Dark Matter in String/M theory:

- Two Generic Predictions for Dark Matter.

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Lots of Evidence for Dark Matter

BUT

WHAT IS IT?

- 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, 1707.04530, PRL 117, 181802, 2016.

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

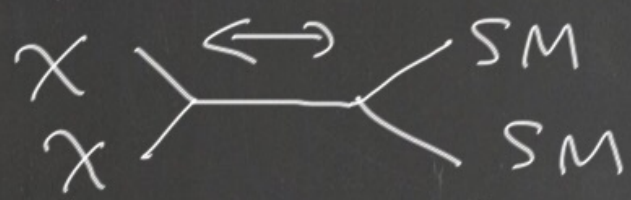
Theorists favourite: WIMPs

- 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!):

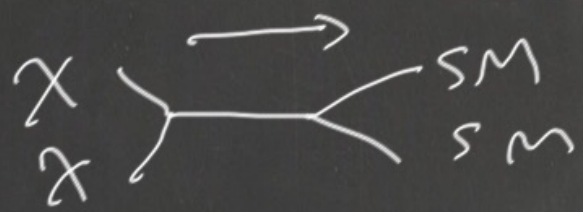
- Assume Universe is radiation dominated with a High $T \gg \underline{m_{EW}} \sim 100\,GeV$
- Standard Model particles are in equilibrium with WIMPs, χ



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

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

$$H \sim T^2/M_{Pl} \qquad \sigma v \approx \frac{\alpha^2}{M_X^2}$$

$$\text{so } n_X \approx \frac{T^2 M_X^2}{\alpha^2 M_{Pl}}$$

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

$$\text{If } T \sim \frac{M_X}{5} \;\&\; \rho/s \sim 10^5 \frac{M_X^2}{M_{Pl}} \sim$$

$$\alpha \sim 10^{-2} \qquad \sim 10^{-10}\,\text{GeV}$$

- 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. *

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

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

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

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

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

$$+$$

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

s_i = moduli a_i = axions

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

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

Similarly $\lambda H \bar{\psi}_L \psi_R$ is really

$$* \rightarrow e^{-\frac{d_i S_i}{M_{pl}}} e^{i\frac{d_i a_i}{f}} H \bar{\psi}_L \psi_R$$

* 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?

- For simplicity assume supersymmetry.

Then $\mathcal{L}_{3\pi}$ 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

$$DW = \underline{\partial W} + \partial K W$$

$$K \sim$$

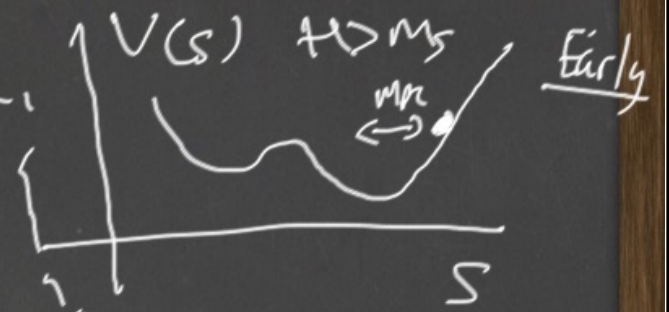
$$V \sim |\partial K|^2 W^2$$

$$\sim m_{3/2}^2$$

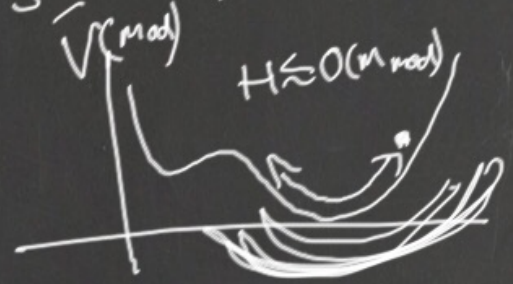
Cosmology of This Theory

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:

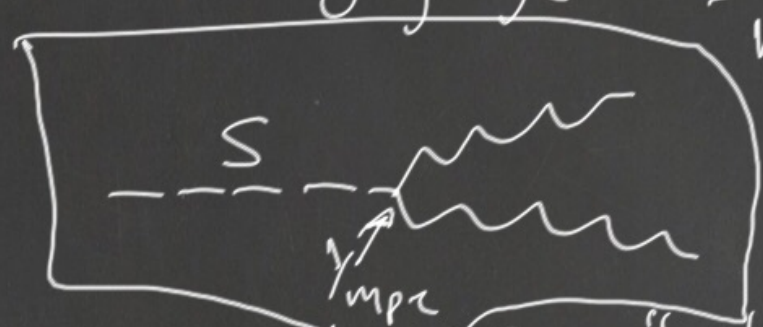


ρ_{moduli} is a MATTER component which QUICKLY dominates over $\rho_{radiation}$ $\left(\frac{1}{R^3} \text{ vs } \frac{1}{R^4}\right)$.

Hence, the Universe becomes $\boxed{\text{matter}}$ dominated by the moduli fields.

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

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

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

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

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

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

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

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

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

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

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 $M_{3/2} \sim O(10)$ 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 matter dominated by the moduli before BBN.

This implies Dark Matter is NON-THERMALLY produced.

This seems quite a generic conclusion.

Caveats

- Could assume $H_{inf} << m_{3/2}$ (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 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.

There is no privelage given to the Standard Model.

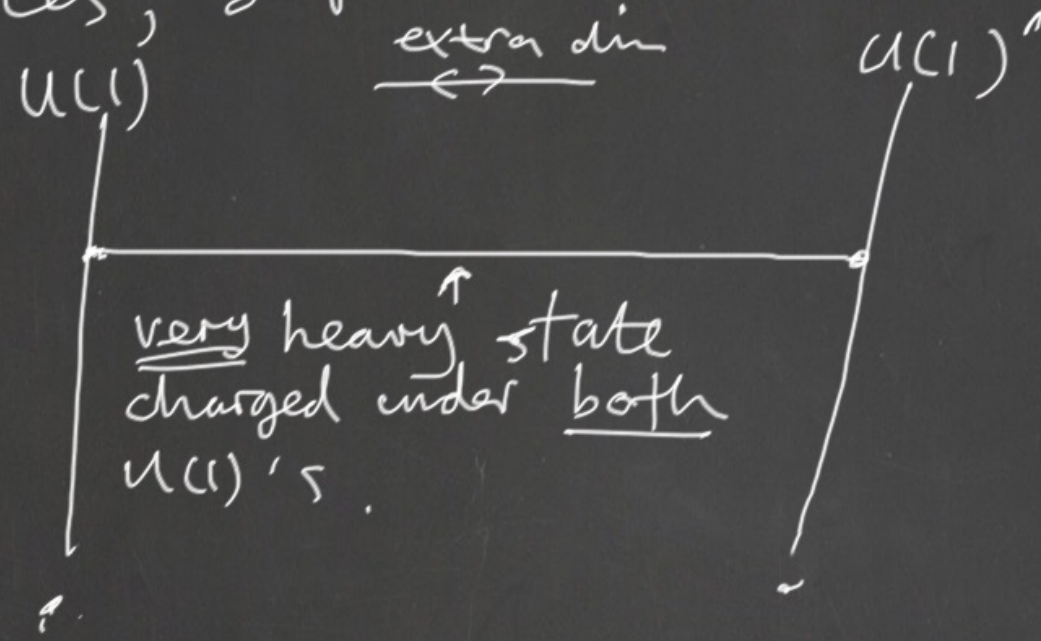
Generically expect additional gauge groups and matter.

HIDDEN SECTOR MATTER IS GENERIC

Consider a Type II string model with

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

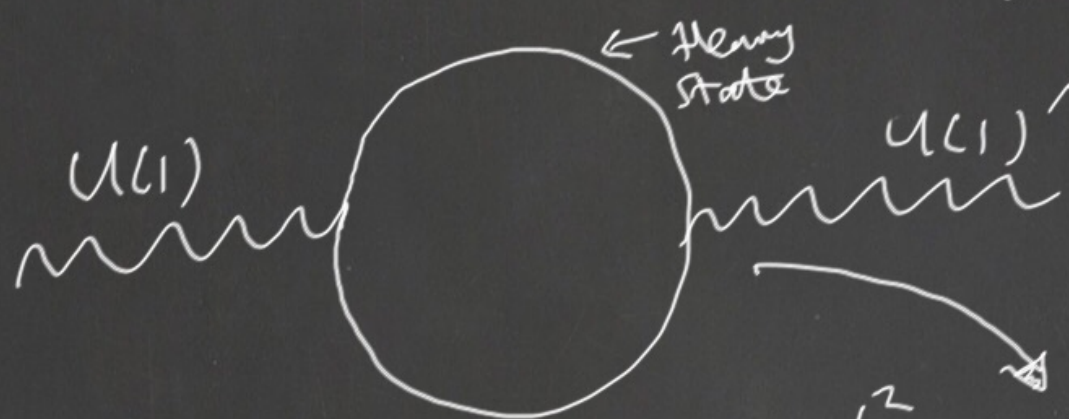
Realise this with two stacks of D-branes, separated in extra dims:



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

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

It induces a renormalisation of kinetic terms:



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

Since FF' is dim 4, $\boxed{\epsilon \text{ is only log sensitive to UV}}$

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

- 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 $\epsilon \lambda \not{D} \lambda'$.

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.

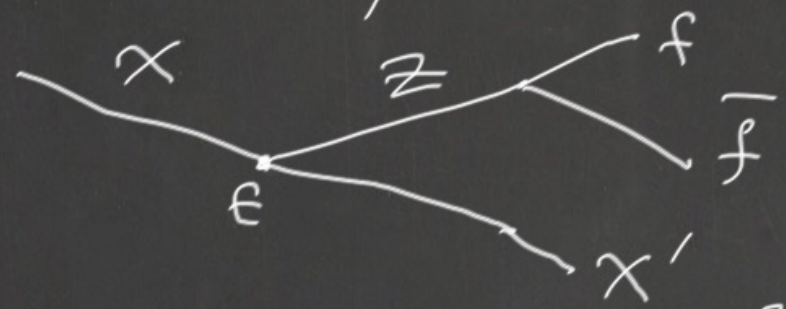
Usually (without Hidden Sectors) this is stable as it is the lightest particle with non zero R-parity.

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

It <u>could</u> happen by accident, but is <u>unlikely</u>.

*LVSP = Lightest Visible Sector Supersymmetric Particle

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



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

for on shell Z

$$\tau_\chi \sim \underbrace{10^{-9}\,s}_{\text{for 3-body decay}} \left(\frac{10^{-3}}{\epsilon}\right)^2 \times \left(\frac{90\,\text{GeV}}{m_\chi - m_{\chi'}}\right)^4 \times \text{angles}$$

This completes the argument that

DARK MATTER IS PROBABLY IN THE HIDDEN SECTOR.

The argument relied on three ingredients:

1: Hidden Sectors are Generic

2: PORTALS are generic

3: The LVSP 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; Glueballs; other composites.

Assume ψ is a stable, hidden sector particle.

When the moduli decay into ψ, there are two cases, depending on the initial number density of ψ, n^0_ψ . . .

I $\quad n^0_\psi \gg \dfrac{H}{\langle \sigma v \rangle_{\psi \to X}}$

II $\quad n^0_\psi < \dfrac{H}{\langle \sigma v \rangle_{\psi \to X}}$

$$n^0_\psi = Br(s \to \psi\bar{\psi}) \frac{M^6_{moduli}}{m_\psi m^2_{pl}}$$

$\langle \sigma v \rangle_{\psi \to X}$ is the x-section for processes $(2 \to 2)$ which reduce n^0_ψ.

Case I: ψ particles annihilate until $n_\psi = 3H/\langle\sigma v\rangle$.

(work in progress)

Case II: ψ particles just hang around.

In case II $m_\psi \lesssim O(100)\,\mathrm{MeV}$.

Heavier ψ's give too much DM.

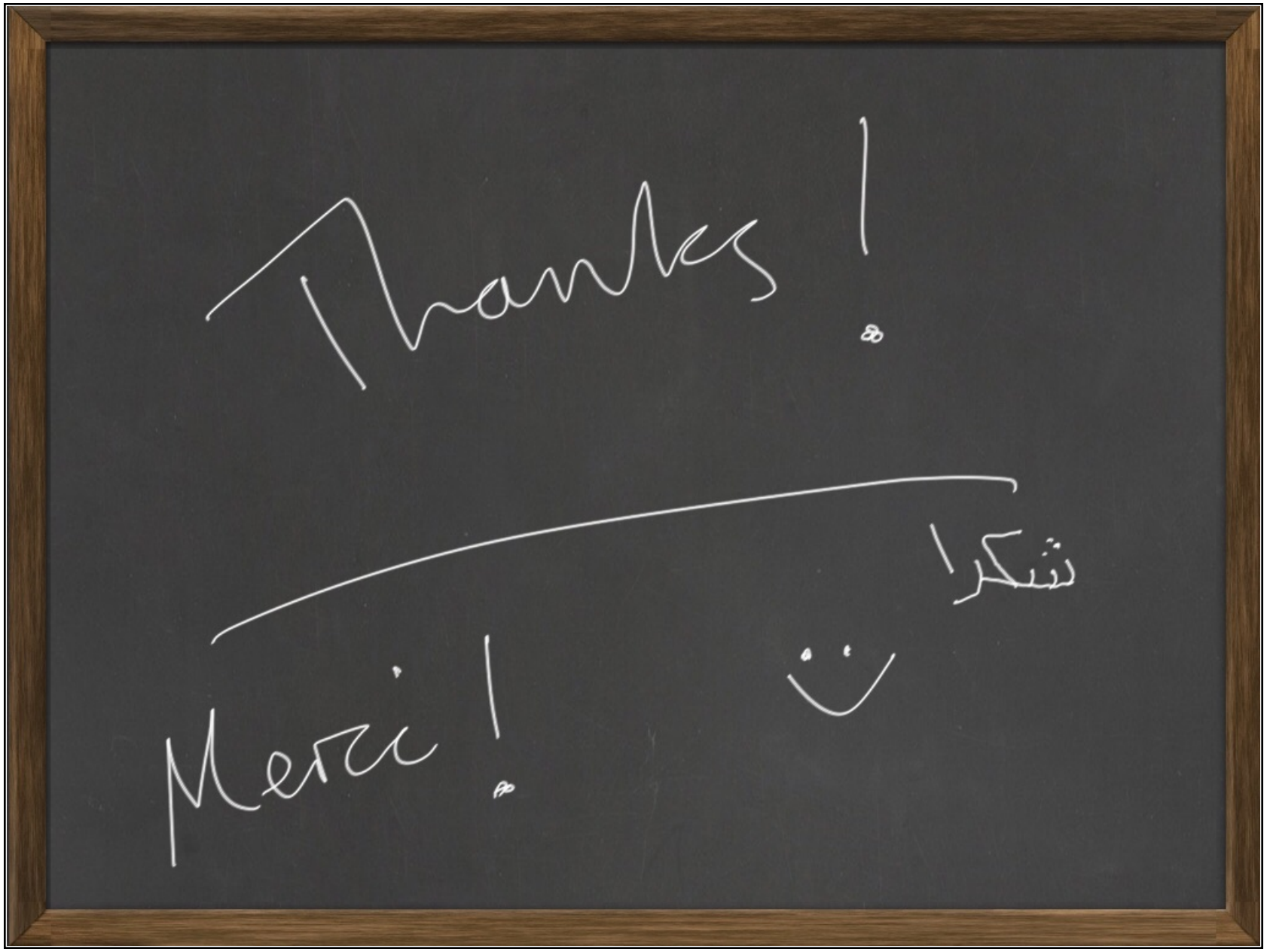
ψ could be a chiral fermion in the Hidden sector, since these can <u>naturally</u> have masses smaller than $M_{moduli} \sim O(100)$ TeV.

This can be realised in various string/M theory models.

Case I: in progress!

Conclusions

- Dark Matter is probably
  * Produced "Non-thermally"
  * In the Hidden Sector


Thanks!
شكرا
Merci!