M theory, G_2-manifolds and Dark Matter

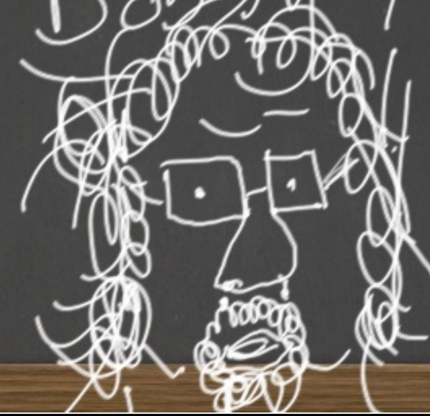
Bobby Acharya

Chris Hull @ 60
Birthday Conference.

IMPERIAL COLLEGE LONDON

My Life with Chris

- I want to share some personal reflections on the impact of Chris Hull on Bobby Acharya.



Three Key Events

1. I arrive at Queen Mary in Sep 94 to start my PhD with Chris.

Autumn 1994:

BSA: "I want to derive particle physics from the Heterotic string theory"

Chris: "Type IIA $\Rightarrow$ 11d sugra = ...

BSA (thinking........ He's probably gone nuts)

Note: this is also what I thought when I heard Juan's first talk on "Type IIB on $AdS_5 \times S^5 = N=4$ SYM"!

2 : G_2.

June 95

(Post U-duality)

BSA: "G_2 manifolds might be to M theory what Calabi-Yau's are to heterotic strings"

Chris: "I've heard that some kid called Joyce has constructed some compact examples"

BSA: "Great!! Can we work on this over the summer?"

Chris: "No - I'm off to Santa Barbara for summer."

A week later: Chris: "But I did get you these Joyce preprints. Maybe you can explain them to me when I get back."

(thx to George/Paul)

3. April 14th 1999 (A fond memory)

- Chris, Sarah and I go to a pub in Islington to watch FA Cup semi-final replay between Manchester United and Arsenal

Tottenham fan

- We are the only 3 people who want Arsenal to lose
- Which happened due to a Ryan Giggs super goal!

Two Generic Predictions About Dark Matter.

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)

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

- M. Fairbairn, E. Hardy, arXiv 1704.01804

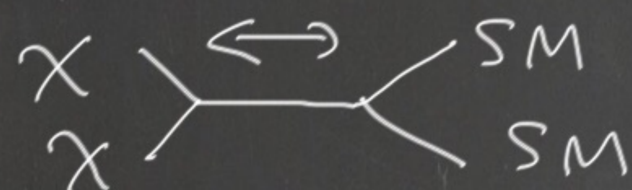
Theorists favourite: WIMPs

- 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!):

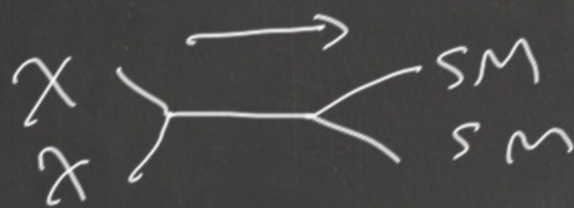
- Assume Universe is radiation dominated with a High $T \gg M_{EW} \sim 100\,\text{GeV}$
- Standard Model particles are in equilibrium with WIMPS, χ



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

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

$H \sim T^3/m_{pl}$ $\qquad \sigma v \approx \dfrac{\alpha^2}{M_x^2}$

so $\boxed{n_x \approx \dfrac{T^2 M_x^2}{\alpha^2 m_{pl}}}$

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

$(s \sim g_* T^3)$

If $T \sim \dfrac{M_x}{5}$

$\alpha \sim 10^{-2}$

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

$\boxed{\sim 10^{-10}\,\text{GeV}}$ ✓

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

- But it doesn't have to be a miracle

- 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:

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

or

$$M^{10,1} = X^7 \times M^{3,1} \qquad \text{M theory, eg } G_2.$$

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

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

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

$+$

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

$+ \dots$

s_i = moduli $\quad a_i$ = axions

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

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

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

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

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

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

<u>What about the moduli masses?</u>

- For simplicity assume supersymmetry.

Then $\mathcal{L}_{3H}$ is a supergravity theory.

In particular, there is only ONE MASS SCALE, $M_{3/2}$, the gravitino mass.

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

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

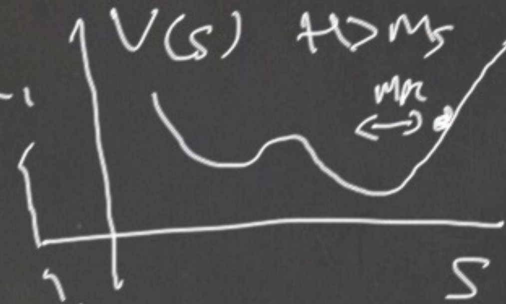
$$K \sim$$

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

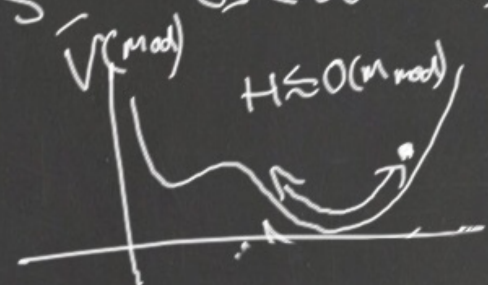
$$\sim \quad m_{3/2}^2$$

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:

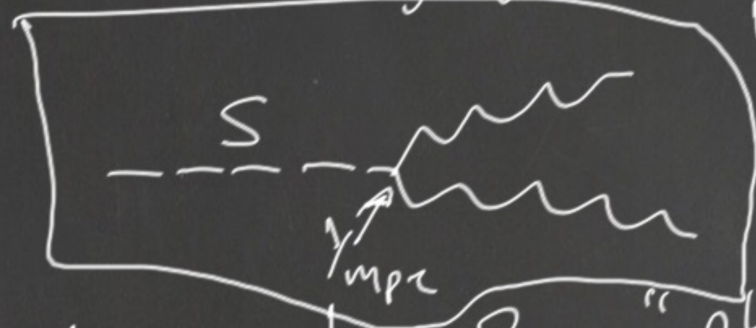


ρ_{moduli} is a MATTER component which QUICKLY dominates over $\rho_{\text{radiation}}$ $\left(\frac{1}{R^3} \text{ vs } \frac{1}{R^4}\right)$.

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

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

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

$$\Gamma \sim O(1/M_{PL}^2) \sim G_N \text{ (for gravity!)}$$

$$\therefore \quad \Gamma(s \to \gamma\gamma) \approx \left(\frac{M^3_{\text{moduli}}}{M^2_{PL}} \right)$$

$\therefore$ Lifetime $\tau_{\text{moduli}} \approx \dfrac{M_{PL}^2}{M^3_{\text{moduli}}} \sim$

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 middle 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 $m_{3/2} \sim O(10\ )$ TeV, the moduli decay <u>before</u> BBN, create a radiation dominated universe with $T \sim \underline{10\,\mathrm{MeV}}$ 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 $\underline{H_{inf} \ll m_{3/2}}$
  (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.

There is no privelage given to the Standard Model.

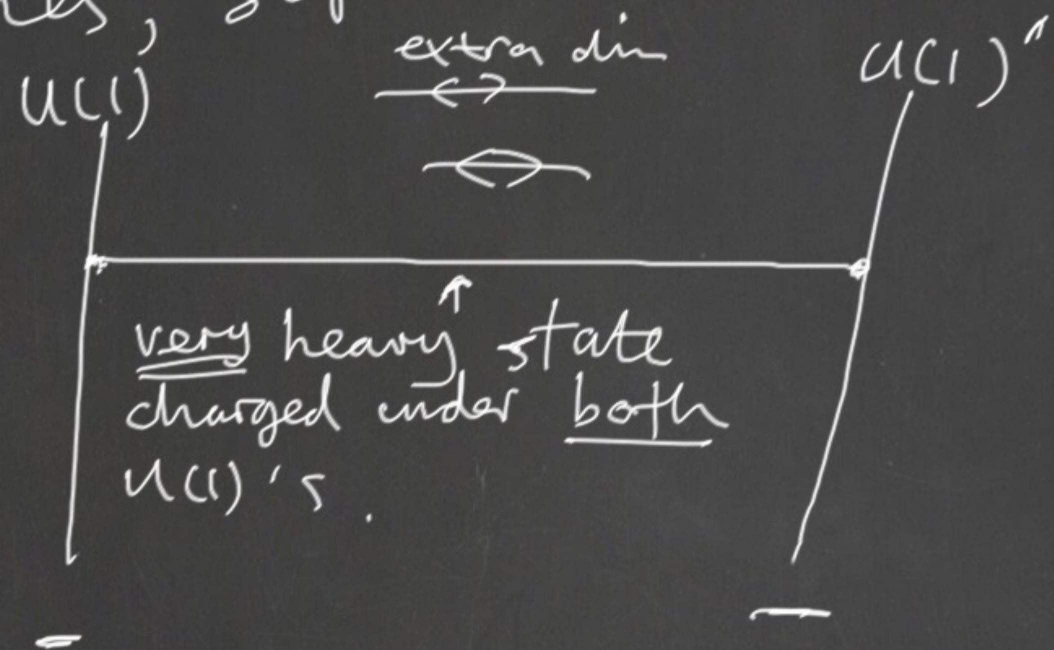
Generically <u>expect</u> additional gauge groups and matter.

HIDDEN SECTOR MATTER IS GENERIC

Consider a Type II string model with

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

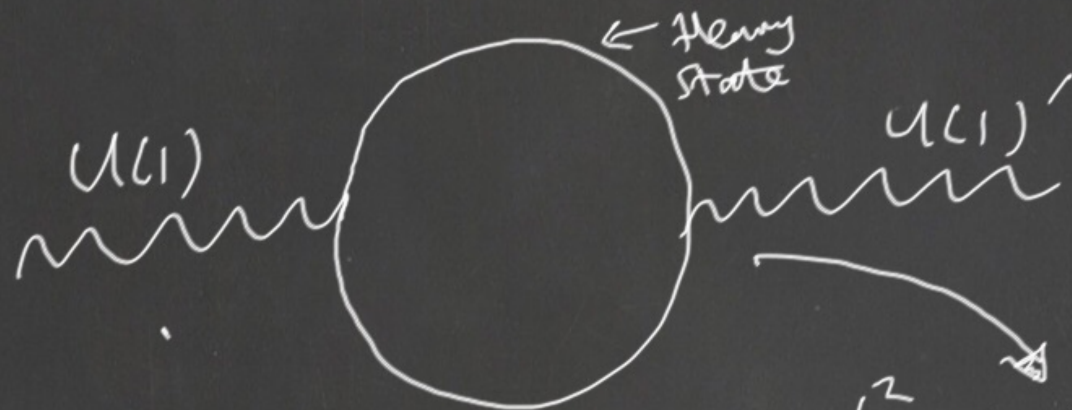
Realise this with two stacks of D-branes, separated in extra dims:



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

$\gg M_{KK}$.

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 $\epsilon F F'$ 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 web 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.

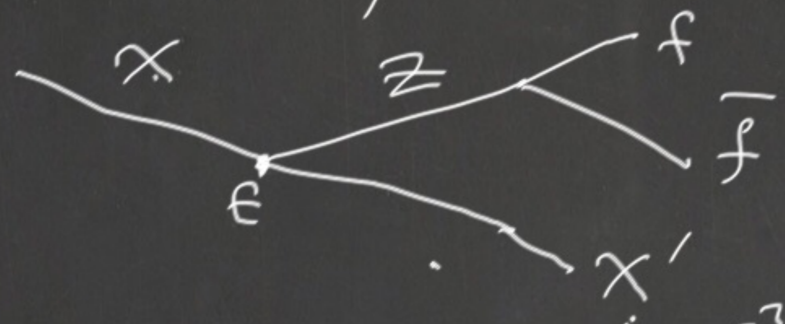
Usually (without Hidden Sectors) this is
stable as it is the lightest particle
with non zero R-parity.

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

for on shell Z

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

for 3-body decay

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 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
- Hidden glueballs, Hidden "electrons" or other elementary states...

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_ψ^0 . . .

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

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

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

$\langle \sigma v \rangle_{\psi \to X}$ 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 $m_\psi \leq O(100)\,\mathrm{MeV}$.
Heavier ψ's give too much DM.

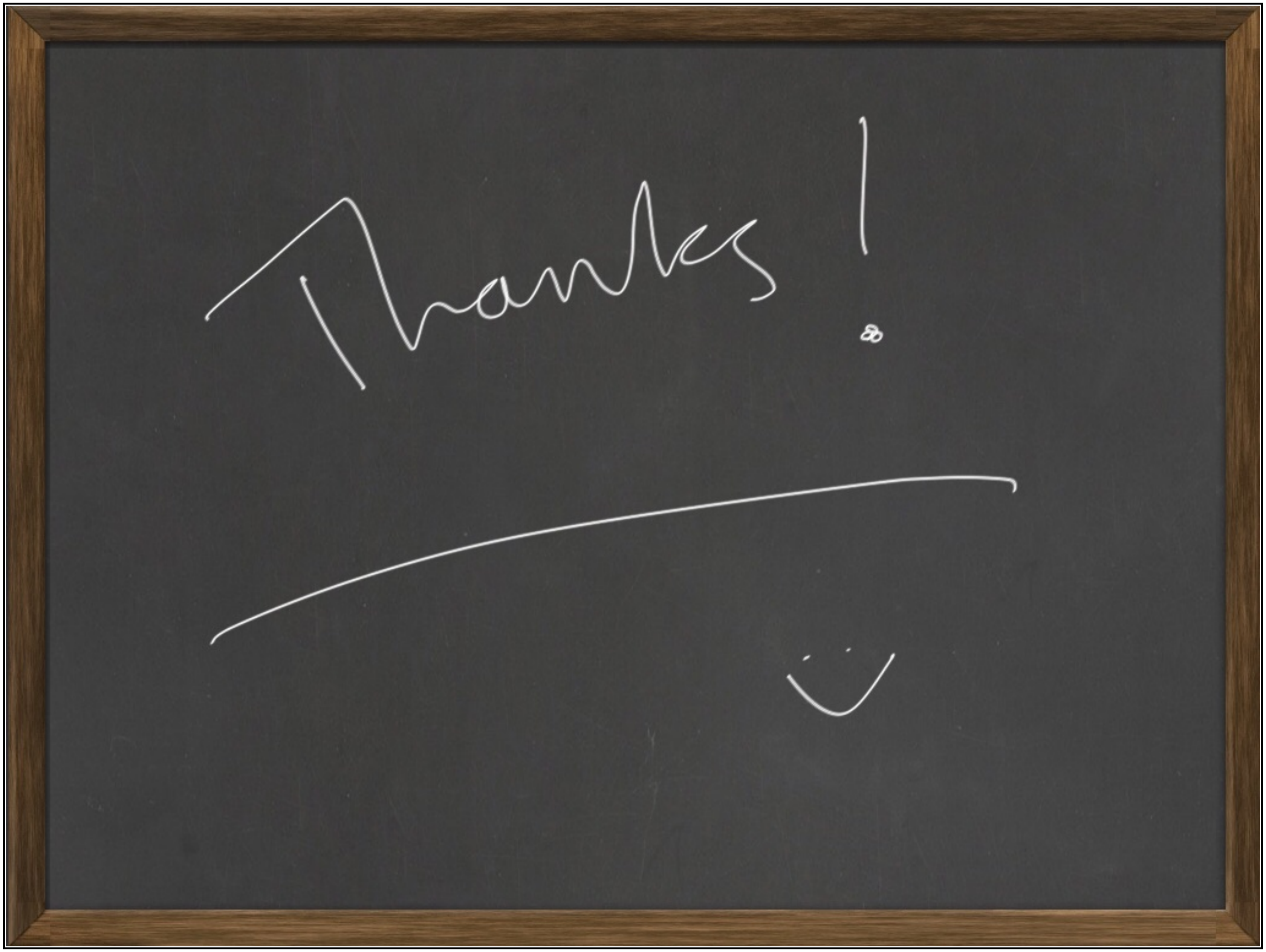
ψ could be a chiral fermion in the Hidden sector, since these can naturally have masses smaller than $M_{\text{moduli}} \sim O(100)\,\text{TeV}$.

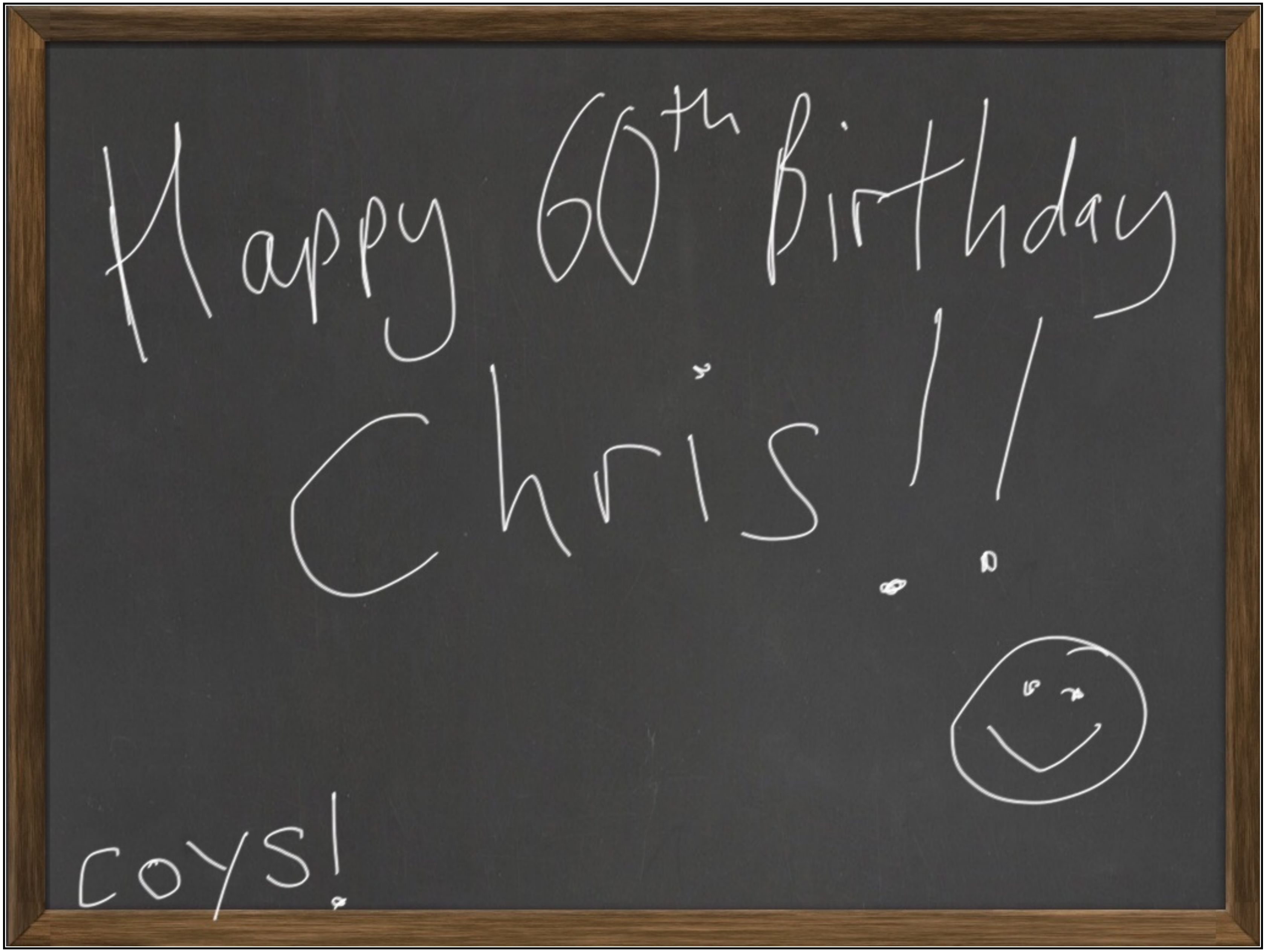
This can be realised in various string/M theory models.

Case I: in progress!

Conclusions

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


Thanks!


Happy 60th Birthday
Chris!!
COYS!