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Unified Origin for Visible and Dark Matter in a Baryon-Symmetric Universe from a First-Order Phase Transition

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Abstract

In a baryon-symmetric universe, the baryon asymmetry observed for visible matter is matched by an equal and opposite asymmetry for dark matter, thereby closely connecting the number densities of both types of matter. This is a necessary step towards the goal of explaining the mystery of why the visible and dark matter densities are observed to be similar. In this talk, a way of producing such a universe from bubble nucleation during a first-order phase transition is reviewed. The process is an analog of electroweak baryogenesis.

Keywords: Asymmetric Dark Matter, Baryogenesis, First-Order Phase Transition, Baryon-Symmetric Universe, Anomalous Symmetry

1. Introduction

The fact that the cosmological mass density of ordinary or visible matter (VM) today is only about a factor of five different from the mass density of dark matter (DM),

$$\Omega_d \simeq 5\Omega_v, \tag{1}$$

suggests a common origin for both. In this talk, I review work performed with K. Petraki and M. Trodden [1] on a model that (partially) explains this fact from the unified production of VM and DM through the agency of bubble nucleation dynamics during a first-order phase transition in the early universe, an analog of the electroweak baryogenesis mechanism [2]. It is a particular scenario drawn from the special class of asymmetric DM models [3] which feature a "baryon-symmetric universe" [4]. This idea is explained below.

We start by discussing the popular Weakly Interacting Massive Particle (WIMP) hypothesis for DM. The idea is that the DM is a new particle with an electroweak-scale mass, typically a Majorana fermion such as the neutralino of supersymmetric theories, whose cosmological density is determined by a weak-scale annihilation cross-section. As the temperature of the universe drops below the WIMP mass, the creation of WIMPs becomes energetically disfavored and their density drops through Boltzmann suppression until they decouple from the VM plasma. With a weak-scale annihilation cross-section, it turns out that the WIMPs decouple when their mass density is in the correct range to explain the cosmological DM observations. This scenario is considered to be attractive because the existence of weakly-interacting electroweak-scale particles is motivated by independent particle physics problems. The neutralino, for example, is required by the supersymmetric solution of the gauge hierarchy problem.

However, the WIMP hypothesis leaves unexplained why the DM density is so similar to the VM density. The latter is *not* determined by the physics of weak-scale annihilation. Rather, it is due to the existence of the cosmological baryon asymmetry: some as-yet unknown physics in the early universe caused the

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baryons to outnumber the antibaryons by about one part in 10^{10}. The baryon-antibaryon annihilations which deplete those species' number densities at temperatures below their masses switch off not because the interactions become too weak, but because the baryons eventually have no antibaryons to annihilate with. The excess baryons form the VM in the universe today. Weak-scale annihilation that becomes ineffective through decoupling compared with strong-sector annihilation that switches off because of a particle-antiparticle asymmetry: these are very different processes, involving different forces and circumstances, yet in the WIMP paradigm they are required to coincidentally produce similar relic mass densities. Acknowledging this necessary coincidence motivates that an alternative to the WIMP hypothesis be given serious consideration.

The obvious alternative is simply to suppose that the DM density is also due to a particle-antiparticle asymmetry, and that there is a dynamical connection between the visible and dark sectors that makes the asymmetries similar, or possibly even identical. This is the "asymmetric DM" hypothesis. The idea is that the DM consists of stable relics from a hidden sector that possesses an analog of baryon number. The dark sector may be its own complicated world, described by some kind of gauge theory. For the special case of "mirror matter" [5], the dark gauge theory is isomorphic to the standard model (SM), but in general it is different. In the low-energy world of the late universe in which we live, we came to know of the other sector through the necessarily common gravitational interaction. But the similar densities suggest that there are also non-gravitational connections to be discovered between our world and the dark world. In asymmetric DM models, the similar VM and DM asymmetries point to a DM particle mass in the few GeV regime. The DAMA, CoGeNT and CRESST anomalies provide some encouragement to take this seriously [6].

A baryon-symmetric universe is one that contains a DM asymmetry that is exactly the opposite of the VM asymmetry, so it is a special case of asymmetric DM. It is attractive because the strong connection between the two asymmetries is driven by a symmetry principle rather than by the specifics of some dynamical scheme. Indeed, many different theories can produce a baryon-symmetric universe, and this talk is about only one of them. Establishing a connection between the visible and dark asymmetries is a necessary step towards the goal of a complete understanding of the similar visible and dark *mass* densities. One also needs a theory for the origin of the few-GeV DM mass scale, but that important problem is beyond the scope of this talk.

Here is the symmetry principle [7]: Call the ordinary baryon number B_1, and let B_2 standard for the DM analog. Form the orthogonal linear combinations

$$B \equiv B_1 - B_2$$
$$X \equiv B_1 + B_2 \,. \tag{2}$$

Now demand that B is either an exactly or essentially conserved quantum number, while X is violated at high energies and in the early universe. (By "essentially conserved" we mean we remain open to the existence of extremely weak non-conserving processes, such as very slow proton decay, but these are so weak that they are cosmologically irrelevant.) Dynamics that violates X through out-of-equilibrium processes that also violate C and CP will, according to the Sakharov analysis [8], produce an X asymmetry. But no B asymmetry develops, so we have that

$$\Delta B_1 = \Delta B_2 = \Delta X/2 \,. \tag{3}$$

The quantity B may be thought of as a generalized baryon number. At low energies and in the late universe, X violation becomes very weak, and B_1 and B_2 become individually conserved. In the visible sector, B_1 conservation ensures the (essential) stability of protons and this accounts for the bulk of the VM density. Electric charge and angular momentum conservation also make the electron and, respectively, the lightest neutrino stable. In the dark sector, B_2 conservation ensures the stability of at least one species. For other reasons, there may be other stable dark species. Non-perturbative sphaleron effects may reprocess some of these asymmetries in one or both sectors.

The requirement that B is never violated is a strong one. To justify such an imposition, it is natural to take $U(1)_B$ to be a gauge symmetry, while $U(1)_X$ is global. In that case, anomaly-freedom suggests that B should rather be replaced by $B-L$, which is indeed what we do below. Any such model must be constructed to ensure that a global $U(1)_B$ is produced after the gauged $U(1)_{B-L}$ is spontaneously broken. There is a standard way to do this, as explained in Ref. [1].

The first consideration in building a model for a baryon-symmetric universe is the dynamics of X asymmetry generation. We may borrow the essential idea from each known way of generating an ordinary baryon asymmetry, and reuse it to produce a nonzero X. Well-studied schemes include out-of-equilibrium heavy particle decays, Affleck-Dine dynamics [9], and bubble nucleation during a first-order phase transition (as used in electroweak baryogenesis). We employ the latter here. See Refs. [7, 10] for papers on baryon-symmetric universe models.