Hidden Sectors, String/M theory and Two Predictions On Dark Matter

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A pleasure to be back at Tata Institute.

~17 years ago, the Strings meeting here made a big impact on my research and life .....


Strings 2001, TIFR, Jan 2001

Lots of Evidence for Dark Matter

BUT

WHAT IS IT?

- very little known

- It behaves like matter
  - → assume it is particular.
- it doesn't have much charge (could have some)
- doesn't self interact much

That's not very much info.

Spin? Mass?

Completely unknown.

How is it produced?

unknown.

When was it produced?

Before BBN most likely?

Using simple properties of string/M theory, I will argue that, generically:

* Dark Matter is NON-THERMAL

and

* Dark Matter is in the HIDDEN SECTOR.

Based on work done with

- G. Kane, P. Kumar, K. Bobkov, S. Watson
  (Non-thermal) 2006-2013

- S. Ellis, G. Kane, B. Nelson, M. Perry
  (DM is Hidden)
  arXiv 1604.05320, PRL 117, 181802, 2016.
  1707.04530,

- M. Fairbairn, E. Hardy, arXiv 1704.01804 (Hidden Glueballs) JHEP 1707

Hidden Sectors

- Play a crucial role in this talk
- Huge Amount of literature on Hidden Sectors and DM
- This is <u>not</u> a review of Hidden sector models
- Rather, I will present a general picture emphasising those 2 points

Theorists favourite: WIMPs

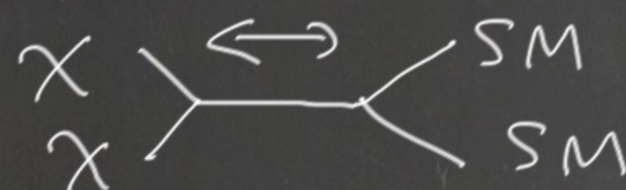
- Overwhelmingly WIMPs are favoured by theorists.
- Also targeted by many search strategies for DM.

Lets review WIMP DM

(see Ibarra and Belanger talks)

At the end of inflation (or whatever solves the Horizon, flatness probs and seeds the CMB!):

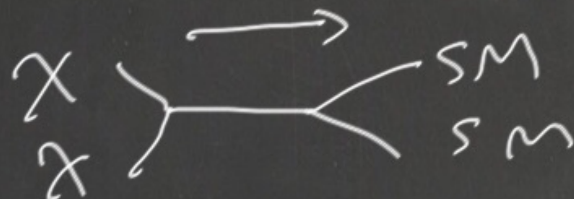
- Assume Universe is radiation dominated with a High $T \gg M_{EW} \sim 100\,\text{GeV}$
- Standard Model particles are in equilibrium with WIMPS, χ



χ is a Stable, electrically neutral particle charged under $SU(2) \times U(1)_Y$.

As Universe expands, T drops.

When T falls below m_χ,



only goes one way

And χ particles freeze out with

$$\frac{H\big|_{T\sim \frac{m_\chi}{\text{few}}}}{\langle\sigma v\rangle_{\chi\chi\to SM}} \sim n_\chi$$

$H \sim T^3/m_{pl}$

$\sigma v \approx \dfrac{\alpha^2}{M_\chi^2}$

so $n_\chi \approx \dfrac{T^2 M_\chi^2}{\alpha^2 m_{pl}}$

$$\rho/s \approx \frac{M_\chi^3}{g_* \alpha^2 T m_{pl}} \qquad (s \sim g_* T^3)$$

If $T \sim \dfrac{M_\chi}{5}$ *, $\alpha \sim 10^{-2}$

$\rho/s \sim 10^5 \dfrac{M_\chi^2}{m_{pl}} \sim$

$\sim 10^{-10}\,\text{GeV}$ ✓

$$\frac{\rho}{s} \simeq \frac{M_\chi^2}{g_* \alpha^2 M_{Pl}}$$

WIMP miracle or coincidence?

- This is a nice coincidence between the weak scale, Planck scale and the DM abundence.
- But it doesn't have to be a <u>miracle</u>
- Also, it assumes ($\rho \sim T^4$) radiation dominated early Universe. *

String / M theory

- Still our "best" UV framework for addressing many aspects of physics, including particle physics and cosmology
- Natural mathematical extension of supersymmetric field theory

We will consider the low energy limits of solutions of string/M-theory

$\exists$ <u>many</u> solutions of the form:

$$M^{9,1} = \underbrace{Z^6}_{\text{compact, small}} \times \underbrace{M^{3,1}}_{\text{large}}$$

or

$$M^{10,1} = X^7 \times M^{3,1}$$

$$g(M^{10,1}) \cong g(X) + g(M^{3,1})$$

$$\mathrm{Hol}(g(X)) = G_2 \, !$$

EXTRA DIMENSIONS

Very generally the massless particles which arise are:
gauge bosons, chiral fermions, scalars, a graviton, a gravitino

Plus MODULI = gravitons in extra dimensions

Manifested as <u>very</u> weakly interacting scalar fields, S_i.

Low energy, d=3+1 Lagrangian is of the form, schematically,

$$\mathcal{L}_{\text{matter + gravity}} = \frac{1}{16\pi G_N}\sqrt{-g_{3+1}}\, R_{3+1} + \frac{1}{g^2} F_{\mu\nu}^2 + i\bar{\Psi}\not{D}\Psi + \lambda H \bar{\Psi}\Psi + |DH|^2 - V(H, H^\dagger)$$

$$+$$

$$\mathcal{L}_{\text{moduli}} = K^{ij}(s_i)\left(\partial_\mu s_i \partial^\mu s_j + K^{ij}(s)\, \partial_\mu a_i \partial^\mu a_j\right) - V(s_i, a_j) + \dots$$

s_i = moduli a_i = axions

Moreover, every term in Standard Model Lagrangian has a coefficient which is a function of the moduli fields:

COUPLINGS = VEVS

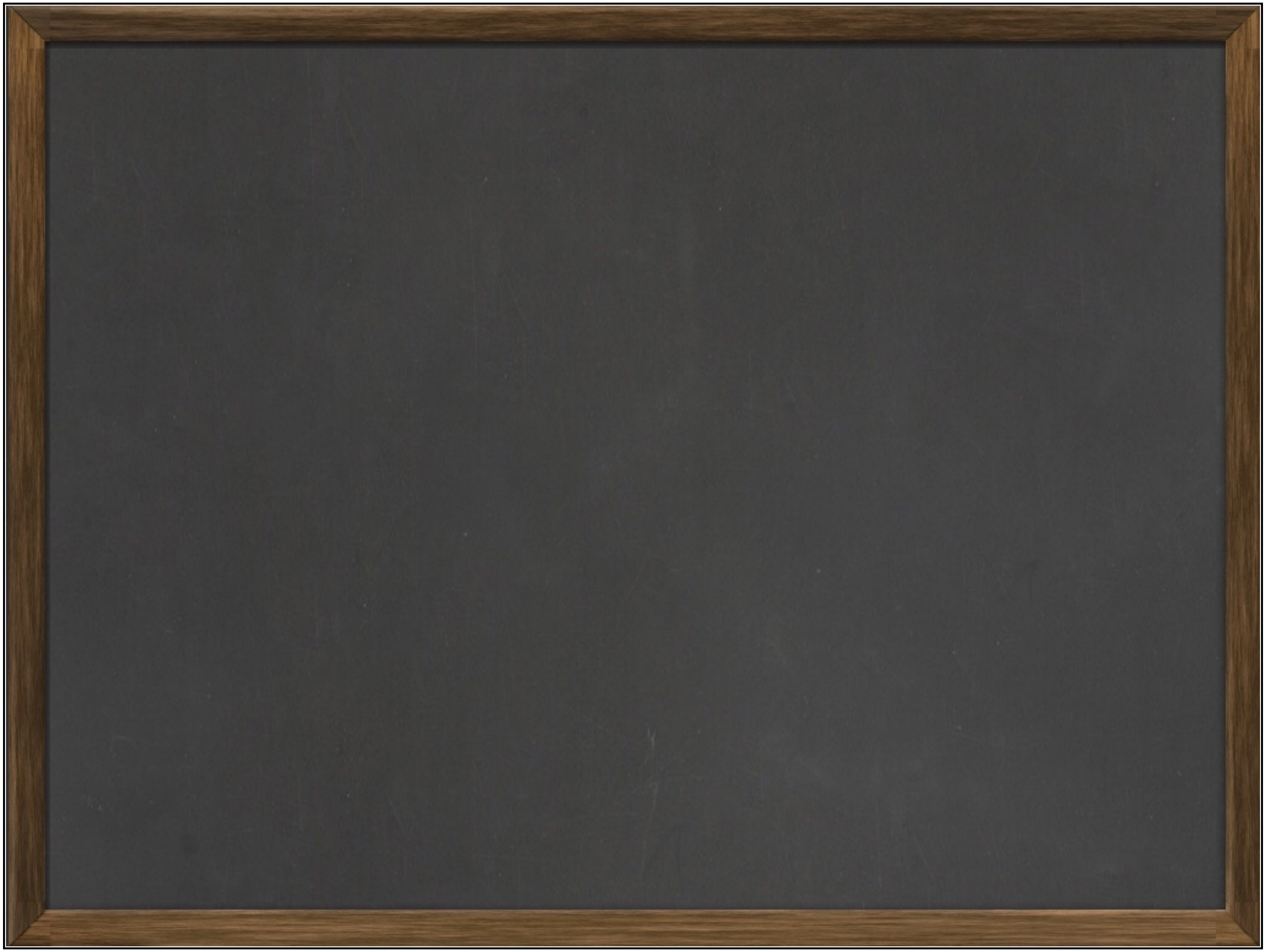
e.g. $\frac{1}{g^2}F_{\mu\nu}^2$ is really

$S\sqrt{G_N}F_{\mu\nu}^2$ $\quad \frac{N_i S_i F_{\mu\nu}^2}{M_{Pl}}$, a dim-5 operator.

Similarly $\lambda H \overline{\Psi}_L \Psi_R$ is really

$$* \rightarrow e^{-\frac{d_i S_i}{M_{Pl}}} e^{i\frac{d_i a_i}{f}} H \overline{\Psi}_C \Psi_R$$

* The moduli dependence of λ varies from theory to theory.



- Moduli vevs control couplings and masses
- Moduli have Planck suppressed couplings to ordinary matter
- Makes sense as Moduli are actually higher dimensional gravitons.

What about the moduli masses?

Supersymmetry:

$\Rightarrow \mathcal{L}_{3\pi}$ is a supergravity theory.

In particular, there is only ONE

MASS SCALE, $\underline{\underline{M_{3/2}}}$, the

gravitino mass.

So $\boxed{M_{\text{moduli}} \sim M_{3/2}}$, without fine-tuning

- Moduli in Cosmology

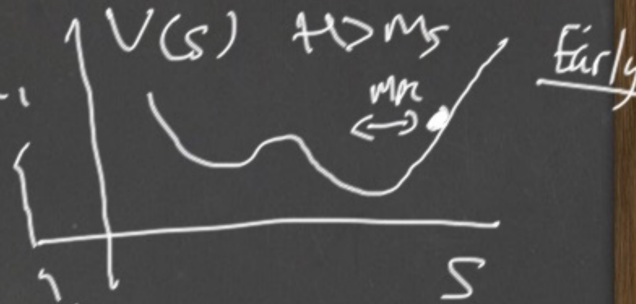
- Polonyi Problem (Coughlan et al 83)
- Cosmological Moduli Problem (CMP)
- Carlos, Casas, Quevedo, Roulet 93

  Banks, Kaplan, Nelson 93

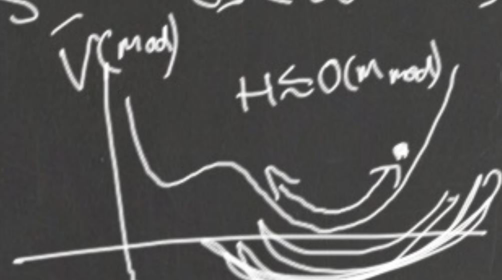
Cosmology of This Theory

At the end of inflation (or whatever.....)

If $H >> m_{3/2} \sim m_{moduli}$, the moduli will be stuck at some $O(1)\, m_{pl}$ place in its potential.



Later, $H \sim O(m_{moduli})$ and S oscillates:



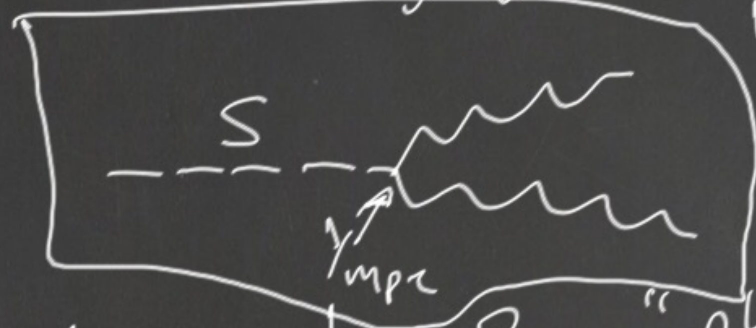
ρ_{moduli} is a MATTER component which QUICKLY dominates over $\rho_{radiation}$ $\left(\frac{1}{R^3} \text{ vs } \frac{1}{R^4}\right)$.

Hence, the Universe becomes **matter** dominated by the moduli fields.

GENERIC PREDICTION OF STRING/M THEORY MODELS WITH LOW ENERGY SUSY.

The moduli are unstable particles.
(They couple to matter particles fairly 'generically' and 'uniformly'.)

Consider, e.g., $\mathcal{L}_{gauge} \sim \frac{S}{M_{pl}} F_{\mu\nu}^2$



S decays to 2 "photons"

Decay width (or probability) is

$$\Gamma(s \to \gamma\gamma) \propto |M|^2$$

$$M \sim 1/M_{pl}$$

$$\Gamma \sim O(1/M_{pl}^2) \sim G_N$$

$$\therefore \quad \Gamma(s \to \gamma\gamma) \approx \frac{M_{moduli}^3}{M_{pl}^2} \times$$

$\therefore$ Lifetime $$\tau_{moduli} \approx \frac{M_{pl}^2}{M_{moduli}^3} \leftarrow$$

So, after dominating $\rho_{universe}$, the moduli will decay after a time

$$t_{decay} \sim \frac{M_{pl}^2}{m_{moduli}^3}$$

equivalently $$H_{decay} \sim \frac{m_\phi^3}{M_{pl}^2}$$

$$\frac{1}{H_{decay}} \sim O(1)\,\text{sec}\left(\frac{\text{TeV}}{m_{moduli}}\right)^3 .$$

This is in the <u>middle</u> of BBN!

So for $M_{3/2} \sim$ TeV, moduli decay during BBN. This is bad as they decay into quarks, leptons and gauge bosons.

This injects charged particles and hadrons into the plasma which can dis-associate nuclei and drastically change the successful predictions of BBN.

But, for $M_{3/2} \sim \mathcal{O}(10\ )\,\mathrm{TeV}$,
the moduli decay <u>before</u> BBN,
create a radiation dominated
universe with $T \sim$ <u>10 MeV</u>
and this is consistent.

Key point:

The Universe is <u>matter dominated</u> by the moduli before BBN.

This implies Dark Matter is NON-THERMALLY produced.

This seems quite a generic conclusion.

Caveats

- Could assume $H_{inf} \ll m_{3/2}$ (not typical)
- Could arrange a late period of inflation to "get rid of the moduli". (Seems 'tuned'?)

NEXT: DARK MATTER IS IN THE HIDDEN SECTOR

Hidden Sectors

Def^n: A particle is in the Hidden sector if it has no tree level gauge interactions with the Standard Model.

ie it has no $SU(3) \times SU(2) \times U(1)_Y$ charge at tree level.

Since we have no idea **why** the Standard Model has $G = SU(3) \times SU(2) \times U(1)_Y$ and 45 fermions and a Higgs doublet; there is no reason **NOT** to consider additional gauge sectors and matter.

This is exactly the picture that emerges from string/M theory

Hidden Sectors in String/M theory

- In Heterotic $E_8 \times E_8$ theory, one E_8 is "hidden" wrt the other.
- In Type II theories, D-branes can be physically separated in the extra dimensions.
- In M/F-theory, singularities supporting gauge symmetries are physically separated. (G_2 or CY_4)

There is no privelage given to the Standard Model.

Generically <u>expect</u> additional gauge groups and matter.

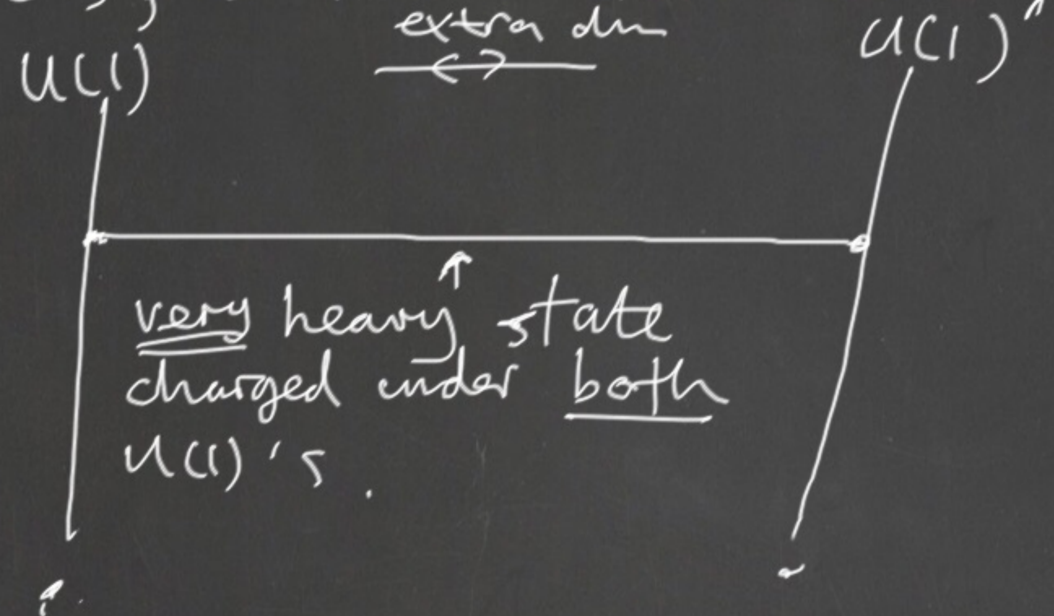
> HIDDEN SECTOR MATTER IS GENERIC

(Talk yesterday by S. Ellis)

Consider a Type II string model with

$G = U(1) \times U(1)'$

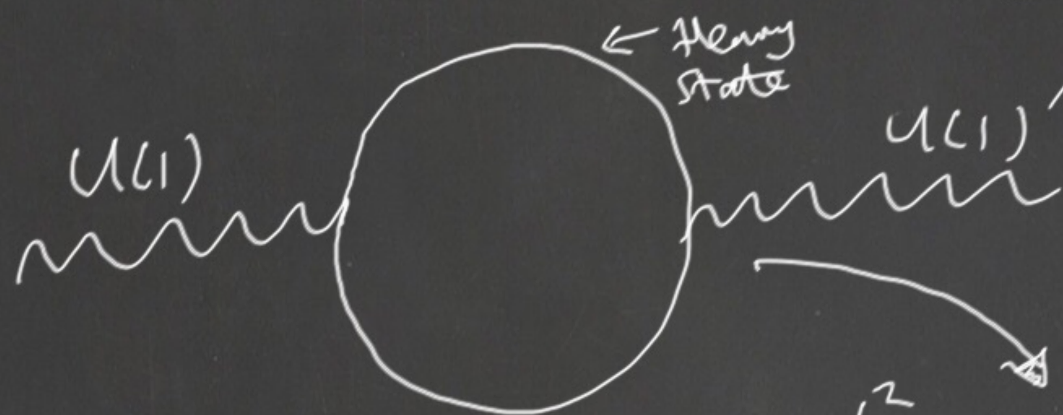
Realise this with two stacks of D-branes, separated in extra dims:



Mass, heavy state ~ $\underline{M_{str}^2 R_{KK}}$

$\gg$ $\underline{M_{KK}}$.

It induces a renormalisation of kinetic terms;



ie $F_{\mu\nu}^2 + \tilde{F}_{\mu\nu}^2 \longrightarrow F_{\mu\nu}^2 + F'^2_{\mu\nu} + \epsilon F_{\mu\nu} F'_{\mu\nu}$

Since FF' is dim 4, ϵ is only log sensitive to UV

$$\epsilon \sim \frac{g g'}{12\pi^2} \ln\left(\frac{\Lambda}{M}\right).$$

- Such mixings are generically present between U(1)'s.
- This has been known for quite some time (Dienes, Kolda, March-Russell '97)

The $\epsilon F F'$ interaction (and those related to it by supersymmetry) provides a **PORTAL** between different hidden sectors.

eg gauge bosons can mix between sectors, as can gauginos, via $\epsilon \lambda \not\partial \lambda'$.

This leads to a picture with several, even many, hidden sectors and a <u>web</u> of portal interactions interconnecting them.

Consider now the (supersymmetric) Standard Model Sector. This has a (so-called) "Lightest Supersymmetric Particle", which is often the WIMP DM candidate.

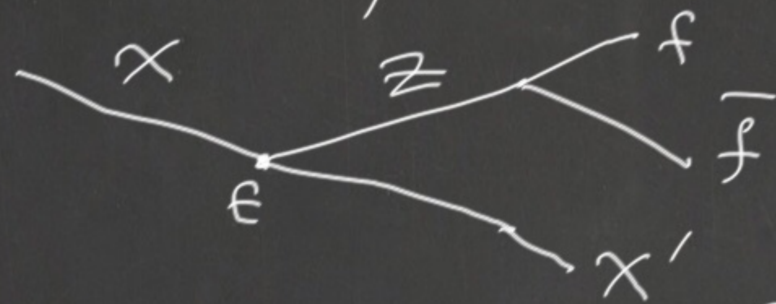
Usually (without Hidden Sectors) this is stable as it is the lightest particle with non zero R-parity.

With multiple hidden sectors, there is NO GOOD REASON why the LVSP* should be the lightest R-parity charged particle in the theory.

It could happen by accident, but is unlikely.

*LVSP = Lightest Visible sector Supersymmetric Particle

Mixing between Hidden $U(1)'$ and $U(1)_Y$ leads to, e.g.



and $\tau_X \sim 10^{-17}\,s \left(\frac{10^{-3}}{\epsilon}\right)^2 \times$ mixing angles *

for on shell Z

$$\tau_X \sim 10^{-9}\,s \left(\frac{10^{-3}}{\epsilon}\right)^2 \times \left(\frac{50\,GeV}{m_X - m_{X'}}\right)^4 \times \text{angles}$$

for 3-body decay

This completes the argument that

DARK MATTER IS <u>PROBABLY</u> IN THE HIDDEN SECTOR.

The argument relied on three ingredients:

1: Hidden Sectors are Generic
2: PORTALS are generic
3: The LUSP is not the lightest super particle.

So, what is Dark Matter?

- Axions are also generic in string/M theory and are very difficult to remove.
- Stable particles produced by moduli decays will also be a component of Dark Matter:
- Light, decoupled (chiral) fermions;
- Hidden sector glueballs, other composites.

Conclude:

- Dark Sector is <u>very</u> rich, perhaps richer than the Standard Model.
- DM is more likely to be non-thermally populated
- Rich phenomenology at LHC and elsewhere.

Thanks!