

Implications of mixed axion/neutralino dark matter for the Cosmic Frontier: a Snowmass whitepaper

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If one simultaneously invokes the SUSY solution to the gauge hierarchy problem and the PQ solution to the strong CP problem, then one might expect mixed axion/neutralino dark matter (DM), *i.e.* two dark matter particles. In this case, dark matter production involves oscillation production of axions, thermal and non-thermal neutralino production and thermal and non-thermal production of axinos and saxions. The latter particles may feed additional neutralinos into the cosmic soup, or dilute all relics via additional entropy production, or feed dark radiation into the cosmos. Depending on the SUSY and PQ model, the PQ scale can easily exist from $10^9 - 10^{16}$ GeV. Axions may lie well beyond the range currently being probed by experiment. In the case of relic WIMPs, theoretical predictions must be rescaled for the possibility that WIMPs only comprise a fraction of the local DM abundance.

1 Introduction

The Standard Model (SM) of particle physics is beset with two finetuning problems. The first– the well-known gauge hierarchy problem (GHP)– pertains to quantum instability of scalar fields as manifested by quadratic divergences. The GHP can be solved by enlarging the spacetime symmetry group to include supersymmetry (SUSY). Realistic supersymmetric models invoke softly broken SUSY at the weak scale leading to the prediction of a host of new states of matter: the so-called superpartners [1]. The lightest SUSY particle (LSP) in R -parity conserving SUSY theories is absolutely stable and can be a dark matter (DM) candidate. In the case of a neutralino LSP, the DM particle would be a weakly interacting massive particle (WIMP) with relic abundance from thermal freeze-out:

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{ cm}^3/\text{s}}{\langle \sigma_A v \rangle}. \quad (1)$$

Relic WIMPs are being searched for in underground, space-based and ice-based detectors.

The second finetuning problem arises in quantum chromodynamics (QCD). The approximate global chiral symmetry of QCD $U(2)_L \times U(2)_R$, arising from the presence of two light quark fields, provides an understanding of the origin of isospin symmetry and baryon number conservation. At the same time it naively predicts four instead of three light pions: the $U(1)_A$ problem. 't Hooft's solution of the $U(1)_A$ problem via the QCD theta vacuum and instanton effects requires an additional CP violating term in the QCD Lagrangian:

$$\mathcal{L}_{QCD} \ni \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^A \tilde{G}^{A\mu\nu}. \quad (2)$$

Measurements of the neutron EDM imply that both this term along with another arising from the quark mass matrix are very tiny, *i.e.* $\bar{\theta} \equiv \theta + \text{Arg}[\det(M_q)] \lesssim 10^{-10}$. Peccei and Quinn (PQ) explained the absence of $\bar{\theta}$ by invoking an additional global $U(1)_{PQ}$ symmetry along with an axion field a [2]:

$$\mathcal{L}_{QCD} \ni \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G_{\mu\nu}^A \tilde{G}^{A\mu\nu}. \quad (3)$$

The potential energy develops a minimum at $a/f_a + \bar{\theta} = 0$ and the offending term dynamically vanishes. A consequence of this elegant mechanism is the existence of a physical axion state with mass

$$m_a \simeq 6.2 \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right) \quad (4)$$

where the PQ scale $f_a \gtrsim 10^9 \text{ GeV}$ to avoid excessive cooling in supernovae. While the axion can decay via $a \rightarrow \gamma\gamma$, its lifetime is longer than the age of the universe. Thus, the axion is also a good CDM candidate. A population of cold relic axions can be produced via coherent oscillations starting at $T_{QCD} \sim 1 \text{ GeV}$ leading to a predicted abundance

$$\Omega_a h^2 \simeq 0.18 \theta^2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{1.19} \left(\frac{\Lambda_{QCD}}{400 \text{ MeV}} \right). \quad (5)$$

Relic QCD axions are being searched for in microwave cavity experiments such as ADMX [3].

Usually the neutralino and axion are considered as dark matter candidates in separate scenarios. However, in order to solve both finetuning problems in the SM, it is natural to invoke simultaneously the SUSY and PQ symmetries. Thus, both neutralino and axion are co-existing dark matter candidates, and we can investigate the new possible scenarios of cosmology in the pre-Big Bang nucleosynthesis (pre-BBN) era and dark matter properties.

2 Mixed axion/neutralino dark matter production in the early universe

If one invokes the SUSY solution to the GHP and the PQ solution to the strong CP problem, then the axion field must be elevated to a superfield. In four-component notation,

$$\hat{a} = (s + ia)/\sqrt{2} + i\sqrt{2}\bar{\theta}\tilde{a} + i\bar{\theta}\theta_L \mathcal{F}_a \quad (6)$$

where s is the R -even spin-0 *saxion*, \tilde{a} is the R -odd spin-1/2 *axino*, \mathcal{F}_a is an auxiliary field and in this case the θ s are anticommuting superspace co-ordinates. In gravity-mediated SUSY breaking models, both s and \tilde{a} are expected to receive soft masses $\sim m_{3/2}$. Both s and \tilde{a} can be produced thermally in the early universe; since their interactions are suppressed by $1/f_a$, the s and \tilde{a} are quasi-long-lived, and in the case where \tilde{a} is the LSP, it is absolutely stable and can even be a component of CDM. In the case where the neutralino is the LSP, one expects mixed axion/neutralino CDM, *i.e.* CDM composed of two different particles. The interplay of a , \tilde{a} , s and \tilde{Z}_1 modifies the pre-BBN cosmological history, and greatly impacts dark matter production rates. The early universe cosmology then depends on exactly which SUSY axion model one invokes. In the following, we will discuss two types of SUSY axion models and their physical characteristics.

2.1 SUSY Kim-Shifman-Vainshtein-Zakharov (KSVZ) cosmology

In the SUSY KSVZ approach[4], one introduces vector-like heavy quarks with interaction

$$\int d^2\theta_L \lambda f_a e^{\hat{a}/f_a} \hat{Q} \hat{Q}^c \quad (7)$$

leading to the axion supermultiplet coupling to MSSM particles via QQ^c loops. The derivative coupling of s and \tilde{a} to gluons leads to thermal production rates[5] which depend on the re-heat temperature T_R :

$$\frac{\rho_s^{TP}}{s} \simeq 1.33 \times 10^{-5} g_s^6 \ln \frac{1.01}{g_s} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)^2 \left(\frac{T_R}{10^8 \text{ GeV}} \right) m_s, \quad (8)$$

$$\frac{\rho_{\tilde{a}}^{TP}}{s} \simeq 0.9 \times 10^{-5} g_s^6 \ln \frac{3}{g_s} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)^2 \left(\frac{T_R}{10^8 \text{ GeV}} \right) m_{\tilde{a}}. \quad (9)$$

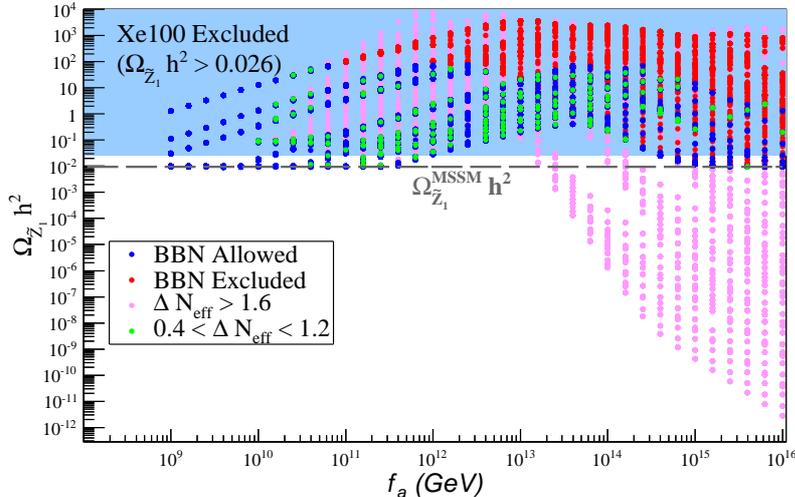


Figure 2: Relic abundance of neutralinos in the PQMSSM with KSVZ axions for a SUSY model with a standard underabundance of higgsino-like neutralinos. The green points accommodate a slight excess in dark radiation ΔN_{eff} .

2.2 SUSY Dine-Fischler-Srednicki- Zhitnitsky (DFSZ) cosmology

The SUSY DFSZ model[12] is highly motivated in that it provides a solution to the supersymmetric μ -problem [14, 15]: *i.e.* why is the superpotential higgsino mass $\mu \sim m_{\text{weak}}$ instead of $\sim m_{\text{GUT}}$? One may invoke a superpotential of the form

$$\hat{f} \ni \lambda_H \frac{\hat{P}^2}{M_P} \hat{H}_u \hat{H}_d \quad (12)$$

where the singlet superfield \hat{P} carries PQ charge +1 and each Higgs superfield carries PQ charge -1 . After PQ symmetry breaking, then $\langle \hat{P} \rangle \simeq v_{PQ} = f_a/\sqrt{2}$ and the superpotential becomes

$$\hat{f} \ni \mu \hat{H}_u \hat{H}_d \quad (13)$$

where now $\mu \simeq \lambda_H (v_{PQ}^2/M_P)$. With $v_{PQ} \sim 10^{10}$ GeV, then $\mu \sim 100$ GeV is generated, in accord with recent SUSY naturalness arguments [13]. As a byproduct, one also obtains a direct coupling of the axion superfield with the higgs multiplets:

$$\hat{f} \ni 2 \frac{\mu}{v_{PQ}} \hat{a} \hat{H}_u \hat{H}_d. \quad (14)$$

In the SUSY DFSZ model, the direct axion-higgs-higgs coupling leads to an axino production rate roughly independent of T_R [16, 17]:

$$Y_{\tilde{a}}^{TP} \simeq 10^{-5} \zeta \left(\frac{\mu}{\text{TeV}} \right)^2 \left(\frac{10^{11} \text{ GeV}}{f_a} \right)^2, \quad (15)$$

where $\zeta \sim 1$ depends on the spectra. Although a full calculation of thermal saxion production remains to be completed, one would expect $Y_s^{TP} \sim Y_{\tilde{a}}^{TP}$.

Also, since the axino and saxion directly couple to the Higgs multiplets, then the \tilde{a} and s decays tend to occur much sooner than expectations from the KSVZ case. Typically for the lower range of $f_a \sim 10^9 - 10^{12}$ GeV, one expects decay prior to neutralino freeze-out. In such cases, the standard thermal production rate for neutralino dark matter continues to hold, and cases of overproduction of neutralinos would be cosmologically excluded. Such a scenario favors models with a standard underabundance of neutralinos, *i.e.* models with either a wino-like or higgsino-like WIMP. Then the remaining abundance is filled by axions. In these cases, one expects the CDM to be axion-dominated.

An exception to this situation occurs for large $f_a \sim 10^{13} - 10^{16}$ GeV where thermal saxion and axino production is suppressed, but where CO-production of saxions is enhanced. In this case, depending on PQ parameters, saxion decay to SUSY particles will enhance the neutralino abundance, while decay to SM particles will dilute all relics and decay to axions will add to and possibly exceed limits of dark radiation.

3 Implications for dark matter detection

In this Section we draw broad implications of the mixed axion/neutralino dark matter picture for dark matter direct and indirect detection.

3.1 Detection of axions

In the case of axion detection, most of the current experimental effort has been focussed on searching for relic axions in the few μeV range where the standard CO-production rate saturates the measured abundance with misalignment angle $\theta_i \sim 1$. One implication of the SUSY scenario is that *all of the measured dark matter abundance need not be axions*. Thus, the local abundance may only be a fraction of what is expected from an axion-only scenario. The second implication is that the allowed range for f_a can really range from very small values $f_a \sim 10^9$ GeV where the axion may comprise only a fraction of the relic density all the way to $f_a \sim 10^{16}$ GeV where a combination of small misalignment angle plus entropy dilution still allows for axions to comprise the bulk of dark matter. No serious experiments have been proposed so far which can probe the higher range of f_a values. But even if axions are not found by ongoing searches, then the SUSY axion picture will not have suffered a significant blow to its allowed parameter space.

3.2 Direct WIMP detection

As with axions, the relic WIMP abundance will only be a fraction of its usually assumed value, where one supposes $\rho_{DM}^{local} \sim 0.3 \text{ GeV}/\text{cm}^3$. In the case of relic higgsino or wino-like WIMPs, one must adjust theoretical predictions to (conservatively) account for the ξ factor where $\xi \equiv \Omega_\chi h^2/0.12$. For instance [18], the spin-independent direct detection rate for higgsino-like WIMPs with $m_\chi \sim 100$ GeV is $\sigma^{SI}(\chi p) \sim 5 \times 10^{-9}$ pb. At first glance, these values seem excluded by recent Xe-100 searches [19] which require $\sigma^{SI}(\chi p) \lesssim 3 \times 10^{-9}$ pb. However, the local higgsino-like WIMP abundance is typically a factor 10-15 lower than the measured value $\Omega_{CDM} h^2 \simeq 0.12$, so the limits must be adjusted accordingly.

3.3 Indirect WIMP detection

Likewise, indirect WIMP detection limits must be adjusted for the possibility of WIMPs fulfilling only a portion of the local dark matter density. In the case of neutrino telescopes such as IceCube, the neutrino flux from WIMP annihilation in the core of the sun depends more on the ability of the sun to sweep up WIMPs: if equilibration between capture and annihilation is attained, then no ξ factor is needed. However, in the case of searches for WIMP-WIMP annihilation in space into γ -rays or anti-matter, then theoretical projections must be multiplied by a ξ^2 factor.

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