String/M theory Compactification and Phenomenology

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Lecture Notes Part III

- We have seen that there are generic predictions of string/M theory compactifications for particle physics (chiral fermions, Yukawa hierarchies...)
- In this last part we will try to extract some generic predictions for Dark Matter and Cosmology

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.

- Cosmological Moduli dynamics will be extremely important in the story.

$\boxed{\text{* Carlos, Casas, Quevedo, Roulet 93}}$

also Banks, Kaplan, Nelson 93

Some more recent useful refs include

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

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

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

- Type IIB LVS detailed studies :
  Aparicio, Cicoli, Dutta, Krippendorf, Maharana, Muia, Quevedo arXiv 1502.05672
  and arXiv:1607.00004

Hidden Sectors

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

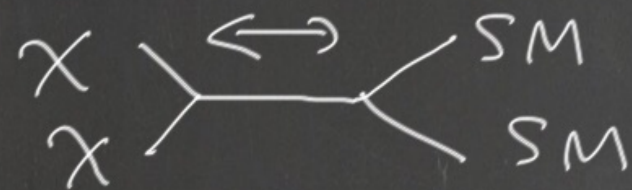
Theorists favourite: WIMPs

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

Lets review WIMP DM

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

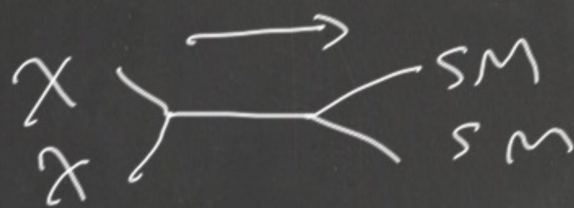
- Assume Universe is radiation dominated with a High $T \gg \underline{M_{EW}} \sim 100\,\mathrm{GeV}$
- Standard Model particles are in equilibrium with WIMPS, χ



χ is a stable, electrically <u>neutral</u> 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

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

$$\underline{H \sim T^2/m_{pl}} \qquad \sigma v \approx \frac{\alpha^2}{M_x^2}$$

$$\text{so } \underline{n_x} \approx \frac{T^2 M_x^2}{\alpha^2 m_{pl}}$$

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

$$\text{If } T \sim \frac{M_x}{5} \; * \; \rho/s \sim 10^5 \frac{M_x^2}{m_{pl}} \sim$$

$$\underline{\alpha \sim 10^{-2}} \qquad \boxed{\underline{\sim 10^{-10}\,\text{GeV}} \; \checkmark}$$

$$\rho/s \simeq \frac{M_X^2}{g_* \alpha^2 M_{pl}}$$

WIMP miracle or coincidence?

- This is a nice coincidence between the weak scale, Planck scale and the DM abundance.

- But it doesn't have to be a miracle

- 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

$\exists$ many 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,

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

$$+$$

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

s_i = moduli a_i = axions

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

$\boxed{\text{COUPLINGS} = \text{VEVS}}$

e.g. $\frac{1}{g^2}F_{\mu\nu}^2$ is really $\frac{N_i S_i F_{\mu\nu}^2}{m_{Pl}}$, a dim-5 operator.

$s\sqrt{G_N}F_{\mu\nu}^2$

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

$$* \quad \longrightarrow e^{-\frac{d_i S_i}{m_{Pl}}} e^{i\frac{d_i a_i}{f}} H \bar{\Psi}_L \Psi_R$$

* 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:

$\Rightarrow \mathcal{L}_{3+1}$ 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

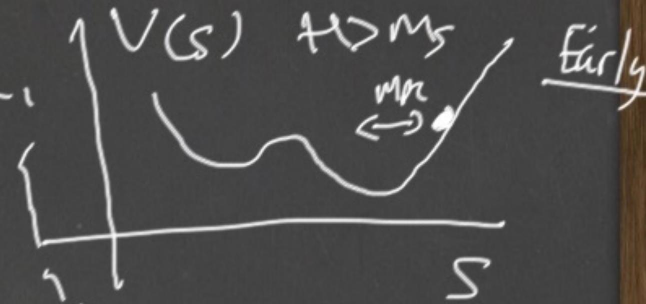
- Moduli in Cosmology

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

Cosmology of This Theory

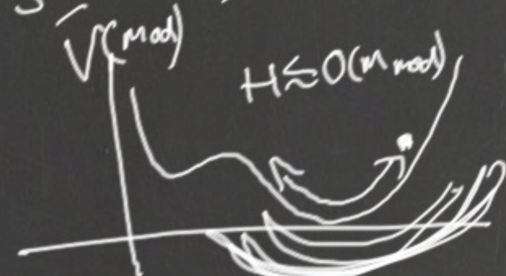
At the end of inflation (or whatever.....)

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



Later, $H \sim O(m_{moduli})$

and S oscillates:



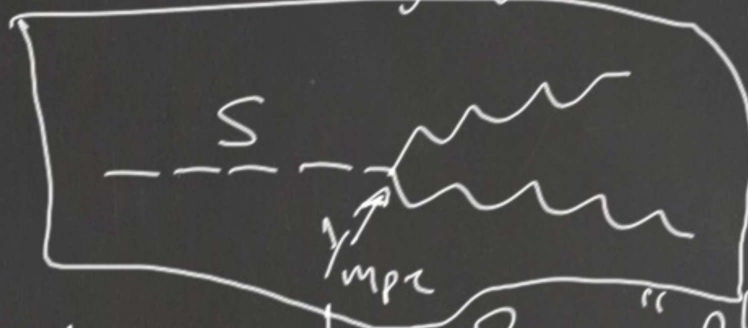
ρ_{moduli} is a MATTER component which <u>QUICKLY</u> dominates over $\rho_{radiation}$ $\left(\underline{1/R^3} \text{ vs } \underline{1/R^4} \right)$.

Hence, the Universe becomes $\boxed{\text{matter}}$ 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

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

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

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

$$\therefore \quad \Gamma(s \to \gamma\gamma) \approx \frac{M^3_{moduli}}{M^2_{Pl}} \times$$

$\therefore$ Lifetime $\quad \tau_{moduli} \approx \underline{\underline{\dfrac{M_{Pl}^2}{M^3_{moduli}}}} \leftarrow$

So, after dominating 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 <u>bad</u> 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 before BBN, create a radiation dominated universe with $T \sim 10\,\mathrm{MeV}$ and this is consistent.

Key point:
The Universe is matter dominated by the moduli before BBN.

This implies Dark Matter is NON-THERMALLY produced.

This seems quite a generic conclusion.

Caveats

- Could assume $\underline{H_{inf} << m_{3/2}}$
  (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 <u>why</u> 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 <u>NOT</u> 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.

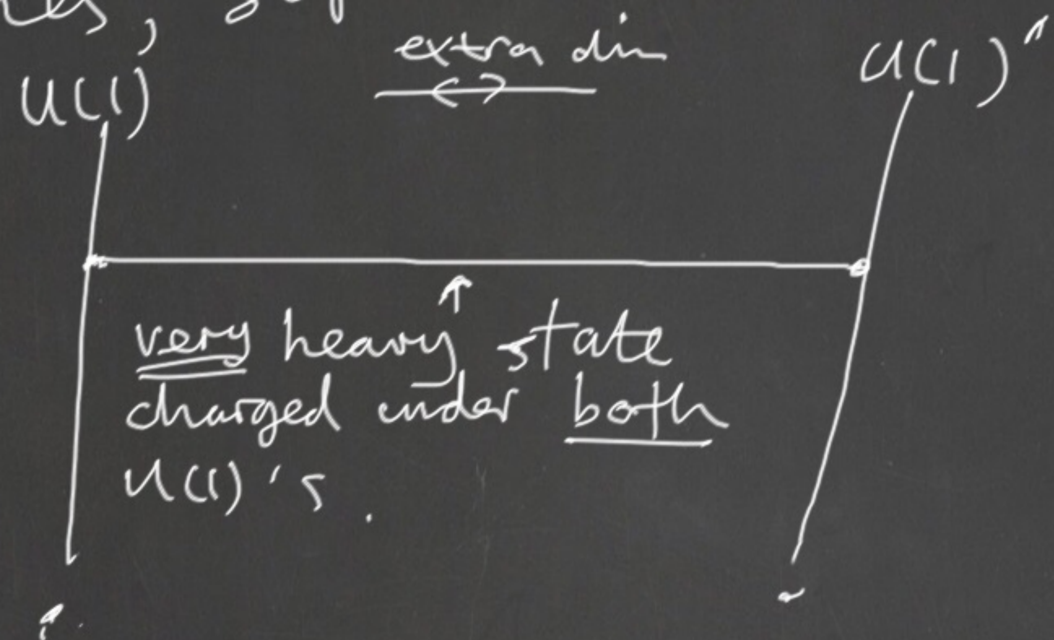
Generically <u>expect</u> additional gauge groups and matter.

$$\boxed{\text{HIDDEN SECTOR MATTER IS GENERIC}}$$

Consider a Type II string model with

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

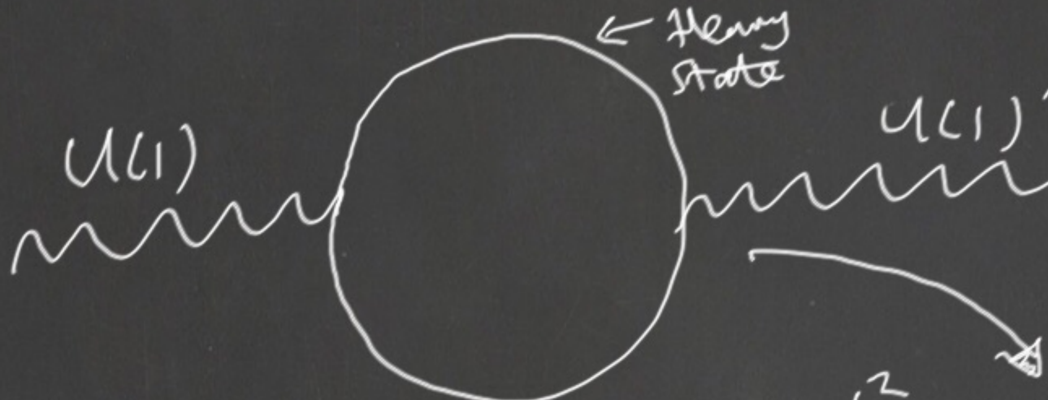
Realise this with two stacks of D-branes, separated in extra dims:



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

$\gg M_{KK}$.

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 $\epsilon F F'$ interactions (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 $\underset{\sim}{\epsilon \lambda \not{\partial} \lambda'}$.

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.

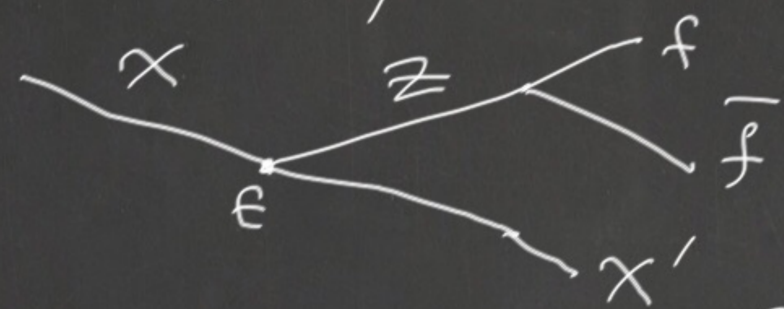
Usually (without Hidden Sectors) this is stable as it is the lightest particle with non zero R-parity.

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 $$\tau_\chi \sim 10^{-17} s \left(\frac{10^{-3}}{\epsilon}\right)^2 \times \text{mixing angles} \;\ast$$

for on shell Z

$$\tau_\chi \sim \underbrace{10^{-9} s}_{\text{for 3-body decay}} \left(\frac{10^{-3}}{\epsilon}\right)^2 \times \left(\frac{50\,\text{GeV}}{m_\chi - m_{\chi'}}\right)^4 \times \text{angles}$$

This completes the argument that

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

The argument relied on
three ingredients:

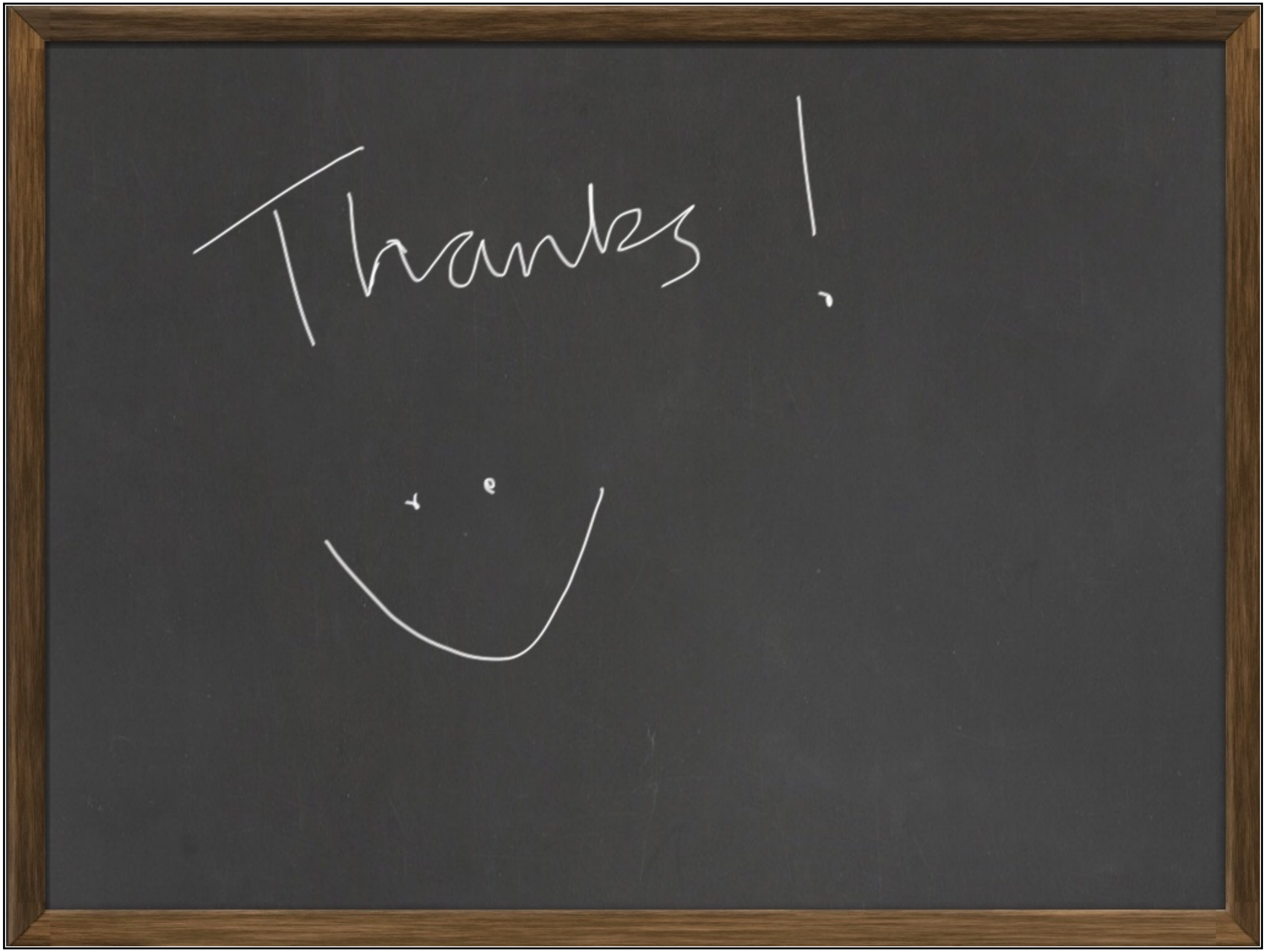
1: Hidden Sectors are Generic
2: PORTALS are generic
3: The LUSP is not the
lightest super particle.

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!