Dynamical Explanation of the Dark Matter and Baryon Energy Density Coincidence

Dawid Brzeminski[*] and Anson Hook[†]

Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, Maryland 20742, USA

(Received 26 October 2023; revised 4 April 2024; accepted 16 April 2024; published 16 May 2024)

The near equality of the dark matter and baryon energy densities is a remarkable coincidence, especially when one realizes that the baryon mass is exponentially sensitive to UV parameters in the form of dimensional transmutation. We explore a new dynamical mechanism, where in the presence of an arbitrary number density of baryons and dark matter, a scalar adjusts the masses of dark matter and baryons until the two energy densities are comparable. In this manner, the coincidence is explained regardless of the microscopic identity of dark matter and how it was produced. This new scalar causes a variety of experimental effects such as a new force and a (dark) matter density-dependent proton mass.

DOI: 10.1103/PhysRevLett.132.201001

Introduction.—The large hierarchy between the proton mass and the Planck scale was a cause of great consternation back before QCD was first discovered. Eventually, a beautiful and elegant solution to this problem was discovered in the form of dimensional transmutation. The QCD confinement scale, which determines the proton mass, is *exponentially* sensitive to UV parameters. An $\mathcal{O}(1)$ number that happened to be ~ 10 is exponentiated giving the 18 orders of magnitude difference between the proton mass and the Planck scale.

The measured dark matter energy density ($\Omega_c = 0.26$) and baryonic energy density ($\Omega_b = 0.05$) are within a factor of ~ 5 of each other [1]. This coincidence is extremely surprising given the extreme sensitivity of the proton mass (and hence Ω_b) to $\mathcal{O}(1)$ numbers as well as the strong sensitivity of production mechanisms to various parameters. Because of this, it is extremely surprising that Ω_b is within a factor of 5 of Ω_c. In this Letter, we seek to solve this coincidence problem.

Historically, the coincidence $\Omega_c \approx 5\Omega_b$ has had only a single class of solution, whose general approach is as follows [2]. First, a cosmological history is chosen such that the number densities of dark matter and baryons are approximately equal, $n_B \approx n_{\rm DM}$. Typically, this is done via a $\mathbb{Z}_2$ discrete symmetry [3,4] or by a shared asymmetry between dark matter and baryons [5–10]. Second, the masses of the proton and dark matter are set to be approximately equal, $m_p \approx m_{\rm DM}$. This second step is typically ignored, but it can be accomplished by either a broken discrete symmetry [11–16], unification [17], coupled CFTs [18–20], or sometimes simply by fiat. Alternatively, the previous starting point can be modified to include correlated deviations in the mass and number density while maintaining the product [21].

In this Letter, we take a new approach to this coincidence problem. We posit that the proton mass and the dark matter mass both depend on the expectation value of a scalar and when this scalar reaches its minimum energy configuration, it sets the total energy density of baryons and dark matter approximately equal. While the details of the model we consider are given in the sections on "Toy model and cosmology" and "Standard model example and cosmology," it is simple to see how the mechanism works. Because of dimensional transmutation, the proton and dark matter mass depend on a scalar ϕ as

$$m_p(\phi) = m_p(0)e^{c_B\phi/f}, \qquad m_{\rm DM}(\phi) = m_{\rm DM}(0)e^{-c_D\phi/f}.$$

In the nonrelativistic limit, the finite density potential for the scalar is

$$V(\phi) = m_p(\phi)n_B + m_{\rm DM}(\phi)n_{\rm DM}$$

so that at the minimum

$$\frac{dV(\phi)}{d\phi} = 0 \Rightarrow \frac{\rho_{\rm DM}}{\rho_B} = \frac{c_B}{c_D} \sim \mathcal{O}(1).$$

As long as the potential for ϕ is dominated by the energy density of baryons ρ_B and dark matter $\rho_{\rm DM}$, it will relax the system to a state where the energy densities of the two are comparable, regardless of initial conditions.

Our new approach has many observational consequences. Our mechanism does not just adjust $\rho_{\rm DM} \sim \rho_B$ cosmologically but also inside of stars and planets, thereby giving the proton mass a dark matter density and normal matter density dependence. This effect is so severe as to exclude the simplest implementation of the model forcing a small modification described in the section on "Standard model example and cosmology." Aside from a density-dependent proton mass, ϕ mediates an attractive fifth force between baryons, a repulsive new force between baryons and dark matter, and an attractive new force between dark matter.

In the section on "Toy model and cosmology," we present a toy model and its cosmology that highlights our mechanism. We write down a standard model version of the toy model and elucidate its cosmology in the section on "Standard model example and cosmology." We discuss the constraints on our model in the section on "Bounds." Finally, we end with the "Conclusions" section.

Toy model and cosmology.—We first discuss a toy model to highlight our relaxation mechanism and its associated cosmology. The star of the show is a scalar ϕ that controls the mass of a baryon (B) and a dark matter (D) via dimensional transmutation. We couple ϕ to our two sectors as

$$\mathcal{L}_{\text{toy}} = \frac{\phi}{f}\left(\frac{\beta_B c_B}{32\pi^2} G_B^2 - \frac{\beta_D c_D}{32\pi^2} G_D^2\right). \quad (1)$$

$G_{B,D}$ are the field strength of confining sectors determining the mass of their respective particles and $\beta_{B,D}$ their beta functions. The linear coupling of ϕ to $G_{B,D}$ shifts their gauge couplings, and due to dimensional transmutation, this translates to a change in their corresponding confinement scales

$$m_B(\phi) = \Lambda_B(\phi) = \Lambda_B(0)e^{c_B\phi/f},$$
$$m_D(\phi) = \Lambda_D(\phi) = \Lambda_D(0)e^{-c_D\phi/f},$$

where for simplicity, we have taken masses of the particles of interest equal to their confinement scale. One could equally well consider other dark matter particles, e.g., axions, where their mass is proportional to the square of the dark confinement scale, $m_a \sim \Lambda_D(\phi)^2/f_a$.

We will be interested in the evolution of ϕ and the confinement scales as a function of time. An example of how the confinement scale changes as a function of time is given in Fig. 1. The equation of motion we will be considering is

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{c_B}{f} m_B^0 e^{c_B\phi/f} n_B + \frac{c_D}{f} m_D^0 e^{-c_D\phi/f} n_D. \quad (2)$$

Without the loss of generality, we shifted ϕ so that the minimum of the potential is located at $\phi = 0$. We assume that baryons and dark matter have already been produced and are a nonrelativistic subdominant energy density to whatever drives the expansion of the universe. For simplicity, we will assume that the starting value of Λ_B is larger than its final value so that Λ_B (Λ_D) is relaxed to a smaller (larger) number. In what follows, we specialize to a radiation-dominated universe only occasionally leaving comments on what changes as one varies the equation of state.

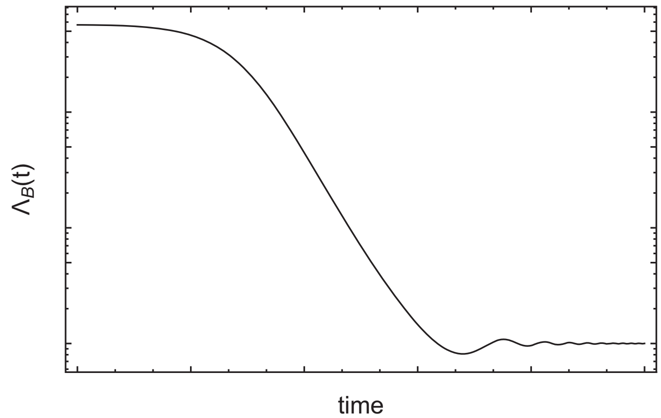

FIG. 1. An example log-log plot of how the confinement scale evolves as a function of time in our toy model. Initially, while ϕ is extremely overdamped, the confinement scale Λ_B does not change. After a while, a pseudo slow-roll with $m_\phi \sim H$ occurs, and the confinement scale relaxes with time. Eventually, it reaches its minimum where $\rho_B \sim \rho_D$, and it starts to oscillate around the minimum with a rapidly decaying amplitude.

As is standard, the evolution of ϕ can be characterized by an underdamped and overdamped state. Because of our assumption that baryons start off heavier than their final value, the mass of ϕ is dominated by the baryon's contribution giving

$$m_\phi^2 = V'' \approx \frac{c_B^2}{f^2} m_B^0 e^{c_B\phi/f} n_B. \quad (3)$$

If initially $H > m_\phi$, then ϕ is frozen in place until $H \sim m_\phi$ where it enters a pseudo slow-roll regime. Unlike the usual slow-roll scenario, $\ddot{\phi}$ and $\dot{\phi}$ terms in the equation of motion are equally important. The mass of ϕ will change as a function of time, ensuring that $H \sim m_\phi$ for a prolonged period of time.

The second scenario is the underdamped fast roll regime where $H < m_\phi$. In this scenario, ϕ oscillates quickly in time. Depending on the amplitude of the oscillation, the exponential form of the potential may play a critical role in changing how various energy densities dilute as a function of time. Our analysis will be done in the limit where, despite the large oscillation of the QCD and dark confinement scales, dark matter and baryons both remain nonrelativistic.

Pseudo slow roll: If $m_\phi \ll H$, ϕ is essentially frozen in place. Once $m_\phi \sim H$, ϕ to a good approximation follows the trajectory $a(t)\exp\left[c_B(\phi/f)\right] = \text{const.}$ We can find the value of the constant by changing variables in the equation of motion to $x = [a(t)/a(t_i)]\exp\left[c_B(\phi/f)\right]$

$$\frac{\ddot{x}(t)}{x(t)} - \left(\frac{\dot{x}(t)}{x(t)}\right)^2 + 3H(t)\frac{\dot{x}(t)}{x(t)} - H(t)^2 + \frac{c_B^2 m_B^0 n_B}{f^2}\left(\frac{a(t)}{a(t_i)}\right)^{-1} x(t) = 0, \quad (4)$$

where we neglected the contribution from the dark sector. Since we are looking for a static solution, we can neglect terms that involve derivatives, leading to a prediction

$$x(t) = \frac{f^2 H(t_i)^2}{c_B^2 m_B^0 n_B(t_i)} = \text{const} \Rightarrow m_\phi(t) = H(t). \quad (5)$$

From this, we see that $\Lambda_B(t) \sim a(t)^{-1}$, so that the confinement scale decreases like temperature [22]. Eventually, ϕ nears its minimum, and the approximation of neglecting dark matter's contribution to the ϕ equation of motion fails. After crossing the minimum of the potential at $\phi = 0$, ϕ oscillates as an underdamped harmonic oscillator, as described in the next subsection.

We next estimate the kinetic energy of ϕ during pseudo slow-roll. We use the relation

$$\dot{\phi} = \frac{f}{c_B}\left(\frac{\dot{x}}{x} - H(t)\right) \approx -\frac{fH(t)}{c_B}, \quad (6)$$

neglecting the small $(\dot{x}/x)$ term to estimate the kinetic energy of ϕ as

$$\frac{1}{2}\dot{\phi}^2 = \frac{f^2 H(t)^2}{2c_B^2} = \frac{m_B(t) n_B(t)}{2} \quad (7)$$

from which we see that during our pseudo slow-roll the kinetic energy in ϕ is comparable but slightly subdominant to the energy density in baryons.

Underdamped regime: When $m_\phi \gtrsim H$, ϕ oscillates quickly around its minimum. The energy in ϕ redshifts differently depending on if the amplitude of the oscillation obeys $\phi \lesssim f/c_B$ or $\phi \gtrsim f/c_B$.

For small amplitudes, as is the case when one transitions into this regime from pseudo slow-roll, ϕ behaves as a harmonic oscillator with a time-dependent mass. As is standard, using the WKB approximation we find $\rho_\phi \propto a^{-9/2}$ coming from a combination of $m_\phi \propto a^{-3/2}$ and $n_\phi \sim a^{-3}$.

For large amplitudes, we find numerically that $\rho_\phi + \rho_B \propto 1/a^5$ while the amplitude of the oscillating confinement scale decays as $\Lambda_B \sim 1/a^2$. As this behavior results in wildly oscillating confinement scales, potentially invalidating the nonrelativistic approximation, we will not consider this limit further.

Standard model example and cosmology.—There are two main differences when generalizing the previous example to the standard model (SM). The first difference is that it is not possible to only adjust the QCD scale as loop effects will result in ϕ adjusting other things such as electric charge. At the loop level, the SM plasma energy density depends on the fine structure constant, and this gives a large temperature-dependent potential for ϕ that is potentially larger than the contribution coming from baryons, see Supplemental Material [23] for a more quantitative description of this problem. We will solve this problem with an entropy dump. The second difference is that the model, as previously written, is excluded by measurements today as it gives the proton an unacceptably large density dependence. This problem is solved by a combination of a bare potential with the aforementioned entropy dump.

The Lagrangian that we consider is

$$\mathcal{L} = \mathcal{L}_{\text{toy}} + \mathcal{L}_0 + \mathcal{L}_{\text{entropy}}. \quad (8)$$

$\mathcal{L}_{\text{toy}}$ is given by Eq. (1) with the baryonic confinement scale replaced by the QCD scale. $\mathcal{L}_0$ is a potential for ϕ

$$\mathcal{L}_0 = \Lambda_0^4 \cos\left(\frac{\phi}{F} + \theta\right). \quad (9)$$

Meanwhile, our entropy dump can take any form, but for concreteness, we take

$$\mathcal{L}_{\text{entropy}} = \kappa \Phi_E H H^\dagger, \quad (10)$$

where a heavy (heavier than a TeV) mass scalar Φ_E reheats the SM via decays into the Higgs boson.

A pictorial representation of our cosmological history is shown in Fig. 2. There are four energy densities that are important. First, there is the relativistic species Φ_E, which dominates the energy density at early times and whose decays reheat the standard model and provide an entropy dump. Second, there is Λ_0^4, which is the bare potential for ϕ. Third, there is the energy density in baryons ρ_B, which dilutes like radiation while the QCD scale is being scanned and later decays away like matter. Finally, there is the thermal energy density in the SM that is not in the rest mass of the baryons, ρ_{SM}.

Let us first give a word-level explanation of our cosmology. Initially, $m_\phi \ll H$ and no relaxation is taking place. At a scale factor a_i, the QCD scale begins to be adjusted in a radiation-dominated universe so that $\Lambda_{\text{QCD}} \sim 1/a(t)$. Eventually, at a scale factor a_{relax}, the QCD scale reaches its minimum where $\rho_D \approx 5\rho_B$. At a scale factor $a_0 \gtrsim a_{\text{relax}}$, the Λ_0^4 potential becomes important, preventing any further relaxation and fixing $\rho_D \sim 5\rho_B$ in stone. A little bit later, at $a_{\text{eq}} \gtrsim a_0$, the potential from the thermal bath of the SM becomes equal to that of the baryons. Finally, at a scale factor a_{RH}, the entropy dump concludes, and the SM is fully reheated and becomes the dominant energy density in the universe [29].

In what follows, we give a more detailed description of the cosmology. For simplicity, we will discuss our cosmological history in the context of a single data point while

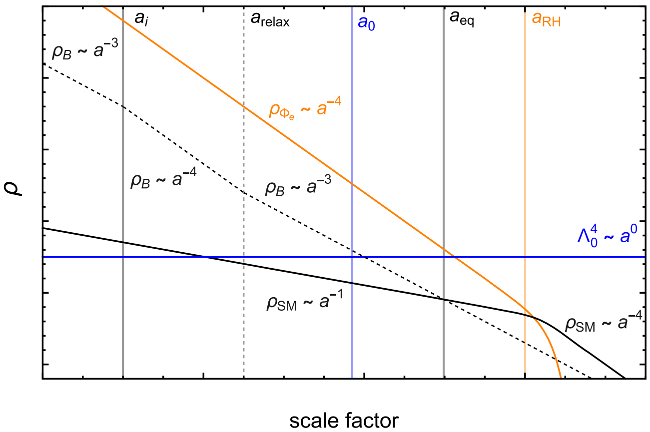

FIG. 2. An example of the cosmological history we are interested in is shown on a log-log scale. In orange, we have the energy density of the relativistic particle Φ_E, which decays at a scale factor $a_{\rm RH}$, reheating the standard model and providing an entropy dump. In blue, we have the bare potential for ϕ which becomes important when $\Lambda_0^4 \sim \frac{1}{2}\dot{\phi}^2 \lesssim \rho_B$. In the dashed black line, we have the energy density in baryons. Initially, it decays away as a^{-3}. At a scale factor, a_i, $m_\phi \sim H$ and it decays as a^{-4} as the QCD scale is being adjusted to its final value. At a scale factor $a_{\rm relax}$, the QCD scale reaches its final value while at the scale factor a_0, ϕ falls into its nearest density independent minimum. Finally, in a solid black line, there is the thermal energy density of the standard model. Initially, the energy density falls as a^{-1} as it is being constantly replenished by early decays of Φ_E. At a scale factor $a_{\rm eq}$, its energy density overtakes that of the baryons. Finally, after reheating, it falls like radiation.

being slightly cavalier about $\mathcal{O}(1)$ numbers [30]. The scale factors will be related to each other as $a_i = 1\times 10^{-7} a_{\rm RH}$, $a_{\rm relax} = 1\times 10^{-5} a_{\rm RH}$, $a_0 = 2\times 10^{-4} a_{\rm RH}$, and $a_{\rm eq} = 2\times 10^{-4} a_{\rm RH}$. We will take $T_{\rm RH} = 10$ MeV. The initial value of the proton mass is 100 GeV and relaxes to 1 GeV [31]. In order for relaxation to start at a_i, $m_\phi = H$ at that time gives $f/c_B = 1.6\times 10^{12}$ GeV. With an eye on constraints and since F has to be small enough to scan the QCD scale, we take $F = 3\times 10^6$ GeV. Finally, we take $\Lambda_0 = 100$ MeV. A summary of some of the energy densities and their values at different times is shown in Table I.

ρ_{Φ_E}: We take as our initial conditions a universe dominated by a relativistic species Φ_E. This can occur in a number of ways, e.g., if the inflaton decayed into Φ_E. It is important that Φ_E is relativistic so that its energy density dilutes away as radiation since the QCD scale is relaxed as $\Lambda_{\rm QCD} \sim 1/a$ ($\Lambda_{\rm QCD} \sim$ const) in a radiation (matter) dominated universe.

We take the mass of Φ_E to be $M_{\Phi_E} = 10$ TeV. Given a boost γ, its lifetime is

$$\Gamma = \frac{\kappa^2}{4\pi M_{\Phi_E}\gamma}. \quad (11)$$

TABLE I. Some of the relevant quantities for our example data point at the three interesting times: when the QCD scale starts to relax, when it stops relaxing, and when the standard model is reheated.

	Initial	Relax	Reheat
a	$1\times 10^{-7} a_{\rm RH}$	$1\times 10^{-5} a_{\rm RH}$	$a_{\rm RH}$
ρ_{Φ_E}	1×10^{8} TeV^4	1 TeV^4	(10 MeV)^4
$\rho_{\rm SM}$	1×10^{-1} GeV^4	1×10^{-3} GeV^4	(10 MeV)^4
m_p	100 GeV	1 GeV	1 GeV
n_B	2×10^{5} GeV^3	2×10^{-1} GeV^3	4×10^{-7} MeV^3

The universe is reheated when $\Gamma(t) = H(t)$ at a scale factor $a_{\rm RH}$. At this time, the energy density in Φ_E decays away, and the SM becomes the dominant energy density in the universe. For our choice of parameters, the reheating temperature of the universe is $T_{\rm RH} = 10$ MeV with $\kappa \sim 10^{-7}$ GeV and $\gamma = 10^3$ at decay.

Λ_0^4: The bare potential for ϕ is always present. It becomes important when the kinetic energy of ϕ is no longer able to take it over the Λ_0^4 sized barrier. This can occur during relaxation when $\Lambda_0^4 \sim \frac{1}{2}\dot{\phi}^2 \sim \rho_B$, or it can occur afterward as the kinetic energy of ϕ rapidly redshifts away. As long as $2\pi F \lesssim f/c_B$, then there will be a minimum close by where $\rho_D \sim 5\rho_B$.

ρ_B: The energy density in baryons behaves in a manner described in the previous toy model. Initially, it is diluting away as matter when $m_\phi \ll H$. At a_i the QCD scale starts to relax as $1/a(t)$ so that $\rho_B \sim 1/a(t)^4$. Relaxation finishes at a scale factor $a_{\rm relax}$, and afterward the baryons dilute like normal nonrelativistic matter $\rho_B \sim 1/a(t)^3$.

ρ_D: Dark matter has more freedom than baryons as it is not important to the dynamics of ϕ until $a_{\rm relax}$. The simplest cosmology involves dark matter already being present before a_i. Initially, while ϕ is still frozen out, dark matter dilutes away as a^{-3}. At a_i the dark confinement scale rises as $a^{c_D/c_B} \sim a^{0.2}$ so that $\rho_D \sim 1/a(t)^{2.8}$. Again, at $a_{\rm relax}$, dark matter returns to diluting away as cold dark matter.

$\rho_{\rm SM}$: The last piece of the puzzle is the temperature of the SM. As described in Supplemental Material [23], a nonzero temperature of the SM gives a temperature-dependent potential that scales as $10^{-6}T^4$ (or even larger if particles such as pions are present) that prevents relaxation if it is larger than ρ_B. As such, we require that all relaxation occurs before $\rho_{\rm SM} \sim \rho_B$ giving $a_{\rm eq} \gtrsim a_{\rm relax}$.

We take as initial conditions that $\rho_{\rm SM} \ll \rho_B$. This can be obtained through extremely efficient baryogenesis models such as Affleck-Dine baryogenesis where $Y_B \sim 10^3$ [32] or simply by allowing for some red shifting so that matter eventually overtakes radiation.

The thermal energy density in the SM cannot be set arbitrarily small as early decays of Φ_E will give the SM a minimal temperature. This temperature is easily solved for using energy conservation, but a simple parametric estimate can be obtained using the energy deposited into the SM during a single Hubble time

$$\rho_{\mathrm{SM}}(t) \sim \frac{\Gamma(t)}{H(t)} \rho_{\Phi_E}, \tag{12}$$

giving an energy density that falls in time as $1/a(t)$.

Bounds.—Neutron star: While the potential in Eq. (2) works in the early Universe, it will fail today as any macroscopic body is many orders of magnitude denser than the average cosmological density. As a result, we would end up with much lighter protons inside macroscopic bodies than in the vacuum. The most extreme example that we need to clear is the neutron star, $\rho_{\mathrm{NS}} \sim (100~\mathrm{MeV})^4$. Taking into account the bare potential for ϕ, the potential inside of a neutron star is approximately

$$V = \rho_{\mathrm{NS}} \exp\left[c_B\left(\frac{\phi}{f}\right)\right] + \Lambda_0^4 \cos\left(\frac{\phi}{F} + \theta\right). \tag{13}$$

Requiring that the neutron star does not displace the minimum by more than F gives

$$\frac{\Lambda_0^4}{F} \gtrsim \frac{c_B}{f} \rho_{\mathrm{NS}}. \tag{14}$$

This bound is satisfied for the parameters we chose.

Fifth force and stellar constraints: With any light Yukawa coupled scalar, the dominant constraints come from stars and fifth force measurements. ϕ mediates a long-range force between nuclei

$$V \supset \exp\left(\frac{c_B \phi}{f}\right) m_B \bar{\psi}\psi \to \frac{c_B \phi}{f} m_B \bar{\psi}\psi. \tag{15}$$

The example data point we chose barely squeaks by the current stellar constraints [33,34]. Evading fifth force measurements requires this force to have a short enough range. Our ϕ mass is

$$m_\phi = \frac{\Lambda_0^2}{F} = 3~\mathrm{eV}\left(\frac{F}{3 \times 10^6~\mathrm{GeV}}\right)^{-1}, \tag{16}$$

and was chosen to be right on the edge of fifth force constraints [35–42].

ϕ decays: Amusingly, ϕ can very easily be a significant fraction of dark matter as its kinetic energy during pseudo slow-roll is comparable to the baryonic energy density. As discussed in Supplemental Material [23], ϕ is necessarily coupled to photons and thus can decay into them. While in our particular data point, the ϕ lifetime is long enough that it evades current constraints, in some regions of parameter space this is a concern [43,44].

Conclusions.—In this Letter, we presented a new approach toward explaining $\Omega_c \approx 5\Omega_b$. A scalar adjusts the baryon and dark matter masses such that $\Omega_c \approx 5\Omega_b$ regardless of the production mechanism for baryons and dark matter and independent of the identity of dark matter. This approach thus allows one to explain why promising dark matter candidates, such as the QCD axion, have energy density so close to that of the baryons despite their production mechanisms being completely independent.

Our adjustment mechanism is extremely testable. The scalar ϕ mediates a new force, potentially visible in fifth force experiments and astrophysical environments. It also gives the proton mass such a strong environmental dependence that modifications needed to be made to evade this constraint.

What we presented is the essence of a new mechanism. It still remains to explore all regions of parameter space. Additionally, this mechanism is extremely versatile and it would be interesting to see how it meshes with various favored dark matter candidates. Finally, while the EFT is extremely minimal, the UV completion is more complicated. It would be exciting if a more compelling UV completion were to be put forth.

We thank Asimina Arvanitaki and Junwu Huang for useful discussions. D. B. and A. H. are supported in part by the NSF Grant No. PHY-2210361 and the Maryland Center for Fundamental Physics. This work was completed in part at the Perimeter Institute and the Aspen Center of Physics. Research at Perimeter Institute is supported in part by the Government of Canada through the Department of Innovation, Science and Economic Development Canada and by the Province of Ontario through the Ministry of Colleges and Universities. The Aspen Center for Physics is supported by National Science Foundation Grant No. PHY-2210452.

*dbrzemin@umd.edu
†hook@umd.edu

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[22] For a matter-dominated universe relaxation is a very slow occurrence as to leading order $\Lambda_B(t) \sim a(t)^0$, while for a kination dominated universe $\Lambda_B(t) \sim a(t)^{-5}$.

[23] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.132.201001 for an example of UV completion, discussion of finite temperature potential, and parametric resonance, which include Refs. [24–28].

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[29] Our goal is to give an existence proof that our approach is viable. We expect other cosmological histories to be possible, e.g., if ϕ dynamics were driven by dark matter instead of baryons. Alternative cosmologies will have different issues to solve, e.g., it is hard to have non-relativistic very light protons.

[30] Our goal is to give an existence proof that our approach is viable. As such, we will be taking values near current bounds.

[31] If the initial proton mass was larger than 100 GeV but with all other parameters unchanged, then everything would proceed exactly as in our data point, just with a_i slightly smaller.

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