Dark Mass Creation During EWPT Via Dark Energy Interaction

Leonard S. Kisslinger and Steven Casper
Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213

Abstract

We add Dark Matter Dark Energy terms with a quintessence field interacting with a Dark Matter field to a MSSM EW Lagrangian previously used to calculate the magnetic field created during the EWPT. From the expectation value of the quintessence field we estimate the Dark Matter mass for parameters used in previous work on Dark Matter-Dark Energy interactions.

PACS Indices:12.15Ji,12.60.Cn,98.80.Cq,95.35.+x

Keywords: Cosmology; Electroweak Phase Transition; Dark Matter; Dark Energy

1 Introduction

Our present work is based on a Minimal Supersymmetry Model (MSSM) of the Electroweak (EW) Lagrangian which was used to calculate electromagnetic field creation during nucleation[1] and magnetic field creation during bubble collisions[2] during the Electroweak Phase Transition (EWPT) that occurred at a time $t = 10^{-11}$ seconds, when the critical temperature was $T_c = 125$ GeV. In the present work we add terms to the Lagrangian for the Dark Energy quintessence field and the interaction of a Dark Matter field with the quintessence field, based on models introduced in Refs[5, 6].

In the MSSM EW theory the EWPT is first order, so there is critical temperature and bubbles of the new universe form within the old universe. The latent heat for the EWPT is the value of the Higgs field, $\Phi$, which goes from $< \Phi > = 0$ to $< \Phi > = v \simeq 125$ GeV when $T = T_c$. At this time the Higgs gets a mass $M_H$, as do all particles in the standard model except the photon:

$$M_H = v$$
$$M_W = g v/\sqrt{2} \quad g = \text{strong coupling constant}$$
$$M_Z = M_W/\cos(\theta_W) \quad \theta_W = \text{Weinberg angle}$$
$$m_e \propto m_u \propto m_d \propto v.$$
In the Standard Model

\[ M_W = 37 / \sin(\theta_W) \approx 80 \text{ GeV} \]
\[ M_Z \approx 90 \text{ GeV}. \]  

(2)

There have been a number of studies of the origin of Dark Matter mass. If the EWPT is first order, which it is in our MSSM theory, baryogenesis occurs, with more particles than antiparticles. One model of Dark Matter mass generation unifies Dark Matter and baryogenesis[7]. See this reference for references to earlier related publications. More recently a study using Ref[5] for the quintessence field derived Dark Matter mass in terms of mass varying neutrinos[8].

Since all standard model particles got their mass during the EWPT, our present work is based on the hypothesis that Dark Matter also got its mass during the EWPT via interaction with the quintessence field; and we use the techniques developed in Refs[1, 2, 5, 6] to carry out the calculation of Dark Matter mass.

2 MSSM EW equations of motion with quintessence field

We add to the MSSM Lagrangian used earlier to study electromagnetic field creation[1] and magnetic field creation[2] additional terms for the Dark Energy quintessence field and with the interaction of the quintessence field with the Dark Matter Fermion field, from which we calculate the Dark Matter mass.

\[ \mathcal{L}^{MSSM} = \mathcal{L}^1 + \mathcal{L}^2 + \mathcal{L}^3 + \mathcal{L}^{\text{fermion}} + \mathcal{L}^{DM-DE} \]  

\[ \mathcal{L}^1 = -\frac{1}{4} W^i_{\mu\nu} W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \]

\[ \mathcal{L}^2 = |(i\partial_\mu - \frac{g}{2} \tau \cdot W_\mu - \frac{g'}{2} B_\mu) \Phi|^2 - V(\Phi) \]

\[ \mathcal{L}^3 = |(i\partial_\mu - \frac{g_s}{2} \lambda^a C^a_\mu) \Phi_s|^2 - V_{hs}(\Phi_s, \Phi) \]

\[ \mathcal{L}^{\text{fermion}} = \text{standard Lagrangian for fermions} \]

\[ \mathcal{L}^{DE} = \frac{1}{2} \partial_\nu \Phi_q \partial^\nu \Phi_q - V(\Phi_q) \]

\[ \mathcal{L}^{DM-DE} = g_D \bar{\psi}_{DM} \Phi_q \psi^{DM} \]

A cosmological constant was introduced[3] to produce inflation in the very early universe, which solved the problem of our homogeneous universe as shown by the observation of temperature correlations in the Cosmic Microwave Background Radiation. The quintessence field \( \Phi_q \) was used to model inflation, see Ref[4]. In this model \( \Phi_q \) vanishes at a very early time, but recent studies of supernova velocities and galaxies show that dark energy is now about 3/4 of the matter in the universe. We use the model of Refs[5, 6] with the present dark energy being created at the time of the EWPT.
Following Refs[5, 6],

\[ V(\Phi_q) = K\Phi_q^{-\alpha}, \]  

(4)

where \( K \) and \( \alpha \) are parameters which must be chosen.

This gives the differential equation for \( \Phi_q \), neglecting \( \mathcal{L}_{DM-DE} \)

\[ \partial^2\Phi_q - K\alpha \Phi_q^{-(\alpha+1)} = 0. \]  

(5)

For \( K \) we use the value in Ref[5], for \( \alpha \) use the range \( 2.0 - 6.0 \) given in Refs[5, 6]. Ferrar and Peebles[6] showed that the preferred range is \( 4.0 \leq \alpha \leq 6.0 \), so we give our results for this range of \( \alpha \) in separate figures.

The scale of the universe, \( a(t) \), is defined as \( a(t) = R(t)/R_o \), where \( R(t) \) is the radius of the universe at time \( t \) and \( R_o \) is the radius at the present time. The solution to Eq(5) for \( \Phi_q(t) \) is

\[ \Phi_{EWPT} \approx [2\alpha(\alpha + 2)]^{1/2}(\frac{a(t_{EWPT})}{a(t_1)})^{3/(\alpha+2)}, \]  

(6)

with \( \Phi_q(t_{EWPT}) \) the quintessence field at the time of the EWPT and \( t_1 >> t_{EWPT} \) is to be chosen.

Making use of the solutions of the General Theory of Relativity, the radius of the universe has a time dependence in a radiation dominated universe \( R(T) \propto t^{1/2} \). Therefore with \( t_{EWPT} = 10^{-11} s \) and \( t_1 \) in seconds,

\[ \frac{a(t_{EWPT})}{a(t_1)} = \sqrt{\frac{10^{-11} s}{t_1}}. \]  

(7)

We use the model of Ref[5], with the dark matter mass, \( M_{DM} \), given in our theory with \( t \) the time of the EWPT, and \( \mathcal{L}_{DM-DE} \):

\[ M_{DM} = g_D \frac{m_p}{32\pi} \Phi(t_{EWPT}). \]  

(8)

Since the Planck mass \( m_p = 1.22 \times 10^{19} \) GeV, from Eqs(8,6,7), and using[9] \( g_D = \pi \times 10^{-11} \)

\[ M_{DM} = 3.82 \times 10^6[2\alpha(\alpha + 2)]^{1/2}(\sqrt{\frac{10^{-11} s}{t_1}})^{3/(\alpha+2)}. \]  

(9)

For \( t_1 \) we use both \( t_{eq}=1,500 \) years, when the universe went from being radiation dominated to matter dominated, which is consistent with the theory in Refs[5, 6], and \( t_{now}=13.7 \) billion years, in which scenario the Dark Energy field evolved until the present time.

Using Eq(9) we calculate the Dark Matter Mass for these two final times. The results are shown in the figures.
The solutions for $M_{DM}$ for $t_1 = t_{eq} = 1,500$ years with the values of $\alpha$ expected[5, 6] are shown in Figure 1:

Figure 1: $M_{DM}$ for $t_1 = t_{eq}$ for $2.0 \leq \alpha \leq 4.0$ and the preferred values $4.0 \leq \alpha \leq 6.0$
The solutions for $M_{DM}$ for $t_1=t_{now}=13.7 \times 10^9$ years with the values of $\alpha$ expected[5, 6] are shown in Figure 2:

Figure 2: $M_{DM}$ for $t_1 = t_{now}$ for $2.0 \leq \alpha \leq 4.0$ and the preferred values $4.0 \leq \alpha \leq 6.0$
3 Conclusion

We have derived the Dark Matter mass using the concepts that since all standard particles got their masses during the EWPT from interaction with the Higgs field, it would be consistent for Dark Matter, which has only a gravitational force, to get its mass starting from the time of the EWPT via interaction with the dark energy (quintessence) field.

Using the solution for the quintessence field in Ref[5] with the MSSM EW Lagrangian from Ref[1], the Dark Matter masses have been derived for the range of the parameter $\alpha$ from 2.0 to 6.0. For the most preferred values of $\alpha$[5] from 4.0 to 6.0 for the final time $t_1 = t_{eq}$, which is the most appropriate as the universe went from radiation to matter dominated, the Dark Matter masses that have been found are from about 100 GeV to 2 TeV, which is consistent with values that have been predicted. If we use $t_1 = t_{now}$, the predicted value for the Dark Matter masses for values of $\alpha$ from 4.0 to 6.0 go from a few GeV to 140 GeV, which are smaller than expected.

Therefore we conclude that Dark Matter might have obtained its mass via interaction with the Dark Energy field during the EWPT, just as the standard model particles got their masses via interaction with the Higgs field at that time.

References

[1] Ernest M. Henley, Mikkel B. Johnson, and Leonard S. Kisslinger, Phys. Rev. D 81, 085035 (2010)

[2] Trevor Stevens, Mikkel B. Johnson, Leonard S. Kisslinger, Ernest M. Henley, W-Y Pauchy Hwang, Mathias Burkardt, Phys. Rev. D 77, 023501 (2008)

[3] Alan H. Guth, Phys. Rev. D 23, 347 (1981)

[4] K. Dimopoulos and J.W.F. Valle, Astroparticle Phys. 18, 287 (2002)

[5] P.J.E. Peebles and Bharat Ratra, Astrophys. J. 325, L17 (1988)

[6] Glennys R. Farrar and P.J.E. Peebles, Astrophys. J. 604, 1 (2004)

[7] Kazunori Kohri, Anupam Mazumdar, Narendra Sahu, and Phillip Stevens, Phys. Rev. D 80, 061302 (2009)

[8] Gennady Y. Chitov, Tyler August, Aravind Natarajan, and Tina Kahniashvili, Phys. Rev. D 83, 045033 (2011)

[9] Edward W. Kolb and Michael S. Turner, “The Early Universe”, Addison-Wesley Publishing Co. (1990)