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Article

Cosmological Phase Transitions—EWPT-QCDPT: Magnetic Field Creation

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Abstract: We review the cosmic microwave background (CMBR) estimate of ordinary matter, dark matter and dark energy in the universe. Then, we review the cosmological electroweak (EWPT) and quantum chromodynamics (QCDPT) phase transitions. During both the EWPT and QCDPT, bubbles form and collide, producing magnetic fields. We review dark matter produced during the EWPT and the estimate of dark matter via galaxy rotation.

Keywords: evolution of the universe; cosmological phase transitions; magnetic fields

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1. Introduction

The most important experiments which have estimated the amount of dark matter, ordinary matter and dark energy in the present universe are cosmic microwave background radiation (CMBR) experiments, as discussed in Section 2. Dark matter particles have only a gravitational interaction.

In the next section, we review various aspects of the cosmological electroweak (EWPT) and quantum chromodynamics (QCDPT) phase transitions.

After reviewing the evolution of the universe, the EWPT is reviewed. The dark mass creation during the EWPT and the estimate of dark mass in the universe via our Milky Way galaxy rotation is reviewed.

Sterile neutrinos as dark matter mass are also reviewed.

Then, dark energy in the universe, which is anti-gravity, is estimated by supernovae velocities.

In the final subsection, the creation of magnetic fields during the quantum chromodynamics (QCDPT) phase transition is reviewed.

2. Cosmic Microwave Background Radiation (CMBR)

There have been many CMBR experiments, such as Refs. [1–4], which have estimated the total density of the present universe, dark matter density, dark energy density, etc. With Ω as the density of the universe and $\Omega = 1.0$ for a flat universe, recent results from CMBR observations [5] are:

$$\begin{aligned} \Omega &= 1.0023^{+0.0056}_{-0.0054}; \\ \text{Dark energy density (vacuum energy)} &= 0.703 \pm 0.025; \\ \text{Dark matter density} &= 0.273 \pm 0.019; \\ \text{Baryon(normal matter) density} &\simeq 0.04; \\ \text{Age of the universe} &\simeq 1.37 \ \text{ billion years} . \end{aligned} \tag{1}$$

Therefore, about 27% of the universe is dark matter. In Refs [3–5]experiments related to Dark Matter were carried out. About 70% of the universe is dark energy, which is anti-gravity. Dark energy (quintessence) is anti-gravity and produced inflation at a very early time, which is why we now have an almost homogeneous universe. Only about 4% of the universe is normal matter.

3. Cosmological Electroweak and QCD Phase Transitions

The evolution of the universe is shown in the figure below. The time begins from the Big Bang at 10^{-35} s to 14 billion years, when we have our present universe.

From Figure 1 at 10^{-35} s, the universe began to inflate due to about 70% of the universe being dark energy, which is anti-gravity.

THE EVOLUTION OF THE UNIVERSE
(OVERVIEW)

t = Time	T = Temperature Events
10^{-35} s	10^{14} GeV Big Bang, Strings, Inflation Very early. Current particle theory no good
10^{-11} s	100 GeV Electroweak Phase Transition Particles (Higgs) get masses. Particly theory ok. Baryogenesis? (more particles than antiparticles)
10^{-5} s	100 MeV QCD (quark–hadron) phase transition Quarks(elementary) condense to Protons
1–100 s	Nucleosynthesis: Helium, light nuclei formed 1.0X 10^{9} °K Superconducting Universe
380,000 years	0.25 ev, 3,000 °K Atoms (electrically) neutral Last scattering of light (electromagnetic radiation) from big bang: Cosmic Microwave Background
1 billion years	early galaxies form
14 billion years	2.7 °K Now

Figure 1. Evolution of the universe.

The most important events for the present work are the electroweak phase transition (EWPT) at 10^{-11} s and the QCD phase transition (QCDPT) at 10^{-5} s.

Electroweak Phase Transition (EWPT)

Particles get mass, magnetic fields are created, baryogenesis—there are more quarks than anti-quarks;

Standard EW model has the fields with quanta:

Fermions (spin 1/2 particles) are (e^-, ν_e) and the μ and τ leptons. The quarks are (q_u, q_d) and the other two quark generations;

Gauge bosons (spin 1 particle) are W^+, W^-, Z^o and photon (γ);

Scalar boson (spin 0) is Higgs, ϕ_H;

No first order phase transition for Higgs mass greater than 60 GeV;

At the LHC (Large Hadron Collider), one has found the Higgs mass $\simeq$ 125 GeV and CP = charge parity (Figure 2).

With a first order (EWPT):

(1) Critical temperature, $T_c \simeq 100 - 150$ GeV;
(2) Latent heat = $< \phi_H > \equiv v$;
(3) Bubbles of the new universe form ($< \phi_H > \equiv v$) inside the old universe ($< \phi_H > \equiv 0$). This gives the standard model particles their masses:

$$
\begin{aligned}
M_W &= gv/\sqrt{2} \quad \text{g = strong coupling constant} \\
M_Z &= m_W/\cos(\theta_W) \quad \theta_W = \text{ Weinberg angle} \\
m_e &\propto m_u \propto m_d \propto v\,.
\end{aligned} \tag{2}
$$

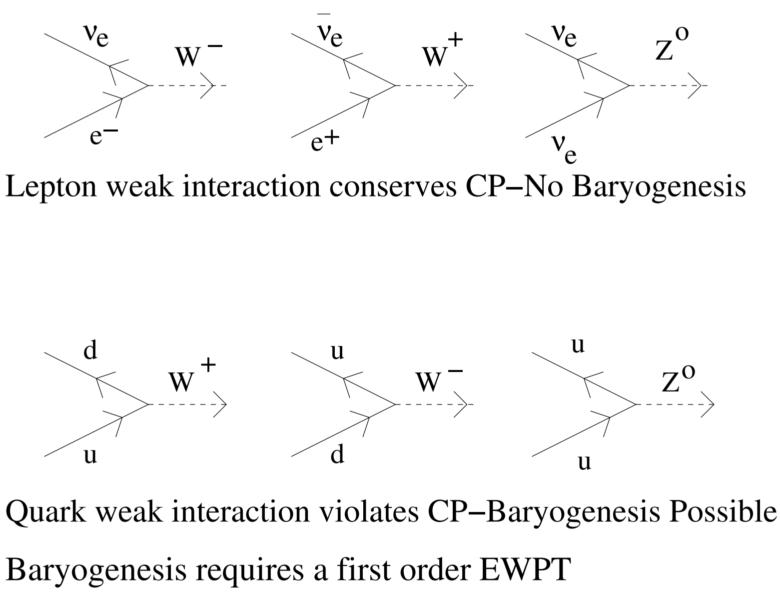

Figure 2. Lepton and Quark weak interactions.

Standard model M_W = 80 GeV and M_Z = 90 GeV.

Bubbles nucleate, creating electromagnetic fields, and collide, creating magnetic fields. These magnetic fields could explain the mystery of gallactic and inter-gallactic magnetic fields, as discussed below.

EW-MSSM theory. The MSSM (minimal supersymmetry model): another scalar boson field, the Stop (ϕ_S), is added to the standard model fermion and boson fields. This has been shown to lead to a first order EWPT.

Electroweak minimal supersymmetry model (EW-MSSM)

All supersymmetry partners of standard model particles except the top quark, ϕ_S, are integrated out, giving an EW-MSSM Lagrangian:

$$
\begin{aligned}
\mathcal{L}^{MSSM} &= \mathcal{L}^1 + \mathcal{L}^2 + \mathcal{L}^3 \\
&\quad + \text{leptonic and quark interactions} \\
\mathcal{L}^1 &= -\frac{1}{4} W^i_{\mu\nu} W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
\mathcal{L}^2 &= |(i\partial_\mu - \frac{g}{2}\tau \cdot W_\mu - \frac{g'}{2} B_\mu)\Phi|^2 - V(\Phi) \\
\mathcal{L}^3 &= |(i\partial_\mu - \frac{g_s}{2}\lambda^a C^a_\mu)\Phi_s|^2 - V_{hs}(\Phi_s, \Phi)\,,
\end{aligned} \tag{3}
$$

where

$$
\begin{aligned}
W^i_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\epsilon_{ijk} W^j_\mu W^k_\nu \\
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu\,,
\end{aligned} \tag{4}
$$

where the W^i, with i = (1,2), are the W^+, W^- fields, C^a_μ is an SU(3) gauge field, (Φ, Φ_s) are the (Higgs, right-handed Stop fields), (τ^i, λ^a) are the (SU(2), SU(3) generators, and the electromagnetic and Z fields are defined as

$$A_\mu^{em} = \frac{1}{\sqrt{g^2+g'^2}}(g'W_\mu^3 + gB_\mu)$$
$$Z_\mu = \frac{1}{\sqrt{g^2+g'^2}}(gW_\mu^3 - g'B_\mu)\ . \quad (5)$$

Electromagnetic and magnetic field creation with EW-MSSM theory:

Electromagnetic field creation during EWPT bubble nucleation (due to spatial symmetry, no magnetic field is created) [6].

The B (magnetic) field creation via EWPT bubble collisions is as follows (Figure 3):

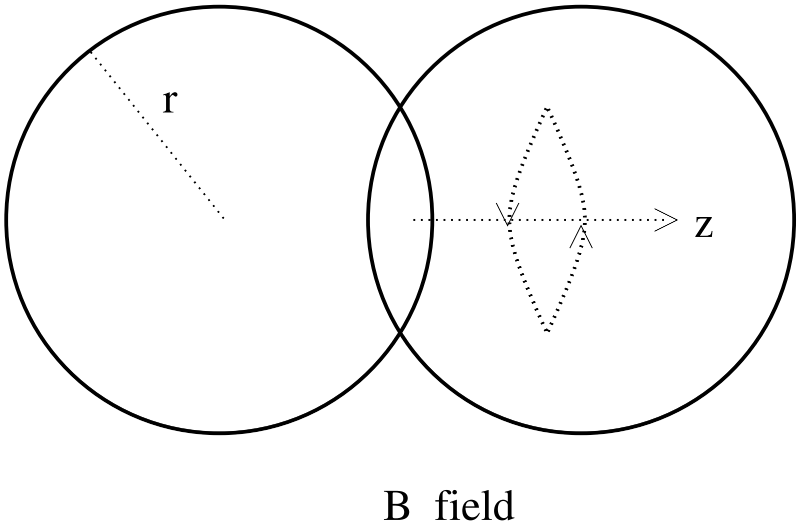

Figure 3. Magnetic field created during EWPT bubble collisions.

Results for B (magnetic) field creation [7] via EWPT [8] bubble collisions (Figure 4):

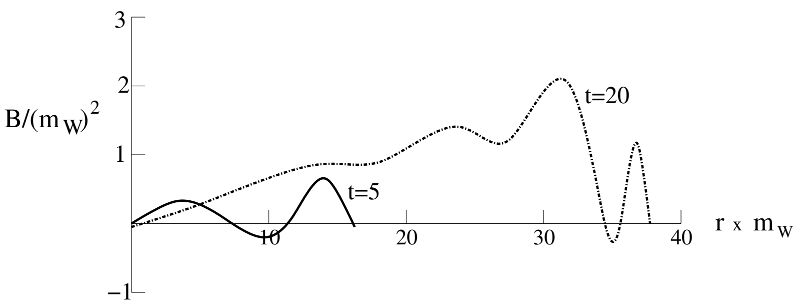

Figure 4. Final Magnetic fields created for two different t as a function of the W mass.

The B field at the end of the EWPT, with the temperature= T_c, was found to be
$B^{EWPT}(T_c) = 10M_W^2$ with $M_W = 80$ GeV.
$B^{EWPT}(T_c)$ is needed for the estimates of gravitational radiation[9,10].

4. Dark Mass Creation During EWPT via Dark Energy Interaction

We add dark matter dark energy terms with a dark energy field interacting with a dark matter field to a MSSM EW Lagrangian previously used to calculate the magnetic field created during the EWPT.

The EW-MSSM Lagrangian with terms for the dark energy quintessence field and with the interaction of the quintessence field with the dark matter fermion field is:

$$
\begin{aligned}
\mathcal{L}^{MSSM+DM-DE} &= \mathcal{L}^1 + \mathcal{L}^2 + \mathcal{L}^3 + \mathcal{L}^{fermion} + \mathcal{L}^{DM-DE} \\
\mathcal{L}^1 &= -\frac{1}{4} W^i_{\mu\nu} W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
\mathcal{L}^2 &= |(i\partial_\mu - \frac{g}{2}\tau \cdot W_\mu - \frac{g'}{2} B_\mu)\Phi_H|^2 - V(\Phi - H) \\
\mathcal{L}^3 &= |(i\partial_\mu - \frac{g_s}{2}\lambda^a C^a_\mu)\Phi_s|^2 - V_{hs}(\Phi_s, \Phi_H) \\
\mathcal{L}^{fermion} &= \text{standard Lagrangian for fermions} \\
\mathcal{L}^{DE} &= \frac{1}{2}\partial_\nu \Phi_q \partial^\nu \Phi_q - V(\Phi_q) \\
\mathcal{L}^{DM-DE} &= g_D \bar{\psi}^{DM} \Phi_q \psi^{DM} \, .
\end{aligned} \tag{6}
$$

Following P.J.E. Peebles and Bharat Ratra [11], and Glennys R. Farrar and P.J.E. Peebles [12].

In Ref. [12], $a(t)$ 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 for $\Phi_q(t)$ is

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

with $\Phi_q(t_{EWPT})$ as 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, with $t_{EWPT} = 10^{-11}s$ and t_1 in s, $\frac{a(t_{EWPT})}{a(t_1)} = \sqrt{\frac{10^{-11}}{t_1}}$.

The dark matter mass, M_{DM}, given in our theory with t as the time of the EWPT is

$$
M_{DM} = g_D \frac{m_p}{32\pi} \Phi(t_{EWPT}) \, . \tag{7}
$$

Using $m_p = 1.22 \times 10^{19}$ GeV and $g_D = \pi \times 10^{-11}$

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

For t_1, we use both t_{eq} = 1500 years: when the universe went from being radiation-dominated to matter-dominated, and t_{now} = 13.7 billion years, in which scenario the dark energy field evolved until the present time. Using $\alpha = 4.0$. Therefore, $M_{DM}(t = t_{eq}) \simeq$ 60.0 GeV and $M_{DM}(t = t_{now}) \simeq$ 0.6 GeV.

5. Sterile Neutrinos as Dark Matter

Sterile neutrinos are a well-known source of dark matter. There are three active neutrinos, $\nu_e = \nu_1, \nu_\mu = \nu_2, \nu_\tau = \nu_3$, and three sterile neutrinos, $\nu_{s1}, \nu_{52}, \nu_{s3}$.

Recently, the MiniBooNE collaboration has carried out a search for sub-Gev dark matter at the Fermilab [13], with the estimate

$$
\begin{aligned}
M_{\nu_{s3}} &> 200 \;\; \text{MeV} \\
M_{\nu_{s3}} &< 1250 \;\; \text{MeV}.
\end{aligned} \tag{8}
$$

Therefore, from $M_{\nu_{s3}}$, one can conclude that it is likely that most of the dark matter in the universe consists of sterile neutrinos.

6. Dark Matter in the Milky Way Galaxy Estimated by Rotational Velocity

If an object with mass m is moving in a circle with radius R and speed v, it has centripital acceleration a_c given by

$$
a_c = \frac{v^2}{R} \, , \tag{9}
$$

and from Newtons law of motion, it feels a centripital force F_c

$$F_c = m \times a_c \ . \tag{10}$$

R, The distance from the center of our Milky Way galaxy to our Sun, is

$$R \simeq 2.5 \times 10^{14} \ , \tag{11}$$

meter and the rotational velocity of the Milky Way galaxy is

$$v \simeq 220 \ , \tag{12}$$

kilometer/second.

From the Figure 5, the mass in the Milky Way galaxy is much more than the normal mass. The dark matter mass in the Milky Way galaxy is about 27%, which is consistent with the CMBR estimate.

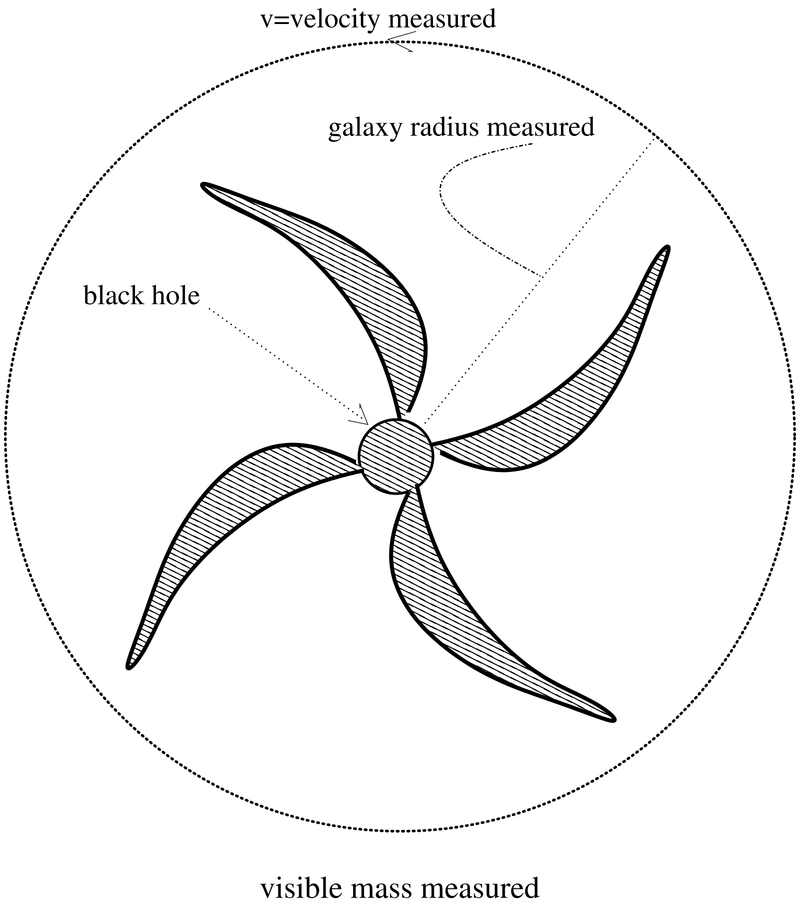

Figure 5. Radius, velocity and mass of the Milky Way galaxy.

7. Dark Energy in the Universe Estimated by Supernovae Velocities

The acceleration of supernovae is shown in the Figure 6.

Without dark energy, supernovae would be decelerating at a large distance due to the gravitational attraction of the larger interior mass. Dark energy, however, is anti-gravity and the supernovae are accelerating, as shown in the figure. Using the supernovae acceleration, one estimates that dark energy is approximately 73% of the matter in the universe. This is consistent with the CMBR estimate of approximately 70%.

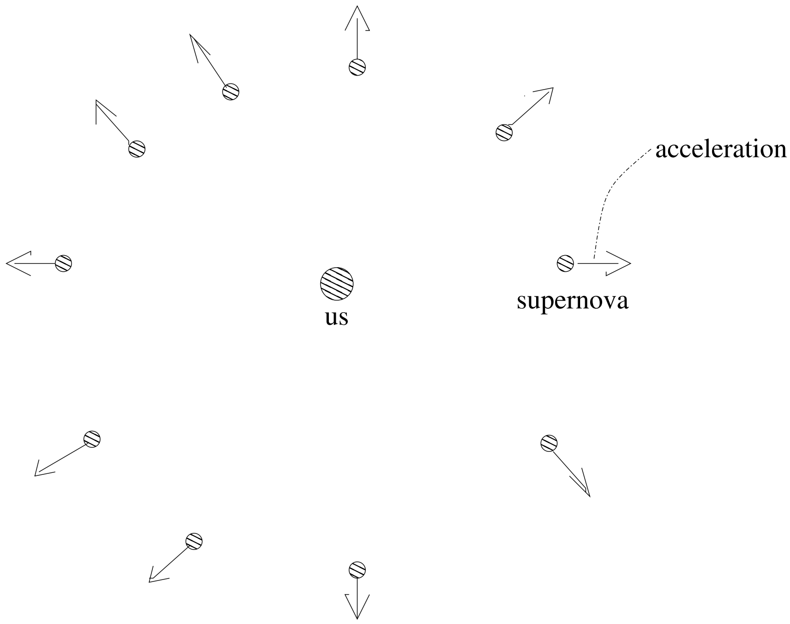

Figure 6. Supernovae acceleration via dark energy.

Quantum Chromodynamic Phase Transition (QCDPT)

QCDPT is a first order cosmological phase transition (see below).

The quark QCD fields and particles and quark condensate:

$$
\begin{aligned}
q(x) &= \text{quark field;} \\
\bar{q}(x) &= \text{antiquark field;} \\
| > &= \text{vacuum state;} \\
< |\bar{q}(x)q(x)| > &= \text{quark condensate;} \\
&= \text{vacuum expectation value of } \bar{\mathrm{q}}(\mathrm{x})\mathrm{q}(\mathrm{x});
\end{aligned}
$$

$$
\begin{aligned}
< |\bar{q}(x)q(x)| > &= 0 \text{ in quark gluon plasma phase;} \\
&\simeq -(0.23\ \text{GeV})^3 \text{ in hadron phase.}
\end{aligned}
$$

$< |\bar{q}(x)q(x)| >$, the quark condensate, is vacuum energy

At time $t \simeq 10^{-5}$ s and temperature $T_c \simeq 150$ MeV, the universe with quark–gluon plasma matter transforms to our present universe with hadronic matter (Figure 7).

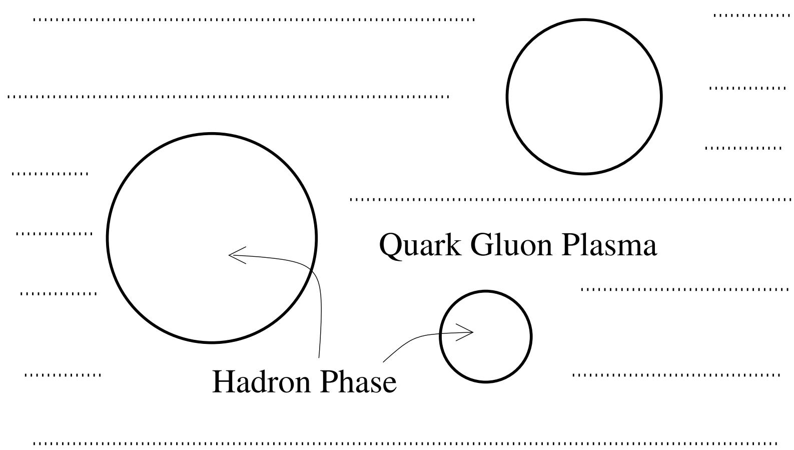

Figure 7. Hadron Phase and the Quark Gluon Plasma.

Since the QCDPT is first order, bubbles of the present universe form within the earlier universe. Here, a gluonic wall created by a bubble collision is shown Figure 8:

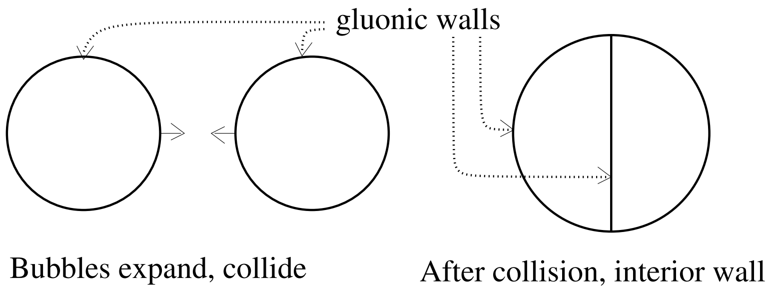

Figure 8. Bubbles collide producing a bubble with a guonic wall.

Magnetic field creation during QCDPT (Figure 9)

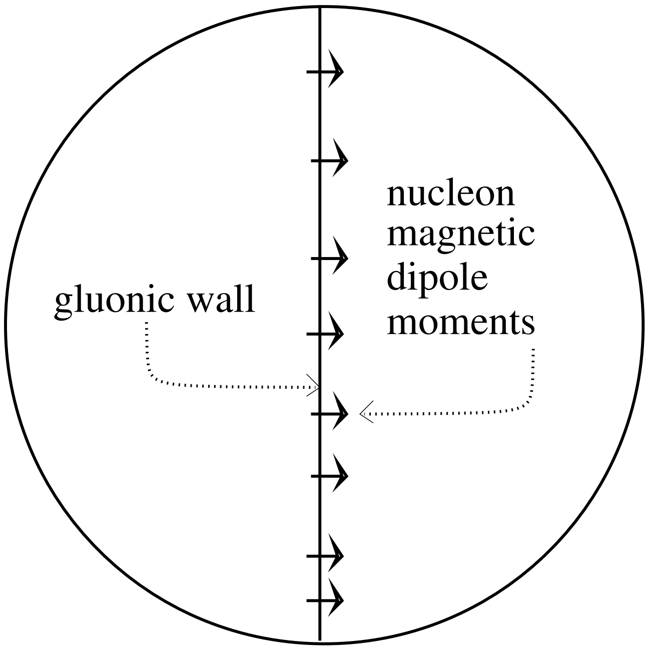

Figure 9. Magnetic field produced during the QCDPT.

The magnetic wall during the QCDPT creates B–B correlations that are much larger than that produced by inflation or string models.

8. Conclusions

The early universe cosmological phase transitions were very important for the evolution into our present universe. During the EWPT, the vacuum expectation value of the Higgs field $< \phi_H >$ went from zero to a finite value, and via interactions with the Higgs field, the masses of all standard model particles were created. During the QCDPT $< \bar{q}q >$, the quark condensate was created, and the universe went from the quark–gluon plasma (QGP) to our universe with baryons, mesons, atoms, etc. During both the EWPT and QCDPT, the magnetic fields were created.

Using a model with a dark mass fermion field interacting with a dark energy quintessence field added to the MSSM EW Lagrangian, it was found that the expected value of the dark matter mass could have been created via the EWPT.

The estimate of dark mass in the universe via galaxy rotation was reviewed. Dark matter of approximately 27% of the universe is consistent with CMBR.

Sterile neutrinos as dark mass was also reviewed. From the MiniBooNE collaboration [13], most of the dark matter in the universe consists of sterile neutrinos.

Dark energy is anti-gravity. The dark energy in the universe estimated by supernovae velocities was reviewed. Dark energy of approximately 70% of the universe is consistent with CMBR.

The magnetic field created during QCDPT bubble collisions via a magnetic wall was reviewed. It was shown that this magnetic wall creates B–B correlations in the CMBR that are much larger than that produced by inflation or string models; however, the magnitude is still too small to be measured at the present time.

Recently, it was shown that the magnetic walls created during the QCDPT could be the primary seeds for gallactic and extra-gallactic magnetic fields, solving a long-standing problem.

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Conflicts of Interest: The authors declare no conflict of interest.

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