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Dynamical Dark Matter: Introduction, Equation of State, and Cosmological Implications

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Dynamical dark matter (DDM) is a new framework for dark-matter physics in which the dark sector comprises an ensemble of individual constituent fields, and in which the usual requirement of dark-matter stability is replaced by a balancing between constituent lifetimes and cosmological abundances across the ensemble as a whole. In this article, we introduce the DDM framework, discuss the general equation of state for dark matter in this new framework, and outline some of its related cosmological implications.

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1. Introduction

Dynamical dark matter (DDM) [1, 2] is a new framework for dark-matter physics in which the dark sector comprises an ensemble of individual constituent fields, and in which the usual requirement of dark-matter stability is replaced by a balancing between constituent lifetimes and cosmological abundances across the ensemble as a whole. Such DDM ensembles have highly non-trivial cosmological consequences, including a constantly evolving composition of the dark-matter relic abundance and a time-dependent dark-matter equation of state [1]. This article will review these theoretical features of the DDM framework while maintaining as much generality as possible. However, despite the general theoretical nature of the discussion presented here, it is important to emphasize that there do exist explicit realizations of the DDM frameowrk in terms of concrete models [2, 3] which satisfy all known collider, astrophysical, and cosmological constraints on dark matter. Moreover, DDM ensembles also give rise to characteristic phenomenological signatures which can differ significantly from those associated with more traditional dark-matter candidates. This is true not only at the LHC [4] but also at the next generation of direct-detection experiments [5]. Thus dynamical dark matter truly represents a new way of thinking about the overall dark-matter question.

2. Overview of the DDM framework

Many theoretical proposals for physics beyond the SM give rise to suitable dark-matter candidates. In most of these cases, the ability of these candidates to serve as dark matter rests squarely on their stability. This in turn is usually the consequence of a stabilizing symmetry. Indeed, any particle which decays too rapidly into SM states is likely to upset big-bang nucleosynthesis (BBN) and light-element abundances, and also leave undesirable imprints in the cosmic microwave background (CMB) and diffuse X-ray/gamma-ray backgrounds.

There is, of course, one important exception to this argument: A given dark-matter candidate need not be stable if its abundance at the time of its decay is sufficiently small. A sufficiently small abundance assures that the disruptive effects of the decay of such a particle will be minimal, and that all constraints from BBN, CMB, *etc.* will continue to be satisfied.

Dynamical dark matter [1, 2, 3] is a new framework for dark-matter physics which takes advantage of this possibility. First, we assume that dark matter comprises a vast ensemble of interacting fields with varying masses, mixings, and abundances. Second, rather than impose stability for each field individually (or even for the collection of fields as a whole), we ensure the phenomenological viability of this scenario by requiring that states with larger masses and SM decay widths have correspondingly smaller abundances, and vice versa. In other words, stability is not an absolute requirement in such a scenario: stability is balanced against abundance! As we shall see, this leads to a highly dynamical scenario in which cosmological quantities such as $\Omega_{\rm CDM}$ experience non-trivial time-dependences beyond those normally associated with the expansion of the universe.

Thus, in the DDM framework, the dark-matter "candidate" is actually an *ensemble* of individual dark component states whose lifetimes are balanced against their abundances. We emphasize that such a balancing is highly non-trivial: while lifetimes are determined by the masses and couplings in the underlying particle-physics Lagrangian, cosmological abundances are determined by the *interplay* between the Lagrangian parameters and a specific cosmological history. This balancing is ultimately the core feature which underlies the DDM framework and which gives rise to distinctive astrophysical, cosmological, and collider signatures that transcend those usually associated with dark matter.

Because of its non-trivial structure, the DDM ensemble — unlike most traditional dark-matter candidates — cannot be characterized in terms of a single mass, decay width, or set of scattering amplitudes. The DDM ensemble must therefore be characterized in terms of parameters (*e.g.*, scaling relations or other internal correlations or constraints) describing the behavior of its constituents as a whole. As a consequence, phenomenological bounds on the DDM dark sector must be expressed and analyzed in terms of a new set of variables which describe the behavior of the entire DDM ensemble as a collective entity with its own internal structures and/or symmetries.

It turns out that theories of large extra dimensions — and by extension, certain limits of string theory — can naturally give rise to dynamical dark matter [1]. Moreover, as we shall demonstrate, DDM ensembles also generically give rise to a rich set of collider and astrophysical pheonomena which transcend those usually associated with dark matter. Indeed, many new and unique signature patterns are possible. Thus, by studying DDM and its phenomenological viability, we are not only exploring a new candidate for dark matter but also providing new phenomenological constraints on large extra dimensions and certain limits of string theory.

To be more specific, let us suppose that the dark matter consists of N states, with $N \gg 1$. Because of the multitude of dark-matter states, no state individually needs to carry the full dark-matter abundance $\Omega_{\rm CDM}$ observed by WMAP so long as the sum of their abundances matches $\Omega_{\rm CDM}$. In particular, each state can have a very small abundance. Of course, if all of these states have the same lifetime, they must continue to be hyperstable in order to evade problems with BBN, CMB data, *etc*. However, the states can carry different lifetimes. As long as those with larger abundances have larger lifetimes, phenomenological constraints can be satisfied. Seen from this perspective, the usual dark-matter scenarios are just a limiting $N = 1$ case of this more general framework. However, taking $N \gg 1$ leaves room for our states to exhibit a whole spectrum of decay widths/lifetimes without running afoul of phenomenological and cosmological constraints.

We can outline the salient features of this scenario more quantitatively as follows. In general, let us assume for simplicity that the universe can be modelled as a Friedman-Robertson-Walker (FRW) universe which progresses through four distinct phases: inflation; reheating [which is a matter-dominated (MD) phase, where the matter comprises coherent oscillations of the inflaton field]; a radiation-dominated (RD) phase; and the final matter-dominated phase (which represents the current epoch). Moreover, let us recall that "stuff" with equation of state $p = w\rho$ (where p is the pressure, ρ the energy density) will have an abundance $\Omega \equiv \rho/\rho_{\rm crit}$ which scales with time as

$$\Omega \sim \begin{cases} t^{(1-3w)/2} & \text{RD era} \\ t^{-2w} & \text{RH/MD eras} \\ \exp[-3H(1+w)t] & \text{inflationary era ,} \end{cases} \tag{2.1}$$

where $\rho_{\rm crit} \equiv 3M_P^2 H^2$ with M_P the reduced Planck mass and $H \sim 1/t$ the Hubble parameter. Recall that $w = 0$ for matter, while $w = -1$ for vacuum energy (cosmological constant). For concreteness, we shall further assume that the individual dark-matter components in our scenario are described by scalars ϕ_i ($i = 1, ..., N$) with masses m_i and decay widths Γ_i describing decays into SM states. If we assume that both the spatial variations in the ϕ_i and the self-interactions among these fields can be safely neglected, the time-evolution of each of these fields follows

$$\ddot{\phi}_i + [3H(t) + \Gamma_i]\dot{\phi}_i + m_i^2 \phi_i \;=\; 0 \,, \tag{2.2}$$

which is simply a harmonic-oscillator equation with a time-dependent damping term. At early times for which $3H(t) + \Gamma_i > 2m_i$, the field ϕ_i does not oscillate, and consequently its energy density scales with time like vacuum energy. By contrast, at later times for which $3H(t) + \Gamma_i < 2m_i$, the field is underdamped and therefore oscillates; at such times, its energy density scales like massive matter. The condition $3H(t) + \Gamma_i = 2m_i$ thus determines the "turn-on" time at which each of the ϕ_i transitions from acting as dark energy to acting as dark matter. Since $H(t) \sim 1/t$ in all non-inflationary epochs, and since we typically have $\Gamma_i \ll H(t)$ when $H(t) \sim m_i$, we see that the turn-on time for each field ϕ_i generally scales as $t_i \sim 1/m_i$. Thus heavier states in the DDM ensemble "turn on" first, and lighter states turn on later. Indeed, at the time t_0 at which the abundances are initially established, those heavy modes with $m_i \gtrsim H(t_0)$ all "turn on" simultaneously, while those with $m_i \lesssim H(t_0)$ experience a sequential, "staggered" turn on. Given these observations, we find that the abundances Ω_i associated with our DDM ensemble generically behave as sketched in Fig. 1.

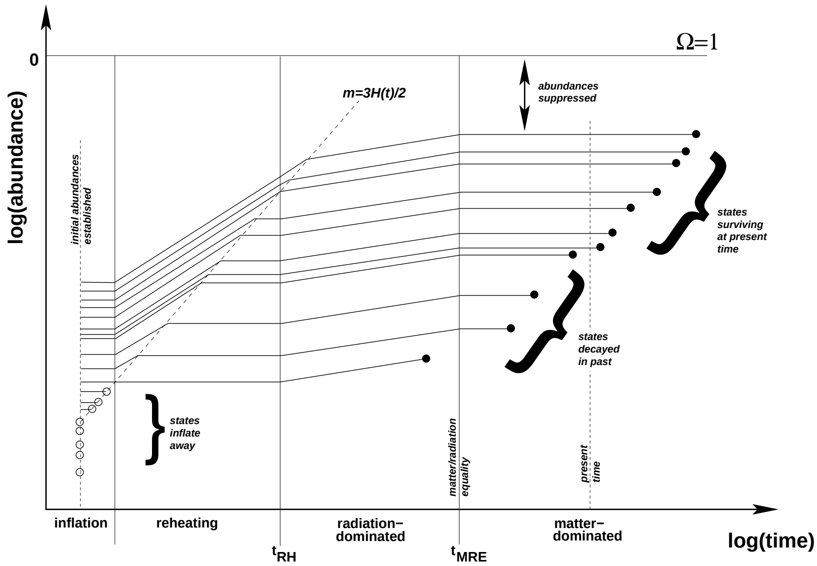

Figure 1: A sketch of the evolution of dark-matter abundances in the DDM framework. For concreteness, we have assumed that the abundances of the DDM constituents ϕ_i are initially established at a common time (chosen here during the inflationary epoch), with values scaling inversely with constituent mass. In this example, the energy density stored in each constituent field scales with time like vacuum energy until the time at which $3H(t) \sim 2m_i$, after which it scales like massive matter. Open circles indicate points at which the corresponding constituent energy densities are inflated away, while closed circles indicate the points at which the corresponding energy densities begin falling exponentially due to decays. The balancing of lifetimes against abundances — the hallmark of the DDM framework — is manifest in the upward-sloping trend among the closed circles. The dynamical nature of the DDM framework — and thus its non-trivial equation of state — reflects the fact that the composition and properties of the dark-matter sector experience a non-trivial time evolution prior to, during, and even after the current epoch.

3. The DDM equation of state

In order to characterize a particular DDM configuration at any moment in time — and ultimately the equation of state for DDM as a whole — we introduce three complementary parameters. First, we define the contribution of the DDM ensemble to the total dark-matter relic abundance. This is simply a sum of the contributions Ω_i of the individual DDM constituents:

$$\Omega_{\rm tot}(t) \equiv \sum_i \Omega_i(t) . \tag{3.1}$$

In principle, this sum should include the contributions of only those constituents which have already "turned on." By contrast, another important characteristic of a given DDM ensemble is the degree to which this total abundance is *distributed* among the DDM constituents. For example, one may ask how significantly $\Omega_{\rm tot}$ is shared between a dominant component and all others. Towards this end we can define

$$\eta(t) \equiv 1 - \frac{\Omega_0}{\Omega_{\rm tot}} , \tag{3.2}$$

where $\Omega_0 \equiv \max_i\{\Omega_i\}$ denotes the largest individual contribution. Thus, η quantifies the degree to which our DDM framework departs from standard dark-matter scenarios: a value $\eta \ll 1$ indicates that a single particle species contributes essentially the entirety of the dark-matter relic abundance, as in traditional dark-matter models, while $\eta \sim \mathcal{O}(1)$ signifies that the entire DDM ensemble contributes non-trivially to $\Omega_{\rm tot}$.

Finally, we may also define an effective equation-of-state parameter $w_{\rm eff}(t)$ which applies to the DDM ensemble as a whole — *i.e.*, as a single collective entity. This can be defined via the relation $w_{\rm eff}(t) \equiv p/\rho_{\rm tot}(t)$, where $\rho_{\rm tot} = \rho_{\rm crit}\Omega_{\rm tot}$ is the total ensemble energy density and where p is the corresponding pressure. Following standard derivations (see, *e.g.*, Ref. [1]), we find that during any matter-dominated (MD) or radiation-dominated (RD) cosmological epoch, this effective equation-of-state parameter may be expressed in terms of the time-derivatives of $\Omega_{\rm tot}$:

$$w_{\rm eff}(t) \equiv -\left(\frac{1}{3H}\frac{d\log\rho_{\rm tot}}{dt}+1\right) = \begin{cases} -\dfrac{1}{2}\left(\dfrac{d\log\Omega_{\rm tot}}{d\log t}\right) & \text{for RH/MD eras} \\ \\ -\dfrac{2}{3}\left(\dfrac{d\log\Omega_{\rm tot}}{d\log t}\right)+\dfrac{1}{3} & \text{for RD era .} \end{cases} \tag{3.3}$$

It is straightforward to evaluate the quantities $\{\Omega_{\rm tot},\eta,w_{\rm eff}\}$ as functions of time. For concreteness, let us focus on the evolution of the DDM ensemble during the final MD era, within which both $\rho_{\rm tot}$ and $\rho_{\rm crit}$ scale with time in the same way. In the approximation that the decay of each ϕ_i can be treated as occurring instantaneously at $t=\tau_i\equiv\Gamma_i^{-1}$, the abundances during this era are given by $\Omega_i(t)\approx\Omega_i\Theta(\tau_i-t)$, where $\Theta(x)$ denotes the Heaviside function. Moreover, from a DDM perspective, we are principally interested in the regime in which the number of ensemble constituents is large and the spectrum of lifetimes across the ensemble approaches a continuum. We therefore find that

$$\frac{d\Omega_{\rm tot}}{dt} = -\sum_i \Omega_i\delta(\tau_i-t) \approx -\int d\tau\,\Omega(\tau)n_\tau(\tau)\delta(\tau-t) = -\Omega(t)n_\tau(t) , \tag{3.4}$$

where the function $\Omega(\tau)$ describes the abundance of those DDM constituents with decay width τ^{-1} and where n_τ denotes the density of DDM states per unit τ across the ensemble.

To proceed further, it is necessary to specify functional forms for $\Omega(\tau)$ and $n_\tau(\tau)$. It is in this way that we are implicitly endowing our DDM ensemble with an internal structure. Towards this end, let us assume that $\Omega(\tau)$ and $n_\tau(\tau)$ can be parameterized through power laws of the form

$$\Omega(\Gamma) \sim A\Gamma^\alpha , \qquad n_\Gamma(\Gamma) \sim B\Gamma^\beta , \tag{3.5}$$

where n_Γ is the density of states per unit $\Gamma \equiv \tau^{-1}$ and where A, B, α, and β are general scaling coefficients and exponents. Note that such functional forms for $\Omega(\Gamma)$ and $n_\Gamma(\Gamma)$ are particularly relevant, emerging naturally in many realistic, theoretically-motivated DDM models [2, 3]. Given these parameterizations for $\Omega(\Gamma)$ and $n_\Gamma(\Gamma)$, we then find that $d\Omega_{\rm tot}/dt = -ABt^{-\alpha-\beta-2}$. We thus see that the collective dynamics of the ensemble as a whole is governed by the *sum* $x \equiv \alpha+\beta$ of the scaling exponents rather than by either exponent individually. It then follows from Eq. (3.3) that the effective equation-of-state parameter for the DDM ensemble takes the general form

$$w_{\rm eff}(t) = \begin{cases} \dfrac{(1+x)w_*}{2w_* + (1+x-2w_*)(t/t_{\rm now})^{1+x}} & x \neq -1 \\ \\ \dfrac{w_*}{1-2w_*\log(t/t_{\rm now})} & x = -1 \end{cases} \tag{3.6}$$

where $w_* \equiv w_{\rm eff}(t_{\rm now}) = AB/(2\Omega_{\rm CDM} t_{\rm now}^{1+x})$.

4. Cosmological implications

If the DDM ensemble under study is to be in rough agreement with cosmological observations, we expect that w_* today should be small (since traditional dark "matter" has $w = 0$). Furthermore, a variety of astrophysical considerations (including limits set by CMB data) also stipulate that $w_{\rm eff}(t)$ should not have experienced strong variations in the recent past. The results in Eq. (3.6) therefore imply that the DDM ensembles which are likely to be phenomenologically preferred are those for which

$$-2 \lesssim x \lesssim -1 . \tag{4.1}$$

However, depending on the detailed properties of the particular DDM ensemble under study, values of x which lie slightly above -1 may also be acceptable. Remarkably, there exist broad classes of DDM models in which this constraint is automatically satisfied [1]. Further cosmological implications of the decays leading to such a non-trivial DDM equation of state are discussed in Refs. [1, 2, 3].

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