SUPERHEAVY DARK MATTER

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If there exist fields of mass of the order of $10^{13}$ GeV and large field inflation occurs, their interaction with classical gravitation will generate enough particles to give the universe critical density today regardless of their nongravitational coupling.

1 Introduction

In the standard dark matter scenarios, WIMPs are usually considered to have once been in local thermodynamic equilibrium (LTE), and their present abundance is determined by their self-annihilation cross section. In that case, unitarity and the lower bound on the age of the universe constrains the mass of the relic to be less than 500 TeV. On the other hand, if the DM particles never attained LTE in the past, self-annihilation cross section does not determine their abundance. For example, axions, which may never have been in LTE, can have their abundance determined by the dynamics of the phase transition associated with the breaking of $U(1)_{PQ}$.

These nonthermal relics (ones that never obtained LTE) are typically light. However, there are mechanisms that can produce superheavy (many orders of magnitude greater than the weak scale) nonthermal relics. Some of this is reviewed in Ref. Although not known at the time when this talk was given, it is now known that if the DM fields are coupled to the inflaton field, then the mass of the DM particles that can be naturally produced in significant abundance after inflation can be as large as $10^{-3}M_{Pl}$ (paper in preparation).

In this article, I discuss the gravitational production mechanism which is a generic consequence of any large field inflationary phase ending. As Ref. shows, the nonadiabatic change in the way that the spacetime expands at the end of any large field inflationary model induces superheavy particle production gravitationally with sufficient efficiency as to render those superheavy DM to be a significant component of the energy density in the universe today. To turn this around, if stable superheavy WIMPs within the mass range $0.04 - 2 \times 10^{-6}M_{Pl}$ exist in the mass spectrum of any particle physics models, then those

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particle physics models may be ruled out by cosmology if the occurrence of large field inflation can be established.\(^5\) Note that this gravitational production of particles is a generic phenomenon which is insensitive to the way that the DM particles are coupled, as long as they are stable. In Ref.\(^5\), we also analyze the particle production's large mass asymptotic dependence which is in general negligibly dependent on the order of adiabaticity of the adiabatic boundary conditions used unless there is a discontinuity in some \(n\)th derivative of the scale factor for \(n \sim \mathcal{O}(1)\). It is also important to note that if the dark matter decays with a lifetime of the order of the age of the universe, they may be observable through cosmic rays.\(^8\) Other observational consequences for the cases in which the superheavy DM is charged or strongly interacting are under investigation.\(^8\)

2 Scenario Requirements

Let me now state the scenario more explicitly and briefly address the requirements of nonthermalization and stability. If large field inflation occurs, then when the universe makes a transition out of the de Sitter phase, there is a nonadiabatic change in the spacetime expansion leading to a nonadiabatic change in the frequency of the Fourier mode defining the particles. Nonadiabatic change means that the rate of fractional change in the particle mode frequency becomes larger than the frequency itself. This gravitational interaction at the end of inflation induces mixing between positive and negative frequency modes, leading to quantum creation of DM particles which we label by \(X\).

Suppose these \(X\) particles never attained LTE. The DM abundance today can be expressed in terms of the DM abundance \(n_X(t_e)\) at the time \(t_e\) of their creation (at the end of inflation) as

\[
\Omega_X h^2 \approx \Omega_R h^2 \left( \frac{T_{RH}}{T_0} \right) \left( \frac{M_X}{M_{Pl}} \right) \frac{n_X(t_e)}{M_{Pl} H^2(t_e)}
\]

where \(H\) is the Hubble velocity, \(T_0\) is the temperature today, \(T_{RH}\) is the reheating temperature, and \(\Omega_R h^2 \approx 4.31 \times 10^{-5}\) is the fraction of critical energy density that is in radiation today. This equation says that for a typical reheating temperature of \(10^3\) GeV, \(\Omega_X h^2 \sim 10^{17}(\rho_X(t_e)/\rho(t_e))\) where \(\rho(t_e)\) is the total energy density and \(\rho_X(t_e)\) is the energy density stored in the DM particles. The fraction of total energy density that needs to be extracted to saturate

\(^5\)The point is that even if large field inflation occurred, particles of masses of the order of the inflaton mass can still pose a threat to consistent cosmology.

\(^8\)Of course, our scenario does not contain any late time second inflation.
the matter density upper bound is indeed very small because the matter energy density grows with respect to the radiation energy density as inversely proportional to the temperature, while the temperature difference between the time of reheating and now is large. Hence, the challenge lies in creating a very small density of \(X\) particles if these are to contribute significantly to the DM abundance today.

Once these particles are created at the end of inflation, they must not reach LTE for this scenario to be distinguishable from the standard one. Using Eq. \(\frac{\sigma_A}{\gamma} \leq 1\) with \(\Omega_X h^2 < 1\) and estimating a conservative upper bound on the WIMP cross section to be \(M_X^{-2}\), we can estimate

\[
\frac{n_X}{H} \leq \frac{7 \times 10^{-19}}{(T_{RH}/10^{16}\text{GeV}) (M_X/M_{Pl})^{3}},
\]

the left hand side of which must be less than one at the end of inflation to avoid LTE. Thus, because of the \(M_X^{-2}\) suppression of a generic WIMP cross section, a superheavy particle will decouple in general irrespective of the exact value of the weak coupling constant.

For the \(X\) particles to serve as DM, they must have a lifetime that is of the order of the age of the universe and be extremely massive. One possible source of these DM particles is the secluded and the messenger sectors of gauge mediated SUSY breaking models where large scale SUSY breaking can give rise to large masses, while at the same time accidental symmetries analogous to baryon number can give large lifetime to these particles. Other natural possibilities include theories with discrete gauge symmetries and string/M theory.

3 Abundance Calculation Results

We consider a massive scalar field theory (representing the \(X\) particle) interacting only with classical gravitational field having a homogeneous and isotropic metric of the form \(ds^2 = a^2(\eta)(d\eta^2 - dx^2)\). We calculate the particle production for various toy models corresponding to different functions \(a(\eta)\). Each model possesses varying degrees of nonadiabaticity in the mode frequency evolution at the point of transition out of the inflationary phase. In order to minimize the boundary effects and minimize the number of particles produced, the toy models are chosen to have the property of admitting infinite adiabatic order vacua at the in-out regions, and the \(X\) particles are conformally coupled to gravity. With effectively infinite adiabatic order boundary conditions, we solve numerically for the quantity \(n_X(t_e)\) in Eq. \(\frac{\Omega_X}{\gamma}\). The results are shown in Fig. 1. The figure clearly shows that for the mass range of \(0.04 - 2 \times 10^{-4} M_{Pl}\), \(X\) can be naturally produced gravitationally in cosmologically significant amounts.
Figure 1: The dark matter abundance today is shown as a function of the particle mass for various models. The mass is given in terms of $H(\eta_e) \approx 10^{-6} M_{Pl}$ (the Hubble parameter at conformal time $\eta = \eta_e$, the end of inflation). In the “discontinuously into radiation” case, $a''(\eta)$ has a discontinuity at $\eta = \eta_e$, while in the “discontinuously into matter” case, $a'(\eta)$ has a discontinuity at $\eta = \eta_e$. The curves labeled “smoothly into” is for $a(\eta)$ that satisfies $(d^n a/d\eta^n)/a^{n+1} < \infty$ for all $n$ and natural numbers $\nu$. The curve labeled $T = H_i/(2\pi)$ shows a thermal density with this temperature. The unshaded region satisfies the conservative nonthermalization condition obtained by considering Eq. (2).

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