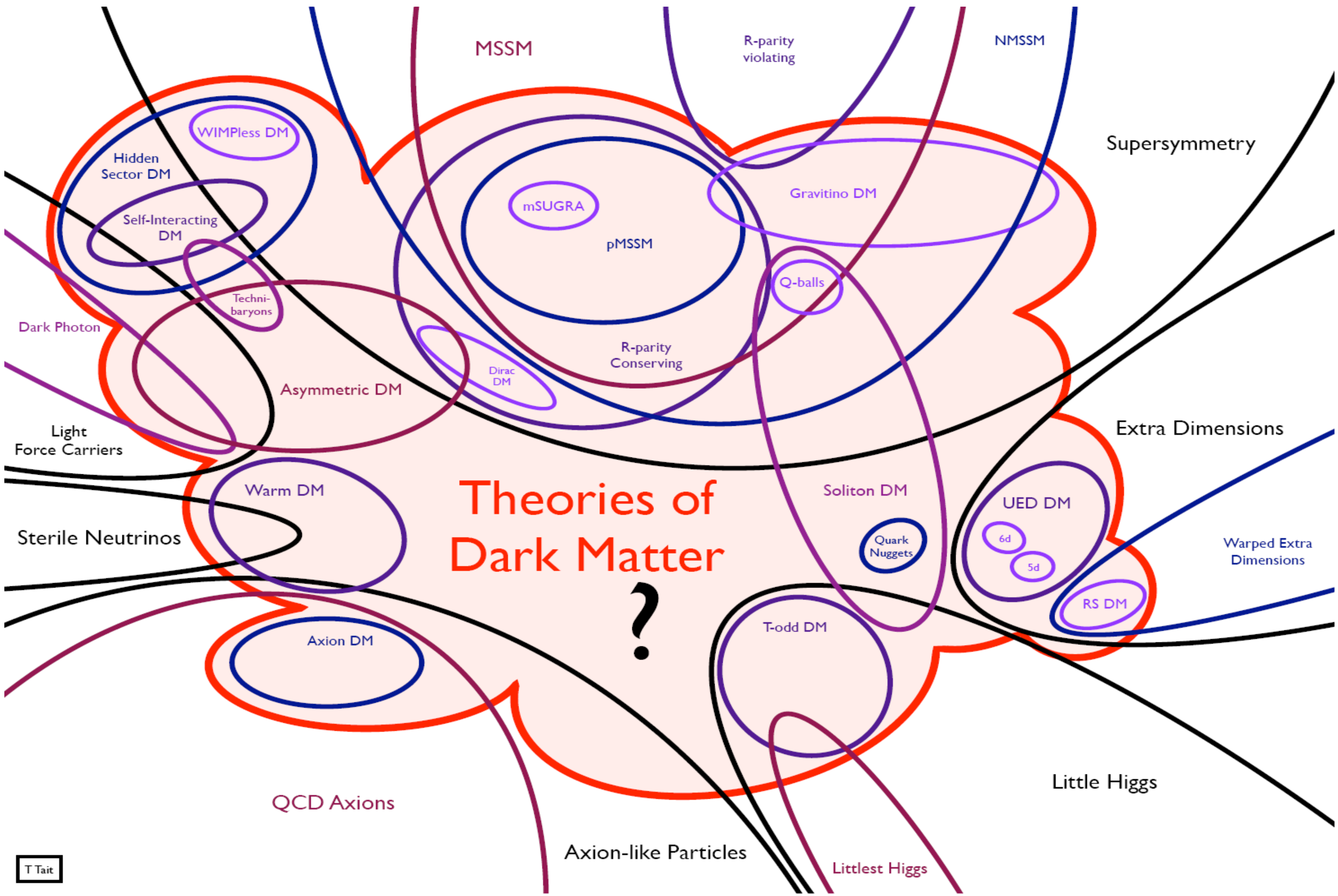


In string theory, not anything goes!

Dark Matter

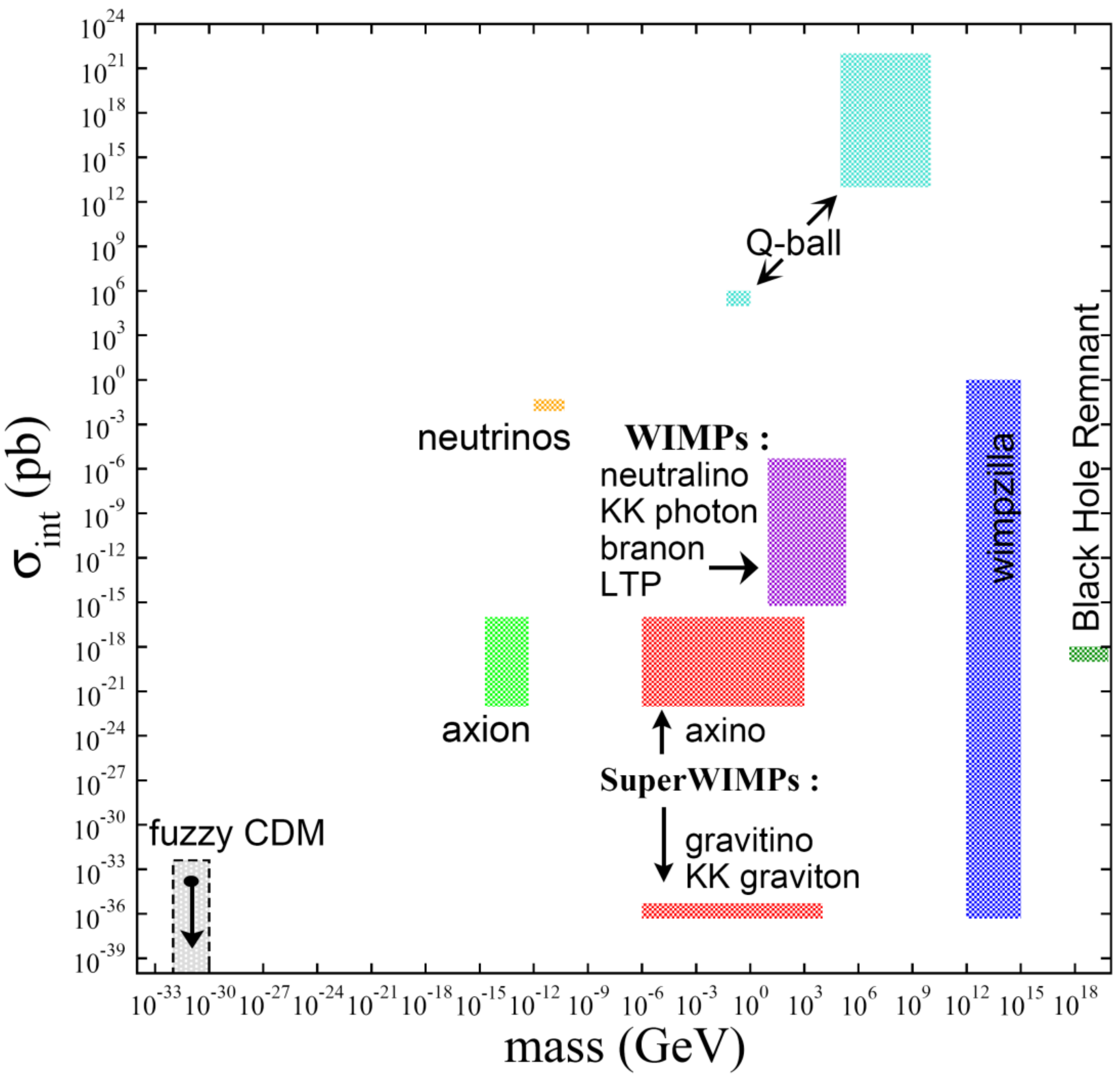


Dark Matter Candidates



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)
- Strong experimental effort put into (in)direct detection of different candidates.
- 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:

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

- Several portals have been proposed to communicate both sectors
  - BEH 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

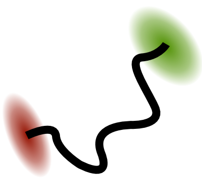
Motivation

- D-brane implementation (intersecting branes)

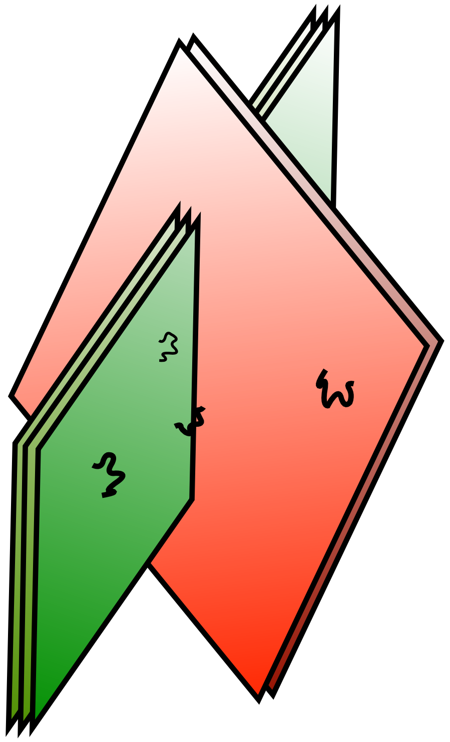
  - The gauge theory on a stack of N_i D-branes:

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

  - Charged chiral matter from intersections

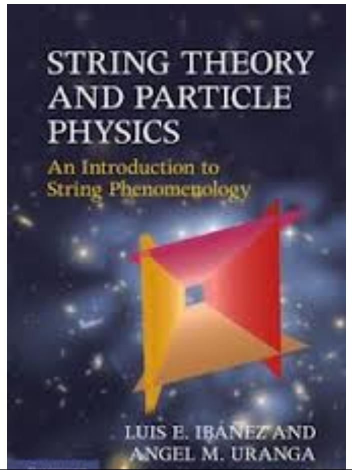


$$\Psi_{ab} : \quad (\overline{\mathbf{N}}_{\mathbf{a}}, \mathbf{N}_{\mathbf{b}})_{(-1,+1)}$$



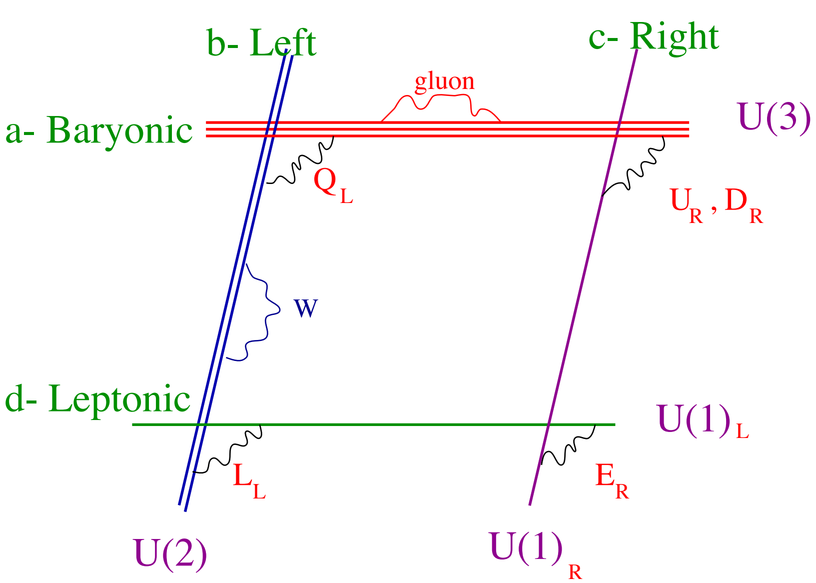
- Simple models can reproduce the SM with extra (massive) U(1)s:

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



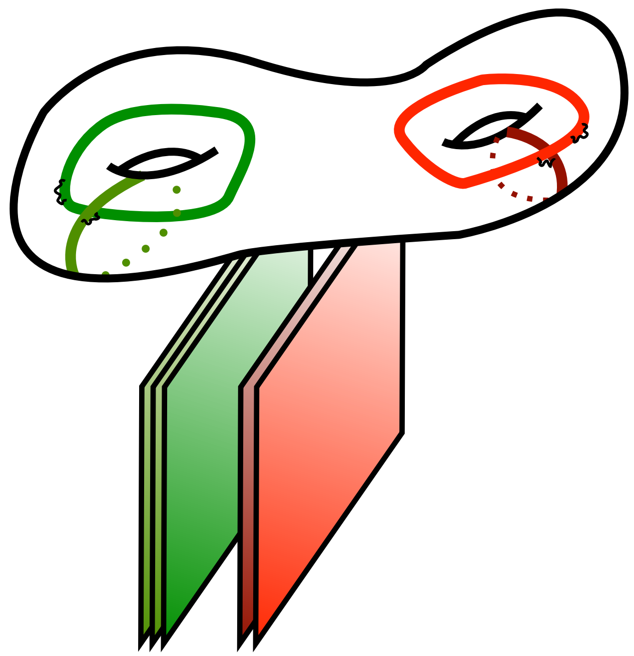
For review, see classic text by Ibanez & Uranga

or [Blumenhagen, Cvetic, Langacker, GS, Ann. Rev. Nucl. Part. Sci.]



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'

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

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

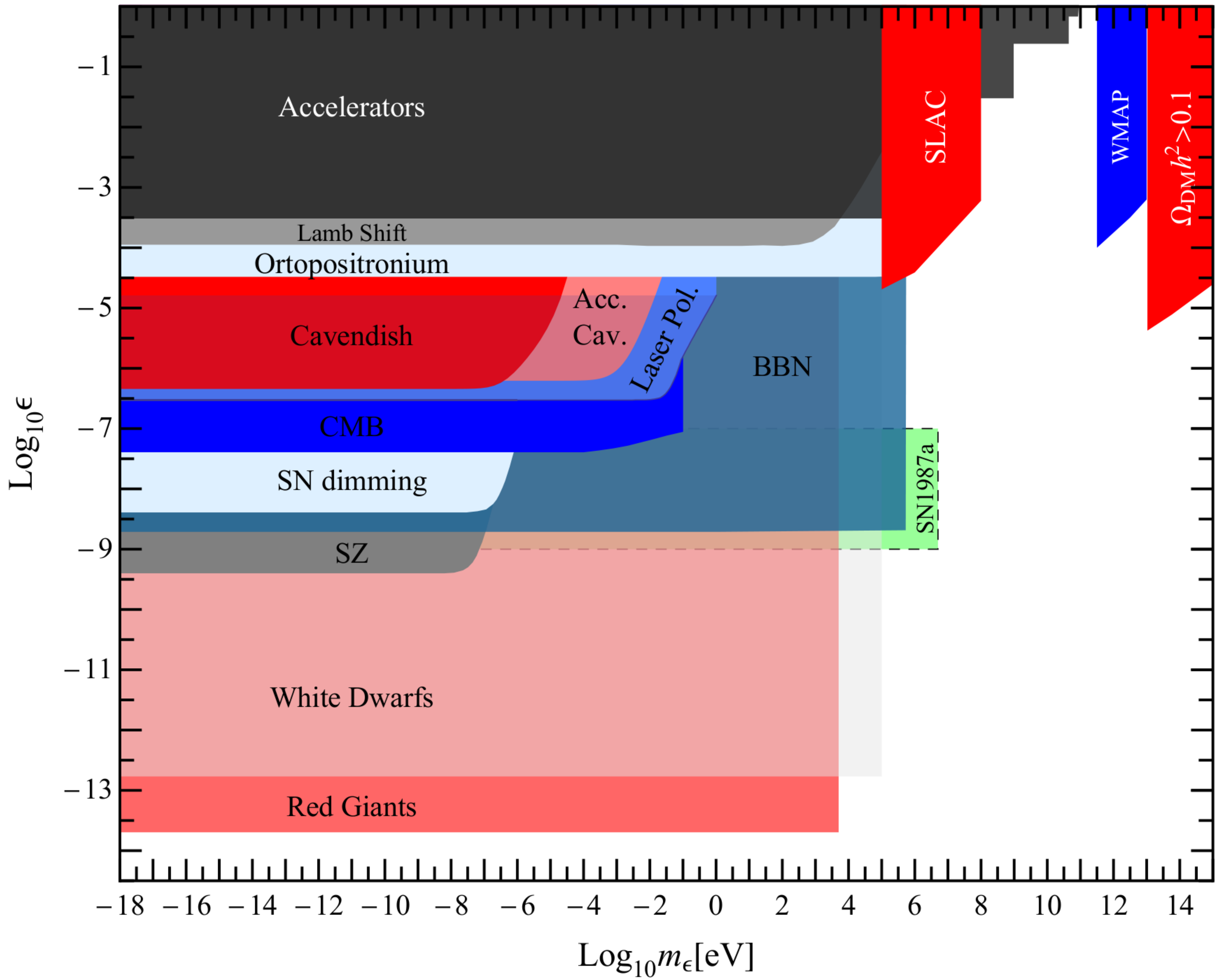
Stueckelberg U(1)'s as mediators of SUSY breaking

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
- 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 **<u>not quantized</u>** 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:

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

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

- Diagonalize kinetic & mass terms: $\left\{ \begin{array}{ll} A_\gamma & \to \hat{A}_\gamma + (\epsilon - \delta)\hat{A}_M \\ A_{\rm h} & \to \hat{A}_M - \epsilon\,\hat{A}_\gamma \end{array} \right.$

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

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

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

B. Körs, P. Nath ’04

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

Minicharged DM in field theory

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

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

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

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

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

Charge quantization:

Minicharge DM scenarios in
quantum gravity

$\bullet \in \mathbb{Z}$

Minicharges & Quantization

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

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

  - 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)

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

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

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

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

$\bullet \in \mathbb{Z}$

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

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

$\bullet \in \mathbb{Z}$

Minicharges & Quantization

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

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

Minicharges & Quantization

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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:

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

Minicharges & Quantization

$\bullet \in \mathbb{Z}$

- Diagonalization revisited:

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

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

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

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

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 $\vec{v}_1$:

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

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

Minicharges & Quantization

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

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

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)

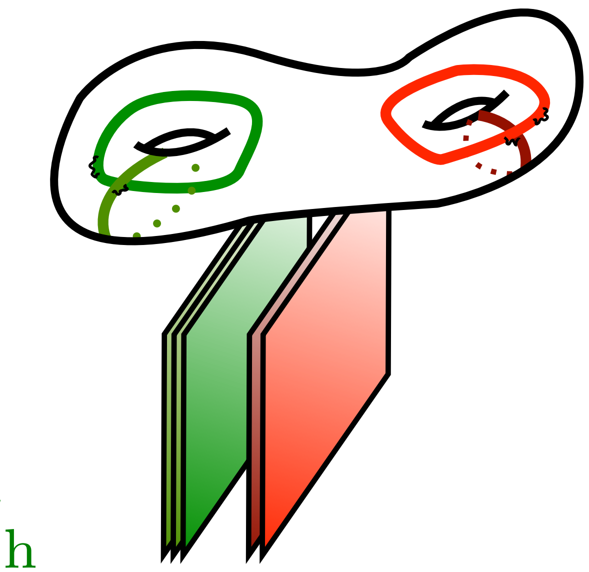
$$\frac{q_i^{(2)}}{q_j^{(2)}} \notin \mathbb{Q}$$

- 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

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

- Hypercharge can mix kinetically (loop-suppressed):
  - With a massless hidden $U(1)_{\rm h}$: mini-charged DM.
  - With a massive $U(1)_{\rm h}$: 'hidden photon' models.
- Massive visible U(1)s can have mass mixing (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:

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

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

- Non-diagonal mass terms mixing visible and hidden U(1)s
  - From non-diagonal metric G.
  - From an axion ϕ^i coupled to different U(1)'s, i.e. $k^i_{a_{\rm v}} \neq 0$, $k^i_{a_{\rm h}} \neq 0$

- Mass mixing from axionic charges k^i_a 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: $\left(U(1)_{\rm v} \;\; U(1)_{\rm h} \right)$
- 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.

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]

- Due to integrality of the axion charges, Z' couples with significant strengths to visible sector, $m_{Z'}$ is at least in the TeV range (LEP II).
- Z-Z' mixing is absent in the toy model but generically arises in string theory implementations (later).
- Charges of visible and hidden matter under Z' (arising from mass mixing) are generically not quantized w.r.t. each other.

  [Do not introduce dangerous gauge invariant couplings between the sectors]

Phenomenological Features

- Since no exotic matter is introduced, dark matter annihilation is only through:

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

- Need to ascertain that this process is sufficient to satisfy current DM relic density (seems OK even for Z'~ multi-TeV, see paper).
- Z' mediation of ~~SUSY~~: differ from earlier proposal of Langacker, Paz, Wang, Yavin in several respects, e.g., no exotics & 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.
- "Hidden valley" with barrier set by lightest Z' scale; much broader choice of U(1)'s (not just B-L & Y as in Han, Si, Strassler, Zurek).
- "Hidden photon" scenario realized by a slightly non-diagonal G.

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:

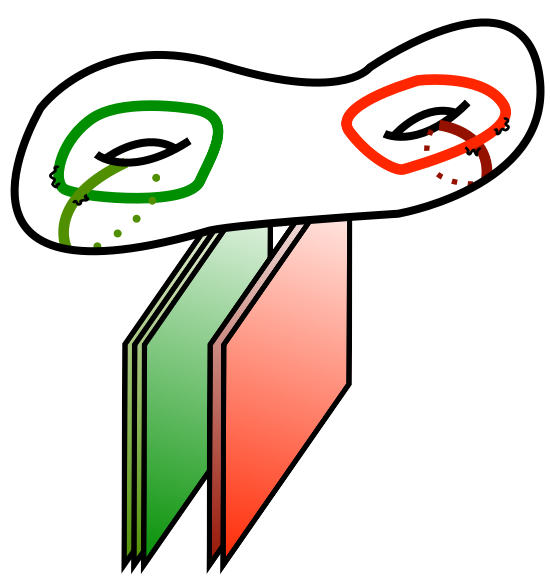
$$M^2 = (NR)^T \cdot G \cdot NR$$

- 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

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



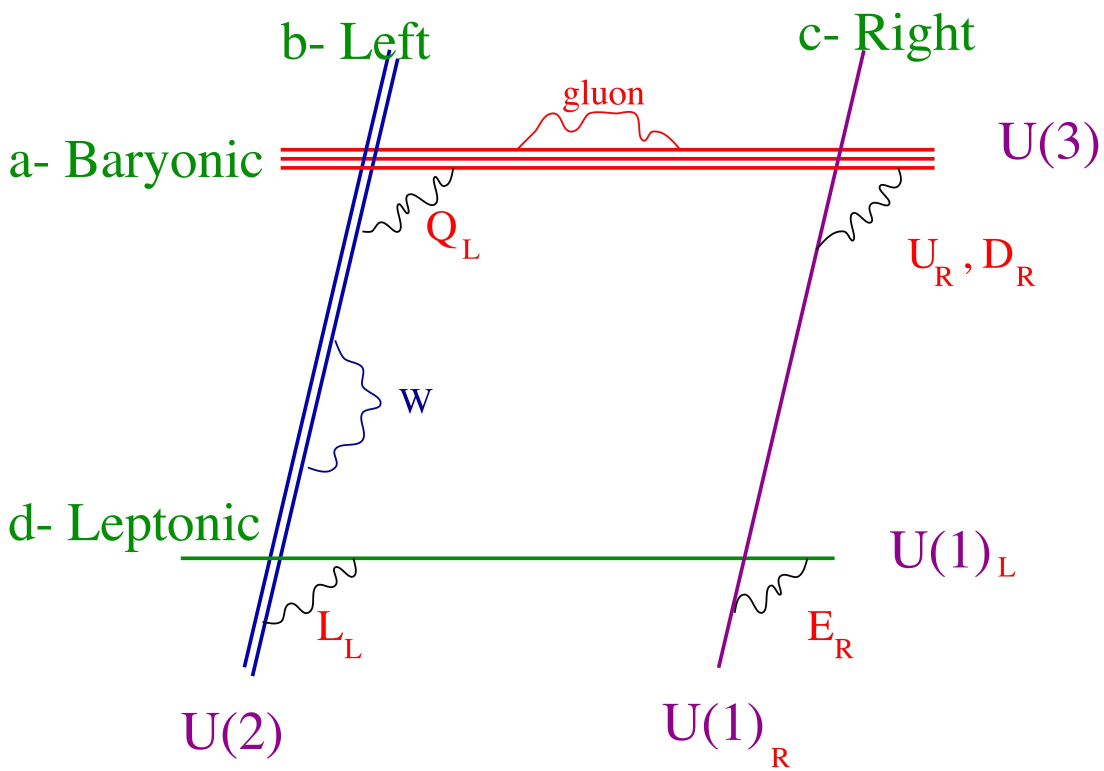
  - Off-diagonal U(1) mass matrix

Massive U(1)'s

- Stueckelberg or Brout-Englert-Higgs?
  - Stueckelberg mechanism arises naturally from **closed** string RR axions that propagate in the bulk.
  - BEH 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

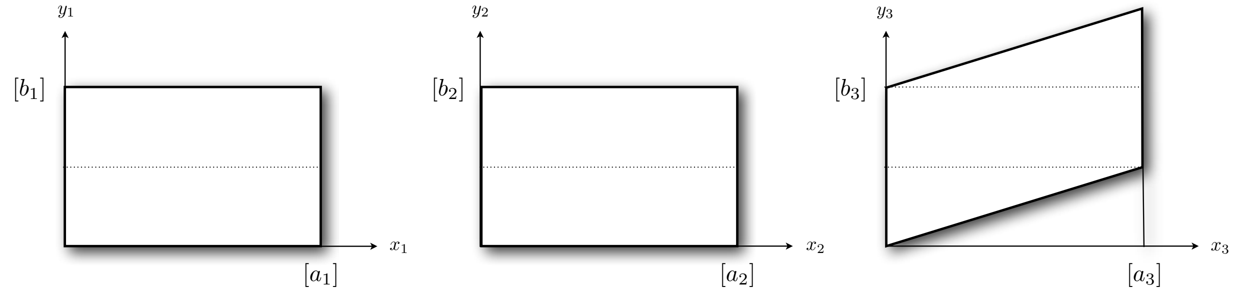
- Extending the (MS)SM Quiver in a toroidal compactification (can in principle be realized in more general CY compactifications):



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

$$[\Pi^{(\mathrm{h})}] = n_{\mathrm{h}}[\alpha^0] - [\beta_0] + 2[\beta_1] + m_{\mathrm{h}}[\beta_3]\,.$$

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



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

Conclusions

Conclusions

- In string theory, not anything goes! (e.g., dS vacua, millicharged DM)
- 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 our forthcoming paper.

Thank you