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Accidental composite dark matter in $SU(5)$-GUT theories

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New "dark" fermionic fields charged under a new confining dark gauge group ($SU(N)_{\rm DC}$ or $SO(N)_{\rm DC}$) can come as embeddings in $SU(5)$−GUT multiplets to explain dark matter (DM). These fermions would form bound states due to the confining nature of the dark gauge group. Such dark baryons could prove to be a good neutral DM candidate stable due to a dark baryon number. The DM relic abundance sets the dark confinement scale to be of $O(100)$ TeV. Previous works require the mass of these baryonic DM-forming light fields m (with m being lesser than the dark confinement scale Λ_{DC}) to be way smaller than the unification scale (GUT scale). This was done assuming that their GUT partners in $SU(5)$ representations have GUT scale mass. In our work, focusing on the role of these heavy GUT states in these models, we find that the dark fermions cannot come in almost degenerate GUT multiplets. We further find that cosmological constraints from Big Bang Nucleosynthesis in addition to unification requirements allow for only certain values of masses for these GUT fermions. However, these mass values give a too large contribution to the DM relic abundance. To evade this, the mass of the GUT states must be lower than the reheating temperature.

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PoS(ICHEP2022)306

1. Motivation

The Standard Model (SM) has been very successful phenomenologically and gives precise agreement with many experimental results. Nevertheless, this model encounters many limitations: unaccountability of dark matter (DM), no explanation for why the SM gauge couplings come so close at high scales, etc. are just two such unexplained aspects. Extensions of the SM can be motivated in answer to these problems using the success of the *SM as a paradigm*.

The SM is now understood as an effective field theory or EFT with the non-renormalizable operators suppressed by powers of a very high cut-off scale. The SM Lagrangian is renormalizable at the energies at which it is probed and gives rise to accidental (or emerging) global symmetries. The visible proton is *accidentally stable* because of such an emerging symmetry: the baryon number (B number). The inclusion of B-violating dimension-5 operator predicts a decaying proton, however, the lower bound on the cut-off scale (or Λ_{UV}) from the non-observation of proton decay is $\sim 10^{16}$ GeV. *Could the dark matter be as long-lived as the universe because of such an accidental symmetry?*

Motivated by the possibility of having an accidentally stable DM, new matter (*dark sector*) and new dynamics (*dark force*) must be postulated to extend the SM sector and gauge forces. Then the dark sector must at least contain one DM candidate which is cosmologically stable or has $\tau \gtrsim 10^{10}$ yr: this implies that the accidental symmetry of the dark sector must be broken by some operator with high enough dimension (also a high enough cut-off scale).

This new dark sector can be strongly coupled or weakly coupled. A very minimal weakly coupled extension of the SM giving an accidentally stable DM was discussed in Ref. [2] where the best candidate is a fermionic 5-plet of $SU(2)_L$ with mass $\sim$ 4 TeV. Such weakly coupled candidates and their phenomenology are interesting in their own right. I will focus, however, on the case in which new fields are charged under a new confining or strongly coupled dark force. The vector-like confinement framework [7] is generally exploited for this involving adding new fermions in vectorlike representations of the SM. Adding chiral fermions instead is much trickier (See [5] for example) due to non-trivial anomaly cancellation. Such new strongly coupled dynamics also provide a rich collider phenomenology (See [7]) in addition to many possible composite DM candidates: dark baryons (See [1, 9] for example), dark mesons, gluequark DM [4].

In this work [3] we consider extending the SM gauge group by a confining gauge group *dark color* ($SU(N)$ or $SO(N)$). We do this by adding new Weyl dark fermions ψ ($\bar{\psi}$) transforming as fundamentals (anti-) under *dark colour* and as vector-like representation under the SM. These dark fermions are *light*: their masses m are lighter than or close to the dark confinement scale, $m \lesssim \Lambda_{DC}$. The bound states in the dark sector would then be dark pions and dark baryon with mass $\sim \Lambda_{DC}$. The dark baryons are considered to be robust DM candidates stable due to a dark baryon number broken by dimension-6 operators. For the DM to be a thermal relic, Λ_{DC} must be of $O(100$ TeV$)$. In our work [3], we consider ψ or dark fermions as low energy remnants of a GUT theory by embedding ψ in $SU(5)$ GUT multiplets such that each viable model has a GUT counterpart. We have raised the question of the role of the GUT partners ψ_H of these dark fermions and their influence on the lower energy dark sector phenomenology and on gauge coupling unification. This is the question we have tackled in our work [3]: *can we find an $SU(5)-$GUT completion for composite dark matter models?*

Previous attempts on tackling the DM problem and the question of gauge coupling unification have been made before (See for example Refs. [6, 8]). In Ref. [8], new higgsinos and bino particles give a thermal DM in the mass range from 100 GeV to 2 TeV but the new unification scale is too low in a 4D GUT. Instead, Ref. [6] considers the addition of χ fields charged under a new confining $SU(3)_H$ group. The χ fields carry both SM colour and EW charge and are part of a GUT multiple (10 or 15) and give bound state GUTZilla DM candidate.

In comparison, our work [3] involves a more rigorous and extensive analysis considering all possible viable models. The viability of any model is constrained by requiring that a) the new light dark fermionic content does not lead to landau poles for SM couplings below the GUT scale, b) give at least one baryonic DM candidate, c) have all species symmetries broken at the yukawa level or by the allowed higher dimensional operators (thereby allowing dark pion states to decay to SM, see also [1]) . The list of viable models obtained was then analysed for SM gauge coupling unification where we use a less conservative requirement and forego the luxury of perfect gauge coupling unification as is required generally in literature. In the next section 2, I explain this relaxed criteria for unification. In the subsequent sections 3 and 4, I briefly discuss our benchmark model and sketch the thermal history.

2. Relaxed criteria for SM gauge coupling unification

Instead of accepting only scenarios which give a perfect SM gauge coupling unification after running with the new physics matter content i.e. the dark fermions, as well as their $SU(5)$ GUT partners as done in [1], we accept a triangle formed in the $(\log\mu, \alpha_i^{-1}(\mu))$ plane with $\alpha_i^{-1}(\mu)$ being the SM gauge couplings with $i = 1, 2, 3$[1], and μ being the energy scale.

We require that the area of the triangle $\mathcal{A}_\Delta$, after running with the BSM content be lesser or equal to the one obtained when running only with the SM content $\mathcal{A}_{SM}$. The barycentre of this *unification triangle* given by $(\tilde{M}_{\text{GUT}}, \tilde{\alpha}^{-1}_{\text{GUT}})$ would give the values of the GUT coupling $\tilde{\alpha}_{\text{GUT}}$ and the GUT scale $\tilde{M}_{\text{GUT}}$ for that model (for a fixed value of M_{H} where M_H i the mass scale of the GUT partners). This barycentre should be above $\alpha^{-1}(\mu) = 1/4\pi$ such that the GUT coupling is perturbative. The barycentre is also constrained by requiring that $M^{\text{SM}}_{\text{GUT}} \leq \tilde{M}_{\text{GUT}} \leq M_{\text{Pl}}$ where $M^{\text{SM}}_{\text{GUT}} = 6.5 \times 10^{14}$ GeV is taken to be the unified scale when running only with the SM without any threshold correction from the $SU(5)$ gauge bosons, and M_{Pl} is the Planck scale.

We used this strategy to scan for any possible viable models giving a DM candidate and successful (albeit imperfect) gauge coupling unification and to constrain the mass scale of heavy GUT partners M_H.

For the $SU(N)_{DC}$ case, we find that only two viable models satisfy the above criteria a) $Q + \tilde{D}$ [2] b) N (See [1] for notation and SM charge assignment). For the $SO(N)_{DC}$, no compatible models are found. To investigate why such few models make it through our unification scan, we plot various low energy models in the plane $(\delta_{12},\ \delta_{32})$ in Fig. 1 where we define δ_i as the contribution to the running of couplings from all new physics as:

$$\alpha_i(\mu)^{-1} = \alpha_i(M_Z)^{-1} - \frac{b_i^{\text{SM}}}{2\pi}\log\frac{\mu}{M_Z} + \delta_i \tag{1}$$

[1] α_1 is obtained from α_Y by using $\alpha_1 = \frac{5}{3}\alpha_Y$

[2] The SM charge assignments are $Q \equiv (3,2)_{1/6}$, $\tilde{D} \equiv (3,1)_{-1/3}$, $N \equiv (1,1)_0$

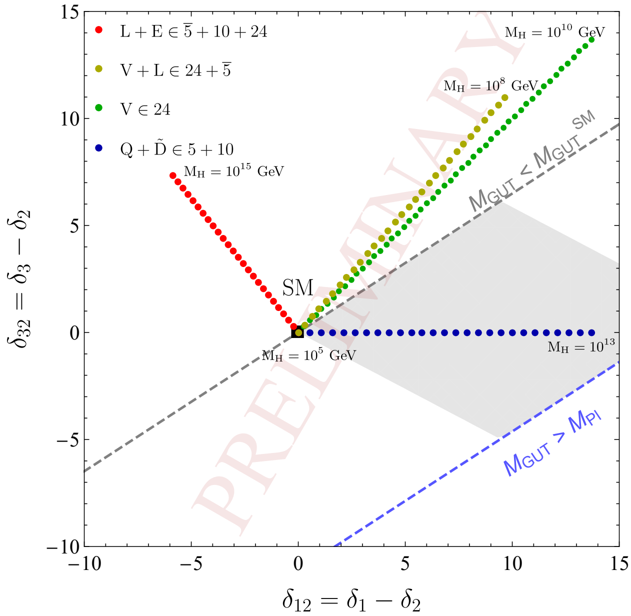

Figure 1: Summary plot showing few chosen viable models (that give an accidentally stable DM candidate) and their respective positions in the $(\delta_{12}, \delta_{32})$ plane for different values of GUT partner mass M_{H}. This plot is drawn for $N_{\mathrm{DC}} = 3$ with N_{DC} being the number of dark colours. The gray-shaded region shows the universal allowed region under our unification conditions that give unification better than the SM. The black point marks the SM for $\delta_{12} = 0$, $\delta_{32} = 0$. In red, olive, green and blue we show the δ_{12}, δ_{32} contribution of models L + E, V + L, V, Q + $\tilde{D}$ (See Table 1 in [1] for definitions and SM charges) coming from the running of light dark fermions and the heavy GUT partners from scale M_{H} onwards. At $M_{\mathrm{H}} = 10^5$ GeV, all models give unification as in SM due to running of the complete GUT multiplet from M_{H}. The region above (below) the light gray dashed (light blue) line shows the region constrained due to a too fast proton decay (GUT scale $> M_{\mathrm{Pl}}$).

where b_i are the 1-loop SM beta function coefficients. In Fig. 1, the grey region shows the universal region in the plane $(\delta_{12},\ \delta_{32})$ where unification is improved with respect to the SM following our criteria described earlier. The respective contributions $\delta_{ij} = \delta_i - \delta_j$ given by various models includes the full running from both light dark fermions and the GUT partners. For a fixed value of M_H this represents a point in the plane $(\delta_{12},\ \delta_{32})$.

3. Our Benchmark Model

The benchmark model that satisfies the condition of giving successful SM gauge coupling unification and an accidentally stable composite DM is the $SU(3)_{\mathrm{DC}}$ model: $Q + \tilde{D}$. The corresponding GUT theory for this model is given by embedding the new fermions in the $SU(5)$ representations 5 + 10. The GUT block will thus comprise the leftover fermions, namely $\tilde{L}, U, E$ [3].

After integrating out the GUT scale states, the low energy renormalisable lagrangian is given by (4-notation lagrangian):

[3] The SM charge assignments are $U \equiv (\bar{3}, 1)_{-2/3}$, $E \equiv (1, 1)_1$ under $SU(3) \times SU(2) \times U(1)$.

$$\Delta\mathcal{L} = -\frac{1}{4g_{DC}^2}\mathcal{G}_{\mu\nu}^2 + \bar{Q}(i\not{D} - m_Q)Q + \bar{\tilde{D}}(i\not{D} - m_{\tilde{D}})\tilde{D} - (y_L\bar{Q}P_L\tilde{D}H + y_R\bar{Q}P_R\tilde{D}H + h.c.) \quad (2)$$

where $\mathcal{G}_{\mu\nu}$ is the dark gauge boson term, P_L, P_R are the projection operators. The allowed yukawa terms break species numbers and allow dark mesons to decay. For this model, the DM candidate is an SM neutral dark baryon namely $QQ\tilde{D}$ which is stable due to $U(1)_{\rm DB}$ (*dark baryon number*) broken by dimension-6 operators.

Once we allow the GUT partners, namely $\tilde{L}, U, E$ to inhabit intermediate energy scales $\Lambda_{DC} < M < M_{\rm GUT}$, we enhance the accidental symmetries in the low energy theory by introducing 2 new symmetries: namely $U(1)_{\rm U}$ (*U number*), and $U(1)_{\rm DL}$ (*dark lepton number*). This implies non-DM bound states carrying U and DL number would be long-lived (baryons such as UUU) and that can only decay via dimension-6 operators generated by the exchange of GUT states. Such SM-charged states are strongly constrained by BBN (*Big Bang Nucleosynthesis)* and must have lifetimes $\tau < 1$ sec.

4. Sketch of Thermal History

Here we sketch the thermal history in the presence of the GUT states. When the mass scales of the GUT partners is much larger than the confinement scale, $M_H \gg \Lambda_{\rm DC}$ (See also [9]), the dark coupling is perturbative i.e. $\alpha_{\rm DC}(M_H) \ll 1$. At temperatures $T \sim M_H$, the heavy GUT fermions undergo a perturbative freeze-out.

As the universe cools down further to $T \sim \Lambda_{\rm DC}$, *dark confinement* takes place and dark hadrons form.

The heavy bound states formed from GUT states (denoted by HHH) can decay to lighter bound states by the exchange of GUT states with a width given by:

$$\Gamma \sim \frac{g_{\rm GUT}^4}{8\pi}\frac{M_H^5}{M_{\rm GUT}^4} \quad (3)$$

where g_{GUT} is the GUT coupling, and the mass of the HHH bound state is $\sim \mathcal{O}(M_H)$. Depending on the value of M_H and subsequent width Γ, we can envisage the following scenarios:

- $M_H \gtrsim 10^{14}$ GeV: the HHH states are short-lived enough that they can decay before the DM freeze-out at $T \sim \Lambda_{\rm DC}/25$. There is no additional contribution to the DM abundance from the decay of these states. Such large mass values of GUT states however give a unification scale which is higher than the Planck scale.

- 10^5 GeV $\lesssim M_H \lesssim 10^{11}$ GeV: the width of HHH states is small enough to spoil BBN so these values of M would be excluded.

- $M_H < 10^5$ GeV: This would imply very long-lived states which are as heavy as the DM and charged under the SM.

- 10^{10} GeV $\lesssim M_H \lesssim 10^{12}$ GeV: In this window (compatible with both BBN and good unification), the HHH states decay after the DM freeze-out and give a non-thermal contribution

PoS(ICHEP2022)306

to the DM relic abundance, thereby, overclosing the universe. To reproduce the correct DM abundance for $\Lambda_{\rm DC} \sim 100$ TeV, the GUT states must not be populated by requiring a reheating temperature $T_{\rm RH}$ lower than M_H.

5. Summary

In this work (talk), I have tried to address the question of finding an $SU(5) - GUT$ completion for composite dark matter models with dark fermions lighter than the dark confinement scale. Previous works have ignored the role of GUT states on model building and thermal history. We have adopted a more relaxed, less conservative gauge coupling unification criteria and analysed all viable models that give an accidentally stable baryonic DM candidate. We find that only one $SU(3)_{\rm DC}$ model given by the low energy content $Q + \tilde{D}$ can give better gauge coupling unification with respect to the SM (moreover it is also giving perfect unification). Including the GUT states in the low energy theory at $M_H < M_{\rm GUT}$ enhances the accidental symmetries and leads to non-DM bound states which can be long-lived and spoil BBN. Thus, we find that dark fermions cannot come in degenerate GUT multiplets.

In general, we find that the heavy dark GUT states impact both cosmological evolution and grand unification. Our study [3] clarifies under which conditions both aspects of the theory are realistic.

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PoS(ICHEP2022)306