Luminogenesis from Inflationary Dark Matter

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A cosmological model is introduced in which dark matter plays a dominant role throughout the history of the universe, and is the only matter present for temperatures \( T \gtrsim T_{15} \sim 10^9 \text{ GeV} \)

The gauge group is \( SU(3) \times SU(6)_{DM} \times U(1)_Y \) and unifies in such a way that luminous matter is generated at \( T \sim T_{15} \) with the correct amount and eventual asymmetry. Construction of more highly sensitive direct detectors of dark matter e.g. XENON1000 is encouraged. We offer a new explanation of why grand unification theories involving only luminous matter may be fatally flawed.

\section*{INTRODUCTION}

From the latest Planck data\cite{1}, it is believed that dark matter makes up for around 27\% of the energy density of the universe while luminous matter makes up around 4.5\%, the rest being in the form of Dark Energy. Furthermore, structure formation in the Universe is generally believed to be driven by Dark Matter. The fact that Dark Matter constitutes the dominant form of matter in the present time is remarkable. If it is so now, it is extremely reasonable to think that it was perhaps also dominant in the early universe. And perhaps, it was the only matter that existed in the very early universe. The generation of luminous matter would come about when a fraction of dark matter converted into luminous matter. The size of that fraction would depend on the efficiency of the conversion process. The temperature (or energy) where this conversion took place would naturally depend on the dark matter mass(es) and its conversion efficiency would vary throughout the history of the universe, and is the only matter present for temperatures \( T \gtrsim T_{15} \sim 10^9 \text{ GeV} \).

\section*{INFLATIONARY DARK MATTER}

\textbf{Dark Matter in SU(6)}

If the dark matter field \( \chi_l \) is to be a singlet under the SM gauge group and if it were to be unified with luminous matter, its own gauge group \( G_{DM} \) (if there were one) should be embedded in a larger dark unification group \( G_{DUT} \) which contains the SM group \( G_{SM} \), namely \( G_{DUT} \rightarrow G_{DM} \times G_{SM} \). This unified group would be one on which inflation is based such that the inflaton will decay into dark matter during the reheating process.

We use the model proposed to unify dark matter with luminous matter in \cite{2}. The unification of the two sectors proceeds via the embedding of \( SU(2)_L \) into a unifying group \( SU(n+2) \) with the following breaking path \( SU(n+2) \times U(1)_Y \rightarrow SU(n)_{DM} \times SU(2)_L \times U(1)_{DM} \times U(1)_Y \). Including QCD, the unifying group would be \( SU(3)_C \times SU(n+2) \times U(1)_Y \) ("unifying" solely in the sense of dark and luminous matter unification and not in the usual sense of gauge unification). In \cite{2}, arguments were given for the selection of the preferred value \( n = 4 \) for the dark matter gauge group and our final choice is

\[ SU(3)_C \times SU(6) \times U(1)_Y \]

with \( SU(6) \) subsequently breaking according to

\[ SU(6) \rightarrow SU(4)_{DM} \times U(1)_{DM} \times SU(2)_L \]  \hspace{1cm} (2)

Here \( G_{DUT} \) is \( SU(6) \) and \( G_{DM} \) is \( SU(4) \). It is convenient to show the various useful representations of \( SU(6) \supset SU(4)_{DM} \times SU(2)_L \times U(1)_{DM} \).

\[ 6 = (1,2)_2 + (4,1)_{-1} \]
\[ 20 = (4,1)_3 + (4^*,1)_{-3} + (6,2)_0 \]
\[ 35 = (1,1)_0 + (15,1)_0 + (1,3)_0 + (4,2)_{-3} + (4^*,2)_3 \]  \hspace{1cm} (3)
where \(U(1)_{DM}\) quantum numbers are indicated by subscripts. Note that \(U(1)_{DM}\) will be spontaneously broken at a scale \(\Lambda_{DM}\) which will be constrained by experimental direct detection limits. The associated massive gauge boson, \(\gamma_{DM}\), is the oft-discussed "dark photon". We shall come back to this important point below. At a scale \(\Lambda_{4}\), \(SU(4)_{DM}\) will become confining and DM hadrons form as has been discussed in [2]. The fact that our model contains strongly self-interacting dark matter is an interesting feature which might resolve the well-known \(\Lambda CDM\) problems [3] of dwarf galaxy structures and of dark matter cusps at the centers of galaxies. From Eq. [3], the representations that contain singlets under the SM \(SU(2)_L\) gauge group are \(\bar{6}\) and \(20\). These are the representations that could contain the desired dark matter particles, namely (4, 1) which appears in both \(\bar{6}\) and \(20\). To see where the dark matter belongs, it is important to classify the fermion representations using Eq. [3]. As discussed above, our unified gauge group is \(SU(3)_C \times SU(6) \times U(1)_{Y}\). The fermion representations are required to be anomaly-free. Representations containing the left-handed SM quark and lepton doublets are respectively \((3, 6, Y_{6q}/2)_L\) and \((1, 6, Y_{6l}/2)_L\) where \(Y_{6q}/2\) are the \((1)_{Y}\) quantum numbers of the quarks and leptons respectively. In addition, the \((SU(2)_L\) quark and lepton singlets are written as \((3, 1, Y_{6q}/2, Y_{6d}/2)_R\) and \((1, 1, Y_{1}/2)_R\) respectively. The \((U(1)_Y\) quantum numbers are, as usual, \(Y_{6q}/2 = 1/6\) and \(Y_{6d}/2 = -1/2\) for the SM non-singlets and \(Y_{6q}/2 = 2/3\), \(Y_{6d}/2 = -1/3\), and \(Y_{1}/2 = -1\). Since \(\bar{6}\) and \(\bar{6}\) are complex representations, the minimal anomaly-free representations are given by

\[(3, 6, Y_{6q}/2)_L,R + (1, 6, Y_{6l}/2)_L,R + (3, 1, Y_{6q}/2, Y_{6d}/2)_R,L + (1, 1, Y_{6d}/2)_R,L . \tag{4}\]

As we have mentioned in [2], the right-handed quark and lepton doublets, \((3, 6, Y_{6q}/2)_R\) and \((1, 6, Y_{6d}/2)_R\), and left-handed singlets, \((3, 1, Y_{6q}/2, Y_{6d}/2)_L\) and \((1, 1, Y_{1}/2)_L\), are in fact the mirror fermions (distinct from SM fermions) of the model of electroweak-scale right-handed neutrinos in [3]. The details of how right-handed neutrinos, which are members of doublets along with their mirror charged lepton partners, can acquire electroweak-scale mass can be found in [2], where arguments were given for assigning the mirror sector a global symmetry. In light of the newly-discovered SM-like 126 GeV scalar, an extension of the model to endow separately the SM sector and the mirror sector with a global symmetry is needed [4]: a global \(U(1)_{SM} \times U(1)_{mirror}\) is imposed. From Eqs. [3][4], one can see that the \(SU(2)_L\)-singlet and \(SU(4)\)-non-singlet particles transform under

\[SU(3)_C \times SU(4)_{DM} \times SU(2)_L \times U(1)_Y \times U(1)_{DM}\]

as (for both left and right-handed fermions)

\[(1, 4, 1, 1/2, 1)_- + (3, 4, 1, 1/6, -1), \tag{5}\]

where the subscripts \(U(1)_{DM}\) quantum numbers. It is clear from [3] that these particles which belong to the 6 of \(SU(6)\) cannot be candidates for dark matter since they carry \((U(1)_Y)_-\) quantum numbers and are therefore electrically charged. In fact, the color-singlet and colored particles carry charges \pm 1/2 and \pm 1/6 respectively. A suitable representation which is color-singlet and carries no \((U(1)_Y)_-\) quantum number is the following real representation:

\[(1, 20, 0) = (1, 4, 1, 0)_3 + (1, 4^*, 1, 0)_- - (1, 6, 2, 0)_0, \tag{6}\]

where the right-hand side represents decompositions under \(SU(3) \times SU(4) \times SU(2)_L \times U(1)_Y \times U(1)_{DM}\). One notices that \((1, 4, 1, 0)_3 + (1, 4^*, 1, 0)_-\) are inert under the SM gauge group \(SU(3) \times SU(2)_L \times U(1)_Y\) but not under \(U(1)_{DM}\). These particle are the dark matter in our model: note that, when one represents fermions in terms of left-handed Weyl fields, we have \(\chi_{L,R} = (1, 4^*, 1, 0)_-\) and \(\chi_{L}^* = (1, 4, 1, 0)_3\). How the dark matter candidates are produced in the early universe and how luminogenesis, the generation of luminous matter from dark matter, occurs will be discussed in the next two subsections.

**Dark matter genesis**

We assume that the potential for the the adjoint scalar field \(35\) of \(SU(6)\) is sufficiently flat so as to generate sufficient inflation at the scale of \(SU(6)\) breaking. It is beyond the scope of this article to treat this aspect of inflation and we will restrict ourselves to its group theoretic aspects. The inflaton field is the \(\phi_{inf} = (1, 1, 1, 0)_0\) of

\[(1, 35, 0) = (1, 1, 1, 0)_0 + (1, 15, 1, 0)_0 + (1, 1, 3, 0)_0 + (1, 4, 2, 0)_- + (1, 4^*, 2, 0)_3 , \tag{7}\]

where the right-hand-side shows the transformation under \(SU(3)_C \times SU(4) \times SU(2)_L \times U(1)_Y \times U(1)_{DM}\). The fermions that can couple to the adjoint scalar will come from \(20 \times 20 = 1_a + 35_a + 175_a + 189_a\) and \(6 \times \bar{6} = 1 + 35\). Denoting \((1, 20, 0)\) by \(\Psi_{20}\) and \((1, 35, 0)\) by \(\phi_{35}\), one can write the following coupling

\[g_{20} \Psi_{20}^T \sigma_2 \Psi_{20} \phi_{35} . \tag{8}\]

From Eq. [8], one can deduce the coupling of the inflaton to dark matter

\[g_{20} \chi_{L}^T \sigma_2 \chi_{L}^* \phi_{inf} . \tag{9}\]

Since \(\psi_{L}^* = \sigma_2 \psi_{R}^*\), it is clear that \(6 \sim \psi_{6, L}\) comes from mirror fermions and \(6 \sim \psi_{6, L}\) contains SM fermions. As a result, a coupling such as \(\psi_{6, L}^* \sigma_2 \psi_{6, L} \phi_{35}\) is forbidden at tree-level by the \((U(1)_{SM} \times U(1)_{mirror})\) symmetry. The inflaton will decay mainly into dark matter while its decay into luminous matter will be highly suppressed by the aforementioned symmetry. Another interesting point
that one could point out here is quantum fluctuations during the inflationary period can create seeds of structure formation but in our scenario, it is structures of dark matter that were formed first. This is actually the current view of structures in the universe. In our model, structures involving luminous matter came only later when approximately 14 % of dark matter is converted into luminous matter. The next section discusses this conversion of some of the dark matter energy density into luminous matter, a process we call luminogenesis.

**Luminogenesis**

With $\chi_L$ and $\chi_R$ in $\Psi_{20}$ being the inflationary dark matter particles, the crucial question concerns the mechanism of luminogenesis. Since the dark matter is in a $20$ of SU(6) and luminous matter is in a $\bar{6}$ of SU(6), there is no SU(6) gauge boson exchange that can convert dark into luminous matter (in the sense of the X and Y gauge bosons of SU(5) converting quarks into leptons within the same representation for example). We have two options:

**I.** Since both dark and luminous matter carry nonzero $U(1)_{DM}$ quantum number, dark matter can annihilate via the $\gamma_{DM}$ massive gauge boson into particle-antiparticle pairs of the luminous sector. It is well known that an equal number of luminous matter and antimatter would eventually annihilate into radiation, leaving very little behind. An asymmetry is needed. The positive side of the dark photon phenomenon is that one could point out here is quantum fluctuations which is important in direct search. The cross section with $\chi$ via the $\gamma$ will depend mainly on how massive $\gamma$ is. Since both dark and luminous matter carry nonzero quantum number, dark matter can annihilate leaving very little behind. An asymmetry is needed.

**II.** If we assume that there is a dark matter asymmetry (to be presented in a subsequent paper), namely $\Delta \chi = n_\chi - n_{\bar{\chi}} \neq 0$, one must convert some of that asymmetry into the leptonic luminous matter asymmetry. Since the two sectors belong to different representations of SU(6), this can be achieved only through a coupling of the dark and luminous sectors with a scalar field. Since $20 \times 6 = 15 + 105$ and $20 \times \bar{6} = 15 + 105$ (20 is real), the appropriate scalars transform as 15 and 15 respectively. We denote these scalars as $\Phi^{(L)}_{15}(1/2)$ and $\Phi^{(R)}_{15}(-1/2)$ where $\pm 1/2$ denotes the $U(1)_Y$ quantum number. We have the following Yukawa couplings

$$g_{6L} \Psi_{20}^T \sigma_2 \psi_{6L} \Phi^{(L)}_{15} + g_{6R} \Psi_{20}^T \sigma_2 \psi_{6L} \Phi^{(R)}_{15},$$

with $\Phi^{(L)}_{15}$ and $\Phi^{(R)}_{15}$ carrying appropriate global $U(1)_{SM}$ and $U(1)_{mirror}$ quantum numbers respectively. A mass mixing between $\Phi^{(L)}_{15}$ and $\Phi^{(R)}_{15}$ will break the global $U(1)_{SM} \times U(1)_{mirror}$ symmetry and thus allows for the following conversion process to occur: $\chi_L + \chi_R \rightarrow l_L + l_R^M$ where $l_L$ and $l_R^M$ refer to SM and mirror leptons respectively as in [3]. This process can be represented by the following effective Lagrangian

$$\frac{g_0^2}{M_{15}} (\chi_L^T \sigma_2 l_L)(\chi_{L}^T \sigma_2 l_{R}^M),$$

where $l_{L}^{M} = \sigma_2 l_{R}^M$. The various mixing coefficients are embedded in the prefactor of Eq. (11). How effective the conversion of dark matter into luminous SM and mirror leptons as represented by Eq. (11) will depend on this prefactor, especially the luminogenesis scale $M_{15}$ which in the next subsection we shall estimate to be $M_{15} \sim 10^9$ GeV.

The conversion of the leptonic asymmetry to the baryonic asymmetry can proceed via the well-known sphaleron process [3].

**DARK AND LUMINOUS MATTER DENSITIES**

A detailed analysis of the present densities of dark and luminous matter is beyond the scope of this paper. We shall instead present only an estimate which will not be too different. The usual quantity used in the study of relics density is

$$Y(x) = \frac{n_s}{s},$$

where $n$ is the number density, $s$ is the entropy density, and

$$x = \frac{m}{T},$$

with $m$ being the mass of the relic particle. We are interested in the amount of cold dark matter particles that remained after they became non-relativistic. In particular, we are interested in the strength of the interactions as given in Eq. (11) such that, out of the initial amount of inflationary dark matter, about 14 % is converted into luminous matter (corresponding to about 4.5 % of the total amount of the energy density of the universe) and about 86 % remained as dark matter ($\Omega_{DM} \sim 27\%$). Using $sY m_\chi = n_\chi m_\chi = \rho_\chi$ and the usual expressions for the Hubble rate and for the critical density, one can find, with $x = m_\chi/T$,

$$\Omega_{DM}(x) = \frac{\rho_{DM}}{\rho_c} = C Y(x) x,$$

where $C$ is a constant. It follows that

$$\frac{\Omega_{DM}(x)}{\Omega_{DM}(1)} \approx \frac{Y(x)}{Y(1)} x.$$  

Recall that $x = 1$ is when the temperature of the universe is equal to the dark matter mass. The value of $x$ at freeze out i.e. $x_f$ depends on the strength of the
interaction. To arrive at an estimate, one can ask the question about the strength of the interaction if \( t_f \approx 3 \) for example. Let us also assume that at that value of \( x \), \( \Omega_{DM}(3)/\Omega_{DM}(1) \approx 0.86 \). This gives \( Y(3)/Y(1) \approx 0.287 \) or \( \log(Y(3)/Y(1)) \approx -0.542 \). Study of e.g. Fig. 5.1 in [10] shows that this corresponds to a very weak cross section \( < \sigma_A|v| > \). An estimate of \( M_{15} \) appearing in Eq. (11) with the assumption \( < \sigma_A|v| > \approx 1/M_{15}^2 \) and with \( m_\chi \approx 1 \text{ TeV} \) gives \( M_{15} \approx 10^9 \text{ GeV} \) for the pertinent leptogenesis scale. In summary, luminogenesis conversion of 14\% of dark matter into luminous matter proceeds through an extremely weak interaction.

**GRAND UNIFICATION RECONSIDERED**

Since 1974, a great deal of research has proceeded based on the idea that the SM gauge group is contained in a larger grand unified GUT group \( G_{GUT} \). The simplest GUT model is based [9] on \( G_{GUT} \equiv SU(5) \) which, in its minimal form, makes a sharp prediction for the proton decay lifetime based [10] on a GUT scale \( M_{GUT} \gtrsim 10^{14} \text{ GeV} \). Experimental searches excluded this prediction already in 1984 but many alternative GUT theories are viable which survive this test. Accurate unification of the SM couplings at \( M_{GUT} \approx 2 \times 10^{16} \text{ GeV} \) has frequently been cited [11, 12] as evidence for supersymmetry, and GUT theories are an intermediate goal in much of string theory phenomenology.

By contrast, in the present luminogenesis model there is no luminous matter with mass above \( M_{15} \approx 10^9 \text{ GeV} \), so that extrapolation of the SM gauge couplings to orders of magnitude above the \( T_{15} \) scale, while including only luminous matter states in the calculation of the renormalization group flow, is rendered physically inappropriate. This provides a plausible rationale for the non-confirmation of the proton lifetime predicted on the basis of such an extrapolation in e.g. \( SU(5) \). In the present model based on the gauge group of Eq. (11), proton decay is absent.

**DIRECT DETECTION**

The direct detection of dark matter in our model can come about by the exchange of the dark photon, \( \gamma_{DM} \). Dark matter can interact with luminous matter in the direct detection search through the exchange in the t-channel of the massive dark photon, namely through the use of Eq. (11). An estimate of the mass \( M_{15} \) assuming \( g_\theta = O(1) \) using the bound by XENON100 [13] for the cross section for a dark matter mass of e.g. 1 TeV, namely \( \sigma < 10^{-44} \text{cm}^2 \) gives \( M_{15} > O(2 \text{Tev}) \). Nevertheless, we can eagerly await results from the upgraded version of XENON100 to XENON1000 being planned [14] for direct detection of dark matter particles.

**DISCUSSION**

Our principal underlying assumption is that in the very early universe the inflaton decays into only dark matter and that at a later, though still early, cosmological era, luminogenesis converted some 14\% of this dark matter into luminous matter. Our specific model gives rise naturally to strongly-interacting dark matter which can overcome some important short-range problems confronting cold dark matter. Luminogenesis occurs via an extremely weak interaction characterized by a mass scale \( \sim 10^9 \text{ GeV} \). The possible irrelevance of grand unified GUT models which include only luminous matter is clarified in this broader perspective. Finally, higher sensitivity direct detection of dark matter will be of crucial importance in sharpening our understanding of the luminogenesis stage in the early universe.

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