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Flipped Dark Matter

John Ellis
Lawrence Berkeley Laboratory
Berkeley, California 94720
and
CERN, Geneva, Switzerland

John S. Hagelin and Stephen Kelley
Department of Physics
Maharishi International University
Fairfield, Iowa 52556

D.V. Nanopoulos
Department of Physics
University of Wisconsin
Madison, Wisconsin 53706

Keith A. Olive
Department of Physics
University of Minnesota
Minneapolis, Minnesota 55455

Abstract

We study candidates for dark matter in a minimal flipped $SU(5) \times U(1)$ supersymmetric GUT. Since the model has no R-parity, spin-1/2 supersymmetric partners of conventional particles mix with other neutral fermions including neutrinos, and can decay into them. The lightest particle which is predominantly a gaugino/higgsino mixture decays with a lifetime $\tau_\chi \sim (1 \text{ to } 10^9)$ seconds. The model contains a scalar "flaton" field whose coherent oscillations decay before cosmological nucleosynthesis, and whose pseudoscalar partner contributes negligibly to Ω if it is light enough to survive to the present epoch. The fermionic "flatino" partner of the flaton has a lifetime $\tau_{\tilde{f}} \sim (10^{28} \text{ to } 10^{34})$ years and is a viable candidate for metastable dark matter with $\Omega \lesssim 1$.

There are many astrophysical indications for dark matter on scales ranging from dwarf galaxies to large clusters of galaxies. There is also no shortage of particle physics candidates, of which the most favored are neutrinos--which have at least the merit of being known to exist, coherent density waves of a scalar field--with the axion¹⁾ as a prime example, and the lightest supersymmetric particle (LSP).²⁾ Of these, the LSP is perhaps the only one whose cosmological relic density is naturally of the same order as the closure density.^{2,3)} In most supersymmetric theories the stability of the LSP is guaranteed by R-parity, although there are models in which this is broken.⁴⁾

Recently, a supersymmetric flipped $SU(5) \times U(1)$ GUT has been revisited⁵⁾ and shown to have many desirable properties, including natural Higgs doublet-triplet splitting, a seesaw mechanism guaranteeing light left-handed neutrinos, and a long proton lifetime.⁶⁾ Moreover, variants of this model have been derived from four-dimensional formulations of strings,⁷⁾ whilst other GUTs cannot. These advantages have encouraged us to study cosmological aspects of the flipped $SU(5) \times U(1)$ model. This model has recently been shown to avoid a catastrophic intermediate-scale phase transition⁸⁾ and to have adequate baryosynthesis.^{9,10)} In this paper we explore its predictions for dark matter.*

The model contains the four neutralinos (mixtures of gauginos and higgsinos) present in the Standard Model.¹²⁾ Since the minimal model does not conserve R-parity,[†] these mix with the fermionic supersymmetric partner of the

* For an alternative view of some of these questions, see Ref. 11.

† The unbroken $SU(5) \times U(1)$ model contains a global $U(1)$ R-symmetry under which the scalars have $U(1)$ quantum numbers $Q_i = F; \bar{F}; 1^c; H; \bar{H}; h; \bar{h}; \phi = 0; 8/3; -8/3; 0; 4/3; 2; -2/3; 2/3$. This R-symmetry is spontaneously broken at the same time $SU(5) \times U(1)$ is broken by a large v.e.v. for the $\bar{H}$ field, leaving no residual R-parity. This spontaneous breaking of R-symmetry does not lead to a massless Goldstone boson because $U(1)_R$ is explicitly broken by gaugino mass terms.

scalar "flaton" field Φ responsible for GUT symmetry breaking,^{*} with conventional left-handed neutrinos and with conjugate neutrinos. The lightest neutralino therefore decays into $\nu_L + X$ with a lifetime $\sim (1 \text{ to } 10^9)$ seconds.[†] The coherent flaton density waves decay before cosmological nucleosynthesis if $m_\Phi \sim 1 \text{ TeV}$ as we expect. The pseudoscalar companion Ψ of the flaton has a lifetime longer than the age of the Universe if its mass $m_\Psi \lesssim 10 \text{ MeV}$, but in this case contributes negligibly to Ω . The fermionic supersymmetric partner $\tilde{\Phi}$ of the flaton (the "flatino") is unstable because of R-parity breaking, but has a lifetime $\sim (10^{28} \text{ to } 10^{34}) \text{ y}$ if $m_{\tilde{\Phi}} \sim 1 \text{ GeV}$. It is therefore a candidate for metastable dark matter, and could have a present density similar to the closure density.

As a prelude to writing out the neutral fermion mass matrix, we remind the reader of the superpotential for the minimal flipped $SU(5) \times U(1)$ model:⁶⁾

$$\begin{aligned}
 W = & \lambda_1^{ij} F_i F_j h + \lambda_2^{ij} F_i \bar{F}_j \bar{h} + \lambda_3^{ij} \bar{F}_i l_j^c h + \lambda_4 H H h + \lambda_5 \bar{H} \bar{H} \bar{h} \\
 & + \lambda_6^{ij} F_i \bar{H} \phi_j + \lambda_7 h \bar{h} \phi_0 + \lambda_7'^i \bar{h} h \phi_i \\
 & + (\lambda_8/3) \phi_0^3 + \lambda_8'^i \phi_i \phi_0^2 + \lambda_8''^{ij} \phi_i \phi_j \phi_0 + \lambda_8'''^{ijk} \phi_i \phi_j \phi_k
 \end{aligned} \tag{1}$$

where $i, j = 1, 2, 3$, and the $SU(5) \times U(1)$ assignments of the superfields in (1) are

$$F_i, H = (\underline{10}, 1/2), \quad \bar{F}_i = (\bar{\underline{5}}, -3/2), \quad l_i^c = (\underline{1}, 5/2), \quad h = (\underline{5}, -1), \quad \bar{h} = (\bar{\underline{5}}, 1), \quad \phi_{0,i} = (\underline{1}, 0) \tag{2}$$

The effective scalar potential has a unique D- and F-flat direction along which large v.e.v.'s $\langle H \rangle = \langle \bar{H} \rangle = M_G \sim 10^{15} \text{ to } 10^{16} \text{ GeV}$ can develop, breaking

* The flaton Φ has no relation to the *inflaton* proposed by inflationary theory.

† As discussed later, in order to preserve the successes of conventional cosmological nucleosynthesis, one must in fact require $\tau_X \lesssim 1 \text{ s}$.

$SU(5) \times U(1)$ to $SU(3)_c \times SU(2)_L \times U(1)_y$. The components of $H, \bar{H}$ with large v.e.v.'s are identified with those corresponding to conjugate neutrinos: $\nu_H^c, \bar{\nu}_H^c$. There is one light physical scalar combination of these fields corresponding to the flat direction which we call the flaton Φ that is expected to have a mass ~ 1 TeV. It is accompanied by a lighter pseudoscalar Ψ , whose mass we estimate later, and a light fermion $\tilde{\Phi}$, the flatino. In the presence of soft supersymmetry-breaking scalar masses $m_0^2 \sim m_W^2$, the neutral fields $h^0, \bar{h}^0, \phi_0$ acquire v.e.v.'s $v, \bar{v}, x \sim m_W$.⁶⁾

The mass matrix for the 15 neutral spin-1/2 fermions ($-i\tilde{W}^3, -i\tilde{B}, \bar{h}^0, \tilde{h}^0, \tilde{\phi}_0, \tilde{\phi}_i, \nu_i^c, \nu_{L_i}, \tilde{\Phi}$) takes the form

$$\begin{pmatrix}
 -M_2 & 0 & \frac{-g_2 v}{\sqrt{2}} & \frac{g_2 \bar{v}}{\sqrt{2}} & 0 & 0 & 0 & 0 & 0 \\
 0 & -M_1 & \frac{g_1 v}{\sqrt{2}} & \frac{-g_1 \bar{v}}{\sqrt{2}} & 0 & 0 & 0 & 0 & 0 \\
 \frac{-g_2 v}{\sqrt{2}} & \frac{g_1 v}{\sqrt{2}} & 0 & \lambda_7 x & \lambda_7 \bar{v} & \lambda_7' i \bar{v} & 0 & 0 & 0 \\
 \frac{g_2 \bar{v}}{\sqrt{2}} & \frac{-g_1 \bar{v}}{\sqrt{2}} & \lambda_7 x & 0 & \lambda_7 v & \lambda_7' i v & 0 & 0 & 0 \\
 0 & 0 & \lambda_7 \bar{v} & \lambda_7 v & \lambda_8 x & \lambda_8' i x & 0 & 0 & \xi^0 \\
 0 & 0 & \lambda_7' i \bar{v} & \lambda_7' i v & \lambda_8' i x & \lambda_8'' ij x & \lambda_6^{ij} M_G & 0 & \xi^i \\
 0 & 0 & 0 & 0 & 0 & \lambda_6^{ij} M_G & 0 & m_U^{ij} & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & m_U^{ij} & 0 & 0 \\
 0 & 0 & 0 & 0 & \xi^0 & \xi^i & 0 & 0 & M_{\tilde{\Phi}}
 \end{pmatrix} \quad (3)$$

whose entries we now discuss. The conventional neutralino mass matrix in the

top left-hand 4×4 submatrix mixes with $\tilde{\phi}_0$ and the $\tilde{\phi}_i$ via the λ_7 couplings in (1), the $\tilde{\phi}_0$ and $\tilde{\phi}_i$ mix through the λ_8 couplings, the $\tilde{\phi}_i$ and ν_i^c mix through the λ_6 coupling, and the ν_{L_i} and ν_i^c mix through the λ_2 coupling which yields the charged $+2/3$ quark mass matrix m_U^{ij} . The $\tilde{\phi}_{0,i} - \tilde{\Phi}$ mixings $\xi^{0,i}$ occur through the diagrams in Fig. 1, which are of order

$$\xi^{0,i} \sim \frac{3\lambda_7^*(\lambda_7, \lambda_7'^i)A_7x}{16\pi^2 M_G} \quad (4)$$

where $A_7 \sim m_W$ is a trilinear soft supersymmetry-breaking parameter. The $\tilde{\Phi}$ acquires a mass¹¹⁾ through the diagram in Fig. 2a, which is of order

$$m_{\tilde{\Phi}} \sim \frac{3A_{4,5}\lambda_{4,5}^2}{16\pi^2} \quad (5)$$

The soft supersymmetry-breaking parameters $A_{4,5,7}$ in equations (4,5) must be evaluated at a renormalization scale $\sim M_G$, where they are not enhanced by any large logarithms. From Fig. 2b, we estimate

$$A_{4,5} \sim \frac{195}{5} \left[\frac{g_{5,1}^2}{32\pi^2} \right] m_{1/2} \quad (6)$$

where $g_{5,1}$ are the $SU(5) \times U(1)$ coupling constants and we have assumed that the primary source of soft supersymmetry breaking is a gaugino mass $m_{1/2} \sim m_W$ to 1 TeV. Combining equations (5) and (6), we see that probably $m_{\tilde{\Phi}} \lesssim 10$ GeV, depending on the magnitude of $\lambda_{4,5}$.

Our analysis of the neutral fermion mass matrix (3) begins by noting the presence of large Dirac mass terms $\lambda_6^{ij} M_G \tilde{\phi}_i \nu_j^c$, leading to supermassive Dirac eigenstates of the form $\tilde{\phi} + \nu^c$, $\tilde{\phi} - \nu^c$ apart from small admixtures $\sim m_W/M_G$ of other fields. The nine remaining light fields split into a 5×5 extended

neutralino sector composed of $\tilde{W}^3, \tilde{B}, \tilde{h}^0, \tilde{h}^0, \tilde{\phi}_0$, a massless neutrino sector ν_{L_i} , and the $\tilde{\Phi}$, with small mixings $\sim m_W/M_G$ among the various light sectors.

Expanding in powers of m_W/M_G , it is easy to incorporate the effects of mixing among these sectors: defining the lightest neutralino eigenstate as $\chi = \alpha \tilde{W}^3 + \beta \tilde{B} + \gamma \tilde{h}^0 + \delta \tilde{h}^0 + \epsilon \tilde{\phi}_0$, we find that the χ and the $\tilde{\Phi}$ mix by an amount

$$\theta_{\chi\tilde{\Phi}} = \epsilon \xi^0 / (m_\chi - m_{\tilde{\Phi}}) \sim m_W/M_G \quad (7)$$

We also observe that the ν_L acquires a small admixture $\theta_{\chi\nu_L}$ of χ :

$$\theta_{\chi\nu_L} = (\gamma\lambda_7'^{i-} + \delta\lambda_7'^{i-} + \epsilon\lambda_8'^{i-})m_U^{ij}/\lambda_6^{ij}M_Gm_\chi \sim m_W/M_G \quad (8)$$

and an even smaller admixture $\theta_{\tilde{\Phi}\nu_L}$ of $\tilde{\Phi}$:

$$\theta_{\tilde{\Phi}\nu_L} = \left[\xi^i - \epsilon \xi^0 (\gamma\lambda_7'^{i-} + \delta\lambda_7'^{i-} + \epsilon\lambda_8'^{i-})/m_\chi \right] m_U^{ij}/\lambda_6^{ij}M_Gm_{\tilde{\Phi}} \sim m_W^2/M_G^2 \quad (9)$$

and acquires a mass

$$m_{\nu_L} = \left[\lambda_8'^{ij} - (\gamma\lambda_7'^{i-} + \delta\lambda_7'^{i-} + \epsilon\lambda_8'^{i-})^2/m_\chi \right] m_U^{ij}/(\lambda_6^{ij}M_G)^2 \sim m_W^3/M_G^2 \quad (10)$$

which is too small to be of astrophysical interest. As a consequence of (8,9), the χ and the $\tilde{\Phi}$ are unstable against decay into neutrinos, with neutral current decay rates given by

$$\Gamma(\chi \rightarrow \nu_L \bar{f}f) = \frac{G_F^2 m_\chi^5}{192\pi^3} \theta_{\chi\nu_L}^2 \quad (11a)$$

$$\Gamma(\tilde{\Phi} \rightarrow \nu_L \bar{f}f) = \frac{G_F^2 m_{\tilde{\Phi}}^5}{192\pi^3} \theta_{\tilde{\Phi}\nu_L}^2 \quad (11b)$$

A detailed analysis⁶⁾ of radiative symmetry breaking in $SU(5) \times U(1)$, in which $m_{1/2}$ is assumed to be the dominant source of supersymmetry breaking in the observable sector, finds that the χ contains a large Higgsino component with $(\gamma\lambda_7'^i \bar{\nu} + \delta\lambda_7'^i \nu + \epsilon\lambda_8'^i \chi) \sim M_W$, and that m_χ ranges from several GeV to several hundred GeV.* Taking $|m_U| \sim m_t \sim 100$ GeV and $M_G \sim 10^{15}$ GeV in (8), we estimate

$$\Gamma^{-1}(\chi \rightarrow \nu_L f \bar{f}) \sim 10^6 \text{ s} \cdot \lambda_6^2 \left(\frac{100 \text{ GeV}}{m_\chi} \right)^3 \sim (1 \text{ to } 10^9) \text{ s} \quad (12)$$

where the lower estimate $\Gamma^{-1} \sim 1$ s follows from taking $\lambda_6 \sim 10^{-3}$ as suggested by a recent analysis¹⁰⁾ of baryosynthesis in a weak reheating scenario. For the purposes of our cosmological analysis, we also note that the χ can decay into $\tilde{\Phi}\gamma$ through a triangle graph involving Higgs color triplets,¹¹⁾ with a branching ratio

$$\text{BR}(\chi \rightarrow \tilde{\Phi}\gamma) \sim \left(\frac{9\alpha^2 m_\chi^3}{128\pi^3 M_G^2} \right) / \Gamma(\chi \rightarrow \nu_L f \bar{f}) \sim \lambda_6^2 \quad (13)$$

The flatino decay rate $\Gamma_{\tilde{\Phi}}$ may be estimated by combining (4,9,11b). Taking $A_7 \sim x \sim m_W$ in (4) gives

$$\Gamma^{-1}(\tilde{\Phi} \rightarrow \nu_L f \bar{f}) \sim 10^{34} \text{ y} \cdot \frac{\lambda_6^2}{\lambda_7^2} \left(\frac{1 \text{ GeV}}{m_{\tilde{\Phi}}} \right)^3 \quad (14)$$

If we take $\lambda_7 \gtrsim 1$ to ensure that the $\tilde{\Phi}$ decays prior to primordial ${}^4\text{He}$ synthesis⁹⁾ and $\lambda_6 \sim 10^{-3}$ as suggested by weak reheating baryosynthesis,¹⁰⁾ then for $m_{\tilde{\Phi}} \sim 1$ GeV we obtain $\tau_{\tilde{\Phi}} \sim 10^{28}$ years.

* In certain regions of parameter space, the sneutrino is the lightest supersymmetric particle. Since the sneutrino also has mixings $\sim m_W/\lambda_6 M_G$ with the $h^0, \bar{h}^0, \phi_0$, it is unstable and its cosmological properties would be similar to the χ .

Before embarking on a discussion of the resulting cosmology, we first discuss the likely properties of the flaton Φ and its pseudoscalar companion Ψ . The flaton mass is proportional to the soft supersymmetry-breaking scale $m_{1/2} \sim m_W$, and is given by one-loop diagrams at the GUT scale. In model calculations⁶⁾ $m_\Phi^2 \gtrsim 0.1 m_{1/2}^2$, where $m_{1/2}$ could be as large as 1 TeV. The Φ is expected to decay with comparable rates into both supersymmetric and non-supersymmetric particles. The supersymmetric modes are potentially dangerous, since they repopulate the χ subsequent to $\chi\chi$ annihilations, resulting in matter domination during cosmological nucleosynthesis unless the χ decays quickly enough. The squared pseudoscalar mass m_Ψ^2 is of 3-loop order¹¹⁾ relative to m_Φ^2 :

$$m_\Psi^2 \sim \left(\frac{\lambda^2}{16\pi^2} \right)^3 m_\Phi^2 \quad (15)$$

where λ is a generic Yukawa coupling, and its decay rate into $\gamma\gamma$ ¹¹⁾

$$\Gamma(\Psi \rightarrow \gamma\gamma) = \frac{\alpha^2 (M_G)^2 g_5^2}{36\pi^3} \frac{m_\Psi^3}{M_G^2} \quad (16)$$

gives a lifetime longer than the age of the Universe if $m_\Psi \lesssim 10$ MeV.

Having introduced our cast of light characters, we now assume that the Big Bang populates the early Universe with them, and discuss how they exit the stage more or less gracefully. The first to leave is the flaton. If the Universe was subjected to strong reheating after an early inflationary epoch, the Φ field energy density would have been incoherent, whereas it would have been coherent if there was only weak reheating to a temperature $T_R \lesssim \sqrt{m_\Phi M_G}$ subsequent to inflation. In either case, the Universe would have been matter-dominated before the non-relativistic flatons decayed when the expansion rate $H = \Gamma_\Phi = \epsilon' m_\Phi^3 / M_G^2$: $\epsilon' = 9\lambda_{1,2,3\text{or}7}^4 / 2048\pi^5$. They then reheat the Universe to a temperature¹⁰⁾

$$T_D' \approx 50 \text{ MeV } \epsilon'^{1/2} \left(\frac{m_\Phi}{1 \text{ TeV}} \right)^{3/2} \left(\frac{10^{15} \text{ GeV}}{M_G} \right) \quad (17)$$

In order to preserve standard Big Bang nucleosynthesis, it is necessary to require $T_D' > 1 \text{ MeV}$, which occurs if $m_\Phi \gtrsim 1 \text{ TeV}$ and $\epsilon'^{1/2} \gtrsim 1/50$, e.g., if $\lambda_7 \gtrsim 2$ or 3. In addition, since Φ decay repopulates the χ , it is also necessary that the χ decay prior to nucleosynthesis in order to avoid matter-dominated nucleosynthesis and/or ${}^4\text{He}$ fission by χ decay fragments after nucleosynthesis. This requires $\tau_\chi \lesssim 1 \text{ second}$, which is possible provided $\lambda_6 \lesssim 10^{-3}$ (12).

Note that in intermediate scale models with unbroken R-parity, $\chi \rightarrow \nu_L + X$ is forbidden, and the repopulation of χ 's by Φ decays poses a potentially serious problem. This can occur in non-minimal $\text{SU}(5) \times \text{U}(1)$ models derived from the superstring,⁷⁾ or if the minimal $\text{SU}(5) \times \text{U}(1)$ model (1) were subject to an additional discrete symmetry $\bar{H} \rightarrow -\bar{H}$, $\phi_i \rightarrow -\phi_i$ ($i=1,2,3$), under which $\lambda_7' = \lambda_8' = \lambda_8''' = 0$.¹¹⁾ In such models, it may be possible to avoid an overdense universe through $\chi \rightarrow \tilde{\Phi} + X$ decays, provided $m_{\tilde{\Phi}} \lesssim (1 \text{ to } 100) \text{ MeV}$. Alternatively, it is conceivable that $m_\Phi < 2m_\chi$, thereby avoiding the problem of χ repopulation by Φ decays. In this case, unless the supersymmetric spectrum is quite heavy ($\gtrsim 1 \text{ TeV}$), it is difficult to understand how the Φ could decay prior to primordial nucleosynthesis (17).

The entropy increase Δ due to Φ decays is different for the strong

$$\Delta \sim \frac{M_G}{\epsilon^{1/2} m_\Phi^{3/2} M_P} \quad (18a)$$

and weak

$$\Delta \sim \frac{m_\Phi^3 M_G}{\epsilon^{1/2} M_{PT}^3} \quad (18b)$$

reheating scenarios. Adequate baryosynthesis seems feasible in both cases, though in the case of weak reheating, this requires extra Higgs triplets to overcome the large entropy factor (18b). A formula analogous to (17) can also

be used to estimate the reheating temperature T_D' subsequent to Ψ decays in the strong reheating scenario:

$$T_D' \approx \left(\frac{m_\Psi}{m_\Phi} \right)^{3/2} T_D' \quad (19)$$

for which a typical value is ~ 1 keV. Equation (18a) suggests an increase in entropy by a factor $\sim (m_\Phi/m_\Psi)^{1/2}$ from Ψ decays relative to Φ decays. This may be unacceptable from the standpoints of both baryosynthesis and nucleosynthesis, but does not present the worst problem for strong reheating, as we will see shortly. In the case of weak reheating, equation (18b) implies that Ψ particles do not contribute significantly to the entropy. Indeed, one expects the coherent Ψ field density $\rho_\Psi \sim (m_\Psi^2/m_\Phi^2)\rho_\Phi$ and hence

$$\frac{n_\Psi}{s} \sim \left(\frac{m_\Psi}{m_\Phi} \right)^2 T_D' \quad (20)$$

subsequent to flaton decay. Using equation (17) for T_D' this becomes

$$\frac{n_\Psi}{s} \sim 10^{-9} \left(\frac{m_\Psi}{1 \text{ GeV}} \right) \quad (21)$$

or

$$\frac{n_\Psi}{n_B} \sim (1 \text{ to } 10^2) \left(\frac{m_\Psi}{1 \text{ GeV}} \right) \quad (22)$$

if we assume $n_B/s \sim (10^{-9} \text{ to } 10^{-11})$. Hence, the danger from Ψ decay is not so much entropy generation, but rather that its decay products would dissociate the light element produced previously. This danger is avoided if $m_\Psi \lesssim 10$ MeV, so that τ_Ψ (16) is greater than the age of the Universe. In this case, (22) implies that its contribution to the cosmological mass density $\rho_\Psi \lesssim \rho_B$, and probably $\rho_\Psi \ll \rho_B$ if τ_Ψ is long enough to satisfy experimental constraints on cosmic γ -ray fluxes.¹³⁾

Although the neutralino χ decays too soon to constitute dark matter, if the $\chi \rightarrow \tilde{\Phi}\gamma$ branching ratio (13) is non-negligible, χ decays will yield flatino dark matter with a number density

$$n_{\tilde{\Phi}} = \text{BR}(\chi \rightarrow \tilde{\Phi}\gamma)n_{\chi} = \text{BR}(\chi \rightarrow \tilde{\Phi}\gamma)n_{\tilde{\Phi}} \quad (23)$$

where $n_{\tilde{\Phi}}/s \approx T_D'/m_{\tilde{\Phi}} \sim 10^{-6}$. Hence

$$\frac{n_{\tilde{\Phi}}}{n_B} \sim (10^3 \text{ to } 10^5) \text{BR}(\chi \rightarrow \tilde{\Phi}\gamma) \sim (10^3 \text{ to } 10^5) \lambda_6^2 \quad (24)$$

for $n_B/s = 10^{-9}$ to 10^{-11} , and the $\tilde{\Phi}$ can contribute significantly to Ω even for small values of λ_6 .^{*}

Neutralino decay would not be the dominant source of $\tilde{\Phi}$ relics in a strong reheating scenario. In that case there would be a large initial abundance of flatinos $\tilde{\Phi}$ subsequent to inflation, which would cause the Universe to be matter-dominated during nucleosynthesis unless $m_{\tilde{\Phi}} \lesssim 1$ MeV, and cause the Universe today to be overdense unless $m_{\tilde{\Phi}} \lesssim 2$ keV, which seems unlikely in the face of our previous estimate (5,6) of $m_{\tilde{\Phi}}$. The only way to avoid this disaster for the the strong reheating scenario is to require $m_{\tilde{\Phi}} > m_{\chi}$ and $m_{\tilde{\Phi}} \gtrsim 1$ TeV, so that the $\tilde{\Phi}$ can decay to the χ early enough to be innocuous. This also seems unlikely given our previous estimate of $m_{\tilde{\Phi}}$, and we are therefore inclined to reject strong reheating and only retain weak reheating as a serious possibility.

The cosmological status of this scenario can be summarized as follows. Adequate baryosynthesis can be obtained if there are at least two Higgs triplets and antitriplets.¹⁰⁾ The flaton Φ and the conventional neutralino

^{*} The estimated lifetime $\tau_{\tilde{\Phi}} \sim (10^{28} \text{ to } 10^{34})$ y is comfortably consistent with lower limits on metastable relic lifetimes from cosmic γ -ray fluxes.¹³⁾

both decay harmlessly long before the present epoch if certain plausible conditions are satisfied, while the pseudoscalar Ψ contributes negligibly to Ω if it is light enough to survive the age of the Universe. One dark matter candidate is left, namely the fermionic supersymmetric partner of the flaton, called the flatino $\tilde{\Phi}$. A plausible estimate of its mass is $m_{\tilde{\Phi}} \lesssim 10$ GeV, and its lifetime $\tau_{\tilde{\Phi}} \sim (10^{28} \text{ to } 10^{34})$ y. It couples very weakly at low energies, and so is very difficult to detect via annihilation in the galactic halo or in the Sun, or via scattering on ordinary matter in the laboratory.

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Figure Captions

1. Diagrams leading to $\tilde{\phi}_{0,i} - \tilde{\Phi}$ mixing. The $d_H^c, \bar{d}_H^c, D, \bar{D}$ are color triplet components of the $H, \bar{H}, h, \bar{h}$, respectively.
2. Diagrams contributing to (a) $m_{\tilde{\Phi}}$ and (b) soft supersymmetry-breaking trilinear couplings A_4, A_5 . Here, $\tilde{V}_5, \tilde{V}_1$ represent $SU(5), U(1)$ gauginos.

Figure 1

Figure 2